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A SPATIAL MINE-TO-PLAN COMPLIANCE FRAMEWORK FOR OPEN-PIT IRON ORE MINES

Theunis Johannes Otto

A thesis submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering.

Johannesburg, 2019

DECLARATION

I declare that this thesis is my own unaided work. It is being submitted to the Degree of Doctor of Philosophy to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

……

……. day of ……... 2019

ABSTRACT

A major assumption underpinning this PhD thesis work is that the actual financial returns realised by open-pit mines are not only dependent on agreed upon mine plans but, are also dependent on the level of spatial execution of the mine plans. To ensure the sustainable success of a large open-pit mine two major areas need to be effectively managed namely the quality and integrity of the mine planning process and the spatial execution of the “best” mine plan. Existing literature describes improvements in the mine planning process and the development of more robust and optimised mine plans. Despite improvements in the quality and integrity of mine plans, open-pit iron ore mines often struggle to achieve the targets set in these mine plans, especially from a spatial point of view.

Existing literature recognises the value of spatial compliance to a mine plan, but the processes and systems associated with spatial mine-to-plan compliance reconciliation are not adequately addressed. References to practical and integrated approaches for measuring and managing spatial compliance against the approved mine plans are very limited. Where compliance to the mine plan is mentioned, the research has mainly focussed on temporal compliance metrics and have not proposed a comprehensive framework focused on spatial mine-to-plan compliance for open-pit iron ore mines. This thesis took steps towards filling the identified knowledge gaps in existing literature.

The purpose of the thesis was to answer the research question on whether spatial compliance can be improved. This was done through the development, implementation and validation of a spatial mine-to-plan compliance framework for open-pit iron ore mines. The framework defines the components and relationships between the components that determine the level of spatial compliance against the tactical mine plan. This allows measurement and ensure effective management of spatial mine-to-plan execution at open-pit iron ore mines.

The research methodology followed during the execution of this research thesis was to review existing literature with the aim of establishing the extent and depth of current published information. The thesis then conceptualised and developed a spatial mine-to-plan compliance framework. The approach for the measurement and reconciliation of the spatial mine-to-plan compliance at open-pit iron ore mines was defined. This was followed by the development and application of spatial mine-to-plan compliance driver trees (CDTs). Methodologies were defined for determining, quantifying and interpreting the impact of spatial mine-to-plan compliance performance on the achievement of operational targets and mining flexibility. The research developed the concept of the next best action (NBA) leading to effective decision making. Technology solutions were evaluated and

applied to enhance the effectiveness of the framework. Finally, the research was validated through the implementation of the framework at the Kolomela open-pit iron ore mine in South Africa.

The Kolomela spatial mine-to-plan index improved from 74% in 2013 to 99% in 2017, confirming that the adoption of the framework led to a significant improvement in the spatial mine-to-plan compliance to the business plan (BP). Insights gained through the application of the CDT contributed to the improvements. Areas that were planned, but not mined at the time of the assessment were targeted through the NBA methodology and the root causes of adverse spatial mine-to-plan reconciliation performance were addressed. Remotely piloted aircraft systems (RPAS) and high precision global positioning systems (HP-GPS) technologies were implemented, thereby enhancing the effectiveness of the spatial mine-to-plan compliance reconciliation process at Kolomela. This was achieved by utilising the technologies to assist with the visualisation of the actual areas mined in relation to the areas planned for mining.

The results obtained during the validation illustrated the positive relationship between achieving targeted spatial mine-to-plan reconciliation results and the achievement of budgeted total exposed ore (EO) levels. This confirmed the critical role that spatial mine-to-plan compliance performance plays to ensure the sustainability of the mining operation in the longer-term through maintaining the planned level of mining flexibility. This is achieved by generating the budgeted EO levels which are a proxy for mining flexibility.

This thesis contributes to knowledge as a reference based on empirical research validated at Kolomela. The research represents applied knowledge with a significant value contribution that has potential to fundamentally improve open-pit iron ore mining reconciliation practices. The thesis contributes to knowledge in three key areas. Firstly, it developed an integrated spatial mine-to-plan compliance framework for application at open-pit iron ore mines. The framework defined various metrics including a spatial mine-to-plan index. Secondly, it developed and applied spatial mine-to-plan CDTs that provide the ability to drill-down into selected spatial areas within the larger iron ore mine and enable understanding of the root causes of deviations. Lastly, it employed technology solutions (RPAS and HP-GPS) in a novel way to enhance the effectiveness of the spatial mine-to-plan compliance framework.

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PUBLICATION ARISING OUT OF THESIS

The following is a peer-reviewed publication that has already emanated from this research study:

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LIST OF ACRONYMS

3D	Three Dimensional
AGL	Above Ground Level
AR	Augmented Reality
BCM	Bank Cubic Metres
BP	Business Plan
CAA	Civil Aviation Authority
CDT	Compliance Driver Tree
DOH	Direct Operating Hours
DTM	Digital Terrain Model
DSO	Direct Shipping Ore
EBIT	Earnings Before Interest and Tax
EO	Exposed Ore
Fe	Iron
FMS	Fleet Management Systems
FP	Forecast Plan
FTA	Fault Tree Analysis
GMP	General Mining Package
GPS	Global Positioning System
HME	Heavy Mining Equipment
HP-GPS	High Precision Global Positioning System
IMU	Inertial Measuring Unit
KB	Klipbankfontein
KPA	Key Performance Area
KPI	Key Performance Indicator

KS	Kapstevel
LiDAR	Laser Imaging, Detection and Ranging
LF	Leeuwfontein
LOM	Life of Mine
MIS	Mine Information Systems
MTP	Medium Term Plan
MVCR	Mining Value Chain Reconciliation
NBA	Next Best Action
NPV	Net Present Value
PB	Pushback
PGM	Platinum Group Metals
PT	Priority Tasks
RCA	Root Cause Analysis
RDP	Resource Development Plan
ROC	RPAS Operators Certificate
ROM	Run-of-Mine
RPAS	Remotely Piloted Aircraft System
STMP	Short-Term Mine Plan
UAV	Unmanned Aerial Vehicle
VDT	Value Driver Tree
YTD	Year-to-Date

1. INTRODUCTION

1.1 Overview of Chapter 1

The purpose of this chapter is to introduce the thesis by covering the background to the thesis, discussing the purpose of the thesis, identifying the knowledge gaps and lastly describing the structure of the thesis. Section 1.2 anchors the argument that the value realised by mining operations is not only dependent on the quality and integrity of mine plans; it also depends greatly on the level of execution against the mine plans. To sustainably operate a large open-pit mine two major areas need to be managed. These are firstly, the quality and integrity of the mine planning process and secondly, the execution of the mine plan. Justification is provided for focussing the thesis on open-pit iron ore mining in South Africa although application can transcend the South African context. It is illustrated that existing literature describes the importance of execution against the mine plan in general terms and that references to spatial or area-based mine-to-plan compliance are very limited. Section 1.3 describes the purpose of the thesis. The identified knowledge gaps are discussed in Section 1.4 where the relevance of the research is explained, and the research question is framed. Section 1.5 provides a summary of the structure and layout of the thesis.

1.2 Background

The expected net present value (NPV) of a mining operation is calculated using a mine plan as a basis. Mine planning can be described as follows: "*Production planning and scheduling, within the mine design, taking into account such aspects as geological structures and mineralisation and associated infrastructure and other constraints*" (SAMREC Code, 2016, p. 3). The South African code for the reporting of Exploration Results, Mineral Resources and Mineral Reserves (SAMREC Code) sets out the minimum standards, recommendations and guidelines for the public reporting of Exploration Results, Mineral Resources and Mineral Reserves in South Africa. Mine planning broadly involves identifying a strategy to exploit the Mineral Resource in a way that maximises value at an acceptable risk level throughout the life of mine (Tholana and Neingo, 2016). The SAMREC Code defines a Mineral Resource as follows: "*A 'Mineral Resource' is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade, continuity and other geological characteristics of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge, including sampling.*" (SAMREC Code, 2016, p. 18).

Mineral Resources are categorised as Inferred, Indicated or Measured based on increasing geological confidence in their estimation. A Mineral Reserve is defined as "*the economically mineable part of a Measured and/or Indicated Mineral Resource*" (SAMREC Code, 2016, p. 25). Within the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (the JORC Code) the term Ore Reserves is used synonymously with Mineral Reserves.

This thesis covers topics such as mine planning, reconciliation in the mining industry and the spatial execution of mine plans. The thesis also refers to aspects and processes associated with the conversion of Mineral Resources to Mineral Reserves. The SAMREC Code provides industry recognised definitions for various technical terms associated with the public reporting process. The scope for the validation of the spatial mine-to-plan compliance framework ('framework'), developed in this thesis, is based on open-pit iron ore mines in South Africa. Therefore, the definitions provided in the SAMREC Code are applicable throughout this thesis when reference is made to Mineral Resources and Mineral Reserves.

Various studies have been devoted to improvements in the mine planning process with the aim of developing optimal and more robust mine plans in shorter and shorter timeframes. Despite the significant improvements in the mine planning process and the resultant mine plans, open-pit mining remains a high-risk business (Sabour and Dimitrakopoulos, 2008, Badri *et al*, 2012, Zwieg *et al*, 2017). This is evident when considering the variability between the expected and actual outcomes achieved by mining projects and operating mines (McCarthy, 2014). The actual value realised by a mining operation (as opposed to the expected value), is not only dependent on the quality and integrity of the mine plans. It also depends greatly on the level of execution against the mine plan. To sustainably operate a large open-pit mine two major areas need to be managed; namely the quality and integrity of the mine planning process and the execution of the mine plan.

The level of execution or compliance against a mine plan can be measured in two ways. These are time-based (temporal) measurements, and area-based (spatial) measurements. The measurement of performance against temporal metrics is common practice in the open-pit mining industry and these time-based targets typically focus on the shorter term. The measurement of performance against spatial metrics is equally important in an open-pit mine. These area-based metrics provide insight into the longer-term aspects of execution against the mine plan. The development and implementation of a spatial mine-to-plan compliance process is important to ensure (Esterhuysen, 2013):

- long-term sustainable supply of ore;

- that key issues negatively impacting on mine production are identified (e.g. ramp establishment, dewatering, drill and blast quality, pre-split and buffer blocks); and
- the achievement of planned mining flexibility.

The following paragraphs provide the justification for focusing this thesis on iron ore mining and specifically the South African iron ore mining industry. Iron ore is the primary raw material from which metallic iron (Fe) is extracted to make steel. There has been a significant increase in crude steel production over the last decade fuelled mainly by infrastructure development in China. This resulted in major expansions in world iron ore production. Worldwide iron ore production increased from 1 043Mt in 2001 to 2 930Mt in 2012 – a 180% increase. Considering the seaborne trade of iron ore, 1 154Mt of iron ore were exported during 2012. The exports in that year were mainly from Australia (492Mt) and Brazil (327Mt) with South Africa being the third largest iron ore exporting country in 2012 at 54Mt (Holmes and Lu, 2015). The growth in iron ore exports continued since 2012 (although at a slower rate) resulting in the global iron-ore market becoming the largest commodity market after oil and gas and was valued at about US$225bn in 2016 (Zhuwakinyu, 2017). South Africa produced 66Mt of iron ore in 2016 and ranked as the sixth largest iron ore producing country after Australia (825Mt), Brazil (391Mt), China (353Mt), India (160Mt) and Russia (100Mt) (Zhuwakinyu, 2017). South Africa is, thus, a significant player in the global iron ore mining industry.

The extraction of natural resources plays an important role in the South African economy. The mining industry provides employment to thousands of South Africans. The export of commodities contributes significantly to foreign exchange earnings which in turn make it possible to import goods and services that are necessary for the country's development (Chamber of Mines of South Africa, 2017). The South African mining industry has historically been centred around the mining of gold and platinum group metals (PGM) in narrow tabular underground mining operations, and coal mining employing a combination of underground and surface mining (strip - and terrace mining) methods. In the last decade iron ore (mined using open-pit mining methods) has emerged as an important commodity in the South African mining industry. According to the Chamber of Mines of South Africa (2017), iron ore to the value of R39.4bn was exported from South Africa in 2016 and this:

- represented 25% of the value of base metal exports;
- was 12% of the total value of commodities exported; and
- placed iron ore as the fourth biggest earner of foreign exchange behind PGMs (R85.3bn), gold (R60.6bn) and coal (R50.5bn).

The growth in the international iron ore industry was also evident in South Africa. The value of iron ore export sales increased from R3.4bn in 2004 to R39.4 in 2016 (Chamber

of Mines of South Africa, 2017). This equates to an almost twelve-fold increase in the value exported over the 12-year period.

The iron ore mining industry in South Africa is very concentrated and dominated by Kumba Iron Ore (a subsidiary of Anglo American) and Assmang (a 50:50 joint venture between African Rainbow Minerals and Assore). Kumba Iron Ore operates two open-pit mines namely, Sishen and Kolomela both located in the Northern Cape province of South Africa. Assmang operates two open-pit mines namely, Khumani and Beeshoek also located in the Northern Cape province (Zhuwakinyu, 2017). These four mines represent approximately 90% of South Africa's iron ore production and are located within a 100km radius of each other.

The iron ore mining industry represents the bulk of open-pit mining activities in South Africa. The annual open-pit mining activities for 2016 at the Kumba Iron Ore and Assmang mines are summarised in Table 1.1.

Table 1.1. Summary of major open-pit iron ore mining activities in South Africa for the year 2016 (Kumba Iron Ore – 2016 Full Year results, 2017; African Rainbow Minerals - 2016 Mineral Resource and Reserve statement, 2017).

	Product (Mt)	Run of Mine ore (Mt)	Waste (Mt)	Total tonnes mined (Mt)
Sishen	28.4	41.8[1]	138.0	179.8
Kolomela	12.7	13.5[2]	50.0	63.5
Total Kumba	*41.5*	*55.3*	*188.0*	*243.3*
Khumani	13.6	18.7[3]	45.2[5]	63.9
Beeshoek	3.1	4.4[4]	16.7[6]	21.1
Total: Assmang	*16.7*	*23.1*	*61.9*	*85.0*
Total	***58.2***	***78.4***	***249.9***	***328.3***

[1]Sishen run of mine tonnes calculated using published waste and stripping ratio.
[2]Kolomela run of mine tonnes calculated using published waste and stripping ratio.
[3]Khumani run of mine tonnes calculated using published product and plant yield.
[4]Beeshoek run of mine tonnes calculated using published product and plant yield.
[5]Khumani waste calculated assuming the average published stripping ratio of 1:2.41.
[6]Beeshoek waste calculated assuming the average published stripping ratio of 1:3.77.

The level of compliance against a mine plan developed at one of the South African iron ore mines is therefore of critical importance, not only to the relevant mining company operating the mine, but also to the rest of the South African mining industry and the international iron ore industry. At Kumba Iron Ore, where 75% of the iron ore mining activities in South Africa took place in 2016, managing the temporal and spatial compliance against the agreed or approved mine plan is a critical success factor to ensure

consistent and predictable delivery against operational and financial targets in the short and longer terms.

1.3 Purpose of the thesis

As aforementioned the economic objective of mining companies is to maximise the NPV throughout the mine life in a sustainable way. The expected NPV is typically calculated using a mine plan as a basis, while the actual value realised by the mining company depends greatly on the level of execution against that mine plan. It is essential to develop a mine plan with the appropriate levels of quality and integrity, but the effective execution of the agreed upon mine plan is of equal importance to ensure the successful operation of a mine.

When managing the execution against the mine plan, one major Key Performance Indicator (KPI) that is often overlooked in the open-pit mining industry, is the level of spatial compliance to the mine plan; i.e. how well the mine plan was executed spatially. The level of compliance to a mine plan varies significantly depending on factors such as management focus, what level of plan is being tracked, the KPIs used to define the mine-to-plan compliance and the frequency of measurement. Often, the mine-to-plan compliance is tracked using only temporal measures without incorporating the spatial aspects, which consider where the actual open-pit mining activities took place *versus* where the activities were planned to take place.

Existing literature describing the importance of execution against the mine plan in general terms and references to spatial compliance are very limited. Angelov and Naidoo (2010) presented a method of monitoring the effectiveness of the mine planning process and the execution of mine plans at underground coal mines. Their method determines the degree of deviation by comparing actual mined areas to initially planned mining areas. When spatial mine-to-plan compliance was addressed, there was no framework in place for spatial mine-to-plan compliance reconciliation that interpreted the results and provided insights into the root causes as well as the impact on current and future mining operations. It can be said that existing literature does not provide a comprehensive framework for the management of spatial mine-to-plan compliance at open-pit iron ore mines. Morley and Arvidson (2017, p. 281) also underscored the importance of establishing such a compliance framework by stating that "*Spatial reconciliation is routinely one of the worst performing metrics on any mine*".

This thesis proposes to take steps towards filling this knowledge gap in existing literature by developing a framework that can be used by the open-pit iron ore mining industry to

measure and manage spatial mine-to-plan compliance. The framework is then validated through its application at an operational open-pit iron ore mine in the Northern Cape province of South Africa, owned and operated by Kumba Iron Ore.

The implementation of the proposed framework should ensure that the optimal mine plan is executed thereby realising the planned value (expressed as NPV or unit cost or production targets) whilst ensuring the long-term sustainability of the mine. In order to achieve this objective, spatial mine-to-plan compliance could potentially be measured and managed through the proposed introduction of:

- standard reports;
- management processes;
- value driver trees; and
- the application of appropriate technologies.

It is foreseen that this will be done alongside temporal KPIs and against the tactical mine planning horizons.

The requirement for such a framework is because spatial compliance to the tactical mine plan is critical to ensure that a balance is achieved between the shorter-term operational targets, and the optimal extraction of the Mineral Reserve in the longer term. The implementation of the proposed framework should enable mine management to measure and manage spatial compliance against the agreed upon tactical mine plan. It is envisaged that the framework will contribute to the understanding of the root causes of adverse outcomes and impacts of deviations (both positive and negative) on operational performance as well as on mining flexibility. The framework should further enable mine planning engineers to proactively re-direct mining (if required) using the operational mine planning horizon and to improve the “execute-ability” of future mine plans.

The incorporation of a value driver tree (VDT) concept is expected to lead to an improved understanding of the root causes of deviations from the mine plan. The intention is to model the impact of spatial mine-to-plan performance on mining flexibility by using run-of-mine (ROM) stockpile and exposed ore (EO) levels. It is foreseen that the operational mine planning horizon could be used to re-direct mining to the correct spatial areas, as required. The deployment of appropriate technologies could enhance the measurement and management of compliance.

The spatial mine-to-plan compliance framework developed in this thesis can potentially be applied at open-pit iron ore mines. The framework should define the components as well as the relationships between those components, that determine the level of spatial compliance against the tactical mine plan. This could allow measurement and ensure effective management of the spatial mine-to-plan execution.

There is an opportunity to present a framework for the measurement and reconciliation of spatial mine-to-plan compliance at open-pit iron ore mines. It is envisaged that the proposed framework could facilitate an effective understanding of the spatial mine-to-plan compliance reconciliation process. This could enable open-pit iron ore mines to measure the spatial mine-to-plan compliance and implement corrective actions with the aim of improving spatial execution of the tactical mine plan. The end goal of the development and implementation of the framework is to ensure the achievement of shorter-term operational targets whilst also ensuring the long-term sustainability of the mine.

1.4 Identified knowledge gaps

1.4.1 Expected value versus realised value

The development and improvement of the mine planning process has been progressive, especially in open-pit mining. Various stochastic techniques have been developed to improve the robustness of mine plans. The progression of stochastic mine planning shows that the stochastic approaches can lead to substantially lower potential deviation from production targets, that is, reduced risk (Dimitrakopoulos, 2011). The resultant optimal mine plans are plans with high levels of integrity due to the improved understanding of the variability in the major input parameters as well as the ability to simulate the variability during the mine planning process. Gurgenli (2011), Dimitrakopoulos (2011), and Tholana and Neingo (2016) presented research in support of further improving the quality of the mine planning process and the resultant mine plans. These improvements contribute to improvements in the expected NPV of mining projects as well as an increased ability of established open-pit mining operations to forecast operational performance.

Open-pit iron ore mining has come to a stage where robust mine plans are generated by mining engineers to cover both long-term and short-term mine planning horizons effectively. Most open-pit iron ore mines derive their annual production targets as well as the associated financial performance targets from the tactical (medium-term or budget) mine plan. This thesis assumes the development of a robust tactical mine plan to guide the spatial execution of the mine (in different phases and on different benches) as well as to set operational targets. The initial targets, against which spatial mine-to-plan compliance was measured, were therefore known. The spatial mine-to-plan compliance framework developed in this thesis incorporates the outputs from the tactical mine planning horizon of open-pit iron ore mines.

Despite having robust mine plans, open-pit iron ore mines often struggle to achieve the targets set in those plans, especially from a spatial point of view. This could result in the

actual value realised by the mining company being lower that the expected value derived from the optimal mine plan. There has been commentary on the importance of executing the optimal mine plan by Hall and Hall (2006), Angelov and Naidoo (2010), Morley and Arvidson (2017). Existing literature indicates that where mine-to-plan compliance was measured, most approaches typically focussed on the temporal aspects of the measurement and did not address the complexity of the spatial nature of open-pit iron ore mining operations. These approaches did not put forward an integrated methodology for the measurement and management of spatial mine-to-plan compliance at open-pit iron ore mines. The approaches found in existing literature also did not assess the root causes of adverse outcomes nor apply technology to enhance the effectiveness of the spatial mine-to-plan compliance reconciliation process.

These knowledge gaps suggest that there is space for improvement in spatial mine-to-plan compliance reconciliation at open-pit iron ore mines. Therefore, it was necessary to investigate the development and implementation of a comprehensive framework which could potentially measure and manage spatial mine-to-plan compliance at open-pit iron ore mines. The framework envisaged in this thesis aims to address the knowledge gaps by defining the components and the relationships that determine spatial mine-to-plan compliance against the tactical mine plan. This will allow measurement and ensuring effective management of spatial mine-to-plan compliance at open-pit iron ore mines. It is expected that such a framework will assist open-pit iron ore mines to measure and manage spatial mine-to-plan compliance.

1.4.2 Consistent, predictable and sustainable delivery

The success of open-pit iron ore mines is often determined by the mine's ability to deliver actual value in line with the expected value that was "promised" to investors and other stakeholders based on mine plans. Low levels of spatial compliance to the tactical mine plan is one of the major factors that impact on the ability of open-pit iron ore mines to consistently, predictably and sustainably deliver against budget targets and stakeholder expectations. The low levels of spatial mine-to-plan compliance are often caused by a lack of a comprehensive and integrated spatial mine-to-plan compliance reconciliation approach.

Research related to the execution of mine plans have mainly focussed on temporal compliance metrics and have not proposed a comprehensive framework to include spatial mine-to-plan compliance. This thesis aims to address the knowledge gaps identified in existing literature by putting forward a comprehensive framework for measuring and

managing the spatial mine-to-plan compliance at open-pit iron ore mines. The framework that is envisaged in this thesis focusses on spatial mine-to-plan compliance against the tactical mine plan as that contributes to the longer-term sustainability of an open-pit iron ore mine while traditional temporal KPIs are shorter-term focussed. The framework should provide a platform from which mine management can visualise spatial mine-to-plan performance. The thesis sought to apply VDTs and technology that could further enhance the measurement approach, reporting aspects and improve the pro-active nature of the spatial mine-to-plan reconciliation process.

It could be possible that the implementation of the proposed framework will lead to an integrated measurement approach, improved understanding of root causes of adverse performance and of the impact of deviations, improved spatial mine-to-plan compliance as well as improvements in the quality of future mine plans. This potential improvement in spatial mine-to-plan compliance could improve the ability of open-pit iron ore mines to achieve planned operational targets (in both the short term and long term). This can potentially improve the actual value delivery. This should in turn improve the confidence of investors and other stakeholders in the ability of mines to meet set objectives consistently, predictably and sustainably.

1.4.3 Research relevance and research question

Although significant strides have been made in open-pit mine planning, methodologies for measuring and managing spatial compliance against the agreed mine plans have not been well documented. The problem of managing spatial mine-to-plan compliance in an open-pit iron ore mine has not been studied thoroughly. It is not clear whether a new framework could be developed and applied in the open-pit iron ore mining industry and how it would improve the performance (in the short term and long term) and mining flexibility of open-pit iron ore mines. Furthermore, the application of the VDT concept and technology applications to potentially enhance the effectiveness of such a framework has not been illustrated in previous studies.

In view of the above, an opportunity was identified to develop a framework to address the spatial reconciliation of actual areas mined *versus* areas planned for mining. The proposed framework sought to incorporate appropriate technology, enable understanding of the root causes of deviations and model the impact of spatial mine-to-plan compliance on operational performance as well as on the mining flexibility of the open-pit mining operation.

This thesis therefore, sought to answer the question: *"Can the development and implementation of a spatial mine-to-plan compliance framework, complemented by the application of compliance driver trees and appropriate technology, improve the compliance to the mine plan of an open-pit iron ore mining operation?"*

This thesis further investigated whether evaluating the mine-to-plan compliance of an open-pit mine considering only temporal KPIs provides a false sense of achievement to mine management. Performance against these KPIs could be positive, while mining activities are not occurring in the correct spatial areas in the open pit to the detriment of longer-term KPIs such as timely exposure of future ore. Spatial mine-to-plan compliance is a unique KPI as it provides a bridge between the short-term KPIs that mining companies track on a weekly, monthly, quarterly, and annual basis and the longer-term value expected by (and often promised to) stakeholders.

1.5 Thesis structure

The chapters of this PhD thesis are broadly aligned to the proposed components of the envisaged framework and consist of the following main contents:

- Chapter 1 is an **introduction to the thesis** providing background on why spatial mine-to-plan compliance is important for the open-pit iron ore mining industry, defining the purpose and aim of the thesis, discussing the knowledge gaps that were identified in current knowledge, and framing the research question. The chapter concludes with a summary of the structure and layout of the thesis.

- Chapter 2 contains the **literature review** covering the following themes:
  1. Open-pit mine planning and the mining value chain;
  2. Mining performance and the KPIs that are typically used to measure the performance of an open-pit mine; these include short-term operational KPIs as well as longer term KPIs providing insight into the mining flexibility and sustainability of an open-pit mine;
  3. Reconciliation in the open-pit mining industry and specifically mine-to-plan compliance reconciliation; including a brief background on the alternative approaches towards spatial mine-to-plan compliance in the mining industry in general and specifically in open-pit mines;
  4. The development and application of VDTs and their extension to compliance driver trees (CDTs) to conduct root cause analysis; and
  5. The application of appropriate technologies to enhance spatial reconciliation in open-pit mines.

The literature review provides justification for the need of a systematic and integrated spatial mine-to-plan compliance framework.

- Chapter 3 explains the **research methodology** employed in this thesis.
- Chapter 4 provides a **description of the framework** that was developed to allow measurement and ensure effective management of spatial mine-to-plan execution at open-pit iron ore mines.
- Chapter 5 describes the **South African open-pit iron ore mine** on which the framework was tested and validated.
- Chapter 6 presents the **results obtained from the implementation of the framework**. It includes the validation of the proposed framework. This was done by evaluating the impact of the introduction of the framework on spatial mine-to-plan compliance performance over a three-year period.
- Chapter 7 presents the outcomes of the study, scrutinises the performance of the proposed framework and provides **conclusions** as well as **recommendations** for future research. The **contribution to knowledge** of the thesis is articulated in this chapter.

2. LITERATURE REVIEW

2.1 Overview of Chapter 2

The aim of this chapter is to provide a comprehensive overview of existing literature relevant to the themes associated with the proposed development of a spatial mine-to-plan compliance framework for open-pit iron ore mines. During the literature review process various knowledge gaps were identified.

Section 2.2 provides an overview of the mining value chain, discusses the mine planning horizons and highlights the importance of the tactical mine planning horizon to spatial execution of mine plans. The spatial and dynamic nature of open-pit mine planning are explored. The definition and application of KPIs to improve the performance of open-pit iron ore mines are discussed in Section 2.3. This is followed by an in-depth analysis of one group of KPIs concerned with reconciling planned (estimated) activities with actual activities (measured) in Section 2.4. Section 2.5 describes the conceptual approaches to spatial mine-to-plan compliance reconciliation that were found in existing literature. The spatial mine-to-plan compliance methodologies developed by Angelov and Naidoo (2010) for application at underground coal mines as well as the generic spatial compliance reconciliation approach put forward by Morley and Arvidson (2017) are evaluated in more detail.

Existing literature on the application of VDTs to conduct root cause analysis (RCA) at mining operations are discussed in Section 2.6. Technology applications relevant to the theme of this thesis are covered in Section 2.7.

2.2 Open-pit mine planning

2.2.1 Mining value chain

Value chains are models used to describe the steps for processes associated with adding value to a product or service. Value chains have a value adding or value creating dimension. Each process step adds value to the input it receives before providing an output to the next process step. Value chains are traditionally presented as a set of sequential process steps. There is also an alternative systematic view of value chains which could improve the modelling of complex relationships between process steps. The mine planning process is a well-recognised component in the value chain of an open-pit mine. Figure 2.1 reflects the relative position of mine planning within a typical sequential value chain for the open-pit mining industry.

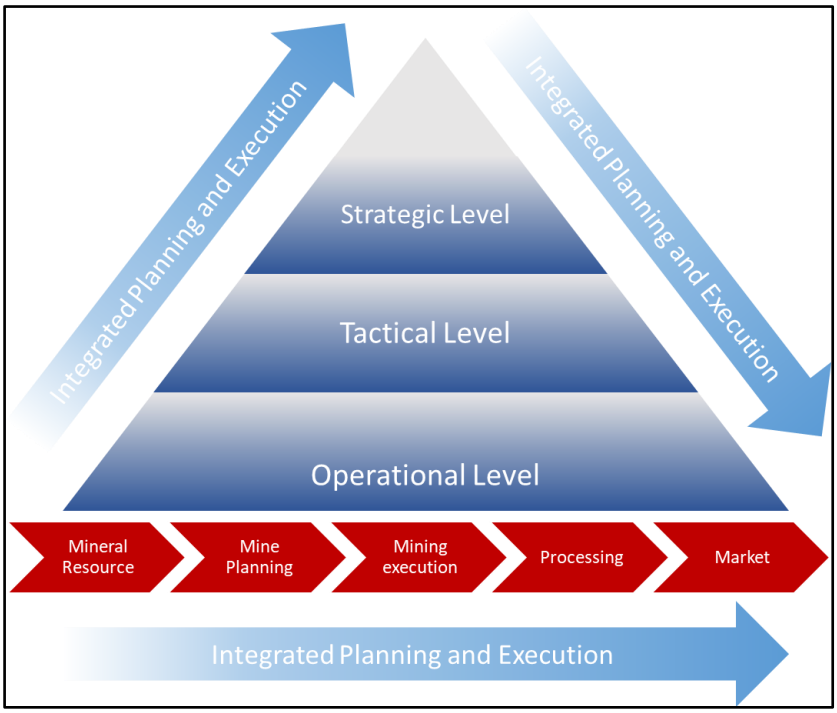


Figure 2.1.Mining value chain from resource to market (Otto and Musingwini, 2019)

Mine planning adds value to the Mineral Resource and precedes mining execution. The mine plan represents a specific value-add point associated with the integration of the Mineral Resource and mining execution. Mine planning is defined as the process of mining engineering that transforms the Mineral Resource into the best productive business (Morales and Reyes, 2016). It is therefore an important value-add step in the mining value chain.

2.2.2 Mine planning horizons

The mine planning process begins with a with a sequence of feasibility studies with gradually increasing detail and level of accuracy concerning the mine plan and continues throughout the life of the mine (LOM) through several long-term and short-term planning processes (McCarthy, 2015). According to Steffen (1997), most open-pit mining operations follow a systematic and disciplined mine planning process involving three distinct levels of mine planning in developing the Mineral Reserves. These levels are:

- LOM plan;
- Long-term plan (LTP), which follows from the LOM; and
- Short-term plan (STP), which in turn follows from the LTP.

Each of these stages of mine planning represents different levels of risk and have different objectives. Tholana and Neingo (2016) also broadly referred to these planning horizons

as the strategic, tactical, and operational mine planning levels. This is also reflected in Figure 2.1. The main objectives of the three planning levels or planning horizons have been summarised as follows (Tholana and Neingo, 2016; Hall and Hall, 2015):

- Strategic mine planning focuses on continual revision of long-term plans as economic and operating conditions change, to maintain an up-to-date plan that defines the future of the operation. The aim is to maximise the value from the exploitation of the known and anticipated Mineral Resource;
- Tactical mine planning focuses on three major areas namely, the availability of mining areas to maintain required production profiles, efficient utilisation of installed infrastructure capacities and optimisation of the production potential of the mineral asset over its life. This horizon is also referred to as business planning and typical results include the Business Plan (BP) and the annual budget; and
- Operational mine planning involves the development of detail plans, typically on weekly intervals, which guide the mining operation to achieve the business targets detailed in the annual budget.

By design, these planning horizons are nested in each other as shown in Figure 2.1. The tactical and operational mine plans and the mine operations should be working within the framework of an optimised long-term plan that best delivers on the company's goals (Hall, 2009). The tactical plans should be seeking to return to the optimum strategic plan if any deviations occur. There is a clear interdependence and tension between the mine planning horizons and managing the horizons at the same time is strategically essential.

The extraction of minerals is an expensive endeavour, with budgets often amounting to billions of Rands. The budget, which is an output of the tactical planning horizon, is the single most important document that regulates the production of a mine. All the strategies, tactics, and plans are ultimately based on attaining the targets set in the budget. Investors and executive managers of resource companies judge performance and make decisions primarily based on the budgets of the mines (Hager *et al*, 2015).

In the tactical mine planning horizon, the tactics required to achieve a strategic objective are developed and implemented. If the tactical component is missing then no matter how well thought out the strategic objectives are, they cannot be realised. Tactical mine planning is a service to the production manager, the function of which is focused on the allocation of resources to meet the long-term plan (Kear, 2006).

2.2.3 Spatial nature of mine plans – the additional dimension

One important aspect, that differentiates mine planning from planning in other industries, is the spatial nature of mine planning. The spatial dimension of mine planning can be described as the combination of a location and its associated mining activities. The mine plan does not simply indicate the amount of the Mineral Reserve to be extracted (i.e. what) in each period, but also importantly which part of the Mineral Reserve (and associated waste material) is to be extracted (i.e. where) in that period. The mine plan, thus, plans and schedules mining operations to optimise the spatial dimensions and footprints of mining activities across three-dimensional (3D) space and time. The production plan or budget is an output of the tactical planning horizon that sets the production goals over the relevant planning period and is supported by a production schedule that indicates which part of the Mineral Reserve must be extracted in each period (Morales and Reyes, 2016). Hager *et al* (2015) also emphasised the spatial aspect of the tactical mine plan of an open-pit mine; the waste and ROM tonnages from the different mining benches are determined and allocated to different destinations, honouring the spatial constraints.

2.2.4 Dynamic nature of mine plans

Mineral Resources are a finite, non-renewable resource. Mine planning aims to produce the optimum exploitation strategy in the context of the mining value chain. Smith *et al* (2009) highlighted another important characteristic of mine planning; the optimum exploitation strategy needs to be dynamic due to the continual changes in commodity prices, rate of extraction and LOM over time. Therefore, the mine planning process typically generates various strategic and tactical planning scenarios that contribute to defining the mining strategy and tactics at a specific point in time. The tactical planning in the open-pit mining industry is typically repeated and reviewed on an annual basis. Despite the need for dynamic mine planning, it is important to note that ultimately, an optimal tactical plan is agreed on for execution.

2.2.5 Improvements in the mine planning process

Literature on mine planning has generally focussed on ways of improving mine plans by incorporating the analysis and evaluation of risk into the mine planning process, thereby improving the expected NPV and/or risk adjusted NPV of the mine. The literature has mainly dealt with the strategic level of mine planning.

Various studies have been devoted to improvements in the mine planning process with the aim of developing optimal mine plans. These include advancements in mine planning software and related systems employed (Gurgenli, 2011) and the application of orebody flexibility to ensure maximum mineral asset utilisation (Tholana and Neingo, 2016) in underground mining applications, as well as the progression of stochastic mine planning techniques. Stochastic approaches can add higher value in production schedules in the order of 25% and leading to improvements of ~30% in the NPV when compared to the conventional approaches to mine planning (Dimitrakopoulos, 2011).

The optimality of mine plans has often been analysed and compared based on their performance against financial parameters such as NPV; i.e. the mine plan with the higher NPV is the more optimal mine plan. Musingwini *et al* (2007) described the importance of developing mine plans that are robust through the introduction of the concept of technical operating flexibility. The ability of mine plans to adjust, adapt or respond to changes is operational flexibility. Flexibility introduces an element of strength that is referred to as robustness. A flexible mine plan is therefore a robust mine plan because it can adapt to changes in the operating environment (Musingwini *et al*, 2007). In an underground tabular mine application, Musingwini *et al* (2007) used ore availability as a proxy for technical operating flexibility. Low ore availability implied reduced technical operating flexibility and high ore availability implied increased technical operating flexibility. This relationship allowed the measurement of technical operating flexibility (Musingwini *et al*, 2007). In the open-pit mining environment the equivalent to ore availability is EO.

EO in a typical open-pit mine can be defined as the amount of ore that can be accessed with little or no further waste stripping required. A portion of the Mineral Reserve is said to be exposed if it is readily available for extraction at the start of the period under review. The concept of exposed Mineral Reserve was introduced by Saavedra-Rosas *et al* (2016) to improve tactical mine plans and is defined at a given time as the set of ore blocks for which all its preceding blocks have already been extracted, but not the ore block itself. Similarly, to the underground tabular mining application described by Musingwini *et al* (2007), EO is a proxy for technical operating flexibility in an open-pit mine.

A more flexible operation potentially has little variation between actual and planned production efficiencies and is therefore likely to experience shorter production shortfall periods (Musingwini *et al*, 2007) and substantially lower potential deviation from production targets, that is, reduced risk (Dimitrakopoulos, 2011). This translates to the following: a more robust (and optimal) mine plan equals a more flexible mining operation equals a potentially higher level of execution against the mine plan.

2.2.6 It is not only about mine plans

In a McKinsey & Company discussion document the issue of deviating from plan at mine level, leading to low compliance to plan, was described as one of the major challenges facing the mining industry (MacNeil, 2016). The potential solutions proposed to address this challenge range from improving the resolution of geological modelling to utilising stochastic mine planning. It was claimed that the application of advanced mine planning techniques can create significant value with NPV increases of 10-30% being quoted (MacNeil, 2016). However, no guidance was provided on how mining companies can ensure that these *expected* increases in NPV are translated to *actual* value. It was not clear how further optimisation of the mine plan on its own will translate to improved mine-to-plan compliance.

Existing literature provides techniques to improve the mine planning process thereby improving the expected value of mine plans as well as the robustness of the mine plans. When faced with the challenge of improving the level of execution against the mine plan, existing literature defaults to a singular focus on improving the mine plans. This approach implies that the only way to improve compliance to the mine plan is by improving the mine plan itself. What is lacking in the literature is the recognition that an effective approach to the execution of the mine plan could equally contribute to improved mine-to-plan compliance. Ultimately, the primary objective of a good mine planning process is to direct the implementation of the optimal mine plan (Hall and Hall, 2015).

2.3 Mining performance and KPIs

A review of actual mining performance and ways of measuring and managing that performance are now considered. Despite the significant improvements in the mine planning process and the resultant mine plans, open-pit mining remains a high-risk business (Sabour and Dimitrakopoulos, 2008, Badri *et al*, 2012, Zwieg *et al*, 2017). There are numerous sources of risk and these can be grouped as:

- External uncertainties such as volatile commodity prices and exchange rate; and
- Internal uncertainties such as geology, chemical quality predictions, operational uncertainties and input cost.

Open-pit mines are dynamic environments that are characterised by a continuous displacement of the working faces of mining operations in time and space (Halatchev and Dimitrakopoulos, 2002). The existence of risk (and opportunity) in open-pit mining is evident when considering the variability between the expected and actual outcomes achieved by mining projects and operating mines. This was noted from benchmark studies

conducted considering mainly Australian mining operations. A survey of 48 Australian mining projects showed that the actual tonnages extracted for 46% of these mines were more than 20% higher or lower than those expected (Sabour and Dimitrakopoulos, 2008). Benchmark studies of 21 open-pit mines by AMC Consultants evaluating the monthly variability between the mine budget and actual production over a 12-month period, showed an average variability of 29% for ore mined (McCarthy, 2015). Ramazan and Dimitrakopoulos (2004) indicated that 60% of the mines surveyed had an average rate of production, which was less than 70% of the designed capacity in the early years of mining. The failure to have actual outcomes close to or the same as planned targets is widely acknowledged in the mining industry as a top risk (Musingwini, 2016).

The actual performance of the mine production system often is somewhat different to that in the optimised plan (Sebutsoe and Musingwini, 2017). The sustainability of the mining industry is increasingly becoming dependent on its ability to manage the performance of its operations well (Dougall and Mmola, 2015). Musingwini (2016) also highlighted the importance of execution against the plan; operations are measured against planned targets to evaluate operational performance.

To achieve the goal of creating longer-term value, mining companies (with operational mines) typically develop short-term measures of value against which operational and financial performance are tracked. A valuable tool for monitoring and managing performance is the use of key performance areas (KPAs). KPAs are essentially areas of interest due to their perceived importance in the success of a mining operation. KPIs are the identified factors that can be measured to determine how the operation is performing in those areas of interest, the KPAs. There are essentially three reasons to measure performance namely to learn and improve, to report externally and demonstrate compliance, and to control and monitor employees (Dougall and Mmola, 2015).

The typical operational KPAs identified by Dougall and Mmola (2015) included producing according to plan. "*A mining operation must be managed to meet the planned production targets. Production is the KPI that measures if the operation is producing to plan, which may be measured as mass of rock in terms of ROM tonnes over a specified time period*" (Dougall and Mmola, 2015 p.1003). What is lacking in this description is the spatial nature of "producing to plan". This is aimed at balancing the short term to the long-term goals. The successful measurement and management of operational KPAs that do not adequately consider the spatial nature of open-pit mining will not give mine management the intended ability to achieve targets and compete successfully.

Kear (2006) confirmed this knowledge gap in existing literature and current mining practice. "*Most production managers are tasked with achieving a goal of some description,*

such as tonnes mined. However, it is important that these come from agreed areas as defined by the long-term mine plans. Waste stripping, for example, is required to expose future ore and therefore has to be removed at the right time and place. Most performance indicators do not take these sorts of considerations into account" (Kear, 2006 p. 96).

A suggested approach put forward by Kear (2006) is to regularly reconcile actual production with the relevant mine plan. The next section will discuss reconciliation in the open-pit mining industry.

2.4 Reconciliation in the open-pit mining industry

2.4.1 Definition and importance of reconciliation in mining

One grouping of KPIs is concerned with reconciling planned (estimated) activities with actual activities (measured). Reconciliation is essentially the process of identifying, analysing and managing variance between planned and actual results in such a way that it highlights opportunities (Riske *et al*, 2010). Mine reconciliation is the comparison of an *estimate* (an Ore Reserve model, grade control information, a mine production plan or schedule) with a *measurement* (survey information, material movement records or the official production report) (Riske *et al*, 2007). Reconciliation in the open-pit mining industry is a broad subject and involves comparing the results of estimated (or planned) *versus* measured (or actual) activities for various KPIs such as the waste production, plant production, chemical and physical qualities of the product for the specific period under consideration.

Blucher (2002) explained that the principal goal of a reconciliation system is to enable the on-going optimisation of all the key components of an operation, leading to the best possible utilisation of the resources on which it is based. Conducting reconciliation ensures that the mining process occurs in a progressively predictable manner (Bester *et al*, 2016). Another reason for embarking on a reconciliation process is performance tracking with the purpose of operational improvement. "*To deliver what we say we will there must be a process by which the performance of our estimates, plans and operations can be assessed, corrected and continuously improved*" (Morley and Arvidson, 2017 p. 279). Reconciliation has an important role to play in the effective management of open-pit mining operations. For mines to successfully implement reconciliation systems those should address the reconciliation needs within a consistent framework. Considering aspects such as the integrity of data (data requirements and data capture systems and technologies), reporting requirements (at the right level, linked to KPIs and focussed on

leading indicators) and appropriate roles and responsibilities. Finally, the system must be auditable and transparent (Macfarlane, 2013).

2.4.2 Types of reconciliation

To define the scope of the reconciliation efforts, literature often refers to the mining value chain and the components (or nodes) of that chain, which are assessed during a specific reconciliation process or initiative. Where the intent of the reconciliation process is to ensure a holistic and integrated understanding or to ensure cross-functional engagement from resource to product, the reconciliation process is referred to as *Reconciliation along the mining value chain* (Macfarlane, 2013) and *Mining Value Chain Reconciliation* (Morley and Arvidson, 2017). Figure 2.2 is a representation of a classic mining value chain and possible areas or nodes of reconciliation focus.

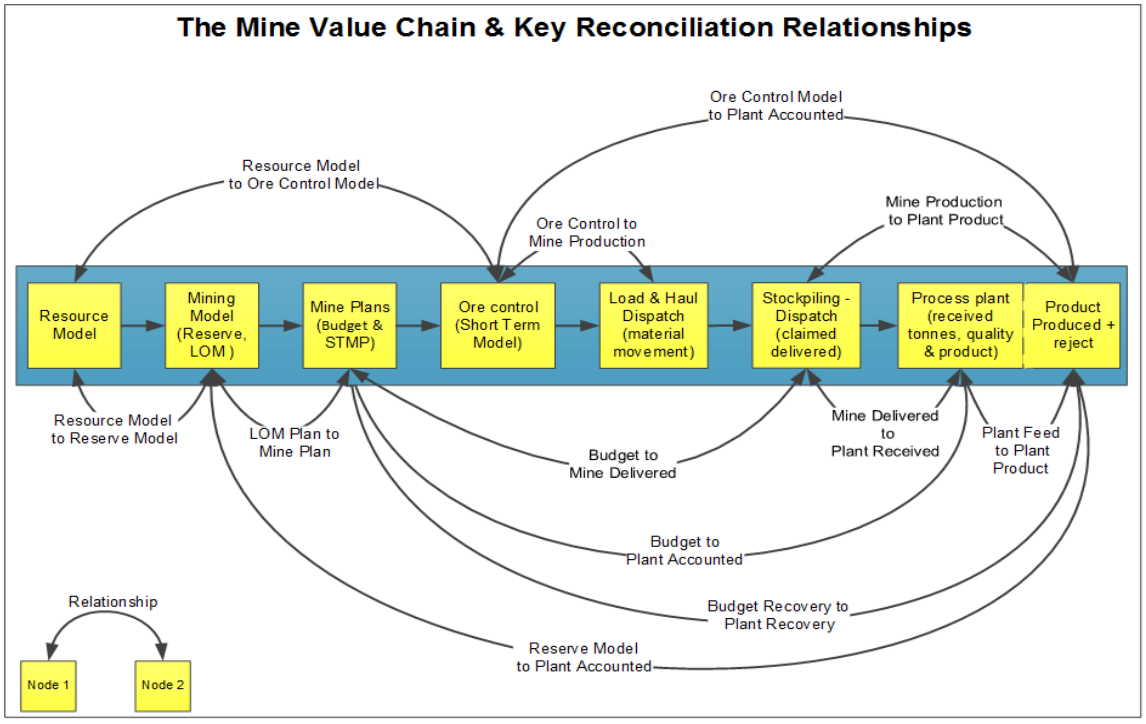


Figure 2.2. The mining value chain – including reconciliation nodes and relationships (Morley and Arvidson, 2017)

Riske *et al* (2010) and Morley and Arvidson (2017) stated that there are three main types of reconciliations that should be undertaken at a typical mining operation and these are:

1. Temporal reconciliation (i.e. reconciliation by period). Here information is compared by day, month, quarter or year. Temporal reconciliation can also be applied on a spatial basis, for example measuring the performance of an individual open-pit mining area over time;

2. Spatial reconciliation or reconciliation by geographic area. This is the three-dimensional or (i.e. “X, Y and Z”) form of reconciliation and can be derived from comparison of predictive models with actual measurements based on a geographic location such as a bench or ore zone; and
3. Physical reconciliation or the reconciliation of quantity and quality (such as tonnes, grade and product). Typically, this is combined with temporal data and is generally reported over long time periods, which can be done quarterly or annually.

Although existing literature clearly identified the spatial aspects of reconciliation, the major shortcoming is that the “as-mined” or actual geographic areas are applied when conducting the spatial reconciliation. For example, the Mineral Reserve model to plant accounted reconciliation node (defined in Figure 2.2) has spatial and temporal components as it compares the tonnages estimated by the Mineral Reserve model for an area mined during a specific timeframe with the tonnages the plant measured for the same timeframe. The reconciliation result does, however, not consider whether the area mined was in fact planned for mining in the time period under consideration. The geographic area considered during the reconciliation process is therefore “normalised” in order to compare the planned number and the measured number for the same area.

It would be easy to assume that the budget-to-mine-delivered or budget-to-plant-received nodes (Figure 2.2) address this shortcoming. However, it does not, as these nodes are purely temporal reconciliation nodes and do not consider the spatial nature of the mine plan underlying the budget tonnages.

Spatial reconciliation is not equal to spatial mine-to-plan compliance reconciliation. When literature refers to an open-pit mining operation conducting spatial reconciliation it cannot be assumed that the spatial execution of the mine plan is being tracked.

One major area of reconciliation that is often overlooked in the open-pit mining industry is the level of spatial compliance to the mine plan that is, how well the mine plan is executed spatially. Not only considering what is being mined when, but also where the mining activities are taking place relative to the areas planned for mining is essential.

2.5 Spatial mine-to-plan compliance reconciliation

2.5.1 Challenges, impact and value proposition

Some quotations from existing literature highlight the pressure on open-pit mine management to meet budget (time-based) KPIs and continuously improve on reconciliation (mainly temporal) results. For example:

- "*Companies get savaged in the market when production guidance is not met*" (Hargreaves and Morley, 2014 p. 411).
- "*Crews are incentivised to produce as many tonnes as possible*" (Kahraman and Dessureault, 2011 p. 819).
- "*Mining is a business that requires the accurate prediction and measurement of quantities and qualities: in the ground, as mined, transported, processed and recovered for various time (temporal) intervals*" (Morley and Arvidson, 2017 p. 279).

An unbalanced drive for short-term operational performance (such as productivity improvements or unit cost reduction) and temporal reconciliation improvements could lead to the prioritisation of mining activities in unplanned areas. Achieving shorter-term targets at the expense of the mine plan is the unintended consequence of such prioritisation decisions. Kahraman and Dessureault (2011 pp. 819) described this typical behaviour as "*deviating from the short-term mine plan is the most common means of balancing the other factors since adherence to the plan is traditionally only measured reactively*" and "*the long-term mine plan is often a victim of unforeseen production interruptions, this results in deviation from the plan*." Spatial mine-to-plan compliance is routinely one of the worst performing metrics on any mine and thus, a significant value creating opportunity (Morley and Arvidson, 2017).

The phenomenon of achieving operational targets at the expense of the tactical mine plan was noted by Hargreaves and Morley (2014 p. 419) when they described a situation where "*the mine was producing product at the targeted quantity and quality, but this was being achieved by use of a number of damaging activities*" such as "*targeting high-grade zones to exceed targets*." This example highlights a situation often encountered at open-pit iron ore mines where short-term planning is more focussed on aligning with the actual production activities than on achieving the objectives of the tactical mine plan guiding it. This short-term focussed behaviour seems to be encouraged by Angelov and Naidoo (2010) where re-planning or the continuous updating of the plan because of "unforeseen circumstances" were proposed as a mechanism to reduce the "inevitable" deviations between the planned and actual mining operation (Angelov and Naidoo, 2010).

This behaviour could reflect a lack of understanding of the value addition of technical mine planning in the mining value chain. The impact of this behaviour, where short-term operational targets (often supported by a re-planned short-term mine plan) are achieved at the expense of spatial compliance to the tactical mine plan, could be devastating to the long-term sustainability of an open-pit mining operation. According to Kahraman and Dessureault (2011) such deviations from the mine plan may be one of the costliest responses to short-term production challenges, as long-term scheduling issues could arise which lead to opportunity loss in the long term (quality/blending issues) or bottlenecks. Angelov and Naidoo (2010) confirmed that deviations from the approved mine plan has the effect of altering the planned yield and overproduction will deplete the Mineral Reserve at a higher rate than initially planned thus lowering the LOM. Given the often-singular focus on achieving budget targets and the short-term nature of incentive schemes in the open-pit mining industry in general, the reality is that the behaviour described above could potentially occur at most open-pit iron ore mining operations.

Hall and Hall (2006; 2015) stated that the major focus of high-performing open-pit mines should be to deliver the operational and financial targets according to the tactical mine plan, without compromising the mine's ability to deliver in future on the KPAs. Hall and Hall (2006; 2015) further indicated that the effective spatial execution of the agreed upon mine plan is critical to the successful operation of an open-pit mine. Spatial compliance with the mine plan is critical to value creation and aligning mine operations with an optimised mine plan provides a substantial opportunity to create value. The value of the spatial mine-to-plan reconciliation process is twofold as it can reveal the effectiveness of the planning assumptions and operational performance (Angelov and Naidoo, 2010).

Existing literature recognises the challenges associated with achieving good spatial mine-to-plan compliance reconciliation results, the potential impacts of poor spatial compliance and therefore the value of reconciling spatial mine-to-plan compliance.

2.5.2 Conceptual approaches to measurement

Angelov and Naidoo (2010) described compliance with mine plans as fundamental to the mine management process and therefore it is important to monitor any deviation from mine plans and effectively remedy the situation if possible. Plan compliance aims to compare actual mining practice to the approved mine plans for a specific time (Angelov and Naidoo, 2010). Kear (2006) suggested an approach where actual production was regularly reconciled with the long-term plan. Importantly, the reconciliation should take cognisance of spatial depletion. The approach allowed for deviations to be identified and action taken

to get back to plan rather than re-planning. It was proposed that this approach could generate useful metrics such as a spatial mine-to-plan compliance index.

It is important to identify where material has been mined to ensure that the progress of mine development is adequate to meet long-term strategic targets such as timely access to future ore targets (Hall and Hall, 2015). Ultimately, senior management, along with the attainment of short-term objectives, should also be tasked with the long-term sustainability of the operations (Kear, 2006). Hargreaves and Morley (2014 p. 411) recognised the challenge of establishing and implementing such a mine-to-plan compliance approach by saying that "*creating plans that can be mined and then mining to those plans spans a multidisciplinary team that must act effectively together if guidance numbers are to be achieved*."

Typical mining value chain reconciliation processes comparing tonnes, grade and product alone do not adequately address the spatial aspect of open-pit mining. According to Morley and Arvidson (2017 p. 281), the ultimate question to answer is "*Did we mine where and when we planned to mine?*" The effective measurement and management of spatial mine-to-plan compliance reconciliation is critical to answer this question.

Up to this point the literature review has not provided detail on the proposed spatial mine-to-plan compliance approaches nor has it indicated that any of the approaches discussed were successfully implemented at open-pit iron ore mines. There is an opportunity for a spatial mine-to-plan compliance framework to be developed to close these knowledge gaps. In the following section, existing spatial mine-to-plan compliance measurement approaches will be analysed and evaluated.

2.5.3 Existing spatial mine-to-plan compliance measurement approaches – relevance and opportunities for improvement

Two references describing approaches that aim to measure spatial mine-to-plan compliance were found in existing literature. Firstly, Angelov and Naidoo (2010) described an approach that determines the degree of deviation from the original mine plans in underground coal mines by comparing actual mined areas to initially planned mining areas. Secondly, Morley and Arvidson (2017) proposed a generic approach for measuring spatial mine-to-plan compliance as an example of good practice that enhances the Mining Value Chain Reconciliation (MVCR) process. Both approaches consisted of the following major attributes: defining the plan against which to measure compliance, methodology, compliance categories and metrics.

It is critical to define exactly **which plan or plans** are to be used for spatial reconciliation as there are a wide range of options including, for example: LOM plans, medium-term, business or 5-year plans, budgets, forecasts, and short-term mine plans (STMP) (Morley and Arvidson, 2017). Both approaches proposed that spatial compliance is measured against the annual budget plan and a version of a short-term plan (referred to by Angelov and Naidoo (2010) as the latest estimate plan). As discussed before, senior management and investors typically focus on performance against the annual budget (or tactical mine plan) and therefore measuring spatial mine-to-plan compliance against this plan supports the achievement of the budgeted outcomes. The STMP is the plan that the mine executes and therefore it is essential to reconcile actual mining activity to this plan also on both a spatial and temporal basis.

The **basic methodology** proposed is to compare the areas, volume or tonnes mined with the areas, volume or tonnes planned for mining. As Angelov and Naidoo's (2010) approach was targeted at underground coal mines (essentially a two-dimensional environment), spatial compliance was defined as the area of overlap between actual and planned mining. Average mining height and relative density were introduced to obtain a tonnes compliance measure. In the second generic methodology put forward by Morley and Arvidson (2017), mine-to-plan compliance was determined using spatial comparisons of volumes measured monthly against the STMP. For application at an open-pit iron ore mine, the approach of using volume measurements has limitations as it does not account for spatial density variations between planned and actual areas mined and does not provide a measurement that can easily be related to and compared to mining performance (typically measured in tonnes). This gap in the methodology can be addressed by comparing planned and actual tonnes in 3D (instead of volumes).

Two areas of overlap were defined in the methodology described by Angelov and Naidoo (2010). Firstly, the area of overlap between the actual mined area and the areas planned for mining in the budget and secondly, the area of overlap between the actual mined area and the areas planned for in the latest estimate or STMP. In contrast, spatial compliance was measured only to the STMP in the methodology described by Morley and Arvidson (2017). Here the premise was that if the STMP is aligned to the annual budget, the cumulative results will show overall compliance to the annual plans/budgets (Morley and Arvidson, 2017). What is lacking here is the recognition that the STMP is often not aligned to the annual budget. In such a situation, measuring mine-to-plan compliance against the STMP only will provide a false sense of compliance when viewed by the mine management.

Angelov and Naidoo (2010) provided an example of the divergence between the budget plan and the STMP. Their results showed that spatial compliance with the budget plan

was less than 10% for both area and tonnes while spatial compliance to the latest estimate plan was approximately 50%. Clearly, these two plans were not targeting the same mining areas. Mine planning reconciliation that incorporates the reconciliation of long-term plans to short-term plans are described by Macfarlane (2013). This provided an approach for ensuring alignment between the mine planning horizons. Neither of the two spatial mine-to-plan compliance approaches discussed, incorporated this concept of plan-to-plan reconciliation to ensure and manage the alignment between plans from different planning horizons. It was therefore, necessary to investigate the inclusion of plan-to-plan reconciliation as an integral part of the proposed framework to address this knowledge gap identified in existing literature.

When comparing the areas or volume or tonnes mined with the areas or volume or tonnes planned for mining, both approaches presented **categories or definitions** for measuring spatial mine-to-plan compliance. Angelov and Naidoo (2010) defined only one category - the area of overlap between the actual mined area and the area planned in the budget or the area planned in the STMP. Figure 2.3 is a graphical representation of actual mining areas and areas planned to be mined in the budget and STMP. The red, blue and green blocks represent the budget areas of specific sections in the mine for a single month (Angelov and Naidoo, 2010).



Figure 2.3. Graphical representation in plan view of actual areas mined (black lines) vs. areas planned for mining in an underground coal mine (Angelov and Naidoo, 2010)

The comparative categories proposed by Morley and Arvidson (2017) are summarised in Table 2.1.

Table 2.1. Categories to explain spatial mine-to-plan compliance (Morley and Arvidson, 2017)

Categories	Description
Mined in plan	Mined from the area planned and, in the month, planned (area with no squares in Figure 2.4)
Mined not planned	Mined, but not in an area planned for the month (area with small squares in Figure 2.4)
Planned not mined	Planned, but not mined in the month planned (area with large squares in Figure 2.4)

The “Mined in plan” category defined by Morley and Arvidson (2017) is equal to the “Area of overlap” defined by Angelov and Naidoo (2010). To obtain the spatial element of compliance to plan in a typical open-pit mine, the volumes must be compared in 3D space. Figure 2.4 illustrates the relationship between these categories in a 2D cross-section view through volumes defined by an existing topographic surface, a planned surface and an “as-mined” surface (Morley and Arvidson, 2017).

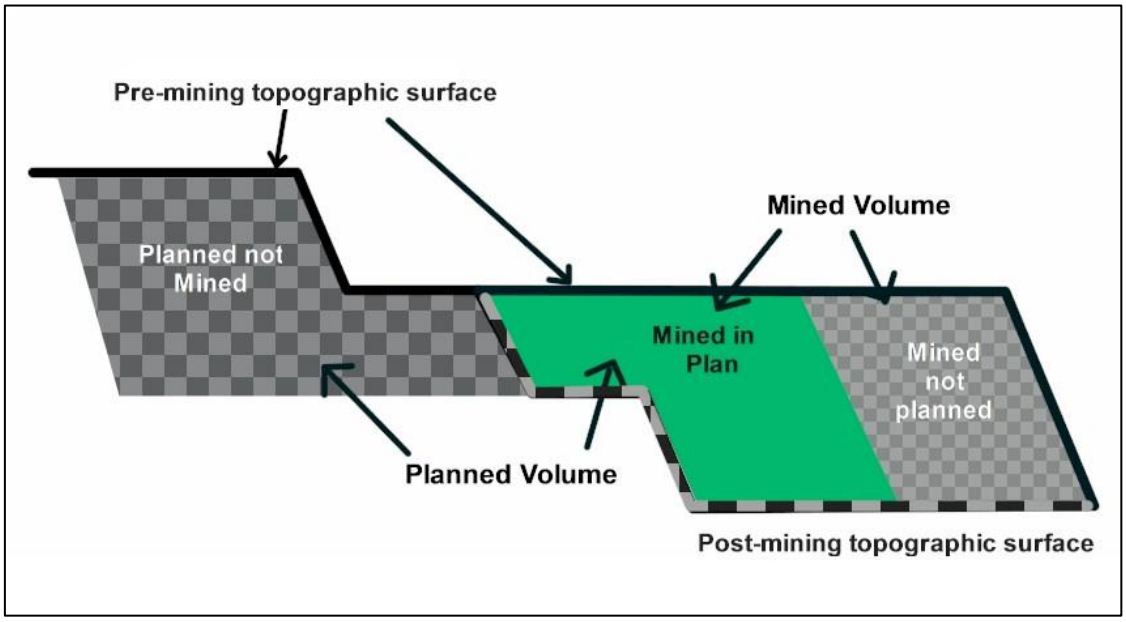


Figure 2.4. Illustration in cross-section of surfaces and spatial mine-to-plan compliance reconciliation categories (Morley and Arvidson, 2017)

Although the categorisation by Morley and Arvidson (2017) was more comprehensive, it lacked the comparison of actual mining to the budget plan. In addition, the approach failed to address the cumulative nature of the spatial mine-to-plan compliance in the articulation of the categories. This is even though this cumulative aspect of spatial mine-to-plan compliance is recognised and mentioned by Morley and Arvidson (2017). The identification and introduction of a compliance category capturing the cumulative nature

of the spatial mine-to-plan reconciliation approach is critical to the effective management of spatial mine-to-plan compliance at an open-pit iron ore mine.

The **mathematical expression** or formula proposed by Morley and Arvidson (2017) for calculating spatial mine-to-plan compliance, using volumes (m^3) on a monthly basis against the STMP, is given in Equation 2.1.

$$Compliance\ to\ plan = \frac{Mined\ in\ Plan}{Mined\ in\ Plan + Planned\ not\ Mined + Mined\ not\ Planned} \quad (2.1)$$

In Equation 2.1 the denominator does not represent the budgeted or planned tonnes. Therefore, the resultant compliance to plan percentage may not have a clear relationship to the performance of the mine against budgeted or planned production targets. This could be a challenge for the application of this formula at an operational open-pit iron ore mine. It could lead to conflicting temporal and spatial reconciliation results and potentially reduce the value of tracking this critical KPA.

Although the formula proposed by Angelov and Naidoo (2010) is not complicated, the challenge described above was eliminated as the budgeted (or planned) area (m^2) or tonnes was used as a numerator as indicated in Equation 2.2.

$$Spatial\ Compliance = \frac{Actual/\ Budget}{Budget}\ x\ 100\% \quad (2.2)$$

where “Actual/Budget” is actual mined from within the planned area.

The following simplified example is used to illustrate the divergent results obtained, when applying the two formulae identified in existing literature, to a set of spatial mine-to-plan reconciliation results. Consider the following data set:

- Planned (budgeted) tonnages for the period: 100 tonnes
- Actual mining tonnes achieved: 110 tonnes
- Actual Mined in Plan: 90 tonnes
- Actual Mined not Planned: 20 tonnes
- Planned not Mined: 10 tonnes

Applying the Morley and Arvidson (2017) expression results in a compliance to plan of 75% while the same set of reconciliation numbers results in a spatial compliance of 90% when using the Angelov and Naidoo (2010) expression. There is an opportunity to address the shortcomings in the existing mathematical expressions used to calculate spatial mine-to-plan compliance by putting forward a holistic set of formulae for application at open-pit iron ore mines.

The **impact** of unsatisfactory spatial mine-to-plan compliance reconciliation performance was discussed in general terms before. A plan compliance risk scenario matrix (Angelov and Naidoo, 2010) was proposed to qualitatively assess the impact of various levels of non-compliance on the LOM and Coal Reserve utilisation at underground coal mines. Six risk scenarios were defined based on both spatial and production performance. The levels of risk were defined based on 100% compliance, less than 100% compliance or 0% compliance.

The fact that there is **value** in good spatial mine-to-plan compliance is also recognised in existing literature. Good spatial reconciliation performance could lead to benefits in terms of cost savings, additional revenue or mitigating value destructive processes. Directly attributing value to improvements in reconciliation results can be complex (Morley and Arvidson, 2017). Extracting value from the reconciliation process is achieved when the process results in the implementation of corrective actions aimed at improving future spatial mine-to-plan compliance. The approaches presented in existing literature, do not provide a means of determining the value-add from improved spatial mine-to-plan compliance and lack a detailed description of the forward-looking management processes associated with identifying and implementing effective corrective actions.

Ultimately, the actual value realised by the mining company (as opposed to the expected value), depends greatly on the level of execution against the mine plan. Angelov and Naidoo (2010) stated that the level of risk increases with a reduced area of compliance to plan. This means that increased spatial compliance to plan reduces the level of risk at a mining operation. To ensure consistent and predictable delivery against the agreed mine plan, it is important that the development of a high-quality mine plan is followed up and supported by a framework that ensures spatial compliance against the plan.

The existing approaches to spatial mine-to-plan compliance reconciliation described above provide guidance, methodologies and metrics for measuring spatial mine-to-plan compliance (with the limitations highlighted). Existing literature did not indicate that a spatial mine-to-plan compliance methodology was successfully applied and validated at an open-pit iron ore mine. What is further lacking is a comprehensive and integrated framework that defines the components and relationships between the components which determine the level of spatial mine-to-plan compliance at open-pit iron ore mines. Such a framework should provide an effective measurement approach and integrating that with root cause analysis, impact assessments, as well as defining and implementing improvements. The main reason for implementing such a framework is to ensure that the expected value, generated during the mine planning phase of the mining value chain, is actively targeted and ultimately achieved during the execution of the mine plan. The development and implementation of such a framework could result in improved spatial

compliance to plan, which in turn can support the operational performance of an open-pit iron ore mine (against plan) while maintaining the operating flexibility of the mining operation.

2.6 Value driver trees (VDT) – its place in reconciliation

This section explores the application of VDTs to conduct RCA on the reconciliation results. The use of VDTs was described by Lane and Wylie (2014) as a means of integrating activities and functions and associated metrics across a mining value chain. Since spatial mine-to-plan compliance also involves combining and analysing information across the open-pit iron ore mining value chain, the application of the VDT concept to the spatial mine-to-plan reconciliation process may add value. To implement a system for reconciliation, it was important that the cause and effect of the value drivers was understood (Macfarlane, 2013).

According to Cambitsis (2012), VDT is a technique of visualising a model of a business in a way that links the value metric (what management or stakeholders care about) to the operational drivers (the things that can be influenced to change performance against the value metrics). In the spatial mine-to-plan reconciliation context, the value metric could typically be the level of spatial compliance to the tactical mine plan. The operational drivers could include spatial compliance in various mining areas, or spatial compliance per material type, or reasons for deviations (such as equipment performance, incorrect deployment and infrastructure delays). A VDT could also be described as the visual representation of a mathematical model of a business or portion thereof (Cambitsis, 2013). In addition, Cambitsis (2013) illustrated that a VDT is useful because it is visually appealing and engaging and it shows how different areas of responsibility link together and affect the value metric. In this thesis, an opportunity was identified to apply the VDT concept to visually represent the root causes of poor spatial mine-to-plan compliance and to show the impact of performance in different mining areas on the overall mine-to-plan compliance reconciliation performance.

Once the degree of deviation from mine plans at underground coal mines was established, Angelov and Naidoo (2010) explored the use of fault tree analysis (FTA) to determine the underlying causes of the deviation. FTAs have similar logic to a VDT. The process of determining the cause of deviation from plans needs to incorporate all the possible areas that can affect the compliance to a given plan. The reasons noted by Angelov and Naidoo (2010) included inadequate plans, incorrect plan assumptions, poor communication of the plan, changes in the mining environment and operational constraints. Although Angelov

and Naidoo (2010) mentioned that correct identification of the reasons for deviation could aid the mine in selecting possible methods to correct the deviation, the application of the FTA to improve spatial mine-to-plan compliance was not presented. What was also lacking in the approach by Angelov and Naidoo (2010) was the use of VDTs to evaluate the mining areas where significant spatial mine-to-plan compliance deviations exist.

The operational drivers of the VDT in a spatial mine-to-plan reconciliation application, typically impacted on the level of spatial *compliance* to the mine plan. Firstly, the VDT approach could provide an ability to identify and evaluate spatial mine-to-plan compliance in individual mining areas such as pits, pushbacks and benches as opposed to only understanding the reconciliation results on a mine-wide scale. The second potential benefit of the application of the VDT approach could be the identification of the root-causes that have the largest impact on spatial mine-to-plan reconciliation performance. Lane and Wylie (2014) described this as "*reason for variance analysis*". Understanding the major reasons for performance variance between the actual and planned areas could give management a powerful diagnostic capability to prioritise corrective management actions.

2.7 Technology applications

Technology plays an ever-increasing part in modern open-pit mining operations. This section explores existing literature on digital mining and the application of technology to enhance the measurement and management of spatial mine-to-plan compliance.

2.7.1 Digital mine

There are various papers and articles dealing with the concept of "Digital mining", the "Intelligent mine" and how "Digital" can bring significant value to the mining industry. Narayanan (2018 p. 12) described "digital" as; "*the presence of ever-increasing information densities and the connectedness of physical resources*" allowing mine management to react faster and more intelligently by analysing data to improve business impact. An Intelligent Mine is one where "*data-driven insight creates sustainable value across an integrated value chain*" (Narayanan, 2018 p. 4). Lyons-Baral and Kemeny (2016) provided a pragmatic description of a digital mine: an open-pit mine with at least daily drone scanning, point clouds and surfaces for any time frame will be available and easily accessible. The future will be about bringing more data sources into one picture, one interpretive model, and one analysis to create one complete picture of the mine.

At the centre of the digital mine lies data (i.e. “big data”), which is transformed to information. The mining industry should value and manage data as an asset, then convert the data asset into meaningful information across the value chain to ensure quality management decisions (Greeff, 2017). Using “big data” allows mines to interpret, analyse and learn from the prior performance of their assets in a way that enables them to improve their decision making and plan better in future (Gray, 2017). According to Hopwood (2018) data is becoming a competitive differentiator in the mining industry and digital thinking should be embedded into the business strategy and practices to transform the way decisions are made.

The Resources Digital Transformation division of Accenture defined five digital mining towers through which technology will enable people to change processes and drive value. These towers are visualisation and alerts, analytics and dynamic scheduling, digital twin and next best action (NBA), integrated automation and cognitive networks (Long, 2017).

The Visualisation and Alerts tower describes the benefits of the visualisation of data across the entire value chain on increased productivity, reduced costs, improved production and safety. This digital mining tower does not recognise the importance of the spatial aspects of data in an open-pit iron ore mining environment nor does it indicate the potential benefits of the visualisation of spatially-referenced data on improved spatial mine-to-plan compliance. At the digital mine, providing real-time information about where everything is and what everything is doing is important. Technologies deployed will combine track-and-trace, visualise and geospatially represent the entire process (Bassan *et al*, 2008). The ideal setup is to have all the data in one place with the person(s) responsible being able to access and use the data to achieve efficient outcomes (Gray, 2017).

The second tower called Analytics and Dynamic scheduling proposed the application of drones for capturing and analysing digital terrain models (DTM) and for monitoring of processing plant related assets. Although, the application of drones for mine-to-plan compliance reconciliation purposes is not explicitly recognised, drones could be utilised to capture the actual areas mined and track against plan in a safe and effective manner and monitor spatial progress of mining assets such as loaders and excavators against plan. Similarly, the use of the latest generation scanners ensure that the actual areas mined are available timely for analysis and comparison with the planned areas. Existing literature on the application of drones in open-pit mines will be explored in more detail later in this thesis.

The third tower dealt with the concepts of digital twin and NBA. Hopwood (2018) described a digital twin as a digital model of the physical environment constructed using asset information—such as ore body models and engineering drawings. The model is

continually updated to enable better planning, prediction, and simulation of future outcomes. The concept of the digital twin offers an immersive virtual environment that merges short, medium and long-term planning horizons to help miners make value-driven decisions across a range of operations (Long, 2017). Fly-over and walk-through views create a context-rich representation of the real world in real-time and provide tacit contextual information (Bassan *et al*, 2008). The application of the digital twin concept to open-pit mining was illustrated by Grobler (2017). A virtual digital open-pit mine was created for display purposes through the integration of various sets of data in an accurate and fast way by applying augmented reality (AR). AR requires data to overlay in context (Grobler, 2017). A 3D model of the open-pit area provided context and was used as a canvas for visualisation, orientation and recognition. This 3D model had to be relatively accurate and current. The overlay was essentially the attributes used to augment the information displayed on the canvas. Here, accuracy was critical and again it had to be current. Existing literature only described the concept of a digital twin without any indication of a practical implementation or case study of actual application in the open-pit mining industry. Therefore, the application of a digital twin to spatial mine-to-plan compliance reconciliation can be explored. The context is typically the updated actual pit surface and geological information while the attributes (or overlay) are the planned mining blocks for the period under review.

The aim of digital innovation is to empower people to make better decisions using data that are more comprehensive. "*Digital enables us to look deeper into our assets*", (Long, 2017 p. 6). It is all about making better, more informed decisions, ensuring collaboration between functions to optimise value across the value chain, integrating information from many business functions, and providing analytical results in real-time (Bassan *et al*, 2008). Greeff (2017) described the relationship between the quality of decision making and the level of data "transformation". Figure 2.5 illustrates the concept. Un-transformed data is for example data without spatial and value chain context. It was contested that decisions driven by un-transformed data are generally poor while intelligence-driven decisions are better (Greeff, 2017).

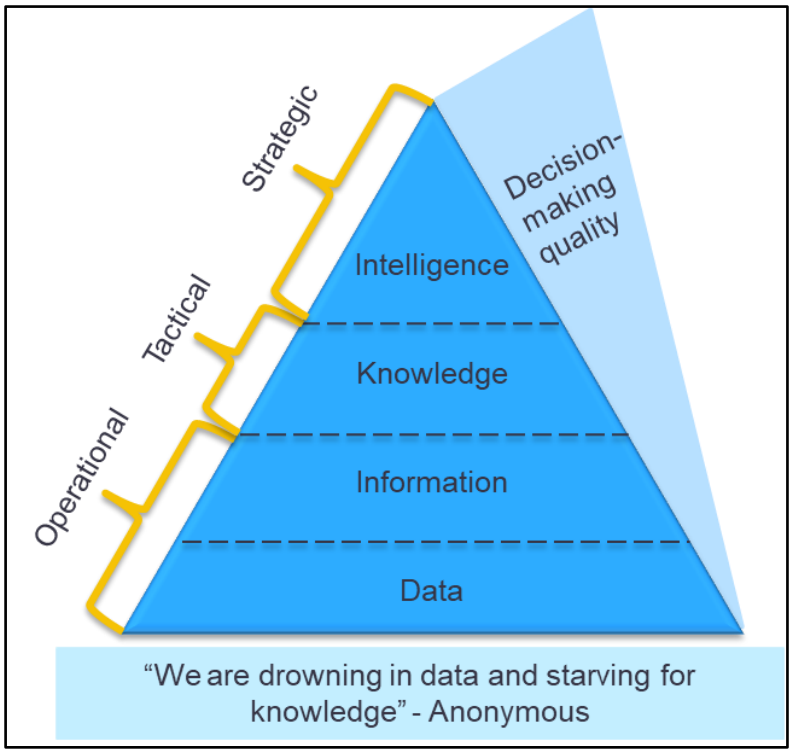


Figure 2.5. Transforming data to intelligence (Greeff, 2017)

According to Hopwood (2018), the real payoff will come when mining companies are able to uncover insights capable of informing their operational decisions in areas such as compliance to mine planning, fleet movement and resource allocation. This thesis considered the challenge raised by Hopwood (2018) and proposed the application of digital technology to inform operational decisions that improve compliance to mine planning. The concept of NBA deals with this aspect of improved and optimised decision making. NBA is about using intelligence derived from transformed and spatially-referenced data to understand the next best course of action that the mining operation should take in relation to present and predicted future conditions. Identified literature did not illustrate how improved decision making was practically implemented and did not directly address the application of the NBA concept to manage spatial mine-to-plan compliance performance. It was however clear that this concept has the potential to contribute to the effective management of spatial mine-to-plan compliance and as such, its application was further investigated in this thesis.

Although the vision of a digital mine was well described in existing literature, no mining organisation is yet doing it in an integrated way. Those that do embrace the concept stand to see productivity benefits (Hopwood, 2018). This thesis considered the concept of digital mining and aimed to apply it to enhance the proposed framework developed for the management of spatial mine-to-plan compliance at open-pit iron ore mines. The fourth and

fifth towers are best addressed through the application of technology as discussed in the next sections.

2.7.2 Drones and scanners

Collecting and providing data and information on the spatial mining progress was a clear pre-requisite for the effective measurement of spatial mine-to-plan compliance in an open-pit iron ore mine. Traditionally, ground based Global Positioning Systems (GPS) surveying tools and techniques have been and continue to be used to capture actual mined surfaces in an open-pit iron ore mine at an agreed frequency. Laser Imaging, Detection and Ranging (LiDAR) or laser scanning and digital photogrammetry both provide a 3D-model of actual mining conditions, but through different technology applications. Lyons-Baral and Kemeny (2016) described LiDAR and photogrammetry as common remote sensing methods employed to measure the coordinates of surfaces in 3D, providing the X, Y and Z locations. Essentially the GPS creates points, points create lines, lines create surfaces and finally surfaces can create volumes when they intersect (Martin, 2016).

Laser scanners send pulses of laser light at a target and record the reflection time. By measuring the laser direction and the reflection time, the 3D-location of the reflection surface is calculated. By sending many pulses in a regular pattern, a scanner can create a point cloud of the scene. A point cloud is a database containing points in a 3D coordinate system and is an accurate digital record of an object such as an open-pit mining area (Ciepka, 2016). These point clouds can then be converted to DTMs. Laser scanning technology provides for the rapid collection of dense 3D spatial datasets of mining surfaces. In addition to capturing the actual spatial mining progress, it has numerous other applications in the open-pit mining industry, such as slope stability monitoring and stockpile measurement (Lichti *et al*, 2002). Digital photogrammetry uses overlapping images of the same area captured with a digital camera from different locations. By finding common points in both images, photogrammetry software can build a DTM of the scene (Adu-Acheampong *et al*, 2013).

In recent years, areal surveying utilising drones, has become a practical way of enhancing and even replacing traditional ground-based survey techniques. Drones or Unmanned Arial Vehicles (UAVs) or Remotely Piloted Aircraft System (RPAS) units are systems for intelligence, surveillance and reconnaissance. These powered aerial vehicles have no human operator on board, can fly autonomously or be piloted remotely and carry surveillance equipment also referred to as attachments. RPAS are smaller than manned aircraft and can carry survey equipment such as LiDAR, cameras and other sensors for

infrared and thermal imaging (Rathore *et al*, 2015; Bester and van Heerden, 2017). Bester and van Heerden (2017) described the two main types of RPAS in use today as rotor wing and fixed wing.

As discussed earlier, utilising RPAS is part of the overall effort to digitise open-pit mining operations. As with all data, RPAS data need to be viewed as a digital asset that should be effectively managed (Snow, 2015). RPAS covers large areas and can provide coverage over a 2 to 6km^2 area per flight (typically 30-50 minutes depending on the attachment being carried) with a spatial resolution of approximately 50mm to 200mm from heights of 150m to 500m above ground level (AGL) (Adu-Acheampong *et al*, 2013 and Mazur *et al*, 2016). Bester and van Heerden (2017) indicated that the primary benefits of RPAS to open-pit mines are:

- the provision of cost-effective and accurate data that is accessible in a fraction of the time that conventional ground-based surveys take;
- improved safety; and
- reduced labour and person-hour costs in a variety of data capturing roles.

There are five main categories for the application of RPAS in the open-pit mining industry namely survey and mapping of pits, tracking productivity, engineering construction and inspections, safety, environmental and community applications, and security applications. The first two applications are linked to the management of spatial mine-to-plan compliance and will be further discussed. Firstly, survey and mapping are being performed in a cost-effective way with the aid of RPAS systems. The topography of open-pit mines is constantly evolving, and drones offer a good way to keep track of those changes (Knight, 2017). By coupling drone-mounted LiDAR systems with vision cameras, advanced computer processing and GPS, it is possible to create a remotely piloted flying LiDAR scanner (McNeil, 2016). Typical output includes DTMs of actual mining surfaces, stockpile mapping and the detection of areas of slope instability (Rathore *et al*, 2015).

In a singular reference to the application of RPAS for spatial mine-to-plan compliance reconciliation, Knight (2017) described how RPAS was used by a government organisation to make sure that the original reclamation plan was adhered to on closed and closing coal mining sites. Capturing actual spatial mining progress at open-pit iron ore mines using ground-based surveying tools as well as the potential benefits and value of using RPAS as part of the mine-to-plan compliance measuring process, was explored in this thesis.

Secondly, Mazur *et al* (2016) and Rathore *et al* (2015) described how mining productivity could be tracked and improved using RPAS units. RPAS technology is highly applicable

and valuable to use for reconciliation purposes through time-lapse photography. Extraction support can be provided by RPAS to quickly map areas of interest, optimise hauling routes and provide control information. RPAS can monitor the production process in open-pit mines and detect deviations and threats. Existing literature only describes the possibilities of RPAS application to improve mining productivity and reconciliation at open-pit mines but does not provide any practical case studies. This thesis aims to address this knowledge gap by providing a practical application where RPAS were deployed to dynamically monitor progress of critical spatial mine-to-plan compliance aspects.

It is also important to note the major challenges that should be considered when deploying RPAS as part of the data collection process at open-pit mines. These include dealing with onerous regulations that vary from geography to geography (Snow, 2015). Additionally, the range and payload carrying capacity limitations, which negatively impact on the application of RPAS units in large open-pit mining environments, should be considered (McNeil, 2016).

2.7.3 Fleet management systems

Other technology applications that have a direct impact on spatial mine-to-plan compliance (potentially positive and negative) are Fleet Management Systems (FMS) and High Precision Global Positioning Systems (HP-GPS) on loaders and excavators. Most modern open-pit mining operations monitor the in-pit operations using GPS and wireless communications. Murphy (2011) described an FMS as a comprehensively integrated mining operations and mobile equipment management system used to optimise productivity, enhance safety and improve machine use and uptime. This incorporates real-time machine tracking, scheduling, assignment and productivity management. An FMS is a real-time in-pit truck allocation, control and monitoring system used to maximise the overall mine production by improving equipment utilisation and reducing production costs. Optimal truck assignments mean more material is moved by routing trucks via the fastest route, with optimised assignments to loading equipment and dumps/crushers. The adoption of FMS, such as the Modular Mining Dispatch system, has resulted in improvements in truck cycle times contributing significantly to improve mine efficiency (Dessureault *et al*, 2007; Nix, 2008; Ferreira, 2011). Dessureault *et al* (2007) further explained that FMS are focused primarily on improving truck and loading fleet productivity. Mining companies have reported productivity gains of up to 15% and a reduction in production costs. "*These systems are designed to direct haul trucks to the right place at the right time, thus increasing the operating efficiency of the mine, subject to constraints like grade control*" (Dessureault *et al*, 2007 p. 2).

Hayes (2011) and Trainor *et al* (2011) described the application of FMS for grade control where the system applies material-blending constraints to ensure that delivered material meets specification. In an oil sand case study, this was achieved by tracking the grade of the ore being mined, tracking the ore blend on the trucks and dispatching the trucks to the proper crusher to maintain the blend target grade.

Most of the existing literature elaborated on the primary focus of FMS, which is truck and loader productivity in open-pit mines. As described in Section 2.4, this drive for increased productivity can occur at the expense of the mine plan, thus, leading to poor mine-to-plan compliance if one of the "constraints" violates the spatial deployment of the tactical mine plan. According to Dessureault *et al* (2007) if the "right place" where haul trucks are directed to, is not derived from the mine plan, the FMS will be driving efficiency at the expense of effectiveness.

It is important to note that a passive production tracking system could be a sensible alternative to an FMS for smaller and less complex open-pit mines. An FMS actively optimises truck assignments and gathers data, while a passive production tracking system records and reports what occurred (only gathers data), leaving operations management to act. "*The focus is to automatically deliver operational performance data to the people that can take corrective action*" (Cantin, 2010 p. 33). From a spatial mine-to-plan compliance perspective, the same challenges exist: productivity should be managed in the context of the spatial deployment of the mine as required by the tactical mine plan.

FMS depend on GPS, a myriad of onboard sensors and computers, and wireless communications technology. Dessureault *et al* (2007) described how the location of major mobile equipment is transmitted in real time to a centralised computer system using wireless communications networks. GPS is a core positioning technology for several activities in open-pit mines, including fleet management (Nix, 2008). As indicated before, the most basic feature of a FMS is optimising the assignments of trucks to loading units (typically loaders, excavators and front-end loaders at open-pit iron ore mines). To maximise production, the FMS needs to know, in real time, the exact location and activity of each equipment unit. Having this real-time data provides the basis for continuous, real-time decisions and optimal re-assignments to maximise production (Crose, 2013). This integration of the FMS capabilities with the HP-GPS to provide spatial production information has possible application in spatial mine-to-plan compliance reconciliation.

Highly accurate real-time kinematic GPS systems can provide position data for a moving machine in 3D with an error of less than 50mm (Seymour, 2004). HP-GPS is a sophisticated system capable of determining accurate loader position data and relaying this data to and from the mine computer network. It can display a loader's real-time

location and elevation to an accuracy of within 50mm to 100mm (Gould, 2002 and Trainor *et al*, 2011).

The major applications and benefits of utilising the integrated FMS and loader HP-GPS technology, such as Modular Mining's ProVision system, include selective mining of ore within geological contacts, mining to planned elevation and mining to the correct dig limits (Richards, 2001; Seymour, 2004; Rojas, 2017). Combined with software capable of graphically showing the operator useful information, the use of this guidance technology increases machine productivity and provides real-time feedback to operators for improved efficiency (Murphy, 2011). Hayes (2011), Trainor *et al* (2011), Ferreira (2011) and Crose (2013) further discussed the power of directly alerting loading equipment operators of undesired behaviour. The system provides real-time feedback to reinforce adherence to operational best practices, plan and profile views of loader position relative to elevation requirements, constant visual confirmation to the loader operator of the material type and quality and issue alarms where loaded material is misdirected. Figure 2.6 is an example of a typical in-cab display on a loader.



Figure 2.6. Example of loader operator in-cab display (Richards, 2001)

Various case studies were discussed in existing literature, but the direct application of this on-board graphical display to improve spatial mine-to-plan compliance was not identified. A significant benefit of HP-GPS is the generation of an actual mined "surface" that is continually updated as the loader bucket digs material. This allows for the automatic generation of "as-builds" in the form of DTMs (Seymour, 2004). Richards (2001) described the application of this technology at Highland Valley Copper in British Columbia. "As-dug"

data was sent from the loaders via the digital wireless network. As loading progressed, the technology measured and recorded the work done which allowed staff to monitor spatial progress throughout the mine in near real time. Figure 2.7 illustrates the generation of actual mined DTMs from the loader's HP-GPS system.

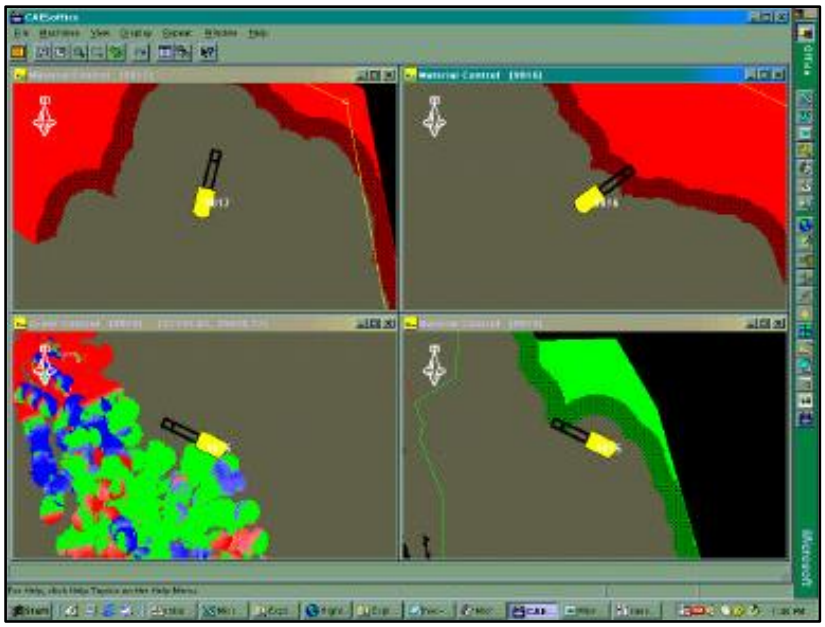


Figure 2.7. Illustration of the generation of as-mined DTM (Richards, 2001)

Most FMS provide real-time feedback on equipment statuses, location and production. However, these systems have not been well integrated into the mine planning process (Kahraman and Dessureault, 2011). This opportunity has been identified by the suppliers of FMSs and has led to the formation of strategic alliances with mine planning software vendors to deliver an integrated solution to bridge the gap between planning and operations (Leonida, 2016). Although, these integrated solutions are being developed, challenges such as poor data quality, inadequate infrastructure, low user proficiency and the large number of different mine planning software solutions being used, result in a limited number of practical implementations (Rojas, 2017). As stated before, the major objective of an FMS is to produce as much tonnes as possible; i.e. improving mining equipment efficiency and productivity. Following the mine plan, while ensuring product quality and maximising production is a challenging balance. Kahraman and Dessureault (2011) also described how these conflicting objectives were managed by deviating from the mine plan at a large coal mining operation in Wyoming's Powder River Basin. Essentially, achieving production, productivity and short-term product quality targets (managed using an FMS) were viewed as being more important than spatial compliance to the mine plan. Again, this is an example of where efficiency was prioritised over effectiveness.

According to Gould (2002) HP-GPS on loaders was being used at the Aurora Oil Sands mine in Canada to aid in mine planning. A mine plan was created that consisted of loader dig locations that required the loaders to mine in a specified area at a specified elevation. With the HP-GPS information, an exact location was known for each loader at all points in time. From a mine planning point of view Gould (2002) broke down the uses of loader HP-GPS into three main categories namely following geological contacts, creating ramps and maintaining a level loader bench. The actual loader positions were shown relative to the planned loading areas as work progressed (i.e. what the current surface is relative to the planned surface in 3D) at open-pit mines such as the Canadian Natural Resources Limited Horizon mine (Trainor *et al*, 2011) and the Highland Valley Copper mine (Richards, 2001). At these mines the mine planning department determined the locations of the loaders (Trainor *et al*, 2011) and plans created with the mine's planning software were loaded to the loading machines as required (Richards, 2001). What is lacking in these case studies is the application of loader HP-GPS as part of an integrated process for tracking and managing spatial mine-to-plan compliance.

Following the challenges experienced at the coal mine in Wyoming's Powder River Basin, Kahraman and Dessureault (2011) extended the application of loader HP-GPS to include tracking performance against the mine plan. They developed a reporting tool that was designed to help FMS operators view their performance and compare it, both in real time and historically, to the mine plan. Its purpose was to give the operators more visibility on the impact of their decisions on the mine plan. Adherence to the mine plan was measured on a per pit basis as part of crew performance in addition to the other productivity and quality related KPIs. Post-implementation results showed that the introduction of the reporting tool made it easier for FMS operators to adhere to the mine plan thereby increasing control of overmining or undermining and eliminating long-term quality and scheduling concerns (Kahraman and Dessureault, 2011).

Literature on the application of FMS and HP-GPS technology at open-pit mines has exposed the very limited integration of this technology with mine planning and mine-to-plan compliance management. Even though most modern open-pit mines employ a FMS coupled with HP-GPS on loaders where this technology can potentially track actual *versus* planned loader positions; only a handful of references to the application of FMS and HP-GPS in the area of mine-to-plan compliance were found. Where the technology was being utilised to provide information on spatial mine-to-plan compliance, it was not done in a systematic and comprehensive way as part of a bigger reconciliation framework. Furthermore, existing literature did not describe the application of this technology as part of the spatial mine-to-plan compliance process at an open-pit iron ore mine. Therefore, it is possible to explore how FMS and associated HP-GPS technology could potentially be

employed to enhance the framework. The technology could provide a tool to accurately track the actual spatial mining progress in real time and compare that to the spatial aspects of the appropriate mine plan (areas planned for mining). This information could also be made available to the loader operator and further evaluated using Mine Information Systems (MIS) such as the Trimble Connected Mine platform.

Despite the limited references in existing literature on the application of digital mining technologies to spatial mine-to-plan compliance reconciliation, it was clear from the literature review that these technologies would enhance the framework to be developed in this thesis. RPAS and scanners, FMS and HP-GPS and ultimately the digital mine presented technology applications and real-time tools to enhance the effective measurement, tracking and management of the spatial compliance of an open-pit iron ore mine. The implementation readiness, practical application and maturity of these technologies were explored as part of the thesis.

2.8 Summary of Chapter 2

Existing literature and available research focussed on improving the mine planning process in a singular fashion implying that the only way to improve compliance to the mine plan is by improving the mine plan itself. The knowledge gap identified was that existing literature did not recognise that an effective approach to the execution of the mine plan could equally contribute to improved mine-to-plan compliance. It was noted that actual performance does not always achieve the mine planning targets and that typical KPIs used in open-pit mines do not adequately consider the spatial nature of the mine plans.

Section 2.5.1 noted that spatial mine-to-plan compliance reconciliation is often overlooked at open-pit mining operations and there was a lack of appreciation for spatial mine-to-plan compliance and the value unlocking potential thereof. The impact of overlooking spatial mine-to-plan compliance was that mining of unplanned areas could lead to achieving short-term targets at the expense of the mine plan with a negative impact on the long-term sustainability of the mine.

Two existing approaches for the measurement and reporting of spatial mine-to-plan compliance reconciliation were reviewed and various knowledge gaps were identified. Most notably, the existing approaches did not provide a comprehensive and integrated framework for the measurement and management of spatial mine-to-plan compliance.

Existing research on the application of the VDT concept to the management of spatial mine-to-plan compliance at open-pit iron ore mines are limited. Therefore, significant

opportunities exist for the better positioning and integration of VDT analysis as part of the framework proposed by this thesis. The final section of the literature review covered technology solutions that might enhance the effectiveness of the framework. Although technology solutions were applied across the mining value chain, the spatial dimension of the applications were often lacking, and technology was mainly deployed to gather data in silos. The knowledge gap that was identified is that technology solutions were not applied in a practical and integrated way to inform decision making that could enhance the effectiveness of the spatial mine-to-plan compliance reconciliation process at open-pit iron ore mines.

The next chapter describes the research methodology followed during the execution of this research thesis.

3. RESEARCH METHODOLOGY

3.1 Overview of Chapter 3

This chapter describes the research methodology followed during the execution of this research thesis. This includes steps taken from the literature review, which informed the components and the proposed spatial mine-to-plan compliance framework and its validation through a case study application.

3.2 Research methodology

The research methodology followed is summarised in the steps below:

- Firstly, existing **literature** relevant to the thesis **was reviewed** with the aim of establishing the extent and depth of current published information. The main themes covered in the literature review are stated in Section 1.4. The literature review provided justification for the need of a systematic and integrated framework for spatial mine-to-plan compliance reconciliation.

- Following the literature review and with the aim of addressing the knowledge gaps identified in existing literature, a holistic **spatial mine-to-plan compliance framework was conceptualised** and developed.

- The **approach for the measurement and reconciliation** of spatial mine-to-plan compliance was then defined by describing the major components required to effectively measure spatial mine-to-plan compliance at open-pit iron ore mines. Aspects dealt with included the appropriate planning horizon to measure against, the establishment of the actual areas mined, defining the categories for calculating spatial mine-to-plan compliance, definitions, metrics, mathematical expressions, reporting formats and target setting. The aspects also included the application of appropriate technology to improve the quality and accuracy of measurement (such as survey data collection) and reporting and highlighting the importance of integration of spatial data across the mining value chain.

- This was followed by the development and application of **spatial mine-to-plan CDTs** that provide the ability to drill-down into selected spatial areas within the entire iron ore mine and enable understanding of the root causes of deviations.

- Next, novel ways of **determining, quantifying and interpreting the impact** of spatial mine-to-plan compliance performance on the achievement of operational

targets as well as on the flexibility of the open-pit iron ore mining operation, were defined for incorporation into the framework.

- The research then defined the concept of the next best action (or NBA). It was shown how this concept is used to improve the spatial mine-to-plan compliance by informing **decision making** that addressed the root causes of non-compliance and providing guidance and direction to the operational mine planning horizon to re-direct mining to the correct spatial areas.

- The last component of the framework introduced feedback loops designed to improve the spatial mine-to-plan compliance. The first feedback loop ensured the implementation of agreed corrective actions (also referred to as **NBA**) and included the deployment of appropriate technologies to enhance short-term visibility of the spatial progress of open-pit mining. The second feedback loop facilitates improved tactical plans in future. This forms part of an integrated management process and associated routines supporting the implementation of the framework.

- Finally, the research was **validated through the implementation of the framework** at the Kolomela open-pit iron ore mine in South Africa. Keeping in mind that the aim was to improve spatial execution against the tactical mine plan, the effectiveness of the framework was evaluated by assessing the impact of its introduction on spatial mine-to-plan compliance performance over a three-year period.

4. THE SPATIAL MINE-TO-PLAN COMPLIANCE FRAMEWORK

4.1 Overview of Chapter 4

This chapter describes the approach or framework for the measurement and reconciliation of spatial mine-to-plan compliance. Section 4.2 provides an overview of the framework and Section 4.3 discusses the major components required to effectively measure spatial mine-to-plan compliance. Section 4.4 describes the spatial mine-to-plan reconciliation approach including categories, expressions and definitions used to define and calculate spatial compliance, reporting formats and target setting. Section 4.5 describes the adaptation of the VDT concept to spatial mine-to-plan CDT that provides the ability to drill-down into selected spatial areas within the entire iron ore mine and enable understanding of the root causes of deviations. Section 4.6 illustrates how understanding and interpreting the impact of spatial mine-to-plan compliance performance, on the achievement of operational targets and flexibility, was incorporated into the framework.

The concept of the NBA is defined in Section 4.7. This section describes how NBA is used to improve the spatial mine-to-plan compliance by addressing the root causes of non-compliance and providing guidance and direction to the operational mine planning horizon to re-direct mining to the correct spatial areas. Section 4.8 discusses how feedback loops are employed to improve the spatial compliance by implementing the agreed corrective actions (or next best actions) and facilitating improved tactical mine plans in future. Effective management processes and routines are also discussed. This chapter also includes commentary on the deployment of appropriate technology solutions to improve the quality and accuracy of measurement and reporting as well as enhance short-term visibility of the spatial progress of open-pit mining.

4.2 Overview of the spatial mine-to-plan compliance framework

The different components of the framework are illustrated schematically in Figure 4.1 and can be described as follows:

1. Components 1 to 3 are the major components required to effectively measure spatial mine-to-plan compliance, definitions, reporting formats, target setting as well as the application of technology solutions to improve the quality and accuracy of measurement and reporting;
2. Component 4 deals with the development and application of spatial mine-to-plan CDT that provides the ability to drill-down into selected spatial areas within the entire iron ore mine and enable understanding of the root causes of deviations;

3. Component 5 illustrates the impact and consequence of year-to-date (YTD) spatial mine-to-plan compliance performance on the forward-looking compliance and the subsequent consequence on the achievement of operational targets as well as on the flexibility of the open-pit iron ore mining operation; and
4. Component 6 defines the NBAs that lead to improved spatial mine-to-plan compliance by addressing the root causes of non-compliance and providing guidance and direction to the operational mine planning horizon to re-direct mining to the correct spatial areas.

Finally, the framework ensures the implementation of agreed corrective actions (also referred to as NBA) through feedback loops designed to improve the spatial mine-to-plan compliance. The first feedback loop includes the deployment of appropriate technologies to enhance short-term visibility of the spatial progress of open-pit mining. The second feedback loop facilitates improved tactical plans in future.

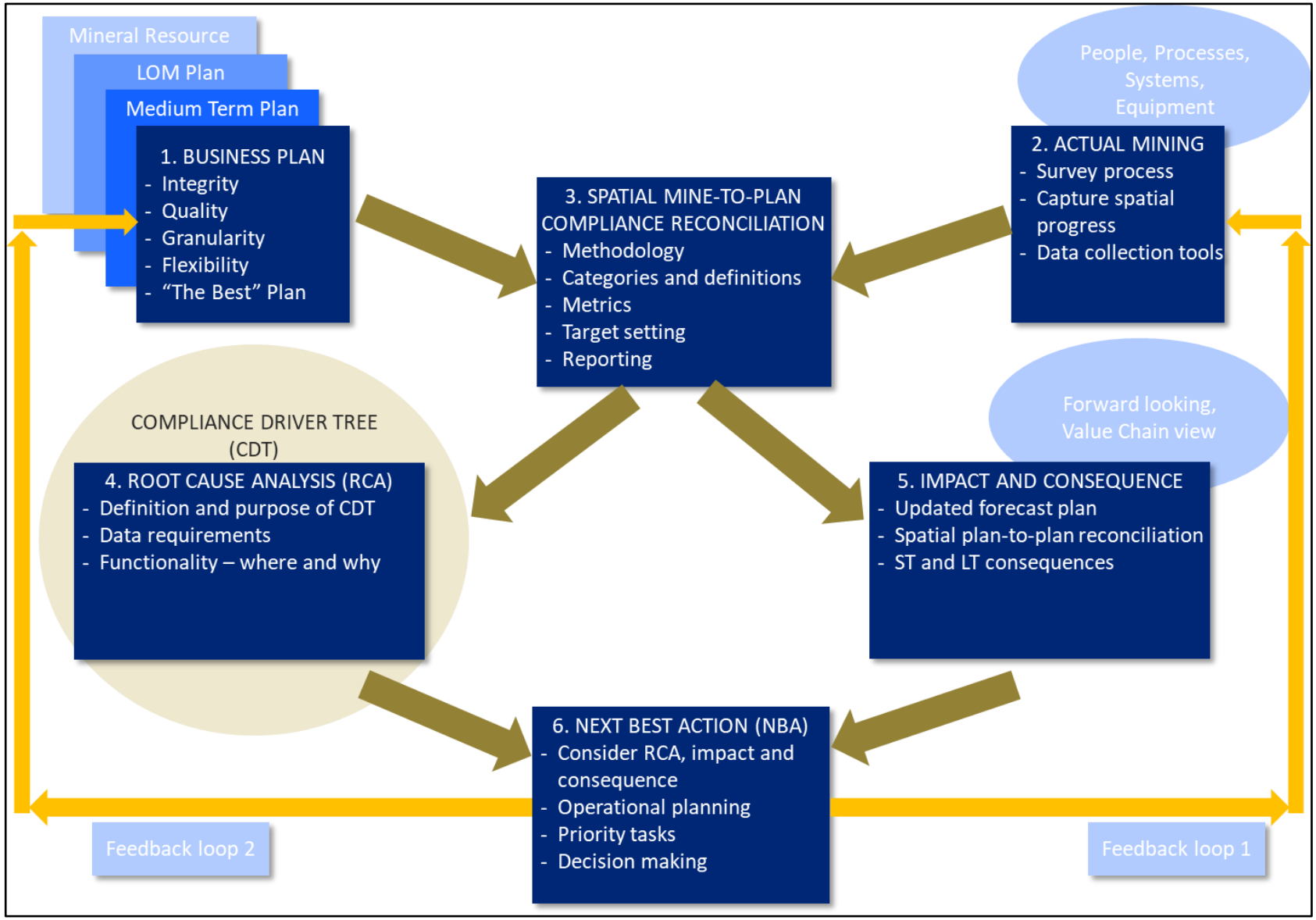


Figure 4.1. Spatial mine-to-plan compliance framework

4.3 Measurement approach

4.3.1 Introduction to the components required for measurement

The measurement of spatial mine-to-plan compliance at an open-pit iron ore mine can be done effectively when the first two components of the framework are in place:

- A quality mine plan (Component 1); and
- A process of capturing and analysing actual mining progress spatially (Component 2).

This section of the thesis deals with the first two components of the framework.

4.3.2 A quality business plan (Component 1)

The mine planning process and the development of an appropriate mine plan as input to the spatial reconciliation process, fell outside the scope of this thesis. The thesis assumed that an optimal and robust mine plan was developed to direct the spatial deployment of the open-pit iron ore mine and to set operational targets. The estimate, against which the actual spatial execution will be measured, was therefore known.

Before moving on to defining the appropriate mine plan to use in the framework, it is important to discuss the dichotomy between the requirement for an “optimal” mine plan on the one hand and agreeing on the “best” mine plan to execute on the other hand. The optimality of a mine plan is ensured by dynamically considering changes in various input parameters (such as macro-economic assumptions, geological assumptions, deployment assumptions and mining equipment related assumptions) and developing stochastic or deterministic mine planning options. At the end of the dynamic mine planning process, one optimal mine plan (the “Best” plan or “The Plan”) must be agreed on and approved for execution.

It was therefore important to **define “The Plan”** against which spatial mine-to-plan compliance will be measured in the framework developed in this thesis. Essentially, there were three main mine plans to consider. Firstly, the LOM plans developed in the strategic planning horizon provided broad spatial guidance to the deployment of typical open-pit iron ore mines, but these plans had certain limitations. These typically included a lack of granularity in terms of the deployment and scheduling of individual pieces of loading equipment and a lack of detailed blast block designs used as input to the LOM scheduling process. Secondly, the use of operational mine plans or STMP were considered. One spatial mine-to-plan reconciliation methodology identified in the literature review measured

spatial compliance against the STMP (Morley and Arvidson, 2017). Although, these plans provided the spatial information to the required level of detail, the critical limitation of the STMP was that the timeframe covered by these plans was too short. Tracking spatial compliance against these STMP would not provide the required assurance to mine management that the spatial execution of the open-pit iron ore mine would support the achievement of the agreed upon operational targets in a sustainable manner.

Thirdly, the **tactical horizon of mine planning** was considered. This horizon encompasses the annual development of tactical mine plans. These plans are also referred to as Medium term plans (MTP), BPs and Budget plans. The tactical plans are successors of feasibility studies and LOM plans, and predecessors of operational plans (Phillis and Gumede, 2011). These production schedules (typically developed annually in monthly increments) are a critical mechanism in the planning of open-pit mines. It deals with the effective management of a mine's production and cash flows in the order of millions of dollars (Ramazan and Dimitrakopoulos, 2004). The BP gives effect to the mining strategy developed in the LOM plan and should enable the ultimate implementation or execution of the mining strategy defined in the LOM plan.

The BP is significant to open-pit iron ore mines as it provides the mining activities and primary heavy mining equipment (HME) requirements that underpin the annual budget of the mine. The BP sets annual operational and financial performance targets. Phillis and Gumede (2011) commented that mine management is expected to deliver against annual mine plans - these plans are a form of contract between a mine and its stakeholders. The BP provides the bridge between strategic mine planning (LOM plans) and operational mine planning (STMP) and translates the expected longer-term value (often expressed as NPV) into operational and financial targets such as monthly waste, ex-pit ore, ROM ore and product tonnes, product quality, unit cost and revenue projections. Importantly, it remains a mine plan and therefore also prescribes the spatial development of the open-pit iron ore mine.

Applying the **BP as estimate** in the framework addressed the shortcomings of both the LOM and STMP discussed above and addresses the knowledge gap identified where spatial mine-to-plan compliance is measured against the STMP. For the effective functioning of the framework the first component is therefore the approved and agreed upon BP of an open-pit iron ore mine. In summary, the main reasons for deciding to apply the BP as the first component of the framework were as follows:

- The BP translates the LOM mining deployment strategy into implementation orientated mining schedules;
- The BP forms the basis of the annual budget; and

- The BP provides appropriate estimates of the spatial development of the mining areas targeted in the budget.

Based on the above, the annual BP was used as the estimate when reconciling spatial mine-to-plan compliance. For the purposes of this thesis, the BP refers to the first 12-month period of the MTP. To enable the use of the BP as estimate in the mine-to-plan compliance reconciliation process, it had to meet certain minimum requirements in terms of quality, spatial nature and granularity of outputs. Firstly, the BP should be a **quality plan**. The quality and integrity of the plan was ensured through various governance processes. Internal and external reviews were conducted focusing on the quality of the input parameters used, the quality of the mine planning process itself and the spatial integrity of the BP. The level of flexibility provided by the plan was a further indicator of the quality of the plan.

Secondly, the BP should provide the outputs required to effectively conduct spatial mine-to-plan reconciliation. The **typical outputs from the BP** of an open-pit iron ore mine include:

- Ex-pit mining information such as ore and waste tonnages, ore classification and qualities (chemical and physical);
- Stockpiling and re-handling of ore;
- Waste dump locations;
- HME related information such as the number of drills, loading units and haul trucks required to execute the plan;
- Plant feed information;
- Plant performance including yields; and
- Product tonnes and qualities.

For spatial mine-to-plan reconciliation purposes, the primary focus is on the spatial and ex-pit mining outputs from the BP. The minimum **spatial outputs** required from the BP were stage plans for the required measuring period (monthly) per pit, pushback (PB) and mining bench. The stage plans were typically provided in the format of a DTM indicating the areas planned for mining per month. In addition, ex-pit ore and waste tonnes for the areas between successive stage plans were calculated from the applicable mining model, which contained the appropriate geological information. These outputs were generated using mine scheduling software and a suitable General Mining Package (GMP).

Figure 4.2 provides an example of an end of period stage plan that was developed from a business planning process and could be applied in the calculation of the spatial estimate of the mining activities. The stage plan is a 3D spatial representation of the estimated position of the mining faces in this area at the end of a specific planning period. It can be

seen that the stage plan is a DTM that combines the actual mined surfaces (also referred to as the surface topography) with the surfaces generated from planned mining blocks. For illustrative purposes, this stage plan represents the estimated position of the mining faces at the end of Period X. Figure 4.3 represents the stage plan at the end of Period X+1 for the same mining area.

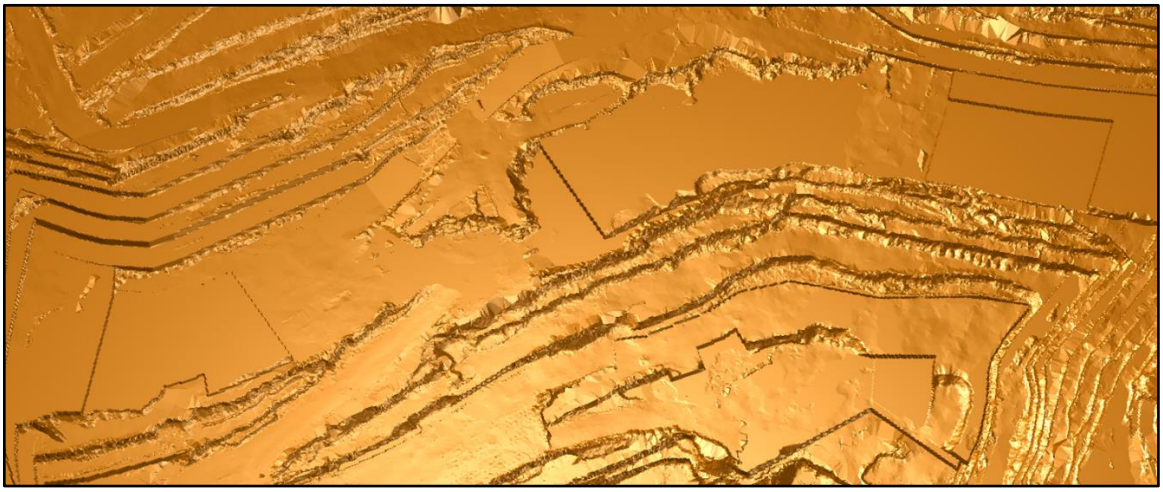


Figure 4.2. Example of a stage plan at the end of Period X

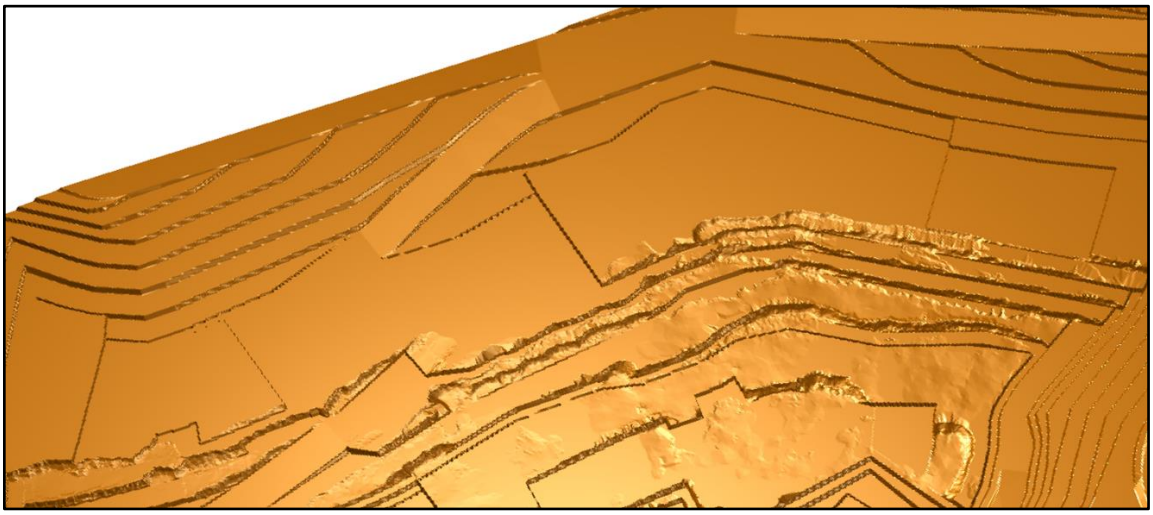


Figure 4.3. Example of a stage plan at the end of Period X + 1

In Figure 4.4 the purple hatched areas represent the planned mining for Period X +1. This is the spatial estimate of the ex-pit material (ore and waste) that is planned for mining during the period under consideration.

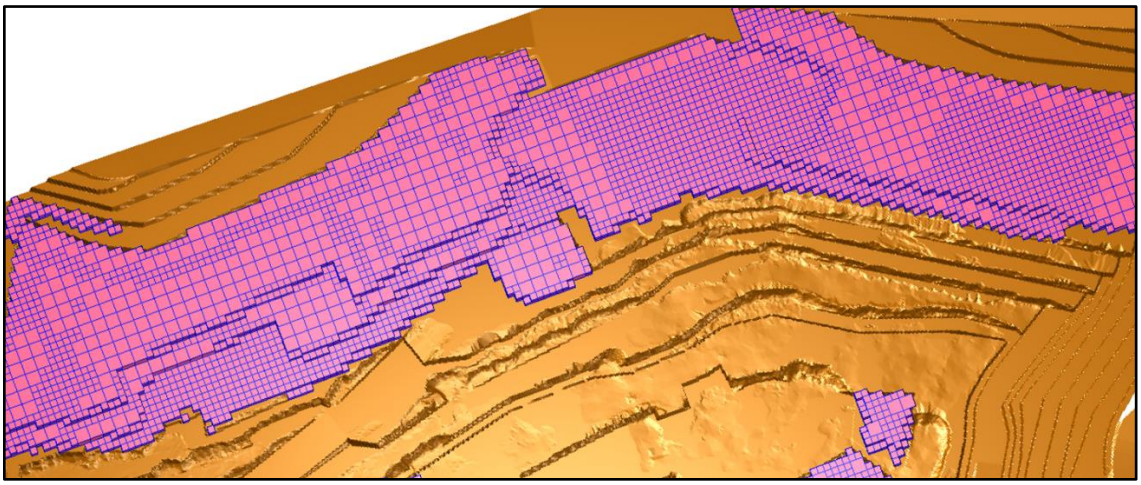


Figure 4.4. Ex-pit material planned for mining in Period X + 1

In addition to the spatial outputs from a BP, the required **temporal outputs** that represent ex-pit mining activities are waste mining, ore mining, total material mined and stripping ratio. The stripping ratio is the ratio of waste tonnes to ore tonnes for a specific period in a BP.

Throughout this chapter, where illustrative examples are used, reference will be made to Mine A. Mine A and Kolomela (which is the case study mine used to validate the spatial mine-to-plan compliance framework developed by this thesis) are two different and separate mines. Mine A is only used as an illustrative example and is in fact a single operating unit with its own trucks, infrastructure, maintenance team and drilling and blasting units. There are no external influences in the analysis caused by sharing resources from other mines. Table 4.1 is an example of the budgeted monthly ex-pit mining activities extracted from a BP of Mine A. This level of detail is not yet sufficient as input into the framework as it does not provide the spatial areas from where the tonnages are planned for mining.

Table 4.1. Example of the monthly temporal outputs from a BP of Mine A

Ex-pit mining	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	TOTAL
Planned Waste (kt)	2,268	2,878	3,210	3,469	4,332	4,444	4,627	4,627	4,627	4,564	4,564	4,389	48,000
Planned Ore (kt)	906	440	728	1,045	1,045	1,135	1,135	1,135	1,135	1,135	1,135	1,025	12,000
Planned Total (kt)	3,174	3,318	3,938	4,515	5,378	5,580	5,762	5,762	5,762	5,700	5,700	5,414	60,000
Planned Stripping Ratio (t/t)	2.50	6.54	4.41	3.32	4.15	3.92	4.08	4.08	4.08	4.02	4.02	4.28	4.00
Cum Planned Waste (kt)	2,268	5,147	8,357	11,826	16,159	20,603	25,230	29,856	34,483	39,047	43,611	48,000	
Cum Planned Ore (kt)	906	1,346	2,073	3,118	4,163	5,299	6,434	7,569	8,704	9,840	10,975	12,000	
Cum Planned Total (kt)	3,174	6,492	10,430	14,945	20,322	25,902	31,664	37,425	43,187	48,887	54,586	60,000	
Cum Planned Stripping ratio (t/t)	2.50	3.82	4.03	3.79	3.88	3.89	3.92	3.94	3.96	3.97	3.97	4.00	

The framework requires a BP that provides detail on the planned ex-pit mining activities per geographic area in the mine. This is a further refinement of the combined monthly ex-pit mining activities of the whole open-pit mine. The geographical areas in an open-pit iron ore mine are typically defined using the following levels: from the lowest level a number of benches will constitute a pushback, a number of pushbacks will constitute a pit and a number of pits will form the mine. Table 4.2 provides an illustrative example of this hierarchy for the total ex-pit material planned for Mine A. Ex-pit mining takes place in five to seven different geographical areas in any given month. A BP that provides this level of granularity on the required spatial deployment of the mine is critical for the effective functioning of the framework.

Table 4.2. Example of the total ex-pit material planned from the BP of Mine A per geographical area

			Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Mon. 10	Mon. 11	Mon. 12	TOTAL
Pit A	Pushback 1	Bench 6	727	98	758	237	200	-	-	-	-	-	-	-	2,020
		Bench 7	-	-	-	-	-	417	315	544	600	253	262	131	2,522
	Pushback 2	Bench 4	910	724	638	1,696	-	-	-	-	-	-	-	-	3,967
		Bench 5	-	-	-	-	1,320	1,259	1,650	1,532	400	-	-	-	6,161
		Bench 6	-	-	-	-	-	-	-	-	648	694	397	515	2,254
	Pushback 3	Bench 2	650	890	1,041	1,053	-	-	-	-	-	-	-	-	3,634
		Bench 3	-	-	-	-	2,057	1,946	1,776	1,601	1,972	2,374	1,000	1,000	13,726
		Bench 4	-	-	-	-	-	-	-	-	-	-	1,030	1,435	2,465
	Pushback 4	Bench 1	104	367	344	380	393	380	393	393	380	393	380	393	4,300
Pit B	Pushback 1	Bench 8	-	535	457	473	-	-	-	-	-	-	-	-	1,465
		Bench 6	-	-	-	-	477	538	579	702	522	502	508	30	3,858
	Pushback 2	Bench 5	783	704	700	-	-	-	-	-	-	-	-	-	2,187
		Bench 4	-	-	-	676	931	1,040	1,049	990	1,240	1,484	2,123	1,908	11,441
			3,174	3,318	3,938	4,515	5,378	5,580	5,762	5,762	5,762	5,700	5,700	5,412	60,000

4.3.3 Capturing actual mining progress (Component 2)

The second component of the framework involved the capturing of the actual spatial mining progress through periodic measurements. The effective capturing of actual spatial mining progress at an open-pit iron ore mine ensured the accurate and timely generation of “as mined” surfaces and DTMs at the required quality. In most open-pit iron ore mines, survey departments are responsible for capturing and evaluating actual mining progress.

Surveyors make use of appropriate data collection tools, technology and software to produce DTMs representing the *measured* mining activities against which the spatial estimate from the BP can then be compared. These survey measurements are typically used to determine the volume expressed in bank cubic meters (BCM) and tonnage that was mined in a specific period (for example, a production month).

The spatial mine-to-plan compliance reconciliation process and the framework put forward in this thesis can only be effective when open-pit mines capture and record the actual spatial mining progress accurately and in a timely manner. Figure 4.5 provides a high-level overview of the **survey process** that should be conducted at open-pit mines to capture the actual mining activities for further application in the framework. The five major activities in the open-pit survey process are: pit measuring, scan registration, scan processing, production calculations and reporting.

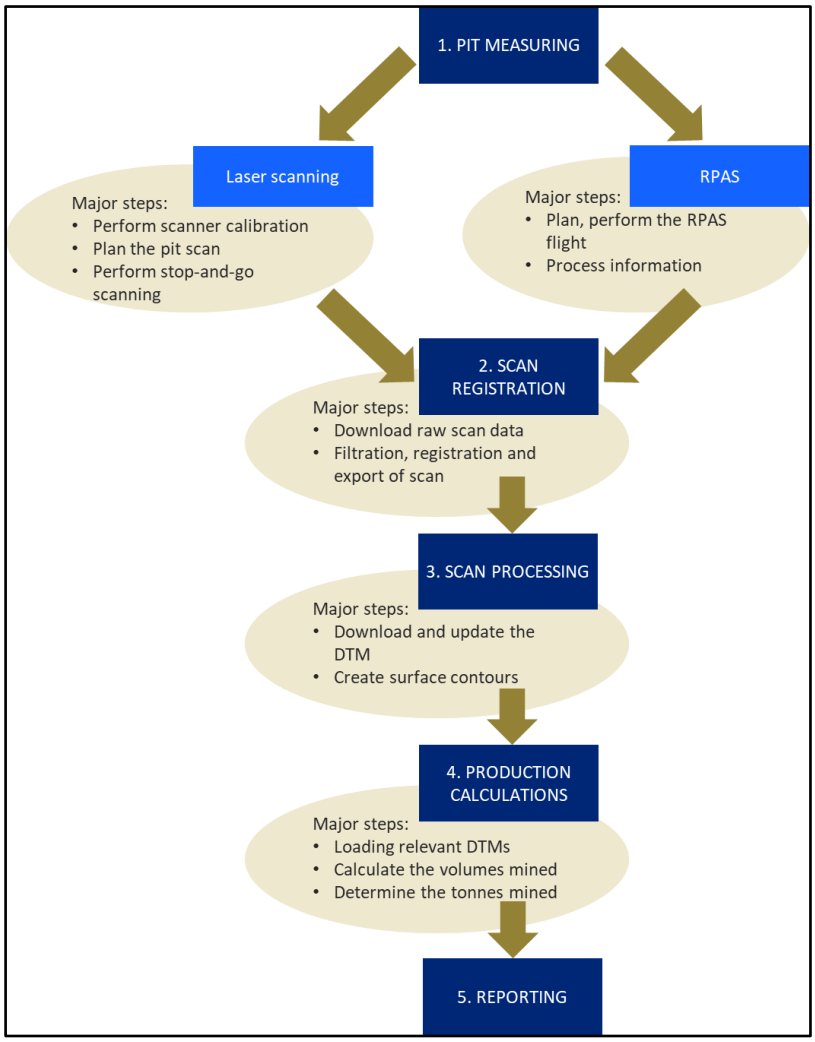


Figure 4.5. Typical survey process at an open-pit mine

Pit measuring involves survey data collection through laser scanners and / or the application of drones. On most open-pit mines data acquisition involves the use of laser scanners to conduct month-end ex-pit production measuring surveys. Riegl and Maptek scanners meet the minimum requirements for the spatial accuracy of surveyed data points and are used at Mine A. Scanners and associated GPS equipment should be checked and calibrated on a weekly basis to ensure their spatial accuracy is within 50mm. Although GPS and Total Stations are also utilised on some sites, laser scanning technology is preferred due to its speed, accuracy, density of survey points captured and the ability to effortlessly work in a 3D environment.

The laser scanning process involves the continuous scanning of open-pit working areas during the production month and again at month end. The working areas are typically scanned in a stop-and-go mode from three positions to ensure that an accurate spatial registration of the scanned data as well as complete coverage of the working areas can be achieved. These working area scans are then registered, and a report is generated which states the spatial accuracy achieved for the scans. The ultimate output of the data

collection through scanners is a point cloud. Figure 4.6 shows a laser scanner mounted on a light vehicle in preparation for a stop-and-go scan of an open-pit mine.



Figure 4.6. Laser scanner mounted on an LDV

In recent years the technology associated with drones has matured to the extent that drones or RPAS now offer a practical alternative for data collection to surveyors on open-pit mines. The planning of the RPAS flight will depend on the type of sensor that will be used for the survey. The following two sensor options could be considered: camera or LiDAR. When using a camera, the flight path should be planned to ensure that a side lap of 65% and an overlap of 70% for the photos are achieved. The flight path must include a transect flight line cross-cutting the other lines. A minimum of four ground control points spaced not more than 200m apart are planned if the RPAS is not equipped with Post Processing Kinematic (PPK) capability. The number of flights will depend on the RPAS endurance, flying height and size of the area to be surveyed. When using a LiDAR, the flight path is planned to ensure that a 20% overlap of the swath width of the LiDAR is achieved. The flight path must also include a transect flight line cross cutting the other lines. The speed and flying height will be planned to ensure an optimum point density. No ground control points are required as the LiDAR is equipped with an Inertial Measuring Unit (IMU). A GPS base station must be setup within 10km of the flight area.

In South Africa, all RPAS flights must comply with the requirements as set out in the RPAS Operators Certificate (ROC) issued by the Civil Aviation Authority (CAA) of South Africa. The RPAS Ground Control Station is continuously monitored to ensure compliance with

the planned flight path. The processing of the RPAS flight data also depends on the type of sensor that was used for the survey. When using cameras, a suitable photogrammetry software such as *Pix4D* or *Agisoft* is used to “stitch” the individual photos together and spatially link them to the ground control points through a process known as Aerial Triangulation. The photogrammetry software is then used to generate a point cloud from the photo. When using LiDAR, a suitable software such as *Post Pac* is used to spatially correct the trajectory of the IMU utilising the base station. The point cloud captured by the scanner during the flight is spatially corrected by linking it with the spatially corrected trajectory and made available for further use. Figure 4.7 shows a rotor wing RPAS unit with a LiDAR scanner mounted to the drone preparing for take- off.



Figure 4.7. RPAS fitted with LiDAR unit

Table 4.3 provides a high-level comparison of the advantages and disadvantages associated with the use of LDV mounted laser scanners and RPAS as survey data collection tools.

Table 4.3. LDV mounted laser scanning vs. RPAS for survey data collection

	Laser scanner	RPAS
Advantages	• Limited legislative requirements. • Unlimited endurance. • Limited impact from environmental conditions.	• Extensive line of sight is easily achievable (vertical from the air to the ground). • Safety – limited LDV and HME interaction is required. • Easy to operate - is controlled by the ground control station. • Does not require periodic calibrations. • Low initial capital cost. • Can be fitted with various sensors such as cameras, thermal cameras and LiDAR.
Disadvantages	• Extensive LDV and HME interaction is required. • Limited line of sight can be achieved (horizontal from LDV to loading face). • Requires constant control from surveyor. • Weekly calibrations are required. • Can only be fitted with a single sensor – LiDAR. • High initial capital cost	• Extensive operating processes to comply with legislative requirements. • Can be impacted by environmental conditions such as strong winds. • Limited endurance.

Once the data acquisition process is complete the **scan is registered**. The raw scan point cloud files are exported from the LiDAR scanner and all the raw scan point cloud files are transferred. The scan is registered and assigned to the correct coordinate system. Various quality and accuracy checks are performed on this first point cloud. Now a boundary is created around the required points in the point cloud, for example, a loader's loading area.

Figure 4.8 represents a point cloud generated from a survey scanning exercise also indicating the scanning locations.

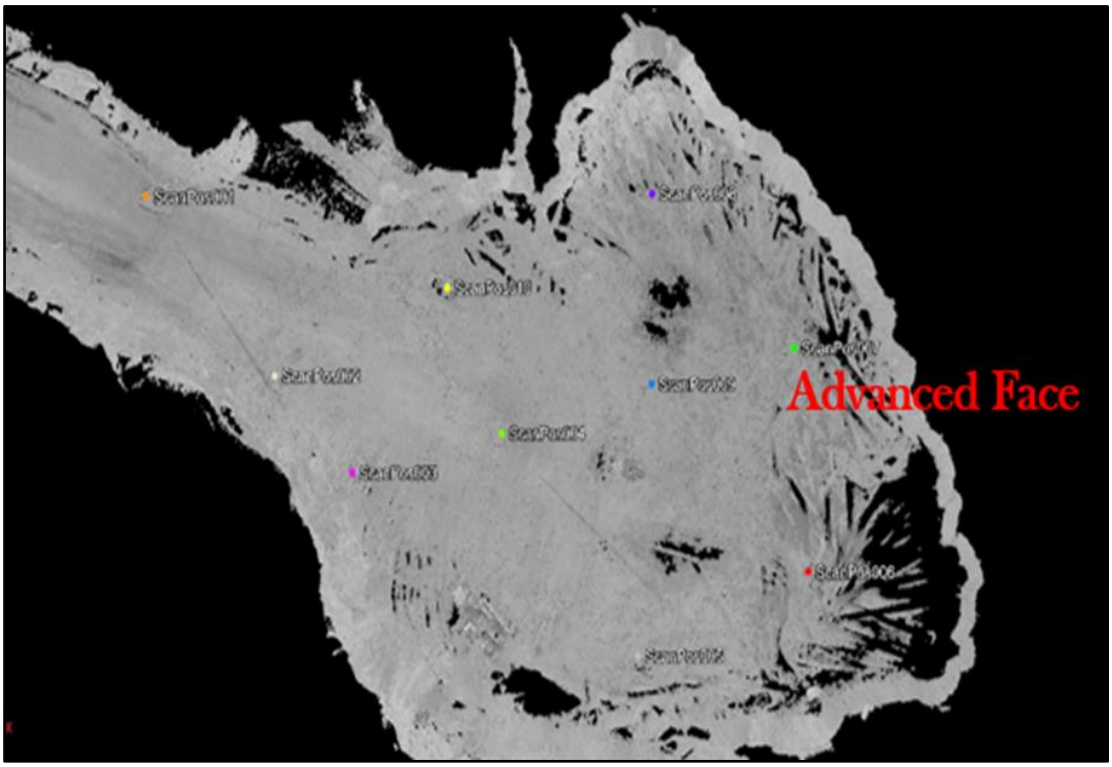


Figure 4.8. Point cloud with scanning locations

The survey DTM or “as mined” surface of the pit is generated by combining all the relevant and selected point clouds. The survey DTM represents the actual pit surface at the time of measurement. **Scan processing** involves combining several point clouds to form a DTM of a mining area. The DTM is processed by grouping the points in the DTM into classes, deleting all the points classified as non-ground and retain only the points classified as model key points. Finally, a surface model and surface contours are created from the DTM.

Figure 4.9 illustrates two DTMs of the same open-pit mining area representing two consecutive survey periods and showing the progress of the mining face towards the west (left) of the DTM.

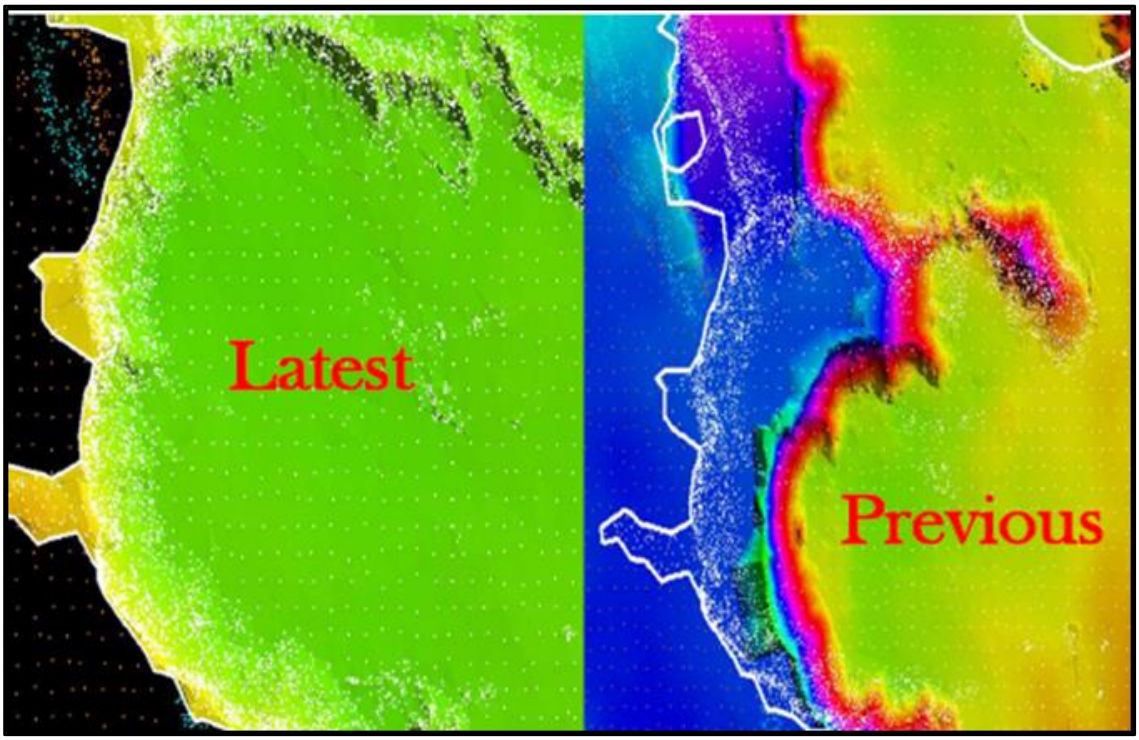


Figure 4.9. Consecutive DTMs of open-pit mining areas

Production calculations and reporting can now be performed. By comparing two sequential DTMs (i.e. the latest survey DTM with the DTM developed at the start of the measuring period), areas where mining took place can be identified. These two sequential month-end DTMs are used for volume calculations. The volume calculations are done on a mining block basis and then combined to represent bench volumes, pushback volumes and ultimately the volume of material mined in the period under consideration. As a check, all the mined blocks in an area are selected, the cumulative volume recalculated and compared to the sum of the volumes from the individual mining blocks. Finally, the volumes are converted to tonnes based on the relative density of the material demarcations against which the survey measurement was calculated.

The actual or measured mining performance, as determined by the survey process, can now be compared to the requirement or estimate from the BP as part of the performance tracking process employed at most open-pit mines. This essentially answers the question: Did the operation mine the tonnages that were planned to be mined in the period under consideration? It is a typical example of a temporal reconciliation process. As discussed before, the achievement of the BP tonnes is a critical KPI for the management of an open-pit mine. When the measured mining performance exceeds the BP targets, mine

management are typically congratulated and when the measured mining performance is below the BP targets, tough conversations take place and a recovery plan is often put forward.

The temporal reconciliation of planned *vs*. actual tonnes mined is a necessary component of the management process at all successful open-pit iron ore mines. However, tracking and managing this KPI without considering the spatial aspects of the mining activities could have negative consequences on future ore supply and the sustainability of the open-pit mining operation in the longer term. The results of such a temporal reconciliation provide limited information on where the actual mining took place and how this compares to the mining areas planned in the BP. The temporal reconciliation of ex-pit mining does not provide a visual indication of the spatial locations of mining activities. Therefore, it is difficult for mine management to assess the effectiveness of waste stripping in providing access to future ore mining areas or facilitating planned in-pit dumping activities as well as the effectiveness of ore mining activities targeting planned ore types and qualities.

The survey measurement is spatial in nature; i.e. the results are associated with specific mining areas, mining pushbacks and mining benches. The spatial nature of the survey measurement is used for volume calculations and reporting of actual tonnes mined. However, these spatial attributes of the survey information are not generally used outside of the survey discipline. The framework took advantage of the spatial nature of the survey DTMs and applied these actual mined surfaces as the measured spatial mining activities for the period under consideration.

4.4 Spatial mine-to-plan compliance reconciliation (Component 3)

4.4.1 Introduction to mine-to-plan reconciliation

The third component of the framework represented the reconciliation of the spatial mining areas planned in the BP (estimate) with the actual spatial mining progress (measurement) captured by the surveyors. The reconciliation approach (including definitions, categories and expressions) compared the areas planned for mining (estimate) with the actual measurement of areas mined. This was a four-dimensional reconciliation – accounting for open-pit mining in 3D space and for temporal aspects; i.e. the reconciliation was done considering a defined time period. This section covers the following aspects: the reconciliation methodology, categories and definitions, mathematical expressions, target setting and reporting formats. It will be shown how the framework addressed the knowledge gaps and limitations identified during the literature review of the two identified

spatial mine-to-plan compliance reconciliation approaches (discussed in Section 2.5.3 of the thesis).

It is important to re-emphasise that the introduction of spatial mine-to-plan compliance reconciliation was not aimed at replacing temporal and other value chain related reconciliation practices. The introduction of spatial mine-to-plan compliance reconciliation enhanced the effectiveness of the overall reconciliation effort at open-pit iron ore mines, specifically, contributing to a deeper understanding of the spatial aspects of the open-pit mining activities compared to the BP.

4.4.2 Basic reconciliation methodology

The basic methodology employed was to compare tonnes (instead of area or volumes) mined (measured) in the relevant mining areas, pushbacks and benches with tonnes planned for mining (estimate). Using tonnes as the basis for the spatial reconciliation accounted for the 3D nature of open-pit iron ore mining and spatial density variations between planned and actual areas mined. It further provided a measurement that could be compared with other temporal mining performance metrics. This comparison was done by firstly importing the relevant stage plans from the BP (estimate) into a GMP and determining the planned ore and waste tonnages between the applicable stage plans using the appropriate geological information. Secondly, the relevant survey DTMs (measurement) were imported and the actual ore and waste tonnages determined using the same geological information. Thirdly, the tonnes associated with the intersection and overlap of the two sets of tonnage information in 3D space were calculated.

Figure 4.10 is a high-level flow diagram illustrating the different steps followed in the spatial mine-to-plan compliance measurement process to determine the intersections and overlaps between planned and actual mining areas in 3D space.

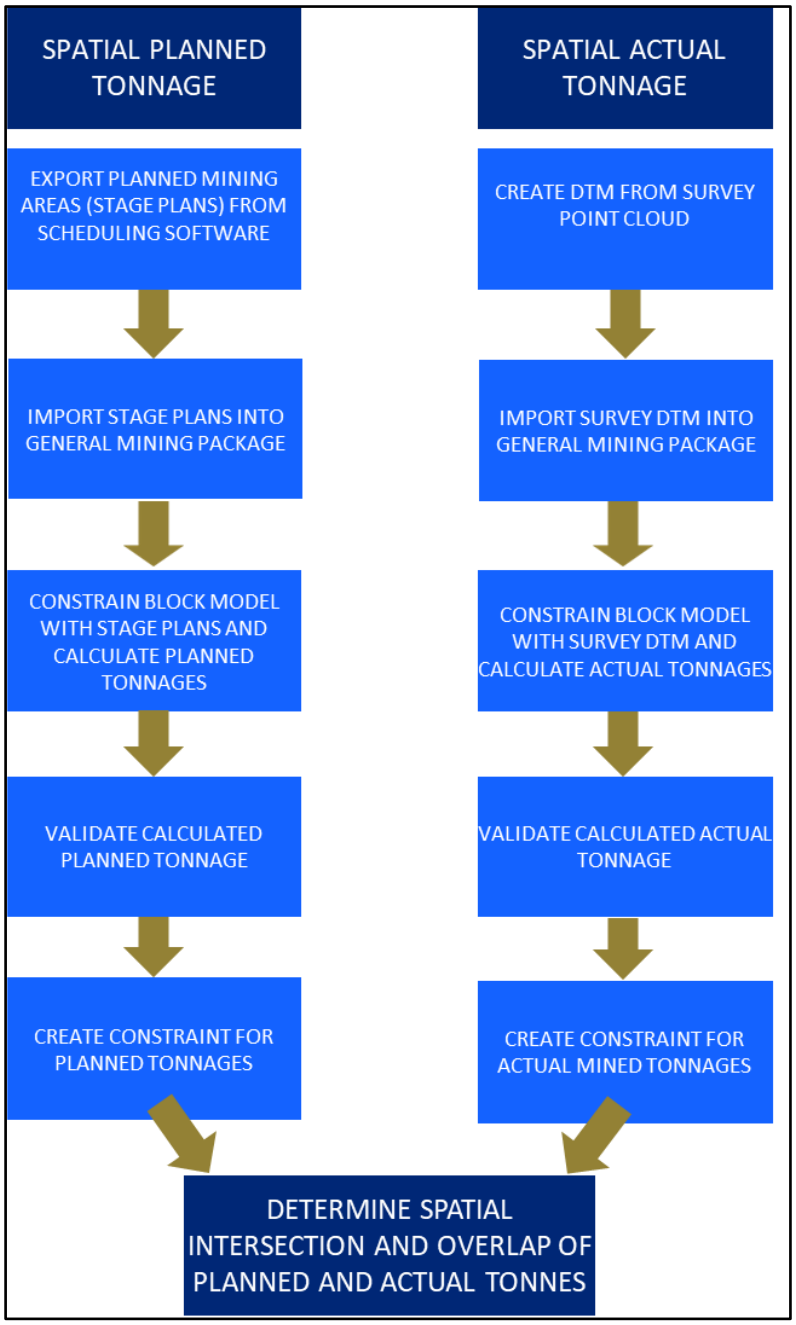


Figure 4.10. Mine-to-plan compliance measurement process flow

Once the annual BP was approved, the planned areas could be exported from the scheduling software in the form of monthly stage plans. These areas represented the estimates of where the mining faces should be at the end of a specific month as a result of the planned mining deployment strategy and the rates being used for the loading equipment. The spatial location of the planned tonnage, assocated with these areas, was calculated on a cummulative basis. Using Month 6 as an illustrative example, the spatial location of the planned tonnage between the start of Month 1 and the end of Month 6 was calculated using the repective stage plans from the scheduling software. The tonnage was calculated by constraining the block model between the two relevant stage plans. This process was repeated for every consecutive month of the year. Validation was done to

ensure that all planned mining areas were accounted for, in-pit dumping areas were correctly handled and the planned and actual starting positions were aligned. At the end a constraint was created in the block model called “Planned tonnage – Month X”.

The spatial attributes for the actual mined tonnage were determined by constraining the same block model between the two relevent survey DTMs on a cummulative basis. Following a validation exercise, the tonnages associated with these actual mining areas were reported. A second constraint called ”Actual mined – Month X” was created. Figure 4.11 represents an example of the spatial nature of actual mining activities in a typical open-pit iron ore mine.

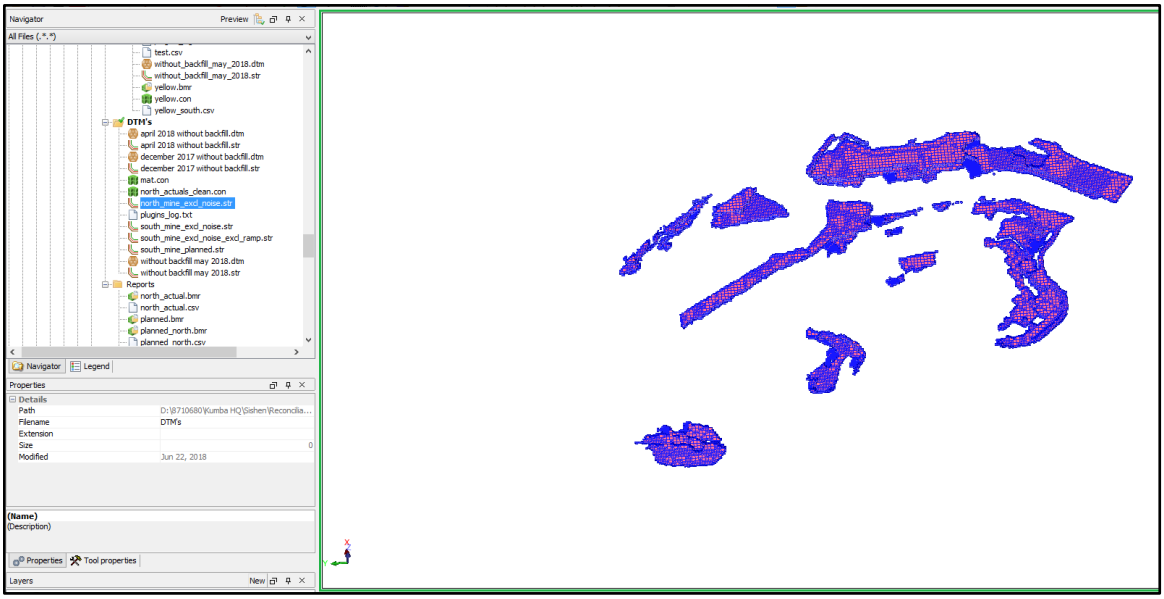


Figure 4.11. Example of a block model constraint for actual mining activities

Now that the spatial attributes of the planned and actual mining activities have been captured, the next section of the thesis will elaborate on the categories and definitions used to reconcile these two sets of information.

4.4.3 Spatial categories and definitions

The framework defined a comprehensive set of categories for spatial mine-to-pan reconciliation to be conducted effectively. These categories were used to describe the relationships between tonnages from areas planned for mining and tonnages from actual areas mined. The overlap and intersection between actual and planned mining tonnages were divided into four main spatial categories namely:

1. tonnages from areas mined in plan and in sequence;
2. tonnages from areas mined in plan and out of sequence;

3. tonnages from areas mined out of plan; and
4. the resultant tonnages from planned areas not mined.

This comprehensive set of spatial mine-to-plan categories addressed the knowledge gaps identified in existing literature describing current approaches to spatial mine-to-plan compliance reconciliation. Firstly, the categories enhanced the “areas of overlap” concept introduced by Angelov and Naidoo (2010) for application in underground coal mines by including categories for areas mined out of plan and planned areas not mined. Secondly, the categories improved the “mined in plan” definition proposed by Morley and Arvidson (2017) by introducing two new components namely, “planned and mined in sequence” and “planned and mined out of sequence” activities. This is to address the cumulative aspect of tactical mine planning.

The introduction of the concepts of “in sequence” and “out of sequence” mining as subsets of mining within the BP provided the ability to further analyse the areas mined in plan. This allowed distinguishing between areas where actual mining took place ahead of the BP sequence at a specific point in time, but still within the larger BP areas (planned and mined out of sequence) and areas where actual mining took place completely outside of the areas targeted by the BP (areas mined out of plan). The spatial reconciliation was therefore, done considering both the total (or annual) area planned by the BP and the incremental (or monthly) areas planned within the larger BP. Actual mining was classified as “in sequence” when it took place within the areas planned in the tactical plan up to the date of measurement. Actual mining was classified as “out of sequence” when it took place within the areas planned in the BP, but after the date of measurement. As an example, for the reconciliation process conducted at the end of Month 6 of a specific year, all actual mining activities that took place in areas planned for months one (1) to six (6) are classified as “in sequence”. Actual mining activities that took place in areas planned for months seven (7) to twelve (12) are classified as “out of sequence”.

The categories applied when reporting spatial mine-to-plan compliance are described in Table 4.4 and illustrated in conceptual plan views in Figures 4.12 to 4.14.

Table 4.4. Description of spatial categories for calculating spatial mine-to-plan compliance (Otto and Musingwini, 2019)

Spatial category	Description	Colour code
Mined in plan and in sequence	Tonnes from areas that were planned to be mined and were mined in sequence.	Green
Mined in plan out of sequence	Tonnes from areas that were planned to be mined but were mined out of sequence.	Yellow
Mined out of plan	Tonnes from areas that were mined completely outside of the tactical plan.	Red
Planned not mined	Tonnes from areas that were planned to be mined but not mined.	Brown

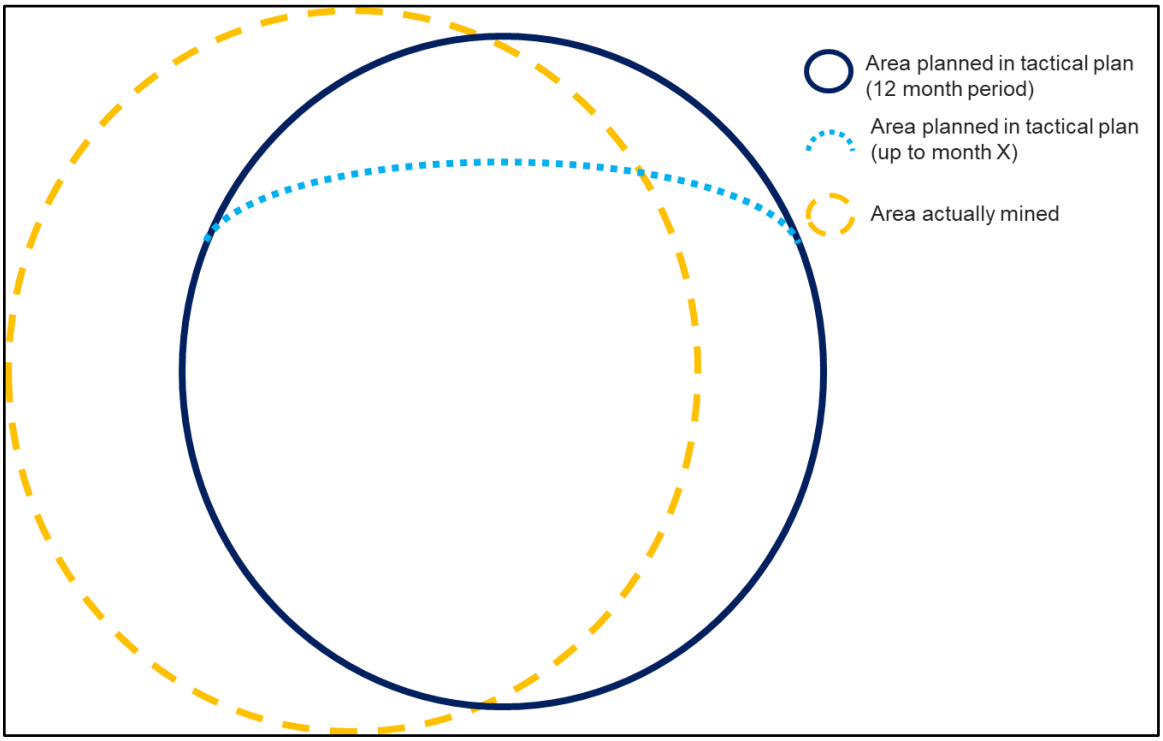


Figure 4.12. Conceptual view of planned and actual mined areas

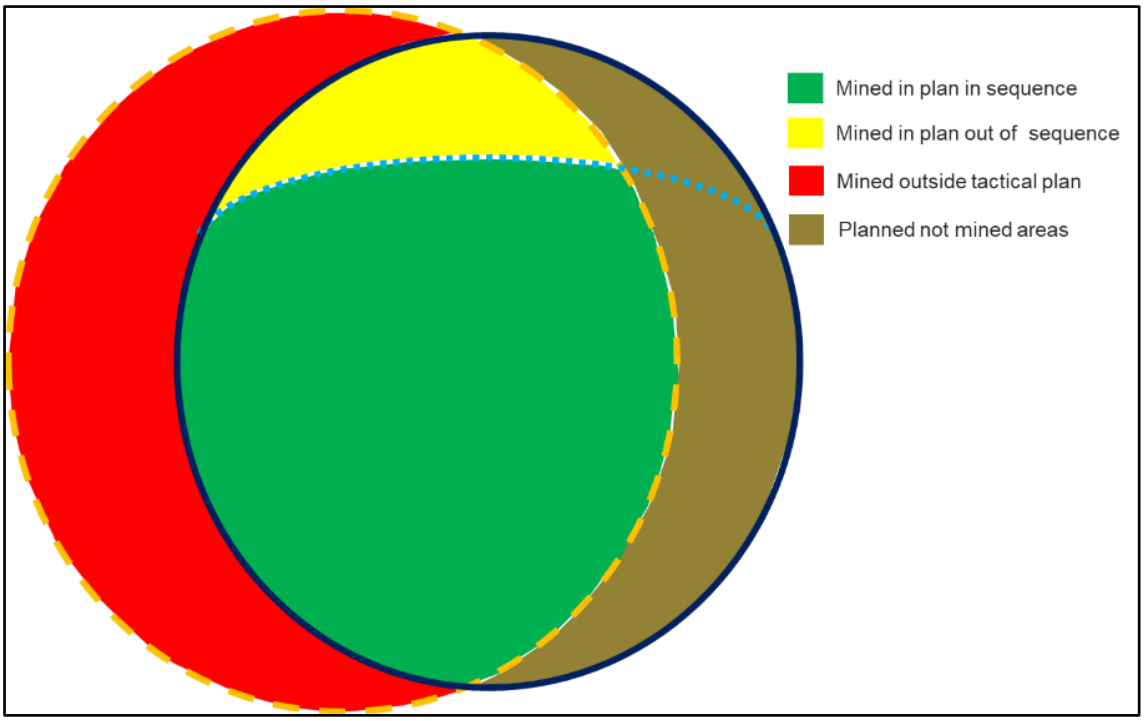


Figure 4.13. Conceptual view of spatial mine-to-plan compliance categories

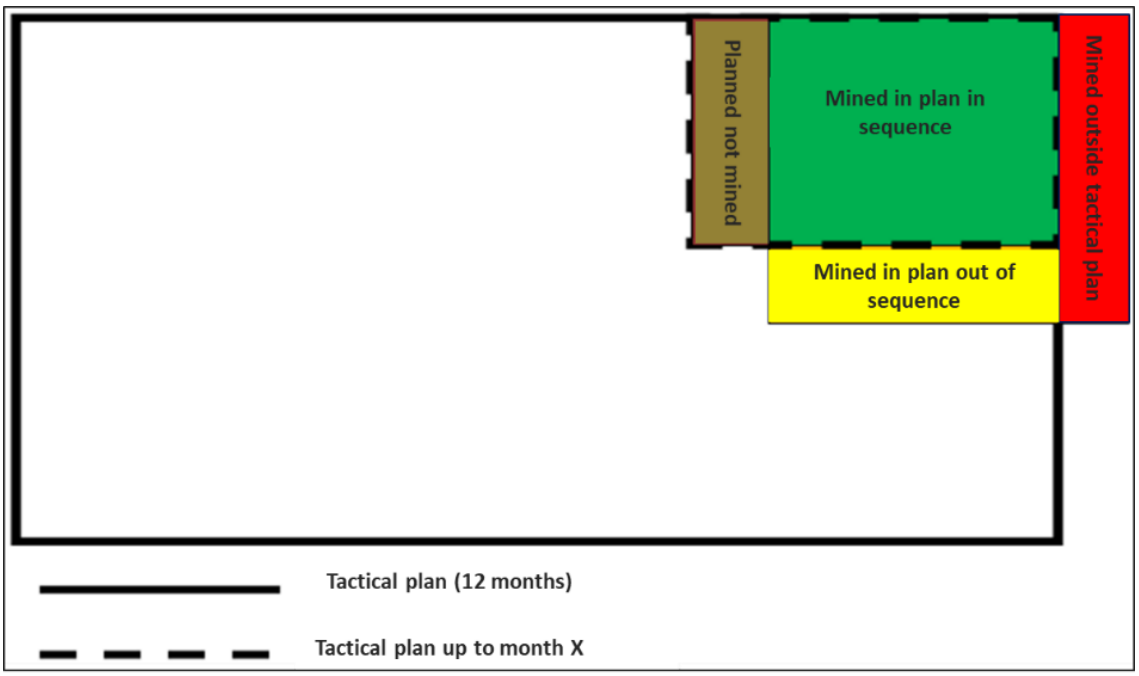


Figure 4.14. Plan view of spatial categories for calculating spatial mine-to-plan compliance following the actual mining of month X (Otto and Musingwini, 2019)

When considering a specific mining area, for example a mining bench, that was loaded out in Month X, Table 4.5 provides a practical spatial mine-to-plan categorisation approach.

Table 4.5. Practical spatial mine-to-plan categorisation approach

Criteria				Spatial category	
Mined (Actual)	Planned in BP before month X	Planned in BP after month X	Not in Plan		
X	X			Mined in plan and in sequence	Green
X		X		Mined in plan out of sequence	Yellow
X			X	Mined out of Plan	Red

The spatial mine-to-plan reconciliation measurement was calculated per spatial mine-to-plan category per mining area as an ore and waste tonnage. Once the tonnages from the planned and actual spatial mining areas had been determined for the period under review, the following main steps were required to classify these tonnages into the four defined categories:

- Firstly, start with the areas in the constraint called “Actual mined – Month X” (actual mined out areas) and further constrain these areas with the relevant stage plans from the BP.
- Secondly, determine the tonnages mined out of plan (Red) by constraining the actual mined out areas with the end of the BP (end of Month 12) stage plan to determine what areas were mined outside of the BP by identifying areas below the end of Month 12 stage plan.
- Thirdly, determine the tonnage mined in plan out of sequence (Yellow) by again starting with the actual mined out areas and removing the areas mined out of plan (Red) as defined in the previous step. The areas remaining reflect all the areas that were mined in plan (in sequence and out of sequence). Now constrain these areas by showing all the areas below the stage plan for which the reconciliation is conducted (Month X).
- Fourthly, determine the tonnages mined in plan and in sequence (Green) by also starting with the actual mined out areas and removing the areas mined out of plan (Red) as well as the areas mined in plan out of sequence (Yellow). The remaining areas now reflect the areas that were mined in plan and in sequence. Validate the calculations up to this point by comparing the sum of the tonnages calculated for these three (3) categories with the actual mined tonnages – there should be no variance.

- The final step is to calculate the planned not mined tonnages (Brown). Now start with the areas in the constraint called “Planned tonnage – Month X” (planned mining areas) and remove all the areas in the constraint for defining actual mined out areas. The remaining areas reflect the cumulative areas that were planned to be mined, but not mined by Month X. Validate the calculation by comparing the planned, but not mined tonnages with the difference between the planned tonnage and the mined in plan and in sequence tonnes.

4.4.4 *Metrics, mathematical expressions and target setting*

The framework employed a holistic set of metrics to ensure that the mine-to-plan compliance reconciliation results were expressed accurately and allowed for benchmarking across different open-pit iron ore mines. The metrics and supporting mathematical expressions were designed to ensure effective communication and reporting of the spatial mine-to-plan reconciliation results to mining operational personnel and senior management. The aim was to facilitate the interpretation of the reconciliation results, enable comparisons to agreed targets and provide the ability to assess performance relative to other iron ore mines. The knowledge gaps, identified during the literature review of current spatial mine-to-plan reconciliation approaches, were also addressed. Although the metrics were historical in nature, the ultimate value of the spatial mine-to-plan reconciliation measurement was that it facilitated the management of improved future spatial mine-to-plan compliance through the implementation of corrective actions to be able to catch up with the identified KPIs in terms of both ore and waste mining according to the mine plan.

The following metrics were defined as part of the development of the framework:

- **Production compliance** as a measure of the total actual mined (in and out of plan) as a percentage of the BP estimate for the period under review (temporal metric);
- **Adherence index** as a measure of actual mined in plan (in sequence and out of sequence) as a percentage of total actual mined;
- **Spatial mine-to-plan compliance index 1** is a measure of actual mined in plan (in sequence and out of sequence) compared to the BP estimate; and
- **Spatial mine-to-plan compliance index 2** is a measure of actual mined in sequence compared to the BP estimate.

The main purpose of each of the defined metrics can be summarised as follows:

- Production compliance is a temporal reconciliation metric which provides insight into the performance of the actual ex-pit mining activities at an open-pit iron ore mine relative to the activities planned in the BP for the period under review, i.e. were the actual cumulative ex-pit mining tonnes after Month X above or below the BP target?
- The Adherence index introduces the spatial aspect to the reconciliation results by expressing the actual mining that took place in the areas planned in the BP (mined in plan in sequence and mined in plan out of sequence) as a percentage of the total actual ex-pit mining activities. This provided an indication of how much of the actual mining activities took place in planned areas.
- The first spatial mine-to-plan index is a combination of the previous two metrics describing the actual mining that took place in the areas planned in the BP (mined in plan in sequence and mined in plan out of sequence) as a percentage of the planned mining activities.
- The second spatial mine-to-plan index differentiates between mined in plan in sequence and out of sequence mining by expressing the actual mining that took place in line with the sequence of the BP as a percentage of the planned mining activities. When reporting the final year-to-date spatial mine-to-plan compliance (at the end of the annual BP period), the two mine-to-plan indices are the same as no out of sequence mining is possible.

The mathematical expressions associated with these metrics were derived by applying the tonnages per spatial mine-to-plan category, as defined before, in straight forward formulae and expressed as percentages. The formulae for calculating each of the four metrics using tonnes (t) monthly against the BP, are provided in Equations 4.1 to 4.4.

$$Production\ compliance = \frac{Total\ actual\ mined}{BP\ estimate} \quad (4.1)$$

$$Adherence\ index = \frac{Mined\ in\ plan\ in\ sequence + Mined\ in\ plan\ out\ of\ sequence}{Total\ actual\ mined} \quad (4.2)$$

$$Spatial\ mine-to-plan\ index\ 1 = \frac{Mined\ in\ plan\ in\ sequence + Mined\ in\ plan\ out\ of\ sequence}{BP\ estimate} \quad (4.3)$$

$$Spatial\ mine-to-plan\ index\ 2 = \frac{Mined\ in\ plan\ in\ sequence}{BP\ estimate} \quad (4.4)$$

In Section 2.5.2, it was noted that Kear (2006) proposed a spatial mine-to-plan reconciliation approach that could generate useful metrics such as a mine-to-plan index. The comprehensive set of metrics and mathematical expressions (including spatial mine-to-plan indexes) developed by this thesis addressed this knowledge gap in existing literature. It further dealt with the practical implementation challenges identified with the application of the compliance to plan formula (Morley and Arvidson, 2017). It did so by ensuring a clear relationship between the spatial mine-to-plan compliance performance and the performance of the mine against budgeted or planned production targets thereby addressing potential conflicting temporal and spatial reconciliation results.

The simplified example developed in Section 2.5.3 was extended to illustrate the holistic reconciliation results obtained when applying the four formulae, defined as part of the measurement component of the framework, to a set of spatial mine-to-plan reconciliation results. Re-consider the previous data set in Section 2.5.3 representing cumulative planned and actual ex-pit mining activities at the end of Month X:

- Planned (budgeted) tonnages for the period: 100 tonnes
- Actual mining tonnes achieved: 110 tonnes
- Actual Mined in plan: 90 tonnes
- Actual Mined not planned: 20 tonnes
- Planned not mined: 10 tonnes

and add more detail for the actual mined in plan tonnes as follows:

- Actual mined in plan and in sequence: 70 tonnes
- Actual mined in plan out of sequence: 20 tonnes

Applying the holistic set of spatial mine-to-plan measurement formulae defined for application at open-pit iron ore mines generated the following results: The Production compliance is 110%, the Adherence index is 82%, the Spatial mine-to-plan index 1 is 90% and the Spatial mine-to-plan index 2 is 70%. This set of results can be interpreted as follows: The actual ex-pit mining activities exceeded the BP estimate by 10% for the period under consideration. Considering only production compliance this seemed to be a positive outcome. However, the adherence index of 82% is the first indication that all is not well from a spatial mine-to-plan point of view. Only 82% of the actual mining activities took place in areas planned in the BP. When comparing the spatial mine-to-plan compliance with the BP estimate, the spatial overlap between actual mining activities and the full year BP was 90% and only 70% for the BP areas planned in the cumulative period under consideration.

It should be noted that the defined metrics could be applied to various combinations of ex-pit material types and mining areas. For material types, the metrics could be calculated using the total ex-pit mining tonnes, using ex-pit waste or using ex-pit ore. For mining

areas, the metrics could cover the whole open-pit iron ore mine or could be determined for a specific geographical area of interest. The level of detail at which data is available determines the level of detail at which the metrics could be calculated as well as the applicability at different levels.

Target setting is of paramount importance for the successful management of open-pit iron ore mines in general and specifically for the management of spatial mine-to-plan compliance. Once the spatial mine-to-plan reconciliation metrics were calculated it was important, for the effective functioning of the framework, that appropriate targets were set. Existing literature did not provide any guidance on the appropriate targets to use for measuring spatial mine-to-plan compliance. In theory, a target of 100% for the spatial mine-to-plan index 1 was achievable. This would imply that all the actual mining activities took place in the areas planned in the BP, no actual mining activities were conducted ahead of plan or out of sequence. In practice, there were many potential reasons that could result in a spatial mine-to-plan index 1 of less than 100%. These will be discussed further in Section 4.5 of the thesis.

It was important to select targets that reflected industry best practice, while taking account of historic performance, levels of flexibility in the open-pit iron ore mine as well as practical considerations. For the framework developed by this thesis the following targets were selected. The target for production compliance was 100% implying that the open-pit iron ore mine has the mining capacity available to achieve the mining activities (tonnes) planned in the BP. An adherence index of 90% was viewed as acceptable. This meant that a maximum of 10% of the actual mining activities could take place outside of the areas planned in the BP. The target of spatial mine-to-plan index 1 was therefore also 90% while the target for in sequence mining represented by spatial mine-to-plan index 2 was defined quarterly and builds up from 60% to 90%. These targets are cumulative, and compliance was tracked against the targets monthly.

4.4.5 Reporting

The effective functioning of the framework required that the results of the measurement of spatial mine-to-plan compliance against the BP are reported on a monthly basis using the categories and metrics described above. It is important to note that the spatial mine-to-plan compliance reporting is essentially re-set with the introduction of the new annual BP typically in January of every year (the specific month will depend on the mine planning cycle). Again, it should be noted that the level of detail at which reports are generated was dependent on the level of material class and geographic area data that is available.

The reporting format consisted of three types of reports. Firstly, an executive summary report providing a high-level overview of the cumulative spatial mine-to-plan compliance performance for the YTD. This report contained a summary of the results achieved for the four metrics defined above and provided consolidated results at a company or regional level where the performance of individual mines is weight averaged. Secondly, monthly graphs where the two spatial mine-to-plan compliance indices were expressed using the four categories defined before. This allowed for the evaluation of the YTD spatial mine-to-plan compliance results as well as an assessment of trends in the spatial mine-to-plan compliance performance over the YTD period. Figures 4.13 and 4.14 provide illustrative examples of the graphs used for reporting of spatial mine-to-plan compliance on a cumulative monthly basis.

When analysing the information provided in Figure 4.15, the following interpretation can be made using the spatial mine-to-plan compliance data. The actual tonnes mined for the 7-month period is 97% of the planned tonnes (Production compliance = 97%). There is a 72% overlap between the actual mining activities and the areas planned to date (Spatial mine-to-plan index 2 = 72%). Adding the 14% out of sequence mining implies that there is an 86% overlap between the actual mining activities and the areas planned in the full year BP (Spatial mine-to-plan index 1 = 86%). Finally, 11% of mining took place in areas outside of the BP (mined out of plan). The monthly trend provides further insight into month-on-month changes in the compliance to the tactical mine plan.

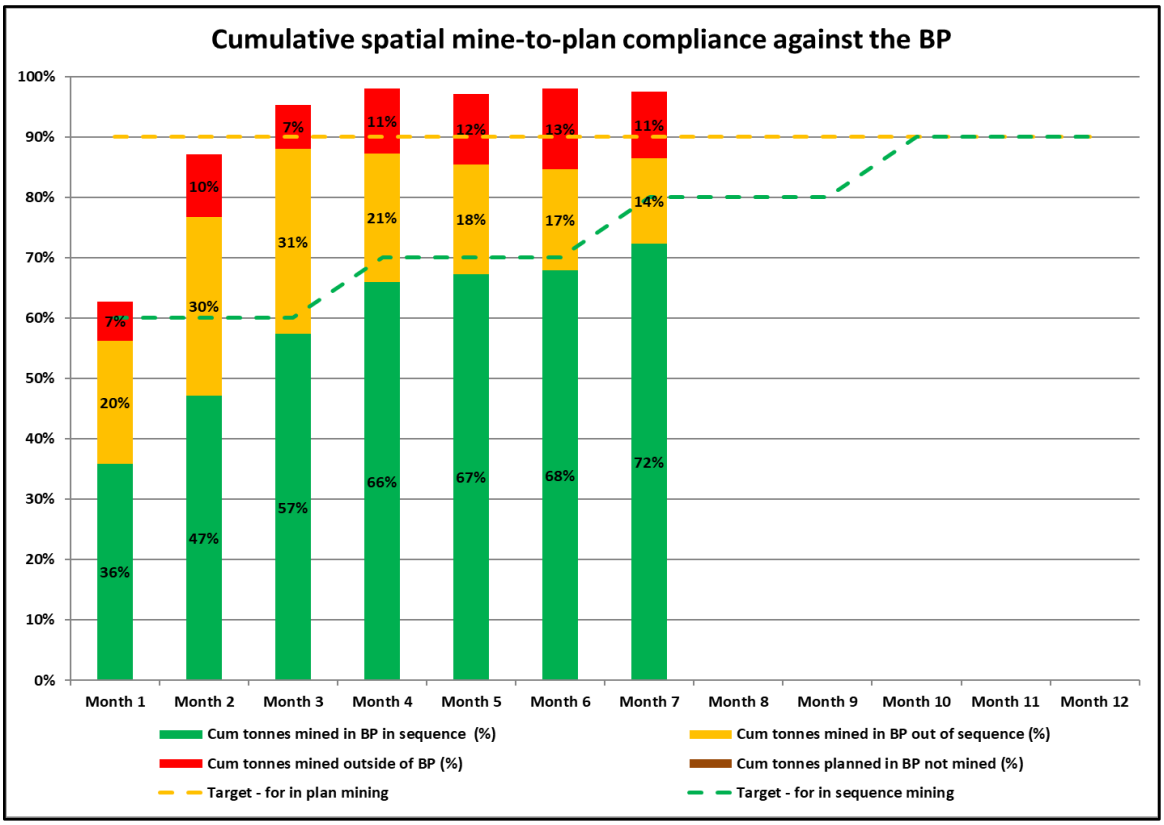


Figure 4.15. Graphical reporting of spatial mine-to-plan compliance

The major implication of below target spatial mine-to-plan compliance was the fact that planned areas were not mined. This means that mining capacity was not applied spatially in line with the BP. In Figure 4.16 the areas planned in the BP, but not mined are indicated as negative percentages. Mathematically, the planned but not mined areas has an inverse relationship with the areas mined in plan in sequence. The planned but not mined areas play a significant role in the framework as these areas become focus areas for the implementation of the NBA activities that will be discussed in Section 4.7.

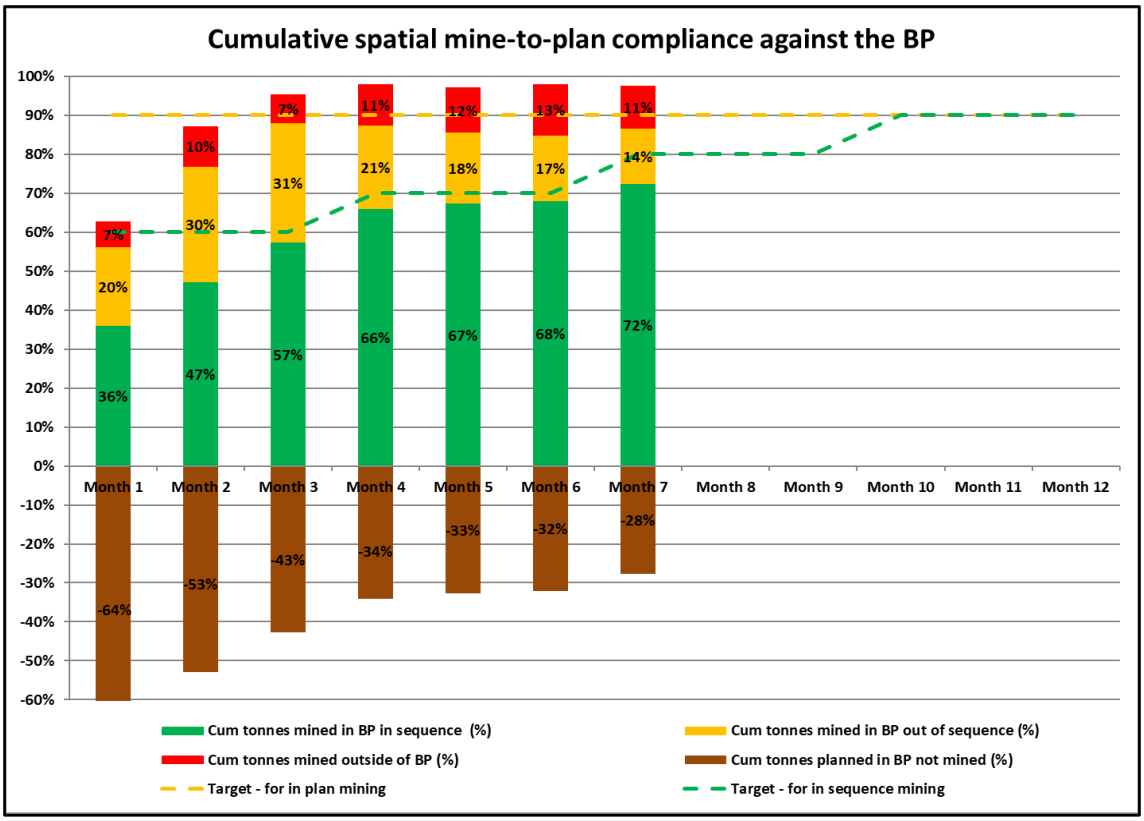


Figure 4.16. Graphical reporting of spatial mine-to-plan compliance including indication of planned not mined percentages

Thirdly, the reporting was enhanced with visualisations of mine plans per mining area illustrating the reconciliation results between areas planned for the YTD and areas where actual mining took place using the defined spatial mine-to-plan categories. This is illustrated in Figure 4.17. These plans allowed for further analysis of the areas mined to understand where actual mining is occurring *versus* the BP. The real value of these visualisations was in spatially evaluating the areas that were planned but not mined. The next components of the framework specifically considered how these areas could be prioritised in the operational mine planning environment. The visual nature of the plans also contributed to understanding the reasons for adverse outcomes with the aim of improving future mine-to-plan compliance.

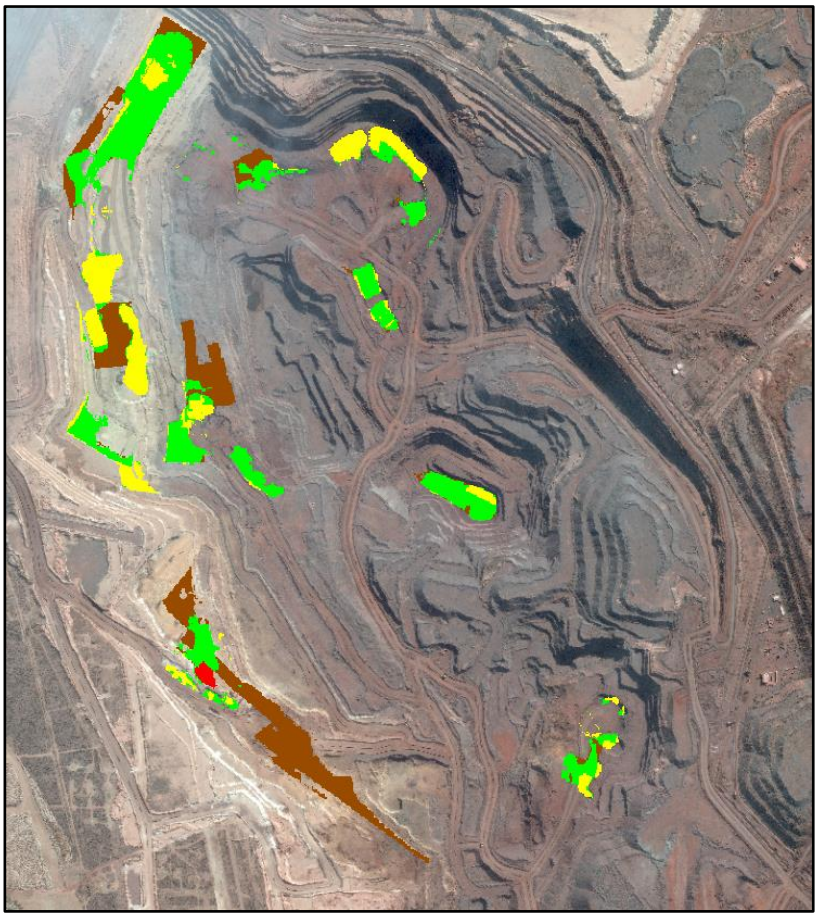


Figure 4.17. Visual plans showing spatial mine-to-plan compliance reconciliation results (Snyman, 2017)

Sections 4.3 and 4.4 have dealt with the first three components of the framework. The sections provided insight into which plan to use for the measurement of spatial mine-to-plan compliance, the process of gathering information on the actual spatial mining progress, the methodology for determining the overlap and intersection between the spatial areas planned in the BP and the actual mining activities, the spatial mine-to-plan categories and metrics to use when measuring compliance to the BP, target setting and reporting formats. When considering the target setting and reporting aspects of the framework it became apparent that the major value of the application of the framework was in the development and implementation of corrective actions with the aim of improving future spatial mine-to-plan compliance. To unlock this value, it was critical to fully understand **where and why** poor spatial mine-to-plan compliance practices occurred. This was done using the CDT concept.

4.5 Root cause analysis (RCA) and Compliance driver trees (CDT) (Component 4)

4.5.1 Introduction to CDT

This section deals with the fourth component of the framework illustrated in Figure 4.1. During the formulation of the different components of the framework it was clear that the framework would have historical components such as spatial mine-to-plan compliance measurement (Component 3) and forward-looking components such as NBA (Component 6). To move from the historical to the forward-looking components, a comprehensive understanding of the drivers of spatial mine-to-plan compliance performance was required. The VDT concept is widely used in the mining industry as a tool to model and visualise the relationship between various value metrics and their operational drivers as well as to conduct RCA.

VDTs are also utilised at open-pit iron ore mines. The use of VDTs in the open-pit mining operational sphere is illustrated with a hauling application. Figure 4.18 represents a VDT for haul truck performance at a typical open-pit iron ore mine.

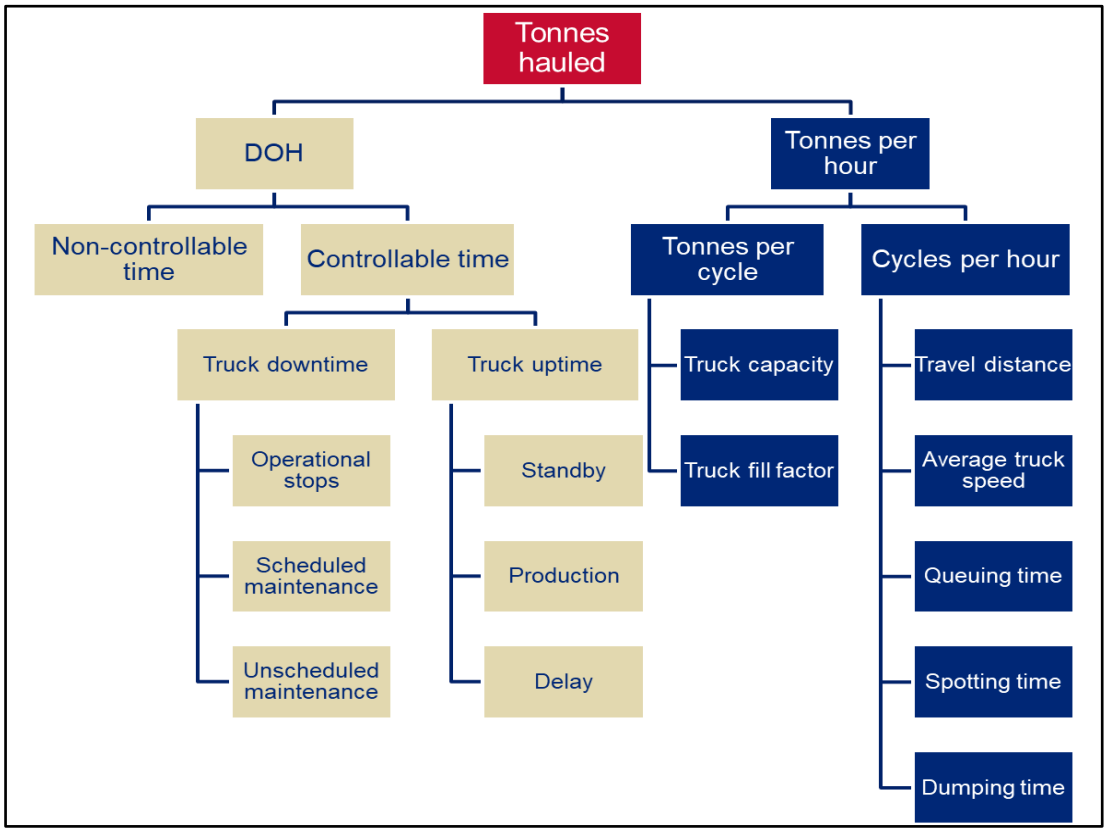


Figure 4.18. Typical VDT for hauling at an open-pit iron ore mine

The performance of the loading and hauling operation is an important value metric at a typical open-pit iron ore mine. This is underpinned by the performance of the haul truck

fleet. The tonnes hauled over a defined period typically depend on two major operational drivers namely direct operating hours (DOH) and the hauling rate expressed in tonnes per hour. Figure 4.18 depicts the relationship between the tonnes hauled (value metric) and the major operational drivers impacting on this value metric and is a visual representation of the mathematical model determining the tonnes hauled.

As discussed in the literature review in Section 2.6, Angelov and Naidoo (2010) explored the use of FTA (which has similar logic to a VDT) to determine the underlying causes of the deviation from mine plans at underground coal mines. To date, the VDT concept has not been applied to spatial mine-to-plan compliance reconciliation in open-pit iron ore mines. This thesis applied the VDT concept to spatial mine-to-plan compliance to identify the operational drivers of spatial mine-to-plan reconciliation performance. The operational drivers of the VDT in this application, impacted on the level of spatial compliance to the mine plan. Therefore, the VDT that was developed and implemented as part of this thesis, was referred to as a Compliance Driver Tree (CDT).

4.5.2 Definition and purpose of the CDT

The CDT, developed as the fourth component of the framework put forward in this thesis, had two main aims. Firstly, the CDT model provided the ability to identify and evaluate spatial mine-to-plan compliance in individual mining areas and for different material types. This was achieved by providing the capability to drill-down into selected spatial mining areas within the entire iron ore mine, thereby providing a detailed understanding of where (in which mining pushbacks and on which mining benches) actual mining took place in relation to the spatial areas planned as opposed to only understanding the reconciliation results on a mine-wide scale. Secondly, the CDT enabled the identification and understanding of the root causes of deviations that have the largest impact on the spatial mine-to-plan reconciliation performance, thus, providing insight into why undesired outcomes occurred.

Based on the first purpose of the CDT defined above, the appropriate value metric was the level of spatial mine-to-plan compliance to the BP (as defined by the spatial mine-to-plan index). The operational drivers included spatial mine-to-plan compliance in different mining areas and spatial mine-to-plan compliance per material type. Figure 4.19 illustrates a CDT providing more detail on spatial mine-to-plan compliance per mining area and per material type.

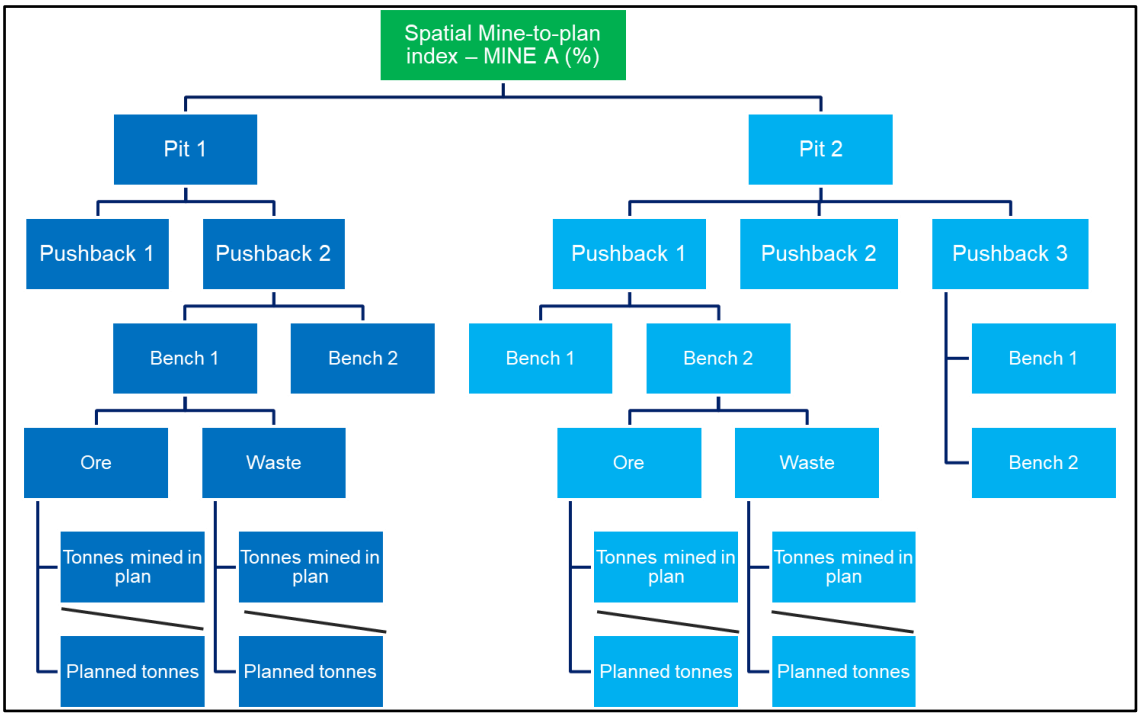


Figure 4.19. Area and material type CDT for spatial mine-to-plan index

When considering the second purpose of the CDT, the appropriate value metric was the tonnes mined out of plan or tonnes planned and not mined. For this application, the operational drivers included spatial compliance in different mining areas, spatial compliance per material type and the various root causes for deviations. Figure 4.20 shows a CDT that enables an improved understanding of the root causes of mining activities that took place out of plan or for planned areas that were not mined.

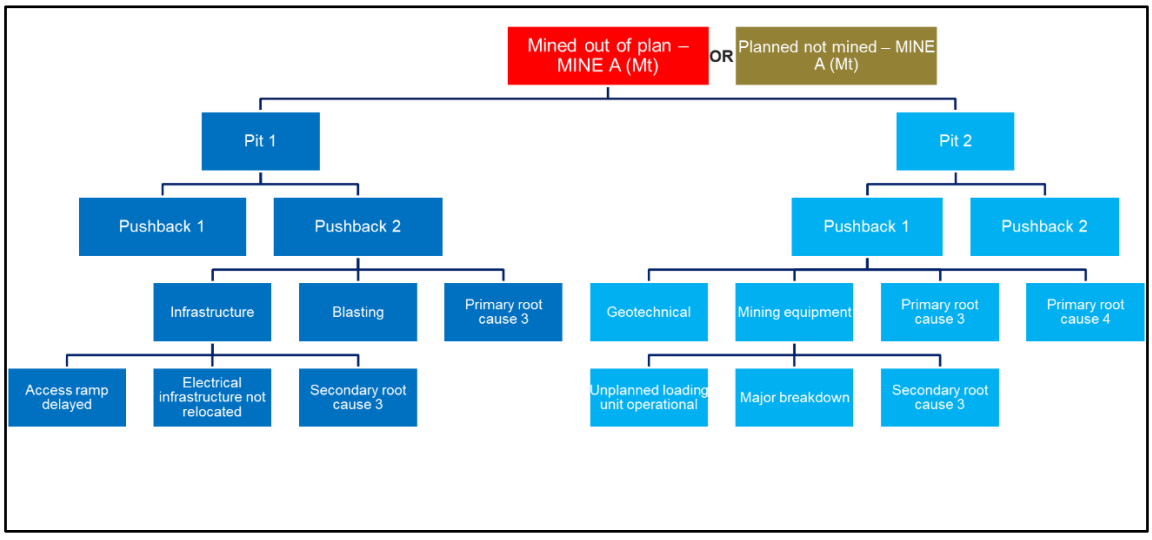


Figure 4.20. RCA type CDT for tonnes mined out of plan

4.5.3 Data requirements and associated process

To implement the CDT model, it was important that the spatial mine-to-plan compliance reconciliation data was available at the appropriate level of detail to feed into the CDT. Table 4.6 provides an illustration of the typical level of spatial detail required to enable the effective functioning of the CDT. Mine-to-plan compliance reconciliation data is required per mining area, per pushback, per bench, for both ore and waste. The compliance data should indicate tonnes that were mined in plan and in sequence, tonnes that were mined in plan out of sequence, tonnes mined out of plan and the resultant planned tonnes not mined.

Table 4.6. Bench level mine-to-plan compliance reconciliation data – Mine A

Month	Mine	Area	Ore/Waste	Pushback	Bench	Planned (t)	Mine in plan and sequence (t)	Mine in plan out of sequence (t)	Mine out of plan (t)	Planned not mined (t)
X	Mine A	Area B	Ore type 1	1	10	585,916	212,084	-	-	373,832
X	Mine A	Area B	Ore type 2	1	10	157,072	71,296	-	-	85,776
X	Mine A	Area B	Waste	1	10	281,690	109,961	-	-	171,729
X	Mine A	Area B	Ore type 1	1	11	1,709,562	1,199,040	314,927	-	510,522
X	Mine A	Area B	Ore type 2	1	11	117,513	76,159	-	-	41,354
X	Mine A	Area B	Waste	1	11	323,515	260,935	-	-	62,580
X	Mine A	Area B	Ore type 1	1	7	23,256	18,189	-	-	5,067
X	Mine A	Area B	Ore type 2	1	7	13,874	11,680	-	-	2,194
X	Mine A	Area B	Waste	1	7	39,797	32,031	-	-	7,766
X	Mine A	Area B	Ore type 1	1	8	21,325	8,811	7,609	9,530	12,514
X	Mine A	Area B	Waste	1	9	146,391	513	-	-	145,878
X	Mine A	Area B	Ore type 1	2	10	17,863	633	-	-	17,230
X	Mine A	Area B	Waste	2	2	8,809	8,809	-	-	-
X	Mine A	Area B	Waste	2	3	6,154	5,850	-	-	304
X	Mine A	Area B	Waste	2	4	7,513	304	-	-	7,209
X	Mine A	Area B	Waste	2	6	38,514	8,921	-	-	29,593
X	Mine A	Area B	Ore type 1	2	7	125,896	122,708	-	-	3,188
X	Mine A	Area B	Ore type 2	2	7	307,798	301,597	-	2,188	6,201
X	Mine A	Area B	Waste	2	7	800,303	708,572	-	49,569	91,731
X	Mine A	Area B	Ore type 1	2	8	1,041,994	743,469	1,342,398	1,165,977	298,525
X	Mine A	Area B	Ore type 2	2	8	216,310	149,399	136,768	82,261	66,911
X	Mine A	Area B	Waste	2	8	1,378,846	888,745	274,883	291,953	490,101
X	Mine A	Area B	Waste	3	2	1,013,768	1,012,249	-	-	1,519
X	Mine A	Area B	Waste	3	3	3,197,330	2,847,967	-	31,861	349,363
X	Mine A	Area B	Waste	3	4	2,511,550	1,624,903	2,439,515	550,580	886,647

In addition to the detailed spatial data required, it was necessary to document the root causes for deviations from the BP per bench and per material type. This ensured that the CDT accurately aggregated the reasons for adverse performance. As discussed before, there are numerous potential root causes that could result in adverse spatial mine-to-plan compliance reconciliation performance at operational open-pit iron ore mines. These root causes are mine-specific and developing a complete list of potential root causes therefore, fell outside the scope of this thesis. It was however necessary to develop a comprehensive list of typical root causes to ensure the effective functioning of the CDT. These potential root causes can be divided into three main classes, namely:

- Class 1: root causes related to the actual rate of ex-pit mining (i.e. actual mining is faster or slower than the BP estimate at a specific point in time);
- Class 2: root causes related to the spatial execution of the open-pit mine (i.e. actual mining taking place in unplanned areas or in a different sequence from what was estimated in the BP); and

- Class 3: root causes associated with the quality of the BP (these will ultimately materialise as one of the abovementioned classes).

For the purposes of implementing the CDT, the focus was on defining mining operational root causes falling into the first two classes described above. Table 4.7 provides an overview of the typical primary root causes and a selection of secondary root causes (typically three to five secondary root causes could be defined per primary root cause) that were defined as part of the development of Component 4 of the framework.

Table 4.7. Typical root causes of adverse spatial mine-to-plan compliance performance

Primary root cause	Secondary root cause	Class
Infrastructure	Access ramp delayed, electrical infrastructure not in place.	2
Blasting	Poor fragmentation, blasting activities delayed.	1 and 2
Geotechnical	Bench failure, pit design compliance.	2
Loading and hauling	Free digging, access delayed.	1 and 2
Mining equipment related	Unplanned loading unit, loading unit breakdown.	1
Ore control	Blending requirements, ore quality	2

Table 4.8 provides an example of an integrated view where the root causes were allocated to the spatial reconciliation results of the various mining areas. In principle, all deviations from the BP were flagged and root causes for the deviation were defined and allocated based on the knowledge of mine planning and mining operational personnel. The input document allowed the allocation of root causes per mining bench and per material type. More than one root cause could also be assigned to a specific deviation on a percentage basis.

Table 4.8. Root causes allocated to mining areas – Mine A

Month	Mine	Area	Ore/Waste	Pushback	Bench	Primary Reason	Secondary reason	Mine in plan and sequence (t)	Mine in plan out of sequence (t)	Mine out of plan (t)	Planned not mined (t)
X	Mine A	Area B	Ore type 1	1	10			212,084	-	-	373,832
X	Mine A	Area B	Ore type 1	1	10	Infrastructure	Access ramp delayed				100%
X	Mine A	Area B	Ore type 2	1	10			71,296	-	-	85,776
X	Mine A	Area B	Ore type 2	1	10	Infrastructure	Access ramp delayed				100%
X	Mine A	Area B	Waste	1	10			109,961	-	-	171,729
X	Mine A	Area B	Waste	1	10	Infrastructure	Access ramp delayed				100%
X	Mine A	Area B	Ore type 1	1	11			1,199,040	314,927	-	510,522
X	Mine A	Area B	Ore type 1	1	11	Equipment	Additional loading unit		100%		
X	Mine A	Area B	Ore type 1	1	11	Blasting	Poor fragmentation				100%
X	Mine A	Area B	Ore type 2	1	11			76,159	-	-	41,354
X	Mine A	Area B	Ore type 2	1	11	Blasting	Poor fragmentation				100%
X	Mine A	Area B	Waste	1	11			260,935	-	-	62,580
X	Mine A	Area B	Waste	1	11	Blasting	Poor fragmentation				100%
X	Mine A	Area B	Ore type 1	1	7			18,189	-	-	5,067
X	Mine A	Area B	Ore type 1	1	7	Mining delay	Buffer blocks				100%
X	Mine A	Area B	Ore type 2	1	7			11,680	-	-	2,194
X	Mine A	Area B	Ore type 2	1	7	Mining delay	Buffer blocks				100%
X	Mine A	Area B	Waste	1	7			32,031	-	-	7,766
X	Mine A	Area B	Waste	1	7	Mining delay	Buffer blocks				100%
X	Mine A	Area B	Ore type 1	1	8			8,811	7,609	9,530	12,514
X	Mine A	Area B	Ore type 1	1	8	Ore control	Blending requirement				100%
X	Mine A	Area B	Ore type 1	1	8	Ore control	Blending requirement		100%		
X	Mine A	Area B	Ore type 1	1	8	Ore control	Blending requirement			100%	
X	Mine A	Area B	Waste	1	9			513	-	-	145,878
X	Mine A	Area B	Waste	1	9	Rain / Water	Areas water logged				100%
X	Mine A	Area B	Ore type 1	2	10			633	-	-	17,230
X	Mine A	Area B	Ore type 1	2	10	Infrastructure	Access ramp delayed				100%
X	Mine A	Area B	Waste	2	2			8,809	-	-	-
X	Mine A	Area B	Waste	2	2						
X	Mine A	Area B	Waste	2	3			5,850	-	-	304
X	Mine A	Area B	Waste	2	3	Mining delay	Previous level delayed				100%
X	Mine A	Area B	Waste	2	3						
X	Mine A	Area B	Waste	2	4			304	-	-	7,209
X	Mine A	Area B	Waste	2	4	Mining delay	Previous level delayed				100%
X	Mine A	Area B	Waste	2	4						
X	Mine A	Area B	Waste	2	6			8,921	-	-	29,593
X	Mine A	Area B	Waste	2	6	Equipment	Additional loading unit				100%
X	Mine A	Area B	Ore type 1	2	7			122,708	-	-	3,188
X	Mine A	Area B	Ore type 1	2	7	Mining delay	Access delayed				100%
X	Mine A	Area B	Ore type 2	2	7			301,597	-	2,188	6,201
X	Mine A	Area B	Ore type 2	2	7	Mining delay	Access delayed				100%
X	Mine A	Area B	Ore type 2	2	7	Mining delay	Access delayed			100%	
X	Mine A	Area B	Waste	2	7			708,572	-	49,569	91,731
X	Mine A	Area B	Waste	2	7	Mining delay	Access delayed			100%	
X	Mine A	Area B	Waste	2	7	Mining delay	Access delayed				100%
X	Mine A	Area B	Ore type 1	2	8			743,469	1,342,398	1,165,977	298,525
X	Mine A	Area B	Ore type 1	2	8	Blasting	Poor fragmentation		100%		
X	Mine A	Area B	Ore type 1	2	8	Blasting	Poor fragmentation			100%	
X	Mine A	Area B	Ore type 1	2	8	Blasting	Poor fragmentation				100%
X	Mine A	Area B	Ore type 2	2	8			149,399	136,768	82,261	66,911
X	Mine A	Area B	Ore type 2	2	8	Blasting	Poor fragmentation		100%		
X	Mine A	Area B	Ore type 2	2	8	Blasting	Poor fragmentation			100%	
X	Mine A	Area B	Ore type 2	2	8	Blasting	Poor fragmentation				100%
X	Mine A	Area B	Waste	2	8			888,745	274,883	291,953	490,101
X	Mine A	Area B	Waste	2	8	Blasting	Poor fragmentation		100%		
X	Mine A	Area B	Waste	2	8	Blasting	Poor fragmentation			100%	
X	Mine A	Area B	Waste	2	8	Blasting	Poor fragmentation				100%
X	Mine A	Area B	Waste	3	2			1,012,249	-	-	1,519
X	Mine A	Area B	Waste	3	2	Geotechnical	Pit wall compliance				100%
X	Mine A	Area B	Waste	3	3			2,847,967	-	31,861	349,363
X	Mine A	Area B	Waste	3	3	Geotechnical	Pit wall compliance				100%
X	Mine A	Area B	Waste	3	3	Geotechnical	Pit wall compliance			100%	
X	Mine A	Area B	Waste	3	4			1,624,903	2,439,515	550,580	886,647
X	Mine A	Area B	Waste	3	4	Infrastructure	Access ramp delayed		100%		
X	Mine A	Area B	Waste	3	4	Infrastructure	Access ramp delayed			100%	
X	Mine A	Area B	Waste	3	4	Infrastructure	Access ramp delayed				100%

4.5.4 Functionality and typical reports

An opportunity was identified to apply the CDT model to represent the detailed spatial mine-to-plan reconciliation results and the root causes of adverse spatial mine-to-plan compliance in a visually appealing and engaging manner. This enabled illustrating the impact of performance in different mining areas on the overall mine-to-plan compliance reconciliation results. Various commercial software packages are available to mining companies for the advanced visualisation of data and the development of value driver trees. The evaluation of alternative products, that could be applied as alternative solutions for the visualisation and display of the CDT developed as part of the framework, falls outside of the scope of this thesis.

Microsoft Power BI Desktop was identified and applied as the product for the display of the CDT. The main reasons for deciding to utilise Power BI included its driver tree and visualisation capabilities, the ability to integrate data from various sources and the fact that the product was available without incurring any extra expenses. "*Power BI Desktop is a free application you can install on your local computer that lets you connect to, transform, and visualize your data. With Power BI Desktop you can create complex and visually rich reports, using data from multiple sources, all in one report that you can share with others in your organization*." Microsoft Docs (2018). The Power BI product was utilised in the following ways to create a spatial mine-to-plan compliance driver tree:

- Used it to connect to the various sources of spatial and root cause data;
- Transformed that data and created an integrated data model of planned, actual and root cause data;
- Created visual CDT reports and graphs; and
- Shared the reports with relevant team members and management.

The capabilities and functionality developed for the compliance driver tree model in Power BI are explained in the following paragraphs using various CDT reports and graphs developed during this thesis and applied to the illustrative Mine A. Figure 4.21 provides an overview of the main CDT analysis report that was developed to improve the understanding of the spatial mine-to-plan compliance reconciliation performance at open-pit iron ore mines. This is done by providing insight into compliance results for mining areas such as pushbacks and benches and by providing a root cause analysis tool.

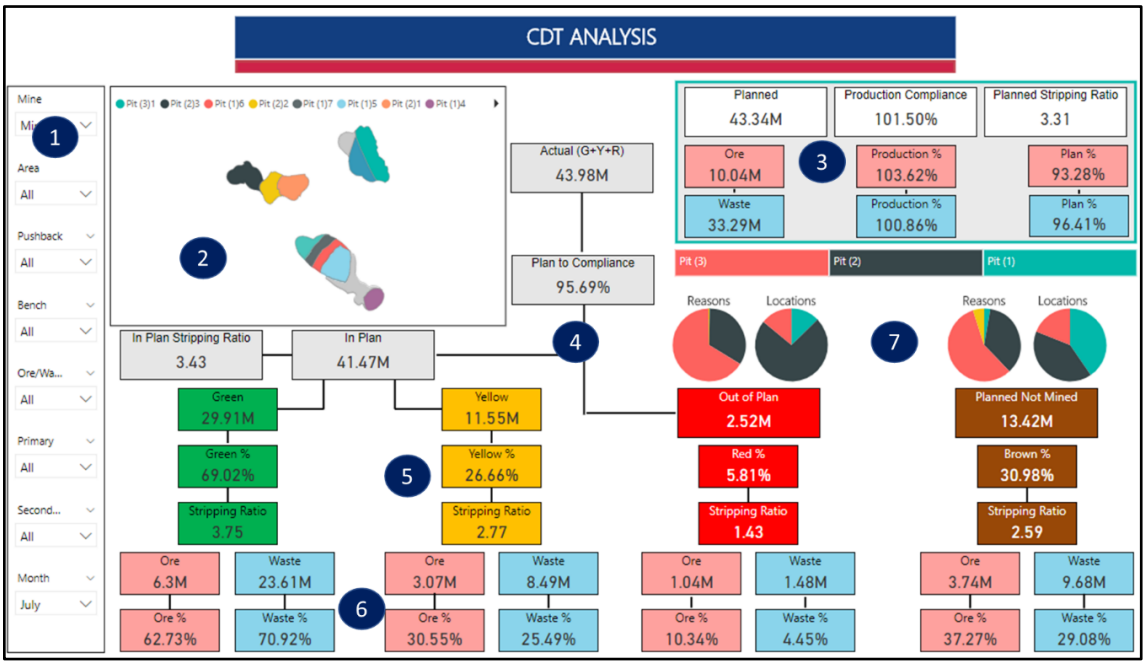


Figure 4.21. Main CDT analysis report – Mine A

The following aspects of the main CDT analysis report indicated by the circled numbers in Figure 4.21 are highlighted below:

- Point 1: This part of the interactive report provides drill-down capabilities. Spatial mine-to-plan compliance information can be displayed for specific mining areas by selecting a specific pit, pushback or bench. Furthermore, the compliance information for ore and waste mining can be viewed separately. Areas where compliance was affected by specific primary and secondary reasons (root causes) can also be interrogated in detail. Lastly, the time period (month) for which the information is assessed can also be selected.
- Point 2: This part of the report is a graphic representation of the open-pit iron ore mine in plan view and pushbacks can be interactively selected to display the relevant CDT information.
- Point 3: This area of the report is a summary of the production compliance metrics providing information on the temporal reconciliation between the tonnes mined (in and out of plan) and the BP estimate for the period under review.
- Point 4: The core of the CDT for spatial mine-to-plan compliance is found in this area of the report. Here the spatial open-pit mining activities are defined into the four spatial mine-to-plan categories defined in Section 4.3.4.
- Point 5: Here more information is provided on the mining activities in each of the four categories. It can, for example, be seen that 11.55Mt of mining took place in plan and out of sequence (yellow) at a stripping ratio of 2.77. This represents 26.7% of planned mining activities.

- Point 6: This area of the report provides a further breakdown of the ore and waste mining activities in each spatial mine-to-plan category. Considering the mined out of plan category (red) the information indicates that although only 4.5% of waste mining took place out of plan, 10.3% of ore mining took place out of plan.
- Point 7: Here the primary and secondary reasons for mining out of plan and for areas planned and not mined are summarised in pie charts. These charts are interactive and have a drill-down capability.

Figure 4.22 provides an alternative view of the main CDT analysis report now drilled-down into a specific pushback (Pushback 5) in the areas of the report indicated by Point 1. In the areas at Point 2 only this pushback is now highlighted, and the CDT information now only relates to this specific pushback. From the information in Figure 4.22 both the production compliance and the spatial mine-to-plan compliance of this area is lower than the average for the mine.

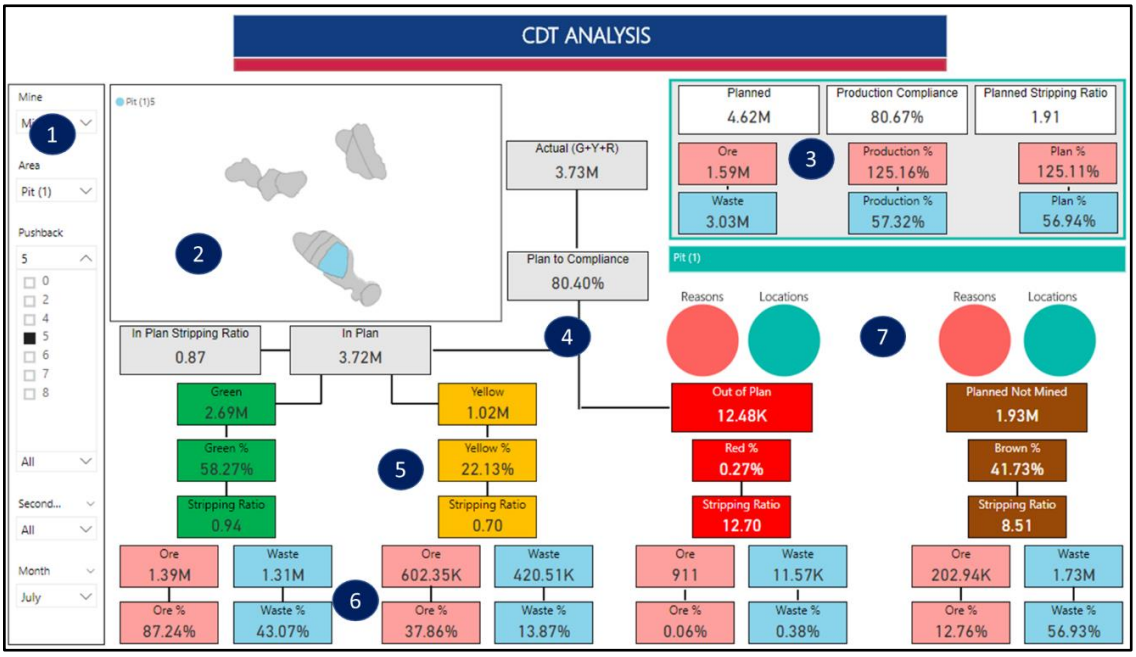


Figure 4.22. Main CDT analysis report – Mine A, Pit 1, Pushback 5

From the spatial mine-to-plan compliance report illustrated in Figure 4.23 further information can be obtained on the spatial mine-to-plan compliance reconciliation results on a tonnage basis.

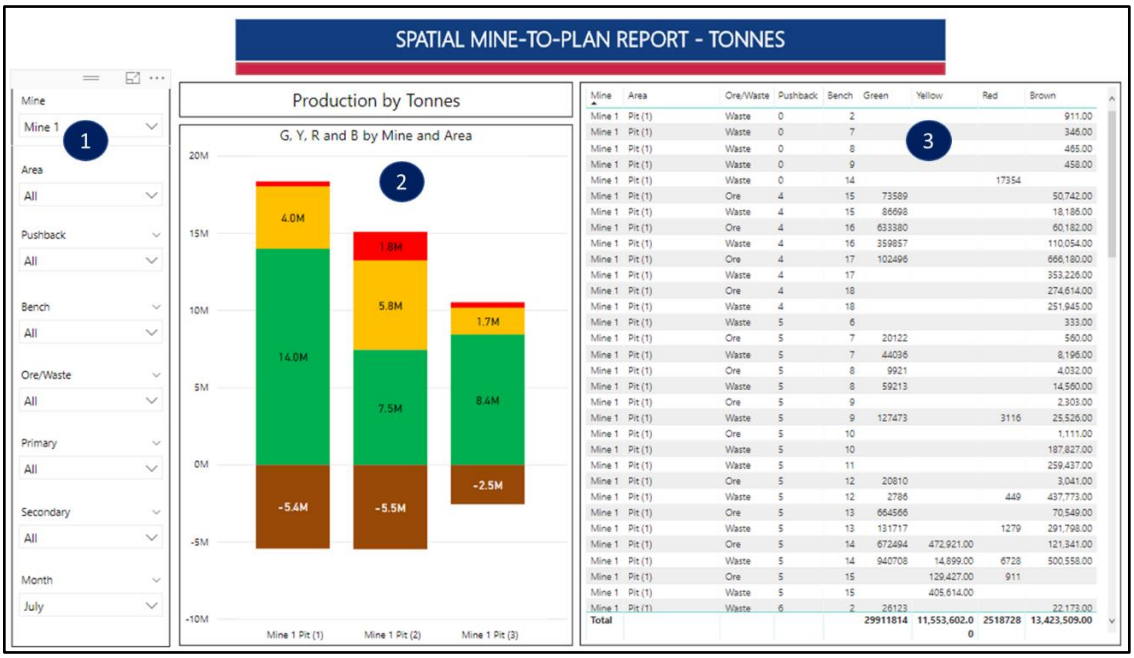


Figure 4.23. Spatial mine-to-plan compliance report - Tonnes

The following aspects of the spatial mine-to-plan compliance report as indicated by the different numbers in Figure 4.23 are highlighted below:

- Point 1: As in the main CDT analysis report, this part of the interactive report provides drill-down capabilities.
- Point 2: This part of the report provides a graphic representation of the spatial mine-to-plan compliance results for Mine A considering the performance of three pushbacks. This is an enhancement of the reporting discussed in Section 4.3.4.
- Point 3: Here the detailed data used to develop the graph discussed in Point 2 is provided.

Figure 4.24 illustrates the drill-down capabilities of the CDT model by providing an example of a spatial mine-to-plan compliance report for a specific bench in a pushback of the entire mine.

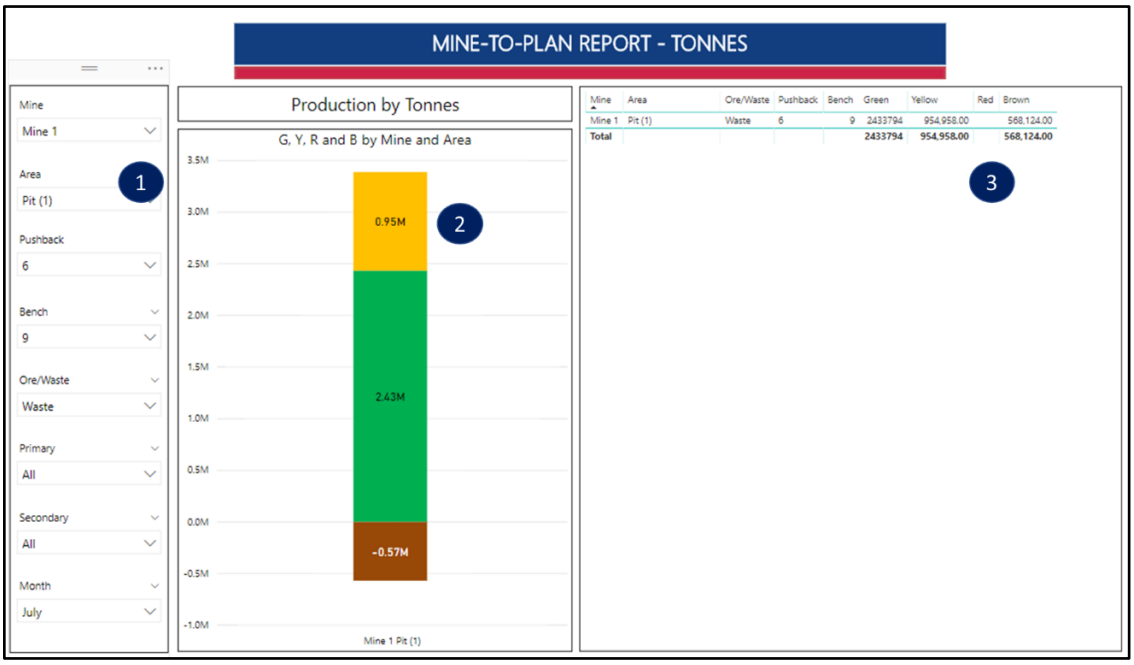


Figure 4.24. Spatial mine-to-plan compliance report (tonnes) for Bench 9 in Pushback 6 of Pit 1

Figure 4.25 provides spatial mine-to-plan reconciliation results for a specific pit and illustrates that the spatial mine-to-plan compliance results can also be expressed as a percentage compliance in the categories defined in Section 4.3.4.

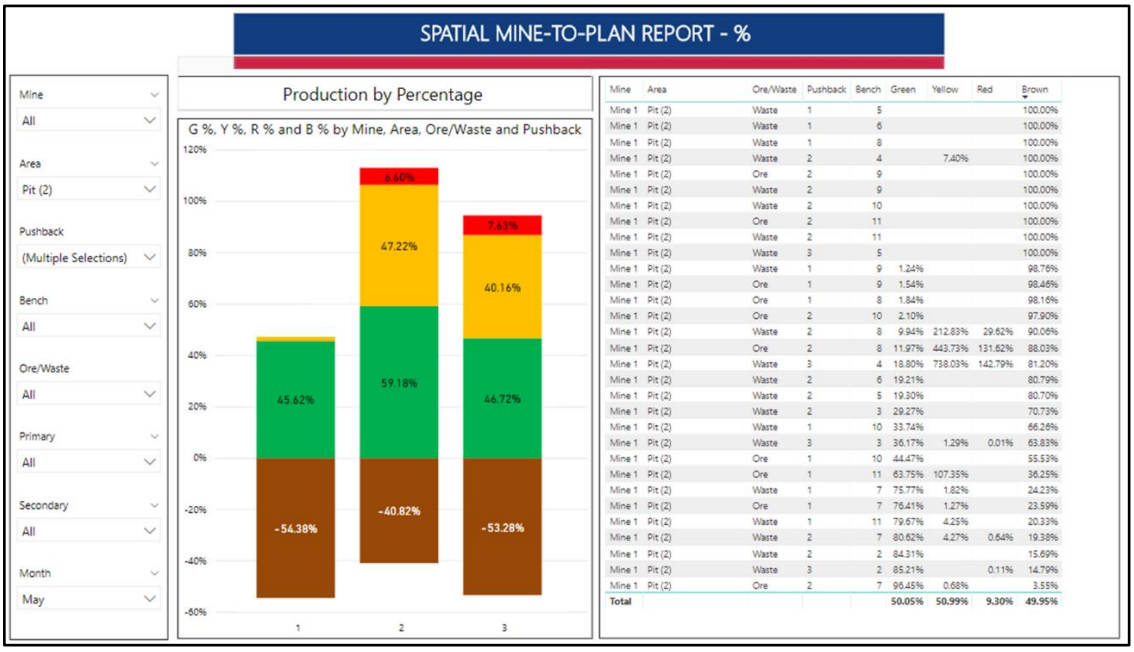


Figure 4.25. Spatial mine-to-plan compliance report (%) for Pit 2

The RCA capabilities of the CDT model are illustrated in Figure 4.26. This figure is an illustration of the main root cause report that was developed as part of the compliance driver tree capabilities of the framework.

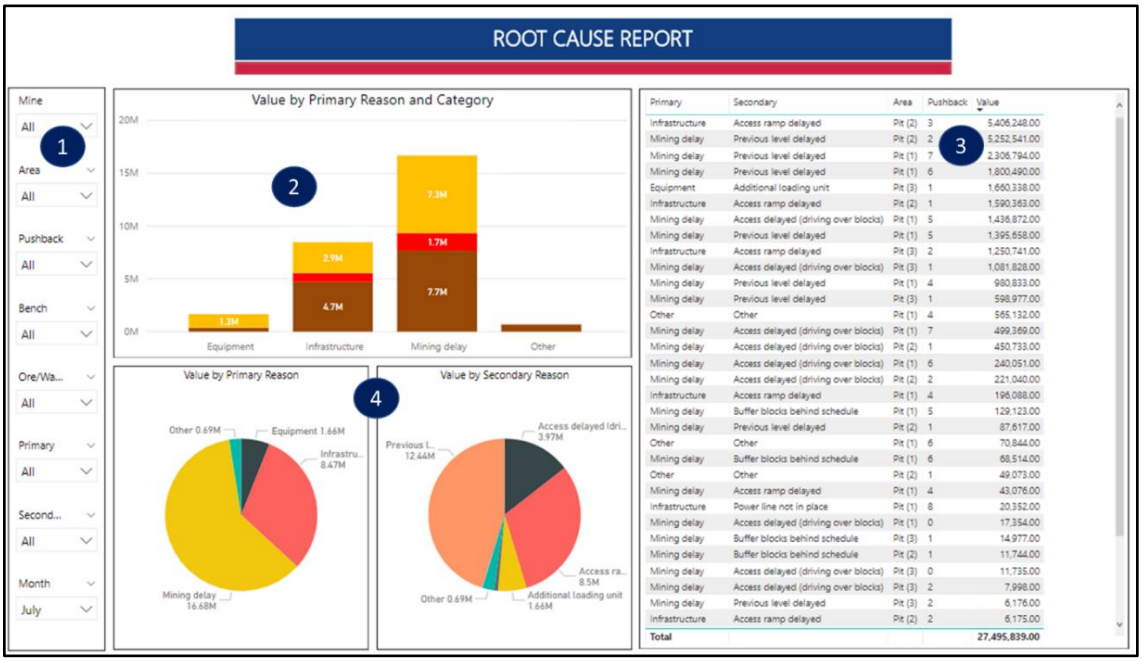


Figure 4.26. Main root cause report

The following aspects of the main root cause report as indicated by the various numbers in Figure 4.26 are highlighted below:

- Point 1: As in the main CDT analysis report, this part of the interactive report provides drill-down capabilities.
- Point 2: This part of the report provides an analysis of the primary reasons or root causes for the tonnes that were mined in plan out of sequence, the tonnes that were mined out of plan and the resultant planned areas not mined. This information is associated with the selection defined in Point 1 above. In this case, for example, mining delays resulted in 1.7Mt of mining taking place out of plan for the spatial mining areas and period under consideration.
- Point 3: Here the detailed data used to develop the graph discussed in Point 2 is provided.
- Point 4: The pie charts in this area of the root cause report provide an interactive view of the impact of the identified root causes on the spatial mine-to-plan reconciliation performance. For example, root causes associated with infrastructure resulted in 8.5Mt of mining activities that were not in plan and in sequence (not green).

In Figure 4.27 the second type of RCA report is shown. In this report the root cause analysis is presented per mine. This is useful to compare the root causes for deviations

between different sites and to drill-down into a specific root cause and its impact on the spatial mine-to-plan reconciliation results.

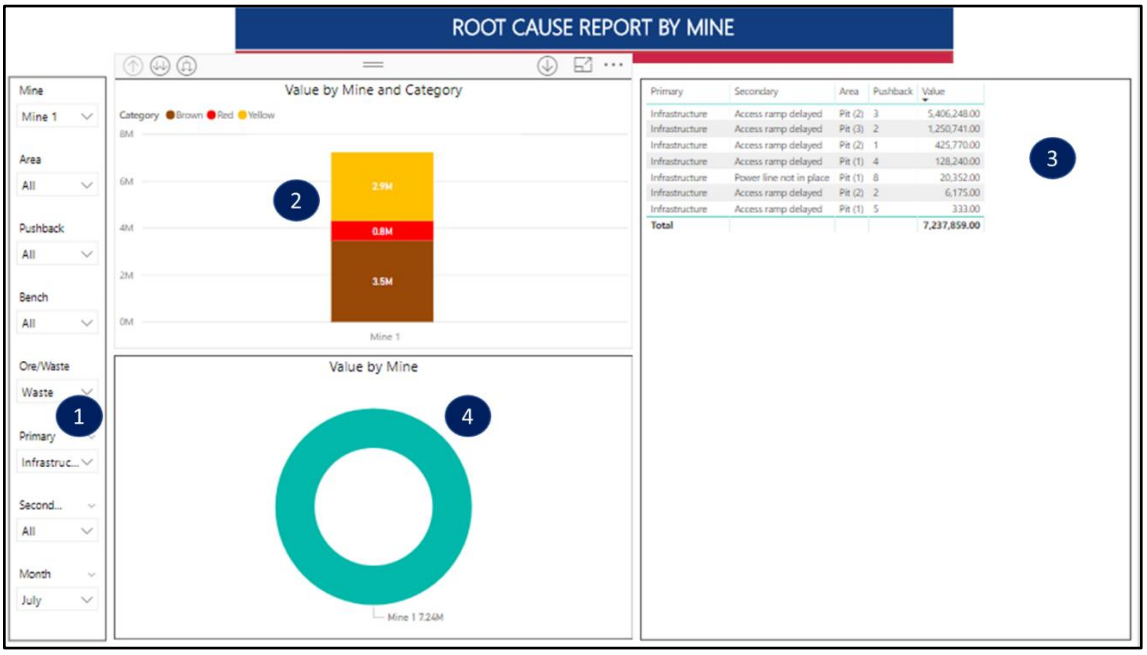


Figure 4.27. Root cause report per mine

The following aspects of the root cause report by mine as indicated by the different numbers in Figure 4.27 are highlighted below:

- Point 1: As in the main CDT analysis report, this part of the interactive report provides drill-down capabilities. Infrastructure related root causes were selected to provide detailed analysis on this aspect.
- Point 2: This part of the report illustrates the impact of infrastructure related root causes on spatial mine-to-plan compliance. This indicates that 2.9Mt of ‘out of sequence mining’, 0.8Mt of mining out of plan and 3.5Mt of areas planned but not mined can be attributed to infrastructure as a root cause.
- Point 3: As before the detailed data used to develop the graphs is provided.
- Point 4: Where multiple mines are considered as part of the CDT model, this area of the report will provide an analysis of the impact of a specific root cause per mine.

The inclusion of the CDT model as Component 4 of the framework effectively addressed the limitations that were identified in the approach presented by Angelov and Naidoo (2010) discussing the application of FTA in spatial mine-to-plan compliance applications. The CDT model that was developed as part of this thesis clearly evaluated the detailed mining areas where significant spatial mine-to-plan compliance deviations exist. The model also provided a tool for conducting effective RCA of adverse spatial mine-to-plan reconciliation results with the main aim of applying the insights from this analysis to

improve spatial mine-to-plan compliance in future periods. The mine-to-plan compliance reconciliation results obtained in Component 3 of the framework and the CDT model developed in Component 4 formed the basis of Component 5. In the remaining components of the framework the focus shifted from a historical analysis of spatial mine-to-plan compliance reconciliation results to a forward-looking assessment and evaluation of the impact of the reconciliation performance and the corrective actions required to improve spatial compliance.

The inclusion of the CDT model in the framework positively contributed to an improved understanding of where spatial mine-to-plan performance challenges existed and the root causes of adverse performance. This provided a powerful diagnostic capability that could be used to prioritise corrective actions. However, before corrective actions can be implemented, it is important to understand the impact of spatial mine-to-plan compliance performance on the achievement of operational targets as well as on the flexibility of the open-pit iron ore mining operation to determine the required “intensity” of the drive for corrective actions.

4.6 Impact and consequence assessment (Component 5)

4.6.1 Introduction to consequence assessment

The fifth component of the framework involved firstly, understanding and interpreting the impact of historical spatial mine-to-plan compliance results on future spatial mine-to-plan performance. Secondly, the consequence on the short-term and longer-term KPIs of the open-pit iron ore mine could also be evaluated. As discussed before, this component of the framework was forward-looking. What will happen next? How does the current level of spatial mine-to-plan compliance to the BP impact on the spatial compliance for the remainder of the BP period? What consequence does this have for the mine’s ability to deliver on operational targets? What consequence does the level of spatial mine-to-plan compliance have for the mine’s ability to maintain mining flexibility?

To answer these questions, the actual spatial progress was incorporated into an updated BP or Forecast plan (FP) and a forward-looking plan-to-plan reconciliation was conducted. The plan-to-plan reconciliation was conducted considering three types of KPIs. Firstly, the temporal production KPIs such as ex-pit waste mining, ex-pit ore mining and product were forecasted. Secondly, the spatial plan-to-plan reconciliation results were determined by evaluating the spatial overlap between the BP and the FPs. Thirdly, the ROM stockpiles and EO estimated from the FP were determined and compared to the BP estimates for the stockpiles and EO. The plan-to-plan reconciliation results provided leading indicators

of the future performance of the open-pit iron ore mine in terms of temporal and spatial KPIs. The forecasted ex-pit mining activities provided a short-term indicator of the consequence of actual spatial mine-to-plan reconciliation results and the ROM stockpile and EO levels provided an indication of the longer-term consequence as these numbers are proxies for the mining flexibility of the open-pit iron ore mine.

4.6.2 Forecast plan and temporal plan-to-plan reconciliation

The development of a FP is an integral part of the business planning cycle and an important aspect of the management routine at most open-pit iron ore mines. The purpose of the FP is to provide a forward-looking estimate of how closely the BP will be achieved given the actual performance to date and an estimate of the performance in the remaining period of the BP. The FP is typically applied as a temporal reconciliation between the BP and the actual performance to date plus the latest forecast. These FPs are developed at quarterly or monthly intervals and are scheduled until the end of the BP. The FP typically utilises the actual mined surfaces, as defined by the survey DTMs, as the starting positions and effectively then re-schedule the BP for the remaining periods (months). For example, the forecast plan for August or Period 8 would be called FP-08. This FP would include the actual temporal and spatial ex-pit mining performance for the preceding periods (the months up to and including July) and the remaining periods (the months from August to December) would be re-scheduled using the same set-up and assumptions as in the BP for the 12-month financial year spanning from January to December.

Figures 4.28 to 4.31 provide a high-level view of the typical temporal outputs for ex-pit waste, ex-pit ore, product tonnes and product Fe qualities from the forecast planning process at Mine A. In this example the FP is completed monthly. At the iron ore mine used in the example, both owner-mining equipment and a contractor fleet are employed to mine ex-pit waste and ore. There are two plants that wash and screen ex-pit ore to deliver product that meets tonnage and quality specifications.

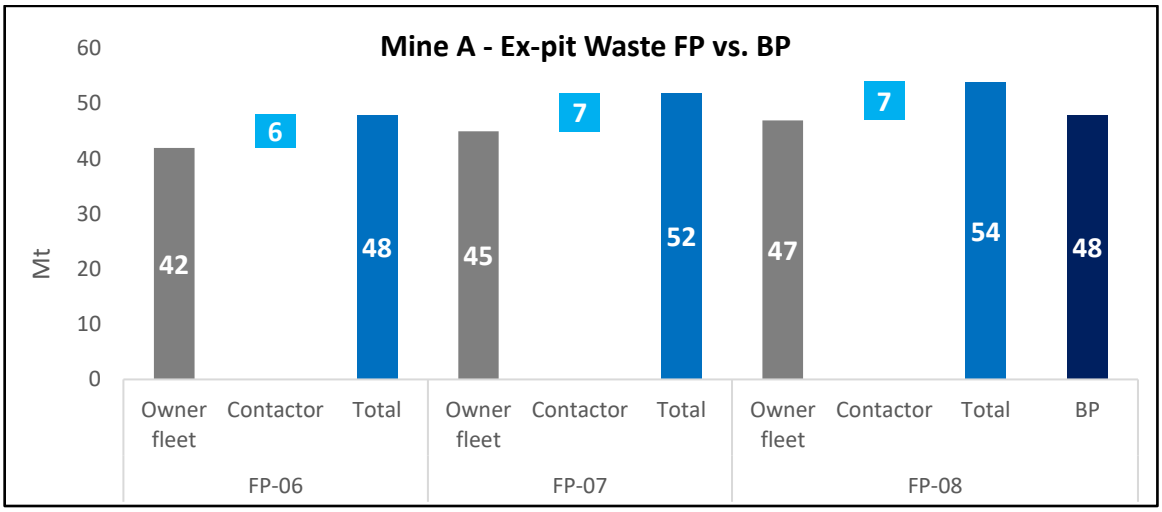


Figure 4.28. Reconciliation of estimated ex-pit waste from three FPs with the BP

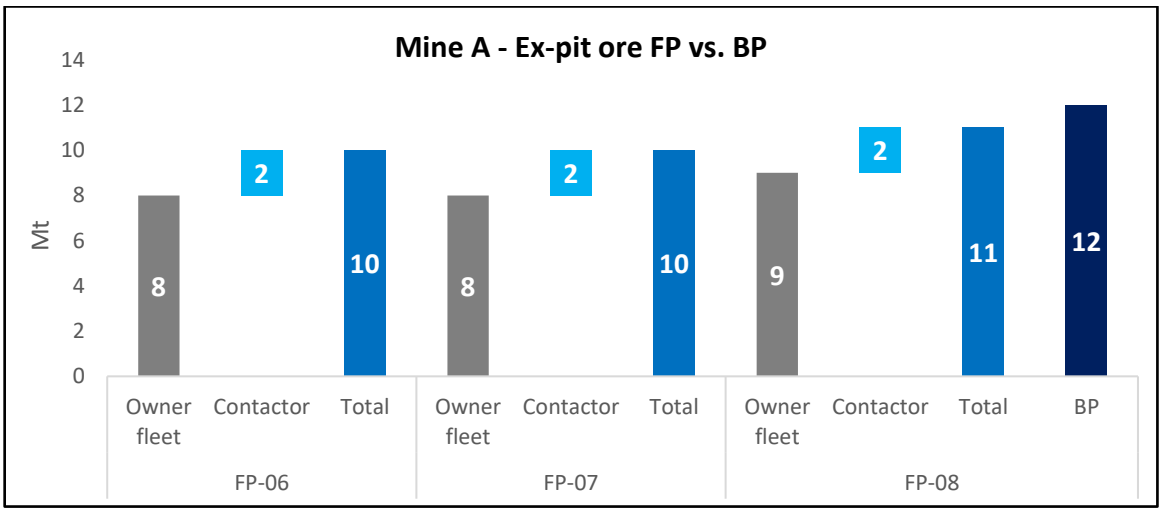


Figure 4.29. Reconciliation of estimated ex-pit ore from three FPs with the BP

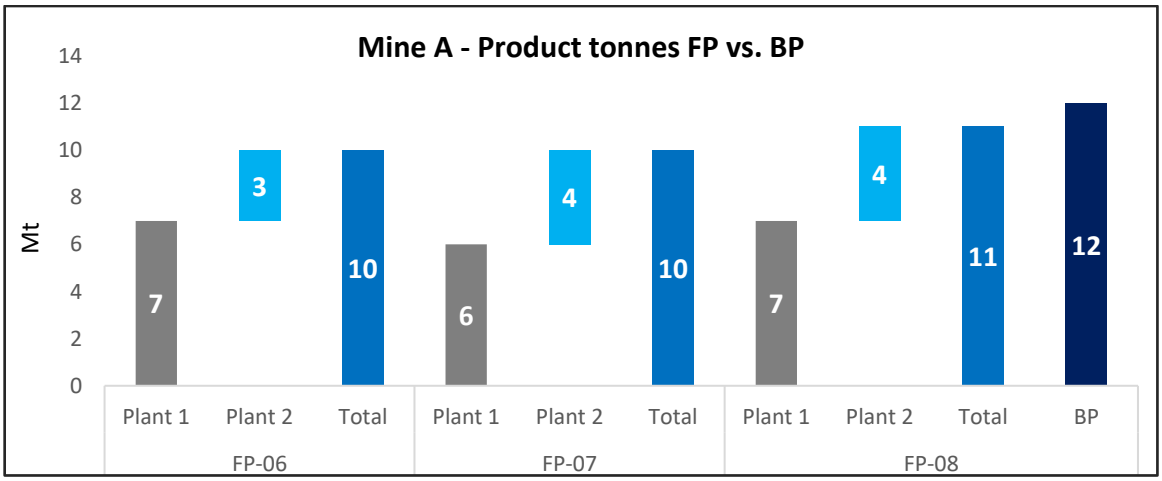


Figure 4.30. Reconciliation of estimated saleable product from three FPs with the BP

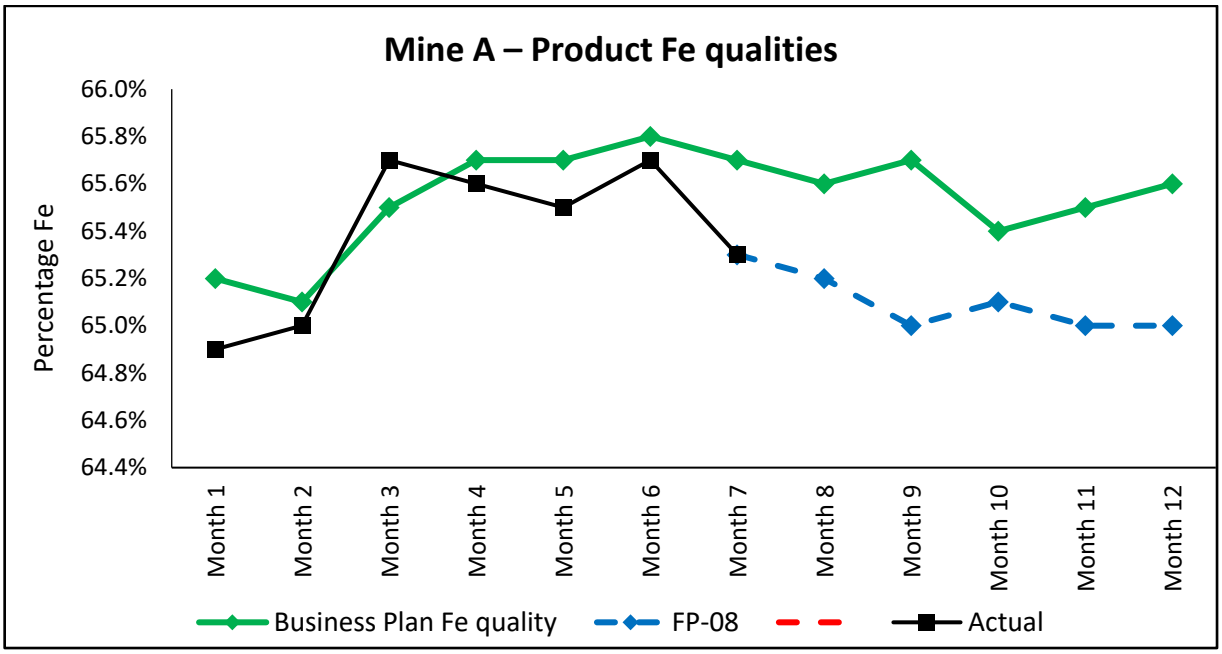


Figure 4.31. BP vs. FP-08 Product Fe quality estimates

The results from the forecast plans indicate the progression between the last three forecasts and indicate the impact of the actual plus forecasted performance on achieving the temporal BP KPIs. Based on FP-08, the annual ex-pit waste target of 48Mt will be exceeded by 6Mt, despite this the annual ex-pit ore and product targets will not be achieved. The budgeted product Fe qualities are also not achieved in the FP-08 forecast. Open-pit iron ore mines, where forecast planning is conducted, typically stop at this level of temporal reconciliation. Conclusions are made on the impact of actual performance plus the latest forecast on the achievement of short-term temporal KPIs such as annual production. Although, this level of temporal reconciliation has value, it does not provide insight into the potential reasons for the FP results. For example, why is the ex-pit ore and product tonnage and Fe quality targets not achieved even though the ex-pit waste target is exceeded by 12.5%? The answer lies in the spatial plan-to-plan reconciliation and the type of material occurring in the areas.

4.6.3 Spatial plan-to-plan reconciliation

Component 5 of the framework developed by this thesis, incorporated novel ways of determining, quantifying and interpreting the impact of YTD spatial mine-to-plan compliance performance on the achievement of annual spatial mine-to-plan compliance targets. This component also enabled the evaluation of the consequence thereof on the achievement of operational targets and the required flexibility of the open-pit iron ore mining operation. For the effective functioning of this component of the framework, it was

necessary to develop the FP using the same tools, models and platforms as those used when developing the BP. The FP would then provide spatial outputs indicating where open-pit mining will take place. Spatial plan-to-plan reconciliation could then be completed thereby addressing the knowledge gap identified in existing literature where the concept of spatial plan-to-plan reconciliation was not explored.

From a spatial mine-to-plan compliance point of view, the focus when developing the FP were twofold: firstly, to limit the generation of further mining areas outside of the BP (red areas) and secondly to reduce the amount of areas planned and not mined (brown areas). This would result in the application of the available mining capacity in a spatially effective way that attempts to maximise the spatial overlap (green areas) between the areas planned in the BP and the areas planned in the FP. This spatial plan-to-plan reconciliation provided a rolling forward-looking view of the likely achievement of the spatial targets set in the BP. The impact of actual spatial mine-to-plan compliance results to date plus the spatial mining forecast of ex-pit mining activities were considered. The value of the plan-to-plan reconciliation process was that it was forward looking, and the results could be utilised to improve the spatial alignment between the BP and the next FP by focussing on maximising the areas of overlap (green areas).

Figure 4.32 illustrates the spatial plan-to-plan reconciliation results for a number of forecast plans in a specific year. Each column in the graph represents an independent consecutive monthly FP. The graph represents the estimated spatial mine-to-plan compliance results that will be achieved at the end of the BP period considering the actual performance to date and the forecast for the remainder of the year. The plan-to-plan reconciliation results should be interpreted incrementally. Again, using FP-08 as example, there is a spatial overlap of 80% between this FP and the annual BP, which means that by following FP-08 the result will be 19% of the mining activities occurring outside of the areas targeted in the BP and 6% of the areas targeted in the BP will not be mined. The progression (positive or negative) between the incremental forecast plans can also be assessed. The target set for the FP estimate is 90% in line with the targets for the adherence index and the spatial mine-to-plan index 1 as discussed in Section 4.4.4.

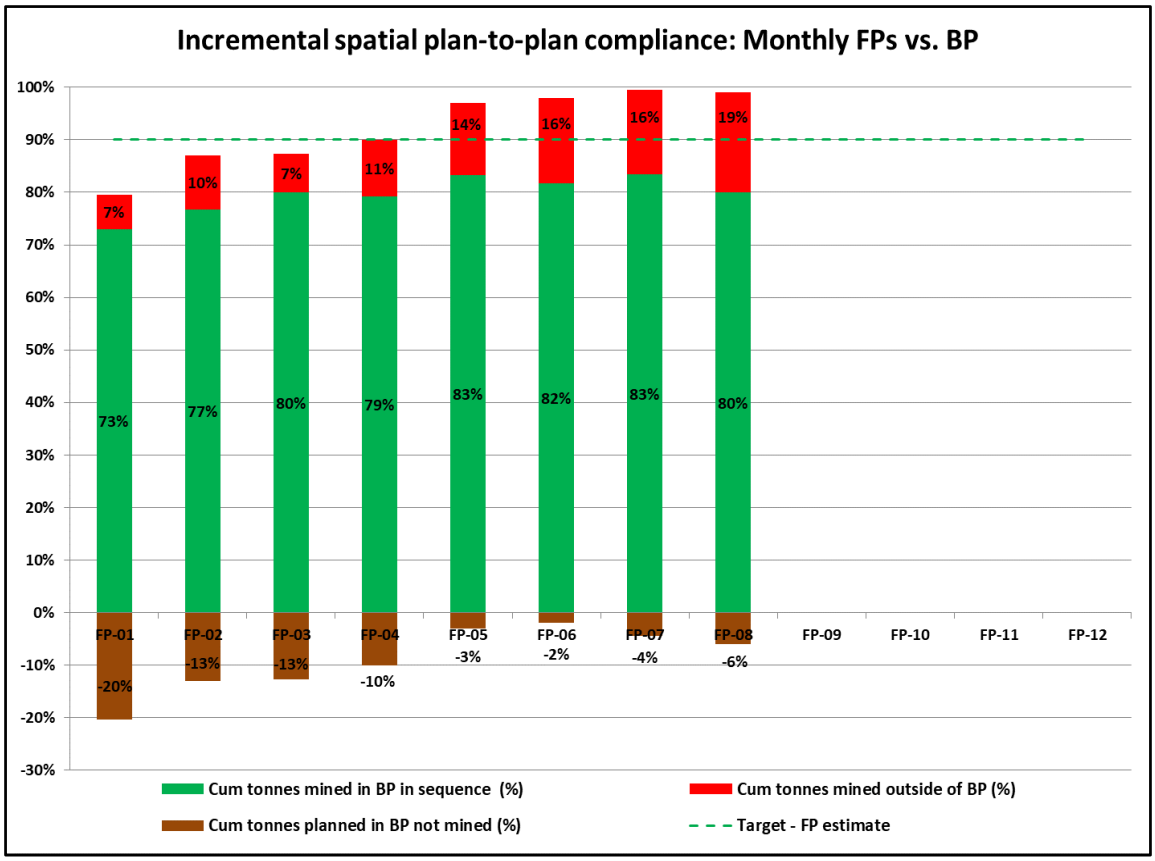


Figure 4.32. Spatial plan-to-plan compliance reconciliation

As indicated before, low spatial alignment between the FP and the BP had two major consequences. Firstly, the forecast ex-pit mining activities (also referred to as operational performance) would be negatively affected when the FP did not achieve the spatial execution required by the BP. Component 5 of the framework involved scheduling the FP using the relevant actual survey DTMs (actual spatial deployment to date) while all other inputs were aligned with the BP assumptions. The consequence of poor spatial plan-to-plan alignment on the forecast ex-pit mining activities can be calculated by isolating the spatial aspects of the plan-to-plan reconciliation. Considering the combination of spatial and temporal plan-to-plan reconciliation results presented before: the reason why the ex-pit ore and product targets were not achieved even though the ex-pit waste target is exceeded by 8% can be found in the poor spatial alignment between FP-08 and the BP. The FP-08 indicated that 19% of the forecast ex-pit mining activities will occur outside of the areas planned in the BP. The consequence of forecasting mining outside of the BP mining areas was that ex-pit waste mining was not targeting the spatial areas required to access the planned ex-pit ore. This is an illustrative example of how this component of the

framework could identify the short-term consequences of poor spatial plan-to-plan alignment on ex-pit mining activities.

Secondly, the consequence of forecasting mining outside of the BP mining areas is that the forecast ROM stockpile and EO levels would be negatively affected when the FP did not achieve the spatial execution required by the BP. The budgeted ROM stockpile and EO levels required by the BP are typically applied as indicators for longer-term flexibility of an open-pit iron ore mine. The ROM stockpiles act as a buffer between the mining and processing operations. Various factors such as the consistency of ex-pit ore delivery, weather-related and other operational disruptions, the need to maintain consistent product qualities, plant yield requirements and the level of complexity of logistics operations determine the size and composition of the ROM stockpiles. Typically, a minimum ROM stockpile level is defined for an operational iron ore mine considering the factors listed above. Operating with a ROM stockpile level below the set minimum is not ideal as it reduces the mining flexibility of the mine to effectively react to risks and opportunities. The FP results for the ROM stockpile levels provide an indication of the longer-term consequence of poor spatial plan-to-plan reconciliation. Another major consequence of the FP not achieving the spatial deployment required by the BP, was that the budgeted ROM stockpile and EO levels were not achieved by the FP.

Figure 4.33 provides an illustrative example of how the ROM stockpile levels of Mine A could be impacted by poor spatial mine-to-plan compliance performance.

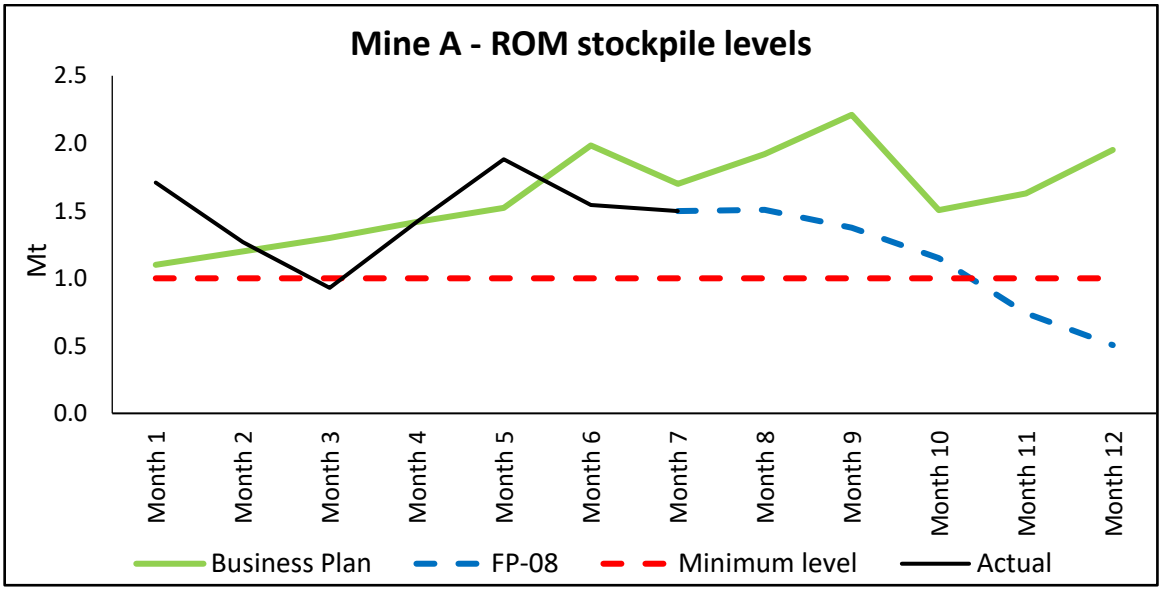


Figure 4.33. BP vs. FP-08 ROM stockpile estimates

The ROM stockpile levels estimated by the BP remain above the minimum level required by Mine A. The actual ROM stockpile levels for the first 7 months of the period under consideration managed to track the required BP levels. The FP-08 ROM stockpile levels,

however, show a downward trend reflecting the misalignment in the spatial execution of the mine plans between the FP-08 and the BP. In the FP-08, saleable product levels are artificially maintained by depleting the ROM stockpiles. This is not a sustainable practice and could lead to production shortages in the following year as the closing ROM stockpile balance will be significantly lower than the BP requirement. The consequence of this practice, where short-term operational targets are achieved at the expense of spatial compliance to the BP, could be detrimental to the long-term sustainability of open-pit mining operations.

This section of the thesis illustrated how a temporal and spatial plan-to-plan reconciliation process, comparing the relevant FP with the BP, contributed to understanding the forward-looking impact of the actual YTD results on the full year mine-to-plan compliance performance. The consequence of spatial mine-to-plan compliance performance on the achievement of operational targets and mining flexibility, was also incorporated into the framework. This effectively addressed the knowledge gaps identified in existing literature where the impact of unsatisfactory spatial mine-to-plan compliance reconciliation performance was only discussed in general terms by Angelov and Naidoo (2010). The plan-to-plan reconciliation process put forward as the fifth component of the framework went beyond the plan compliance risk scenario matrix (Angelov and Naidoo, 2010) by accurately forecasting the impact and consequences of spatial non-compliance to the BP.

In the next section, the concept of the NBA as defined in the literature review will be further explored. It will be shown how this concept could be applied to improve the spatial mine-to-plan compliance performance. This is achieved by providing guidance and direction to the operational mine planning horizon to re-direct mining to the correct spatial areas and addressing the root causes of non-compliance (as identified by Component 4 of the framework).

4.7 NBA and quality decision making (Component 6)

4.7.1 Introduction to NBA

Defining the next best actions, that led to achieving the BP outcomes in a sustainable manner through improved spatial mine-to-plan compliance results, was the sixth component of the framework. The aim of the inclusion of the NBA concept as Component 6 of the framework was to facilitate effective decision making in line with the conceptual framework in Figure 2.5. The NBA concept was about applying the intelligence derived from the previous components of the framework for effective decision making. The transformed and spatially referenced information compiled during the root cause analysis

(Component 4) and impact assessment (Component 5) was utilised to define the next best course of action that the mining operation should take. This was in relation to current (the spatial mine-to-plan compliance results at any point in time) and predicted (the impact on full-year spatial mine-to-plan compliance from the plan-to-plan reconciliation) conditions. The two-pronged approach of the NBA component was to:

1. provide input into the operational mine planning horizon to ensure that the STMP (an output of operational mine planning) directed mining to the correct spatial areas identified in the FP; and
2. ensure that the operational mine planning process resolved the identified root causes of adverse spatial mine-to-plan reconciliation performance by proposing focused actions. These actions were referred to as Priority tasks (PT) aimed at addressing the root causes identified in Component 4 of the framework.

4.7.2 Operational mine planning and priority tasks

In the same way that the BP was positioned as the link between the more strategic LOM plan and the STMP developed in the operational mine planning horizon, the STMP provides the link between the BP (and the FP) and the mining execution activities. The STMP (also referred to as the operational mine plan) represents the “sharp end” of the mine planning process as it is this plan that is physically executed in the pits. Therefore, the operational mine planning process was central to defining the NBA. On open-pit iron ore mines, these operational mine plans typically cover periods of 3 months down to 2 weeks. When developing a STMP it is critical that a balance should be found between spatial adherence to the FP, production deliverables and the practical short-term realities in the mine. This links the STMP to the LOM plan and the reconciliation acts as a guide to maintain alignment between the two plans.

For the effective functioning of Component 6 of the framework, the operational planning process had to address the following two aspects. Firstly, the operational planning environment should actively seek to adhere to the spatial execution direction provided by the FP. Practically, this implied that active spatial direction should flow from the FP as an input to the STMP. The integrity of the STMP should be checked and any misalignment resolved in situations where the STMP either targeted mining areas outside of the FP or failed to target mining areas planned by the FP and which was not yet mined. The reason for this approach was that the timeframe of the STMP was typically too short for this plan to dictate the spatial execution priorities. The STMP should simply conform to the spatial direction from the FP and escalate conflicts for resolution.

Figure 4.34 is a visual representation of the mining blocks planned in a typical STMP being aligned to the FP. It illustrates how the blocks planned in the STMP are targeting the areas planned and not mined (brown areas) identified through the spatial mine-to-plan compliance reconciliation measurement process (Component 3 of the framework).



Figure 4.34. STMP adhering to spatial execution from FP

Secondly, the operational mine planning process should incorporate the identification and actioning of priority tasks linked to the root causes of adverse spatial mine-to-plan compliance performance. These PTs were defined as tasks that will enable the successful execution of the STMP under consideration. PTs are typically a list of key actions or key enablers linked to spatial areas of critical importance in the execution of the STMP and to the major inputs into the STMP. PTs have due dates, responsibilities assigned and KPIs to measure successful completion.

Table 4.9 provides illustrative examples of how the PTs typically related to the root causes of poor spatial mine-to-plan compliance results.

Table 4.9. Priority tasks linked to an RCA of a spatial mine-to-plan compliance

Primary root cause	Secondary root cause	Typical priority tasks
Infrastructure	Access ramp delayed, electrical infrastructure not in place.	Construct access ramp for bench A, establish electrical infrastructure on bench B.
Blasting	Poor fragmentation, blasting activities delayed.	Conduct secondary blasting on bench C, contractors to complete blasting operations on bench D.
Geotechnical	Bench failure, pit design compliance.	Clean up bench failure in pushback 1, Conduct highwall cleanup on bench E.
Loading and hauling	Free digging, access delayed.	Construct access ramp for bench F.
Mining equipment related	Additional loading unit, loading unit breakdown.	Re-assign additional loader.
Ore control	Blending requirements, ore quality	Selectively stockpile lower quality ore from bench G.

4.7.3 Decision making

Now that these two aspects were addressed in the operational mine planning process, the NBAs were defined by the STMP. Essentially, the open-pit iron ore mine should seek to mine the blocks scheduled in the STMP and action the PTs. Effective decision making could now occur to ensure that BP outcomes were achieved in a sustainable manner.

A decision-making matrix was developed to provide more context and ensure effective decision making. As can be seen in Table 4.10, four quadrants were defined using the level of spatial plan-to-plan compliance as the first axis and the forward-looking consequence of the reconciliation results as the second axis.

Table 4.10. NBA decision-making matrix

DECISION-MAKING MATRIX		Spatial plan-to-plan compliance between BP and FP	
		Above 90%	Below 90%
Consequence on FP operational targets and ROM stockpile levels	Low	NBA 1 • Follow the STMP	NBA 2 • Update next FP and then STMP to align with the BP • Then follow updated STMP • Initiate tracking of PTs
	High	NBA 3 • Follow the STMP • Investigate alternative reasons for high consequence as it is not related to spatial mine-to-plan compliance	NBA 4 • Complete FP scenarios - evaluate mining sequence, adding mining capacity, reducing production, etc. • Update FP based on preferred scenario • Update STMP • Then follow updated STMP • Conduct weekly (or daily) PT monitoring

The STMP developed in the operational mine planning horizon was successfully applied to define the appropriate NBAs given current and forecast spatial mine-to-plan reconciliation performance. Component 6 of the framework provided a decision-making matrix to guide effective decision making by defining the four quadrants of NBAs that should be taken to improve spatial mine-to-plan compliance to the BP. A reconciliation process adds value when it results in the implementation of corrective actions aimed at improving future performance (Morley and Arvidson, 2017). The knowledge gap identified in existing literature was that the spatial mine-to-plan compliance approaches lacked a detailed description of the forward-looking management processes associated with identifying and implementing effective corrective actions. This knowledge gap was addressed by applying the NBA concept to manage forward-looking spatial mine-to-plan compliance performance and by illustrating how improved decision making could be practically implemented. The NBAs then inform components 1 and 2 through feedback loops as illustrated in Figure 4.1. The next sections describe these feedback loops.

4.8 Feedback loops

The final aspect of the framework involved ensuring the implementation of the agreed NBA and improved future BPs through feedback loops designed to continuously improve the spatial mine-to-plan compliance. The first feedback loop closes the loop back to the actual mining execution. Effective management processes and routines were established, and appropriate technology was deployed to enhance the short-term visibility of the spatial progress of actual mining. The second feedback loop was a longer-term loop back to the BP. The aim of this feedback loop was to ensure that the results of the spatial mine-to-plan compliance reconciliation process were considered in the development of future mine plans with the aim of improving the quality and integrity of those mine plans.

4.8.1 Feedback loop 1

Feedback loop 1 of the framework is about action; tracking the implementation of the decisions taken using the NBA concept as defined previously. Effective tracking of the implementation of agreed NBA required visibility of the spatial location of actual loading activities in relation to the planned mining blocks as well as visibility of the progress with PTs *versus* the agreed timelines for completion. The management routines employed to track the implementation of the STMP and progress with the completion of the agreed PTs typically involved daily production meetings and weekly mine planning meetings. Various

KPIs could potentially be discussed and tracked at these meetings. From a spatial mine-to-plan compliance perspective, the important KPIs included: spatial compliance to the STMP (were the planned mining blocks being loaded?) and progress with PT (were these tasks being actioned and completed in the agreed timeframes?).

As highlighted in the literature review, technology applications and tools were available to enhance the effective tracking and management of the spatial execution of an open-pit iron ore mine. The effectiveness of the first feedback loop was enhanced through the application of two technology solutions.

Firstly, the effective management of the implementation of the agreed NBAs was enhanced by the application of RPAS technology. Existing literature only described the possibilities of application of RPAS in this space, but this thesis practically applied RPAS technology to dynamically monitor progress of critical spatial mine-to-plan compliance aspects thereby enhancing the effectiveness of the first feedback loop of the framework. Rotor wing RPAS units were deployed to provide timely “as-mined” face positions and to track progress with PTs at an agreed frequency. These RPAS units had high manoeuverability which allowed for more accurate flying and the capability of carrying multiple payloads utilising various gimbals to accommodate the different payloads. The endurance allowed for 18-30 minutes of continuous flying time.

Depending on the criticality of the spatial timing of a specific mining block, RPAS technology was applied to provide as-mined face positions on a frequency varying from daily to weekly. The sensor used for this application was a LiDAR unit and the data capturing and analysis process followed was similar to capturing the actual mining progress on a monthly basis described in Section 4.3.3. of this thesis. Figure 4.35 provides an example of how the scanned as-mined face position in a specific mining area (pit, pushback, bench) was visually reconciled with the appropriate STMP blocks. This enhanced tracking actual mining progress against the STMP in areas of critical importance from a spatial mine-to-plan compliance perspective.

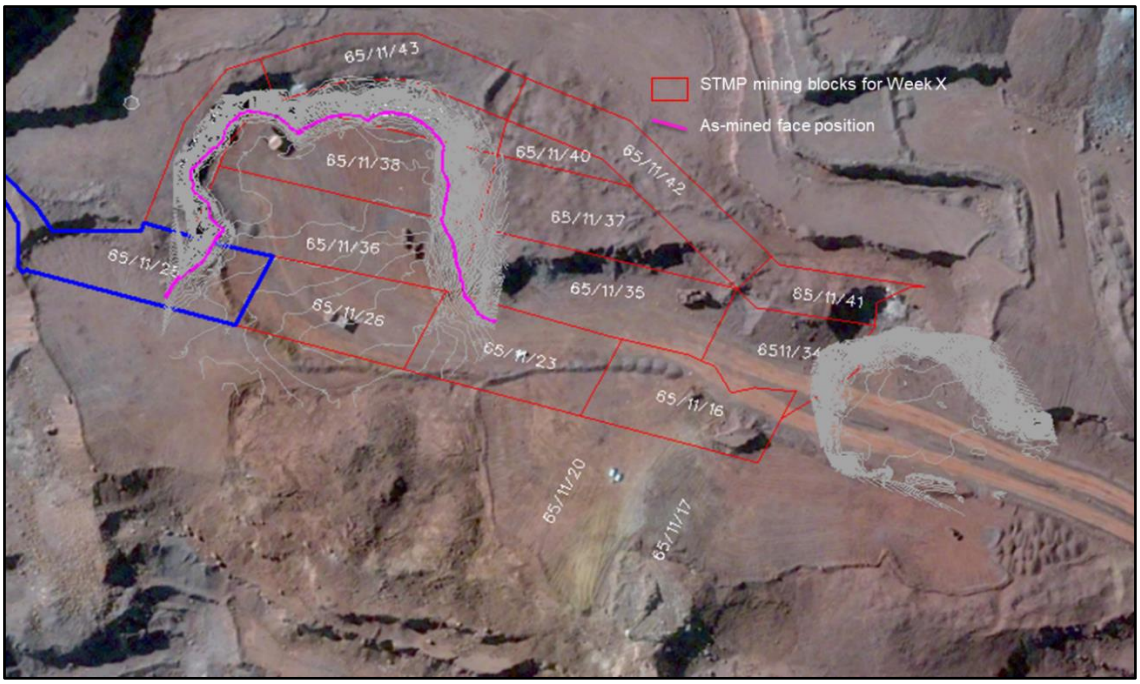


Figure 4.35. RPAS scan of as-mined face position visually reconciled with STMP blocks

Progress with PTs was also tracked using rotor wing RPAS units. Again, the frequency of the tracking process was linked to the criticality of the impact of the PTs on the correct spatial timing of the specific mining area. For this application 30X zoom video cameras and digital cameras were employed. Visual progress tracking information was provided through video footage or time-lapse photography. This allowed management to detect deviations or delays in the completion of PTs in a proactive manner. Figure 4.36 represents a series of time-lapse photos illustrating how information collected via RPAS could be applied to monitor the PTs. The time-lapse photos tracked the establishment of a permanent ramp and the initial loading activities to open a new mining bench in Pit 1 of Mine A. The ramp was established in the correct spatial location, but the establishment and subsequent loading operations were delayed and the planned date for the ramp establishment was not achieved. Through the deployment of additional loading capacity, the loading operation managed to catch up on the lost time.

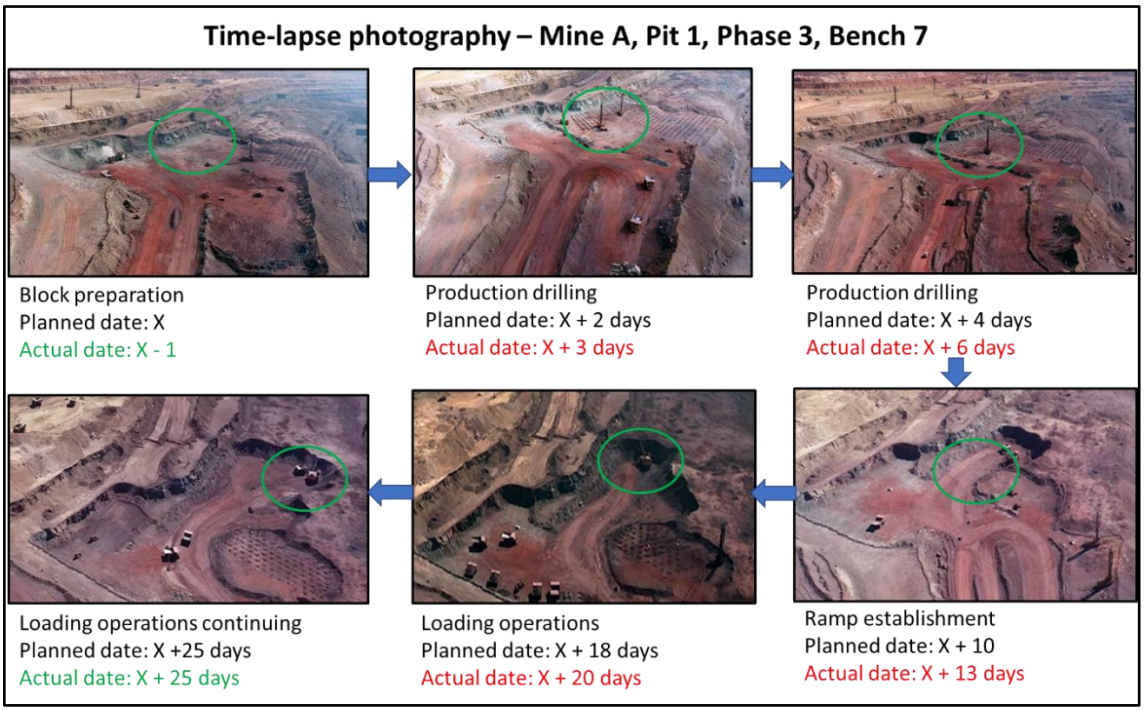


Figure 4.36. RPAS monitoring of PT via time-lapse photography

Secondly, the HP-GPS capability of the Modular Dispatch FMS called ProVision, was utilised to provide real-time spatial feedback to mining production personnel, control room operators and loader operators on the loader's spatial compliance to the mining blocks scheduled in the STMP. Loading units were fitted with ProVision HP-GPS technology which allowed for the real-time and accurate tracking of the positions of the loaders in 3D space. The spatial locations of the relevant loading blocks from the STMP were also uploaded into ProVision. This allowed for the tracking of the NBAs through:

- the direct application of the on-board graphical display providing the loader operator with real-time feedback of the actual loader location *versus* the STMP mining blocks; and
- the near real-time tracking of spatial loader progress against the STMP blocks allocated to that specific loader by control room operators and production personnel.

The real-time knowledge of the actual loader positions relative to the STMP blocks were applied to ensure that the agreed NBA were implemented; i.e. the STMP was spatially executed by tracking loading compliance. Figure 4.37 illustrates the typical ProVision view that is available in the control room. The actual loader position and as-mined dig lines are visualised in relation to the STMP blocks and any spatial deviation can be easily identified and managed.

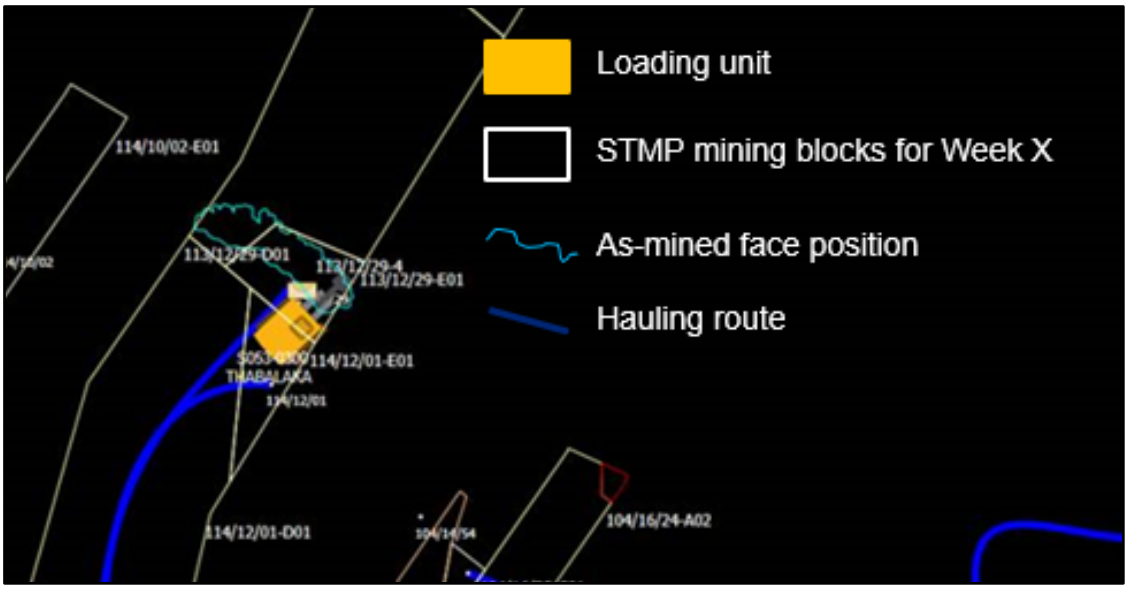


Figure 4.37. ProVision screen indicating loader position relative to planned mining blocks

Feedback loop 1 of the framework effectively utilised RPAS technology and loader HP-GPS as part of an integrated process of tracking and managing spatial mine-to-plan compliance at an open-pit iron ore mine, thereby addressing the knowledge gaps identified in existing literature. This thesis illustrated how RPAS technology and FMS with the associated HP-GPS technology were employed to enhance the framework. These technology applications provided tools to accurately track the actual spatial mining progress in near real-time and compare that to the spatial aspects of the STMP.

4.8.2 Feedback loop 2

The literature review of this thesis commented on the steady progress towards the development of optimal mine plans; i.e. mine plans with high levels of integrity where the variability of inputs is simulated during the mine planning process. The second feedback loop of the framework further contributed to improvements in the quality and integrity of the BP by creating an opportunity to incorporate the spatial mine-to-plan compliance reconciliation results into the next business planning cycle.

This was achieved by actively incorporating previous spatial mine-to-plan compliance reconciliation results during the development of the BP as part of the next planning cycle. Typical examples could be:

- A reduction of the mining rate in an area where geo-technical challenges with the underfoot conditions of the loaders were experienced;
- An enhancement of the spatial execution of the BP by introducing a second ramp system in pushbacks where spillage of blasted material caused mining delays; and

- The proactive identification of a major infrastructure relocation for accessing a new pushback, which is necessary for the successful execution of the BP.

The second feedback loop ensured that the framework became an integral part of the continuous improvement journey of the overall mine planning process at open-pit iron ore mines. In combination with the first feedback loop, the final aspect of the framework closed the loop between annual mine planning cycles, mine planning and execution, thereby improving the spatial mine-to-plan compliance performance.

4.9 Summary of Chapter 4

A comprehensive spatial mine-to-plan compliance framework that addresses the knowledge gaps in existing literature was presented in Chapter 4. The ability to apply the framework at open-pit iron ore mines was illustrated. The six components of the framework were discussed and the relationships between the components were explored. Section 4.4 described the spatial mine-to-plan compliance reconciliation process that utilises the BP and the survey measurement results. Component 3 of the framework addressed four knowledge gaps that were identified in existing literature by:

- defining the BP as the mine plan against which spatial mine-to-plan compliance is primarily reconciled;
- using ex-pit tonnes as the basis for the reconciliation calculations;
- defining a comprehensive set of reconciliation categories including definitions for mining in plan “in sequence” and mining in plan “out of sequence”; and
- defining a comprehensive set of spatial mine-to-plan compliance metrics including the spatial mine-to-plan indexes.

The fifth knowledge gap was addressed through the development and implementation of the CDT (discussed in Section 4.5). This was achieved by adapting the VDT concept in a novel way. The introduction of the forecast plan and the concept of spatial plan-to-plan reconciliation in Section 4.6 give effect to the forward-looking aspects of the framework, thereby addressing the sixth knowledge gap, identified in existing literature, where only a qualitative compliance risk scenario matrix was defined. It was shown how the operational planning horizon could be utilised to define the NBA. The seventh knowledge gap was addressed by directly applying the NBA concept to drive effective decision making with the aim of improving future spatial mine-to-plan compliance.

The two feedback loops of the framework were discussed in Section 4.8. It was demonstrated how the application of RPAS, and HP-GPS technology enhanced the effectiveness of the framework (Feedback loop 1). The eighth knowledge gap was

addressed by illustrating the implementation readiness, practical application and maturity of these technology solutions. Feedback loop 2 ensured continuous improvement in the quality and integrity of future BP.

5. DESCRIPTION OF THE OPEN-PIT MINE ON WHICH THE PROPOSED FRAMEWORK WAS VALIDATED

5.1 Overview of Chapter 5

This chapter aims to provide a description of the open-pit iron ore mine on which the spatial mine-to-plan compliance framework, developed by this thesis, was validated. Section 5.2 provides a general overview of the Kolomela iron ore mine (Kolomela). The location, geological setting and ore types are discussed. The section further describes the 2016 SAMREC compliant Mineral Resource and Mineral Reserve of Kolomela. The mining method, mining equipment employed, the processing activities and logistics are discussed. The production history of Kolomela is also covered.

The relevant challenges faced at Kolomela are discussed in Section 5.3. The successful ramp up of the mine led to a mine plan estimating that a 44% increase in annual production was feasible. Questions were being asked about the sustainability of the proposed production levels given the perception that the actual mining activities were not spatially executed in accordance with the mine plan. Section 5.4 provides the sobering results of the initial spatial mine-to-plan compliance reconciliation which indicated that the spatial compliance to the mine plan was unacceptably low. This confirms the risk associated with the proposed increased production levels and creating the opportunity for the application of the spatial mine-to-plan compliance framework developed by this thesis. The main reasons why Kolomela was an appropriate case study mine are summarised in Section 5.5.

5.2 Introduction to the Kolomela iron ore mine

5.2.1 Location and general overview

The name Kolomela is from the traditional Setswana saying: "*Kolomela, mhata-sediba; ga go lehumo le tswang gaufi*". This means: to explore further and deeper, to persevere, that nothing of great value comes easy and no wealth is easy to reach (Mutangwa, 2018).

Kolomela is in the Northern Cape Province of the Republic of South Africa, approximately 12km south-west of the town of Postmasburg. For map reference purposes the Kolomela Mine location can be plotted using the following WGS84 latitude/longitude geographical coordinates: 28°23'30.05" S and 22°58'46.88" E (Viljoen, 2017).

Kolomela is one of two iron ore mines owned and operated by Anglo American Kumba Iron Ore (Kumba). Figure 5.1 provides a regional overview of the location of Kumba's activities in South Africa. Kolomela is indicated as site 2b on the map.

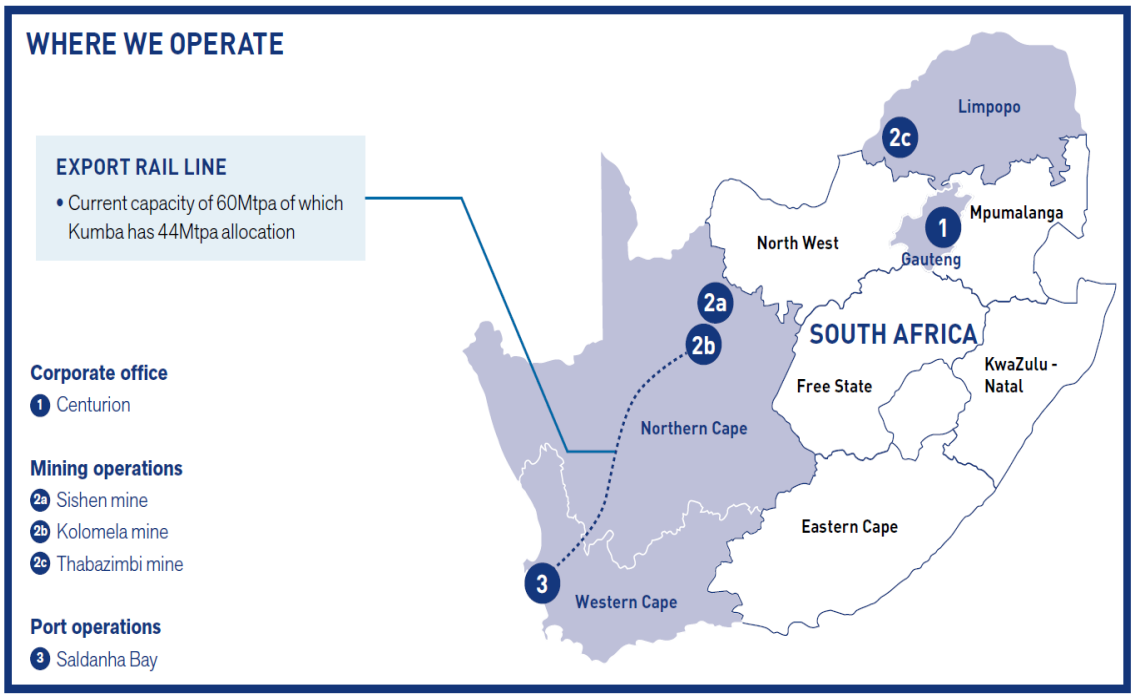


Figure 5.1. Kumba sites in the Republic of South Africa (Viljoen, 2017)

Figure 5.2 provides further detail on the location of the Kolomela mine; indicating the relative portion of the mine to the other Kumba operations mine, the major export rail line and the town of Postmasburg.

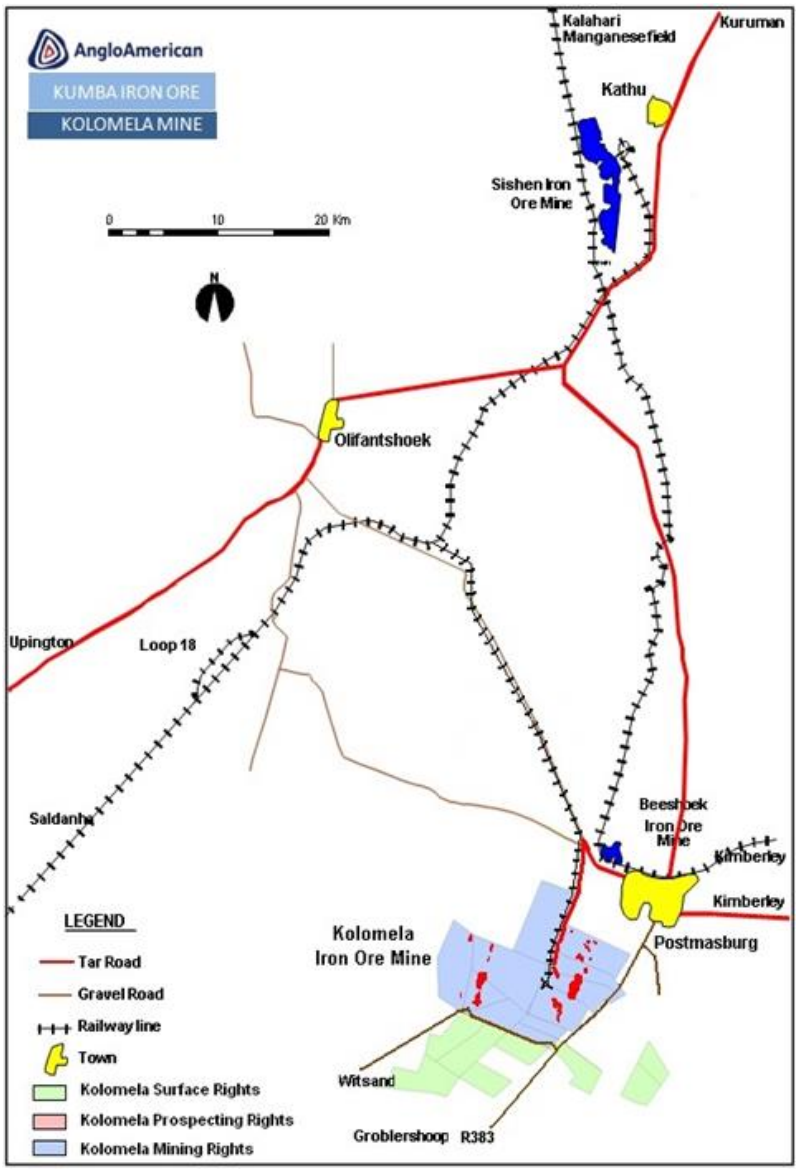


Figure 5.2. Detailed location map of Kolomela (Crawley, 2017)

Kolomela is a conventional open-pit mining operation where drilling, blasting, loading and hauling processes are applied to mine high-grade iron ore and the associated waste material from three different pits. The mine is mainly a direct shipping ore (DSO) operation and product size is controlled via a crushing and screening plant receiving feed from ROM buffer stockpiles and ex-pit ROM material and railed to the Saldanha harbour for shipping to clients in Asia and Europe.

Iron ore is produced for the export market. Blending from ROM stockpiles and product stockpiles are used to ensure that the final product adheres to the required client quality specifications. The lump and fine products are reclaimed from the product stockpiles and loaded onto trains for transport to the Saldanha bay, from where it is shipped to various international markets; with clients in China currently responsible for the largest off-take of the saleable product produced at Kolomela (Crawley, 2017).

Kolomela is a significant open-pit mining operation and makes a substantial contribution to the operational and financial performance of Kumba since 2012 when the designed plant throughput of 9Mtpa was achieved. In the 2016 financial year the ex-pit mining tonnage at Kolomela was 63.5Mt or ~200ktpd, representing 26% of the total tonnes mined by Kumba in that year. The total tonnes mined can be divided into 13.5Mt of ex-pit ore and 50Mt of ex-pit waste resulting in a stripping ratio of 3.7. As a result, Kolomela produced 12.7Mt of saleable product; representing 31% of Kumba's saleable production for 2016. In the same year Kumba achieved earnings before interest and tax (EBIT) of R15,3bn with Kolomela contributing 29% of the company's EBIT (Kumba Iron Ore, Full Year 2016 Annual Results Presentation, 2017).

5.2.2 Geological setting and ore types

Extensive iron - and manganese-bearing lithologies are exposed in a narrow, north-south belt between Kathu and Postmasburg in the Northern Cape Province (see Figure 5.3). Numerous shallow manganese and iron ore deposits were mined in this region between 1900 and 1930. The landscape is dotted with abandoned workings along two sub-parallel ridges (the Gamagararand and Klipfonteinheuwels (Viljoen, 2017). Today this "belt" provides the bulk of South Africa's iron ore needs and enables the country to be a major player in the iron ore export market.

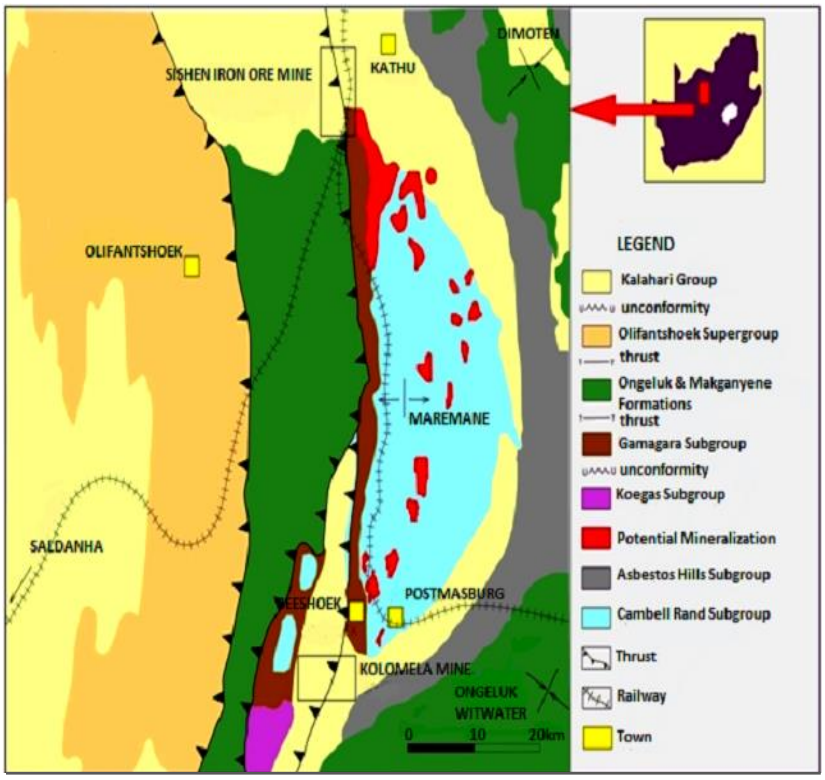


Figure 5.3. Regional geology of the Sishen – Postmasburg sub-region in the Northern Cape province of South Africa (Viljoen, 2017)

Iron ore, mostly hematite and specularite, is defined as four geologically distinct ore types at Kolomela (see Figure 5.4), each with unique physical and chemical characteristics (Viljoen, 2017). These four ore types are:

- Laminated ore constitutes the main ore-type (52.9% of total) and the primary lamination of the precursor banded iron formation is still preserved, suggesting in-situ replacement of silica by iron;
- Clastic textured ore (28.8% of total), which is characterised by distorted, wavy bedding and occurs as lenses and massive units;
- Collapse breccia-type ore (9.8% of total), formed from the ferruginisation of brecciated banded iron formation (BIF) units. The brecciation is probably because of karstification of the underlying dolomites; and
- Conglomeratic ores (8.6% of total), representing ferruginised Gamagara conglomerates.

The iron ore has been preserved as several discontinuous bodies within synclinal, graben and sinkhole structures, which were later influenced by thrusting from the west. Each geological environment contains a unique combination of ore types and associated waste lithologies. There are relatively few, lower-grade, conglomeratic and collapse breccia ores. The overall quality of the iron ore at Kolomela makes it acceptable as a high-grade metallurgical iron ore.

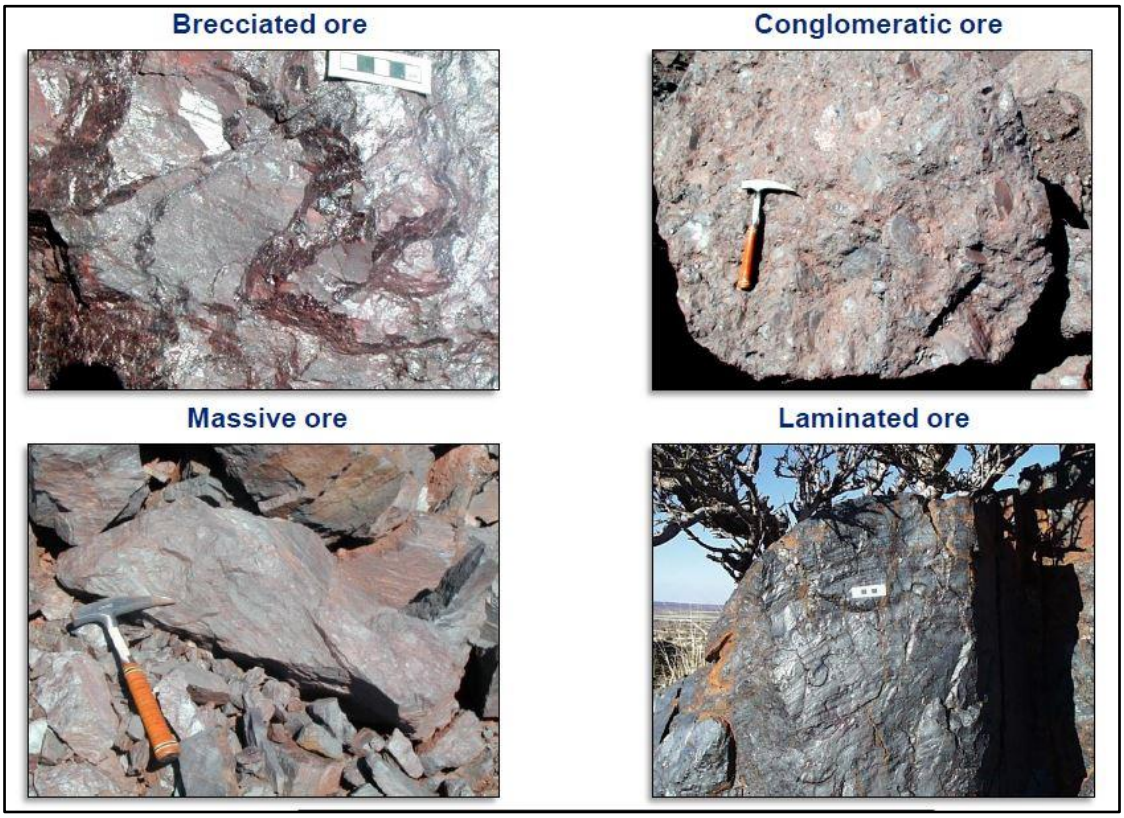


Figure 5.4. Ore types and mineralogy (Viljoen, 2017)

5.2.3 Mineral Resources and Mineral Reserves

On 31 December 2016 Kolomela declared a SAMREC compliant Mineral Reserve of 191.8Mt at an average quality of 64.4% Fe; with 59Mt categorised as Proved Ore Reserve and the remaining 132.8Mt as Probable Ore Reserve. The Ore Reserve was declared at a cut-off grade of 50% Fe and resulted in a reserve life of 18 years at the estimated production rate. The saleable product equated to 186.6Mt at an average quality of 65% Fe (Crawley, 2017).

An exclusive Mineral Resource (in addition to Ore Reserves) of 204.2Mt at an average quality of 63.5% Fe was also declared on 31 December 2016; again, at a cut-off grade of 50% Fe. The classification of the Mineral Resource was: 27.5Mt Measured Mineral Resource, 67.4Mt Indicated Mineral Resource and 109.3Mt Inferred Mineral Resource (Viljoen, 2017).

5.2.4 Mining layout, mining method and equipment

Kolomela applies the conventional open-pit truck and shovel mining method and all ex-pit material is drilled and blasted in 10m high benches prior to loading. Hauling operations ensure that the ex-pit ore arrives at the correct crushing or ROM stockpile location, while waste is dumped on waste dumps or back into previously created voids as part of an in-pit filling process. The aim of the bulk waste mining is high efficiency to reduce the mining cost, while the ex-pit ore mining is a selective mining process with a focus on clean extraction of the ore. A hybrid model of owner mining and contractor mining is employed with approximately 75% of the mining operation conducted with the owner mining fleet.

Mining activities take place in three distinct open pits called Leeuwfontein (LF), Klipbankfontein (KB) and Kapstevel (KS). The correct spatial layout of the pits, pushbacks and mining benches or levels are critical to achieve the planned annual production targets in a sustainable way and make effective use of the available mining capacity. Figures 5.5 and 5.6 provide a general layout of the Kolomela mine showing the three open pits, the processing plant and the rail loop.

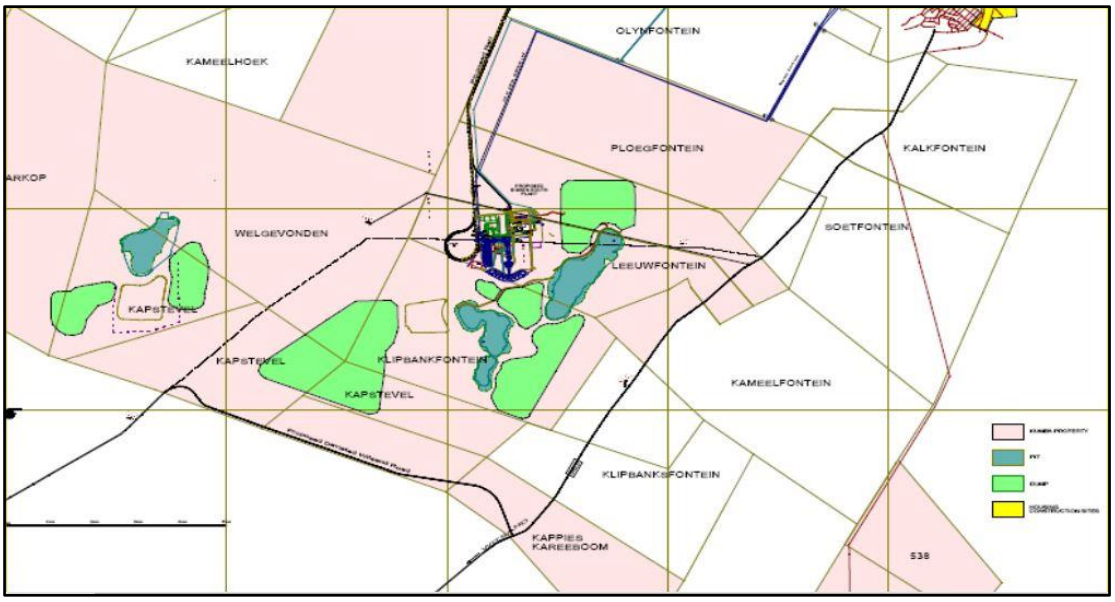


Figure 5.5. General layout of Kolomela mine (Crawley, 2017)



Figure 5.6. Satellite image of the Kolomela mining site (Crawley, 2017)

Open-pit mining activities involve the continuous drilling, blasting, loading and hauling of waste and ex-pit ore in a safe, sustainable and efficient manner to achieve the operational and financial targets set annually in the BP of the mine. Figure 5.7 provides an illustration of the typical planning for the sequence of the mining activities in consecutive benches in a pushback; specifically, pushback 6 in the LF pit. Figure 5.8 is an image of the actual mining activities in the same mining area.

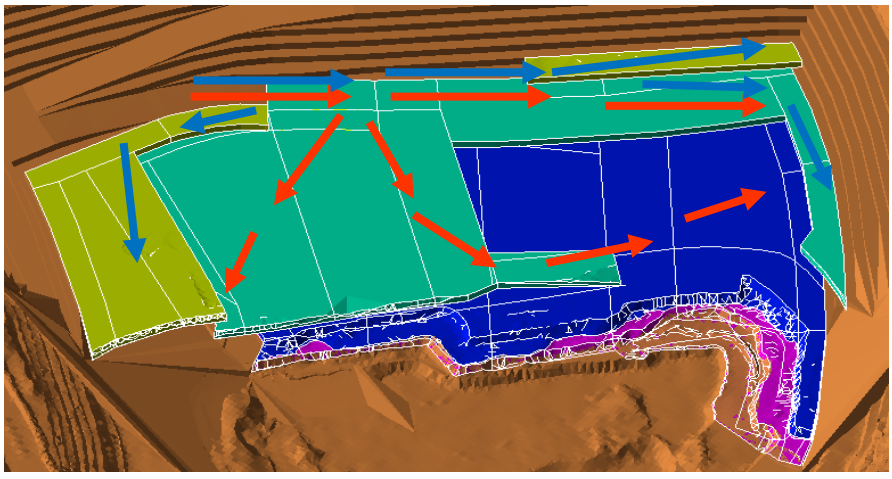


Figure 5.7. Planning of the deployment sequence of PB 6 of the LF pit



Figure 5.8. Actual mining activities in PB 6 of the LF pit

The primary mining equipment employed at Kolomela include:

- Drilling: six Caterpillar MD6540 drill rigs drilling 251mm diameter blast holes;
- Loading: one Liebherr R996 hydraulic face shovel for pre-strip waste mining, four Komatsu PC3000 hydraulic face shovels for waste and ore mining, two Liebherr R9150 hydraulic excavators for selective ore mining and four front end loaders for flexible loading in the pit and re-handling of ROM ore stockpiles; and
- Hauling: 25 Komatsu 730E trucks (190t capacity) and 10 trucks of 100t capacity each (combination of Komatsu 785 and Caterpillar 777 trucks).

Figure 5.9 shows images of the major steps in the open-pit mining process with production blast hole drilling in the top left corner and then in a clockwise direction charging of the blast holes with explosives, loading and hauling activities. Figure 5.10 is an image of a double-sided loading operation where the Liebherr R996 shovel is loading Komatsu 730E trucks.

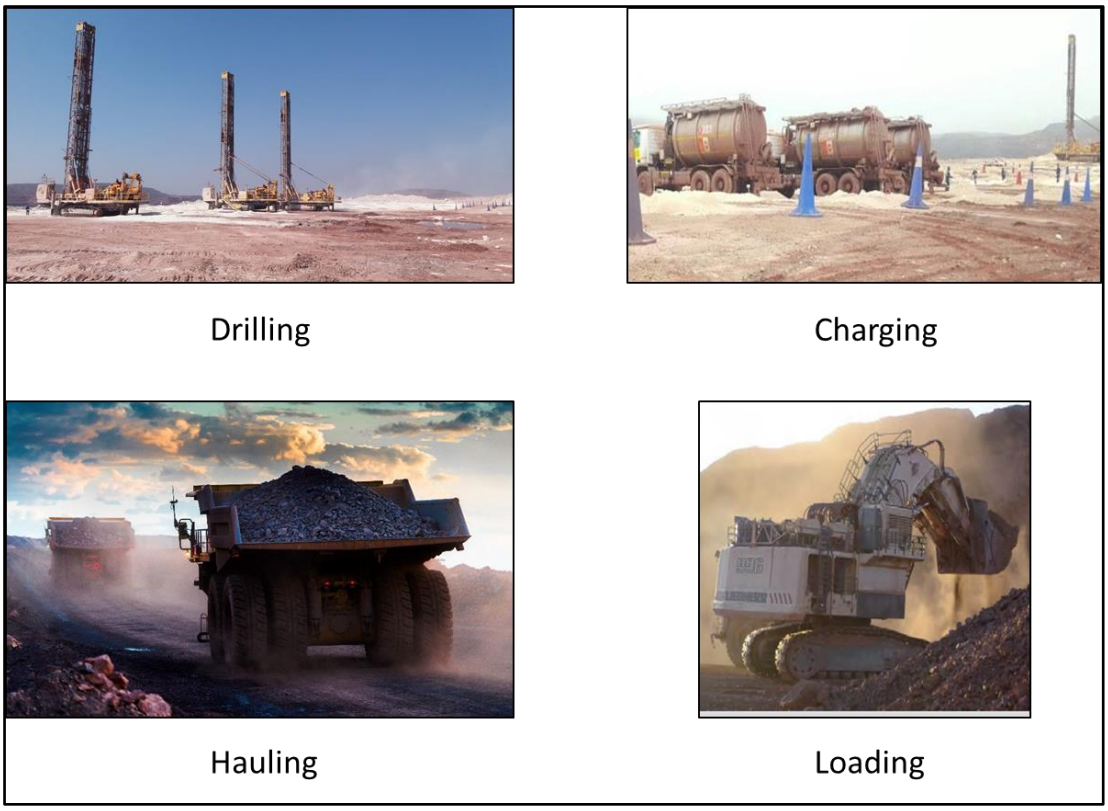


Figure 5.9. Major open-pit mining activities performed at Kolomela



Figure 5.10. Loading of Komatsu 730 trucks with a Liebherr R996 shovel

5.2.5 Processing and logistics

Kolomela is mainly a DSO operation; this means that no beneficiation of the mined ore takes place. To ensure product throughput and quality targets are achieved, it is therefore important that the ex-pit ore is mined according to the plan. The processing flow diagram captured in Figure 5.11 illustrates the flow of iron ore from the primary crusher through secondary crushing, the buffer stockpile, screening into lump and fine product, tertiary crushing, blending beds and the load-out station where the wagons are filled for rail transport to Saldanha port. Figures 5.12 and 5.13 show the primary crusher that receives ore from the mining operations and the primary buffer stockpile, respectively.

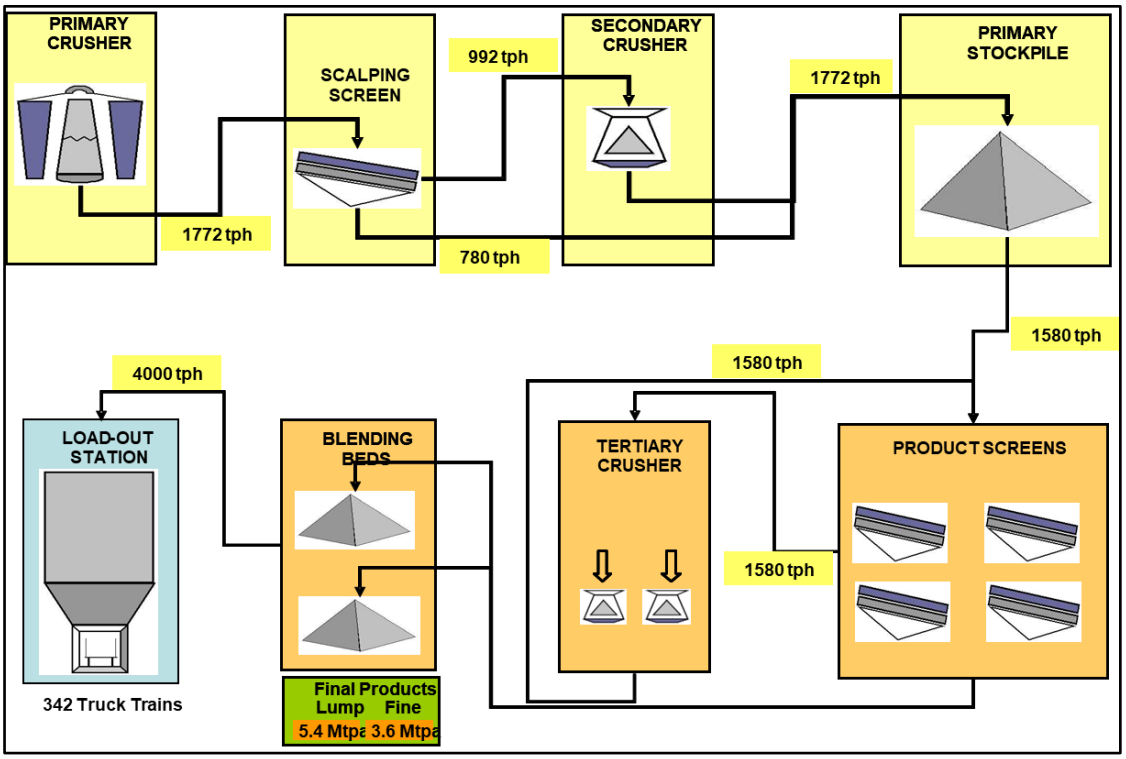


Figure 5.11. Processing flow diagram (Crawley, 2017)



Figure 5.12. Kolomela primary crusher



Figure 5.13. Primary buffer stockpile at the Kolomela processing facility

5.2.6 Production history

Following extensive exploration drilling and a detailed project evaluation process, Kolomela was “born” with the approval of the expansion project in 2008. The business case for the project, at the time, was based on an annual production rate of 9Mt and a mining plan supporting this level of production (Harmse, 2008). The bulk of the plant, rail and infrastructure construction started in 2009. Open-pit mining activities started in the LF pit in September 2009 followed by the KS pit in September 2010. The first train was dispatched in November 2011. Kolomela achieved nameplate production capacity (of 9Mtpa) in 2012. Mining of the third pit, KB, commenced in March 2013 (Mutangwa, 2018).

Figure 5.14 illustrates the production ramp up of Kolomela from 2009 to 2016. Ex-pit waste mining activities ramped up until 2014 when annual waste mining peaked at 75Mtpa. Ex-pit ore mining commenced in 2010 and ramped up to a peak of 15Mtpa in 2014. Annual

product exceeded the project's investment proposal on an annual basis and 13Mtpa was achieved in 2016.

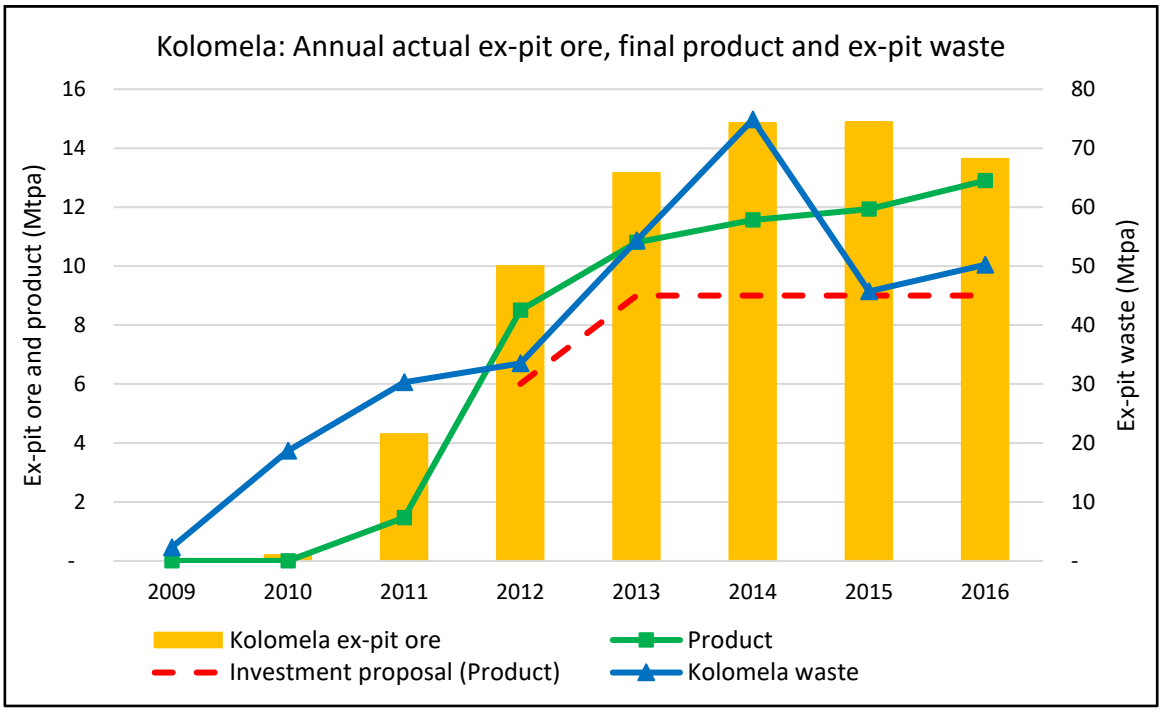


Figure 5.14. Production history of Kolomela mine

The original project production rate of 9Mtpa was, thus, exceeded by between 22% and 44% in the 2012 to 2016 period. The excellent operational performance had a positive effect on the profitability of the mine and contributed significantly to the financial success of Kumba. However, questions were being asked about the sustainability of this performance going forward.

5.3 Challenges faced at Kolomela mine

As indicated in the previous section, Kolomela had a very successful production ramp up exceeding the projections of the 2008 project business case every year since the inception of the mine. From a processing and logistics perspective the increase in annual production was achieved mainly through de-bottlenecking of the installed capacity and with minimal capital spend. The ex-pit mining activities (ore and waste) were also increased to support the higher product throughput. This was achieved through various mining efficiency drives focussed on increasing the DOH of the mining equipment as well as the mining rate of the primary shovels. Additional mining contractor capacity was also brought on line mainly in the KS pit which is geographically isolated from the main Kolomela complex.

In 2013 the Kumba Executive Committee (Exco) expressed a need to incorporate the excellent operational performance that had been achieved into the forward-looking business planning of Kolomela mine. The feasibility was investigated through mine planning scenarios which were developed as part of the annual LOM and MTPs of the mine. During the 2013 business planning cycle the BP was updated to reflect the demonstrated operational efficiencies. The 2013 BP indicated that it was feasible to sustain the increased annual production of 13Mt, thus, increasing the estimated annual production of Kolomela by 44% from 9Mt to 13Mt.

The focus on operational efficiencies introduced two major challenges. Firstly, a reduction in the reserve life of Kolomela was anticipated. The declared Ore Reserve at Kolomela remained relatively constant between 2013 and 2016 at between 190Mt and 210Mt. The effect of the acceleration in mining activities to support the increased production implied a reduction in reserve life from 22 years to 18 years (stated from 2017 onwards) between the 2012 and 2016 reserve statements. This 18% reduction put pressure on the exploration programme and associated resource replacement activities. Secondly, the focus shifted from effective mining to efficient mining. At the mining operation the KPIs that received most of the attention were those measuring the efficiency of the mining equipment, such as DOH per truck and loading tempo per shovel. This over exaggerated drive to achieve short-term focussed temporal KPIs resulted in mining activities not taking place in the planned pits, pushbacks and mining benches as required by the relevant BP. More efficient or “easier” mining areas were prioritised at the expense of mining in the “right” area to ensure planned ore exposure. This meant that the mining performance was not sustainable.

Although the remaining Ore Reserves as well as the mine plans supported and confirmed that the increase in annual production to 13Mtpa was feasible and sustainable, the Kumba Exco was concerned about the level of operational flexibility of the mine and the sustainability of the mining performance given the perception that the pits were not always spatially mined in line with the planned mining areas (van den Brink, 2013). This concern could be worded differently as follows:

- How well was the mine plan being executed spatially?
- Was the available mining capacity being deployed in a spatially effective manner?
- What was the level of spatial compliance to the mine plan?

Thus, not only considering what is being mined when, but also where the mining activities are taking place relative to the areas planned for mining.

To answer these questions confidently, an analysis of the spatial alignment between the relevant mine plan and the actual mining activities was required. At the time such a spatial

reconciliation between areas planned for mining and areas actually mined did not exist at Kolomela.

5.4 Opportunity to apply the spatial mine-to-plan compliance framework

The initial spatial mine-to-plan compliance reconciliation results confirmed the concerns raised by van den Brink (2013). The first reconciliation results become available in mid-2013 and indicated that for the first half of 2013 only 28% of the ex-pit mining tonnes were mined within the areas planned in the BP for the corresponding period (mined in plan and in sequence), a further 43% of the ex-pit mining tonnes were mined within areas planned in the BP (mined in plan and out sequence) and 29% of the mining activities took place outside of the BP. The full year 2013 spatial mine-to-plan compliance performance was equally unsatisfactory: 74% of the ex-pit mining activities took place in areas planned in the BP and 38% of ex-pit mining activities took place outside of the spatial guidance provided by the BP (expressed as percentages of the planned mining activities).

The 2013 spatial mine-to-plan reconciliation performance for Kolomela can be summarised as follows:

- Production compliance of 112%;
- Adherence index of 66%; and
- Spatial mine-to-plan index of 74%.

Even though the actual cumulative ex-pit mining tonnes for 2013 were 12% above the BP target only 66% of the actual mining activities took place in planned areas and the spatial overlap between areas planned in the BP and actual mining was only 74% (expressed as a percentage of the planned mining activities).

These reconciliation results confirmed that the ex-pit mining activities at Kolomela were not being executed in compliance with the spatial plans prescribed by the relevant BP. The available mining capacity was not being deployed in a spatially effective manner. The level of spatial compliance to the mine plan was unacceptably low. This performance introduced a risk to the planned ramp up of the mine from 9Mtpa to 13Mtpa. The planned level of operational flexibility and the sustainability of the mining activities estimated in the mine plans were not ensured through actual spatial mining execution. An opportunity existed to apply the spatial mine-to-plan compliance framework developed by this thesis to improve spatial compliance to the mine plan to mitigate the risk.

5.5 Why was Kolomela an appropriate case study mine?

Kolomela was an appropriate case study mine for the following main reasons:

- Scale and spatial complexity: It is a major open-pit mining operation moving approximately 200 000 tonnes of ex-pit material daily from three different pits each containing several pushbacks. The size and the geographic complexity of the mine require that actual mining activities are executed in spatial compliance to the mine plan;

- Spatially dependent: The mine's relatively high stripping ratio and the DSO nature of the operation necessitate that mining should take place in the spatially correct areas;

- Fleet size: Kolomela utilises a significant fleet of HME. Seven pieces of primary loading equipment ensure the effective extraction of the required ex-pit ore and the mining of the associated ex-pit waste. The loading operations are supported by 6 primary drill rigs and 35 haul trucks. The scale and complexity of the spatial deployment of the HME fleet requires accurate spatial compliance to the mine plan;

- Cost structure: The open-pit mining activities at Kolomela are expensive. In 2016 the operating expenses for the mine were R3.9bn (Kumba Iron Ore, Full Year 2016 Annual Results Presentation, 2017). Assuming 50% of the operating expenses are directly related to the mining activities this equates to R30.47 per ex-pit tonne mined. The high operating cost associated with mining activities makes it imperative that the spatially correct material is mined;

- Proportional contribution: Kolomela contributed 29% of Kumba's EBIT in 2016 and the proper spatial execution of the mine plan is critical to ensure the continuation of this contribution and the financial stability of Kumba into the future; and

- Low historical spatial mine-to-plan compliance: The 2013 spatial mine-to-plan reconciliation performance indicated that the level of spatial compliance to the mine plan was unacceptably low.

5.6 Summary of Chapter 5

Kolomela was presented as the open-pit iron ore mine on which the proposed spatial mine-to-plan compliance framework was validated. Kolomela is in the Northern Cape province of South Africa and is one of two mines owned and operated by Kumba. It is a significant

open-pit mining operation with ex-pit mining activities of ~200ktpd occurring in three distinct pits. The mine employs a sizable fleet of mining equipment including 7 primary loading units and 35 haul trucks.

Mining activities at Kolomela started in 2009 and the name plate production capacity of 9Mtpa was exceeded from 2013 onwards. In 2013 mining plans indicated that an annual production level of 13Mt was feasible and sustainable, but concerns existed around the quality of spatial execution of the mine plans. What was the level of spatial compliance to the mine plan? In 2013 only 66% of the ex-pit mining activities spatially complied to the relevant BP and the spatial mine-to-plan index was 74%. The undesirable spatial compliance results presented a significant risk to the achievement of the proposed increased production levels. In addition, the significant scale of the mine, geographic complexity, relatively high stripping ratio, DSO processing, high cost of mining activities and the mine's contribution to Kumba's performance made Kolomela an ideal case study mine and presented an excellent opportunity to apply the spatial mine-to-plan compliance framework developed in this thesis.

6. RESULTS OF VALIDATION

6.1 Overview of Chapter 6

The results of the validation of the spatial mine-to-plan compliance framework are presented in this chapter. Section 6.2 introduces the validation. Sections 6.3 and 6.4 provide a summary of the temporal ex-pit mining production results at Kolomela for the period 2015 to 2017 (inclusive). Results for ex-pit waste, ex-pit ore and ex-pit Fe quality are discussed. The exposed ore results achieved for this period are presented in Section 6.5. Section 6.6 summarises the spatial mine-to-plan compliance reconciliation results for Kolomela using the definitions, categories and metrics defined in Chapter 4 of this thesis. Commentary is provided on performance against the reconciliation targets. Selected results from the application of the CDT as well as the application of technology solutions (RPAS and HP-GPS) at Kolomela are presented in Sections 6.7 and 6.8. Section 6.9 explores the relationship between the spatial mine-to-plan compliance reconciliation results and the EO levels achieved at Kolomela.

6.2 Introduction to the validation

As discussed in Chapter 5, Kumba first evaluated the spatial mine-to-plan compliance performance at Kolomela during 2013. The initial results were not acceptable and introduced a risk to the medium-term operational performance of the mine. The spatial mine-to-plan compliance framework, presented in this thesis, was rolled out at Kolomela. Kolomela therefore presents an ideal case study mine to validate the effectiveness of the framework. The robustness of the developed framework was validated at the Kolomela open-pit iron ore mine in South Africa to demonstrate the benefits of the application of the framework. The framework was validated over a three-year period from 2015 to 2017, for which data could be obtained to meet the granularity required for the framework.

6.3 Temporal ex-pit mining production results

The ex-pit mining production performance of Kolomela for the three-year period under consideration is presented to provide the necessary context. Figures 6.1 to 6.3 provide a summary of the monthly ex-pit waste and ex-pit ore production relative to the BP targets for the relevant period.

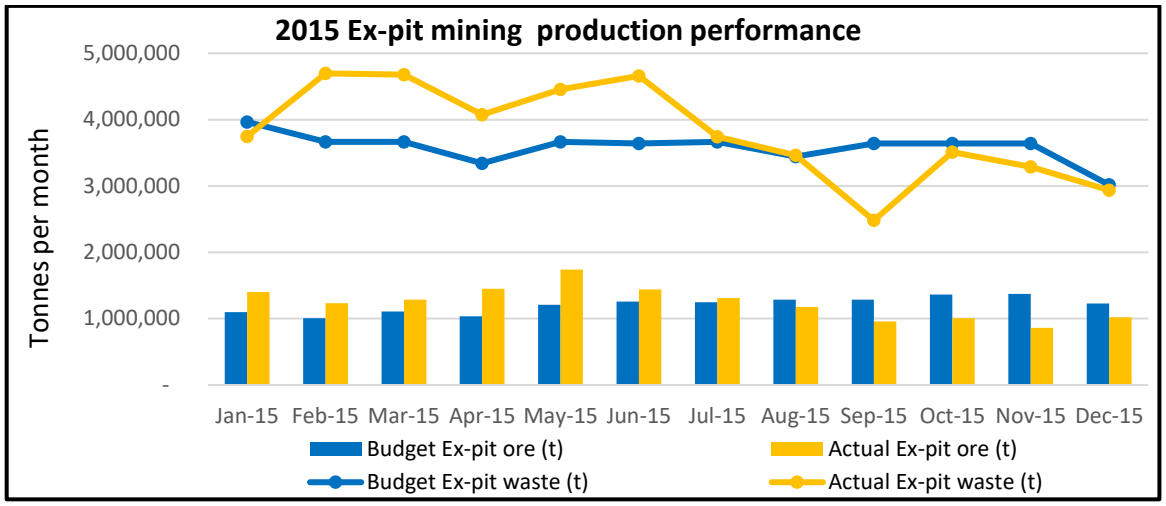


Figure 6.1. Ex-pit mining performance for 2015

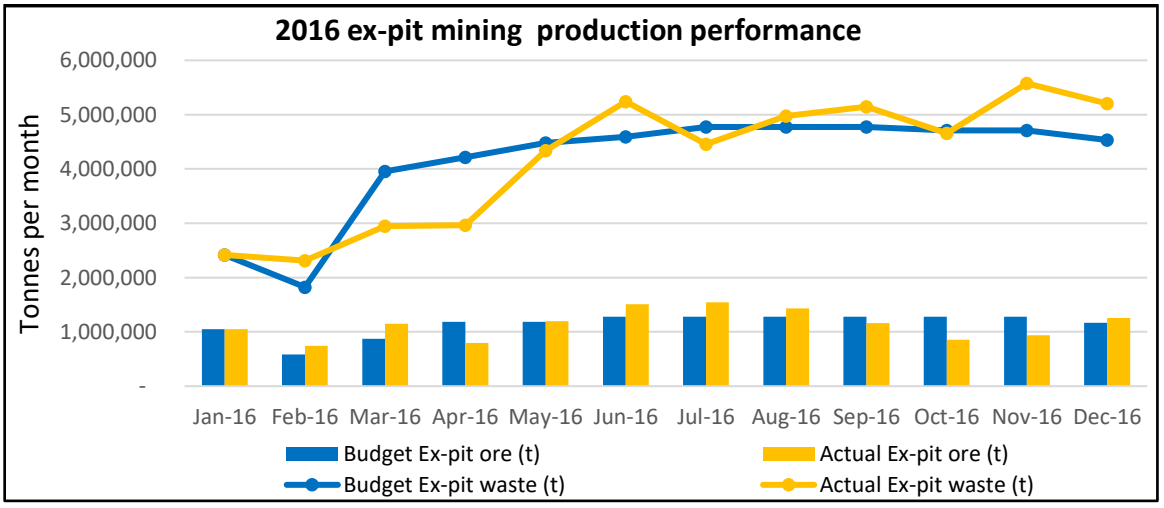


Figure 6.2. Ex-pit mining performance for 2016

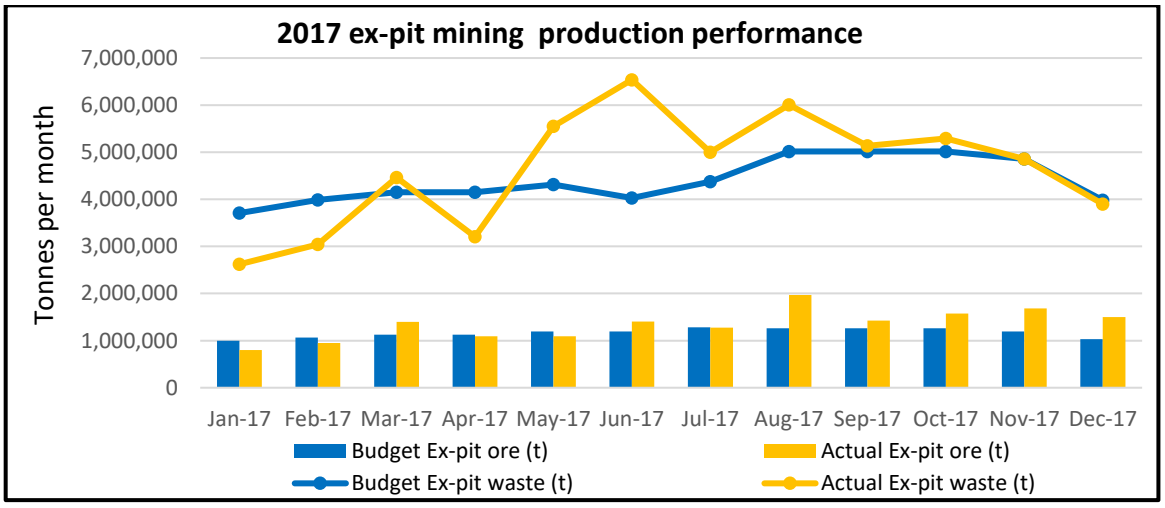


Figure 6.3. Ex-pit mining performance for 2017

The results from the actual *vs.* BP ex-pit mining performance summarised in Figures 6.1 to 6.3 indicate the following:

- In the first half of 2015, the BP targets for both ex-pit waste and ex-pit ore were exceeded and in the second half the BP targets where not achieved. For 2015 the actual ex-pit waste was 45.7Mt against a budget of 43.0Mt (+6.3%) and the actual ex-pit ore was 14.9Mt against a target of 14.5Mt (+2.7%);
- In 2016, the BP targets for ex-pit waste were lower in the first two months of the year reflecting major HME maintenance activities. Actual ex-pit waste performance only recovered from May onwards and then generally achieved the BP targets. Ex-pit ore performance exceeded targets in the June to August period. For 2016, the actual ex-pit waste was 50.2Mt against a budget of 49.8Mt (+0.8%) and the actual ex-pit ore was on budget at 13.7Mt; and
- The actual ex-pit waste tracked below the BP targets for the first four months of 2017 and then recovered in the period to September. Ex-pit ore generally exceeded the BP targets in the second half of 2017. For 2017 the actual ex-pit waste was 55.6Mt against a budget of 52.6Mt (+5.7%) and the actual ex-pit ore was 16.2Mt against a target of 14.0Mt (+15.7%). The increased ex-pit ore was mainly associated with a gain in lower grade ore (not fed to the DSO plant) during the second half of 2017.

In summary, Kolomela performed well against the BP targets over the three-year period, achieving and exceeding both ex-pit waste and ex-pit ore targets. The ex-pit ore quality results are presented in the next section.

6.4 Temporal ex-pit ore Fe quality results

The ex-pit ore Fe quality achieved at Kolomela from 2015 to 2017 is presented in Figures 6.4 to 6.6. The figures indicate that the BP ex-pit ore monthly Fe quality targets were not achieved during 2015. For 2015, an annual actual ex-pit Fe of 62.7% was achieved; this is significantly below the BP target for the year of 64.2%. The BP Fe quality targets were generally achieved in 2016 (63.9% Fe *vs.* the BP of 63.7% Fe) and 2017 (63.7% Fe *vs.* the BP of 63.5% Fe). The actual ex-pit ore quality in the latter part of 2017 reflects the impact of the low-grade ore gain experienced over this period.

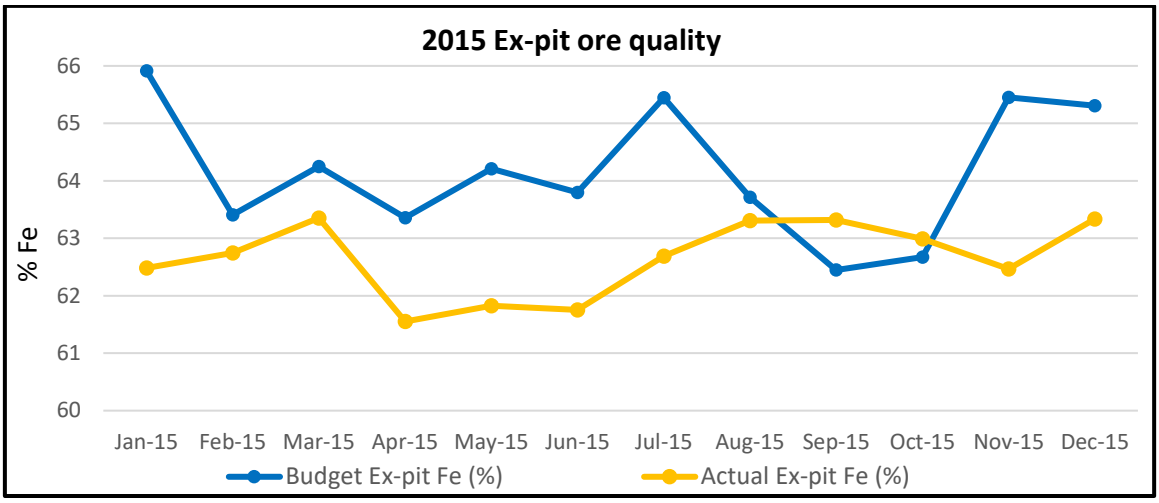


Figure 6.4. Ex-pit ore Fe quality for 2015

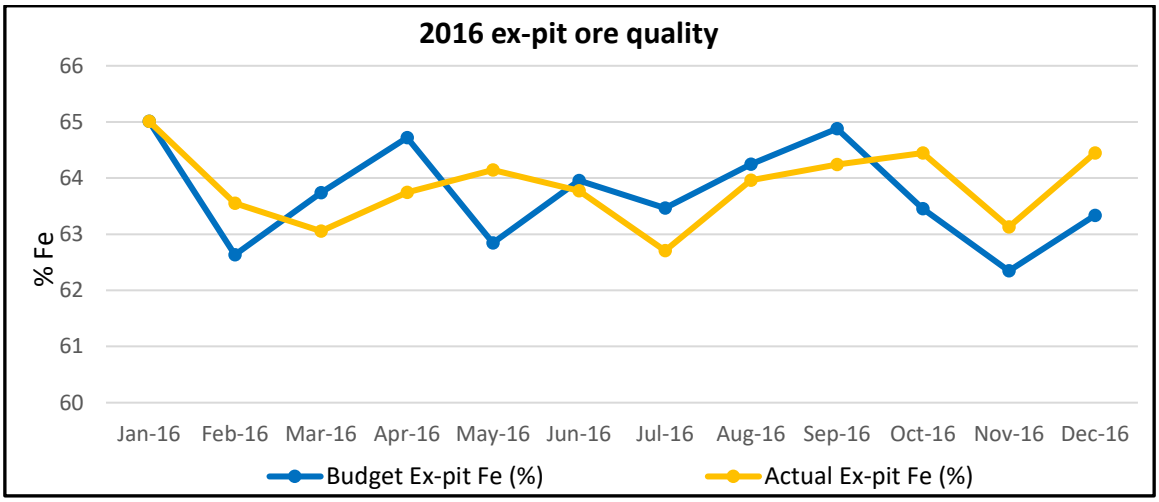


Figure 6.5. Ex-pit ore Fe quality for 2016

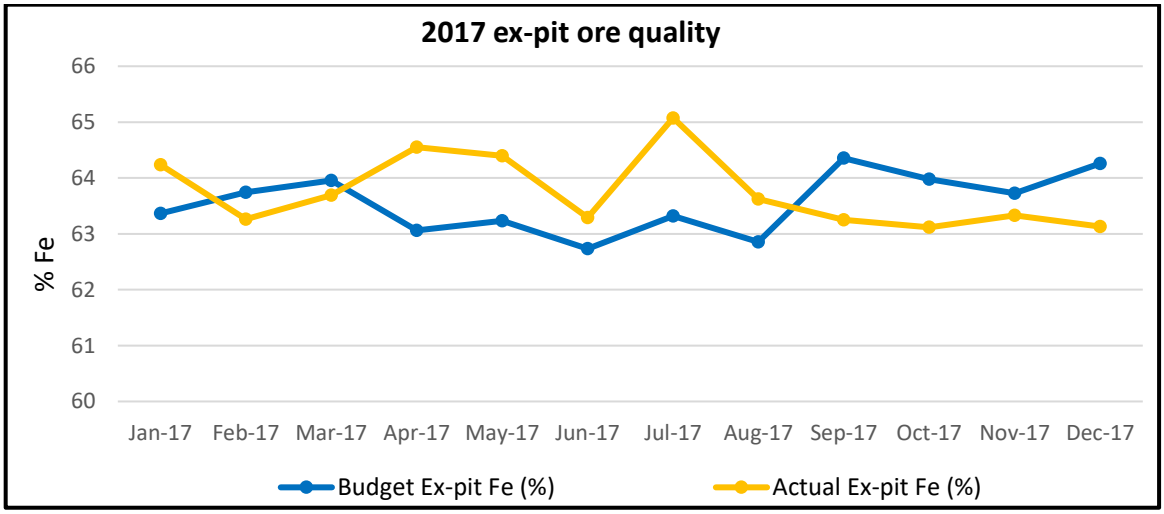


Figure 6.6. Ex-pit ore Fe quality for 2017

6.5 Exposed ore results

EO in an open-pit mine was defined in Section 2.3.5 as the amount of ore that can be accessed with little or no further waste stripping required and it was indicated that EO is a proxy for technical operating flexibility. At Kolomela, a combination of high-grade ROM stockpiles and high-grade exposed ore levels in the pits provide an indication of the flexibility of the open-pit mine. The total EO at Kolomela at the end of a specific period is determined by adding the high-grade ore tonnes available on ROM stockpiles and the high-grade EO exposed on the various active mining benches. Actual performance against the budgeted total EO levels required by the BP are applied as indicator for longer-term mining operational flexibility.

The monthly total EO targets (derived from the relevant BP) and the actual levels of total EO achieved at Kolomela in 2015 are illustrated in Figure 6.7. The monthly BP targets were not achieved during 2015 and Kolomela ended the year with 4.1Mt of total EO; only 77% of the budgeted 5.3Mt.

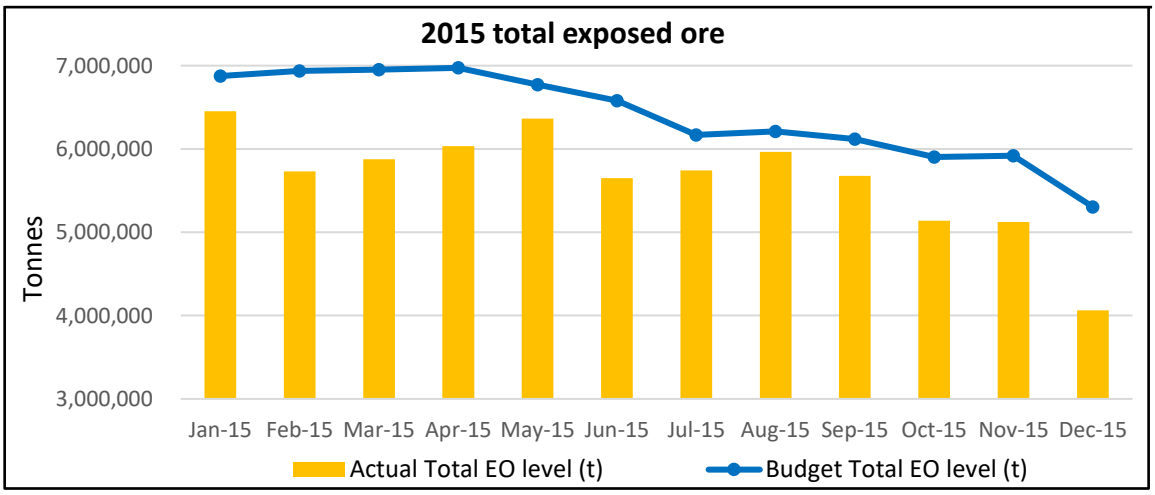


Figure 6.7. Total EO for 2015

The actual *vs*. budgeted total EO performance for 2016 is shown in Figure 6.8. During the first half of 2016 the actual total EO remained between 10% and 20% below the BP targets. The budgeted total EO targets were only achieved from quarter 3 of 2016. The mine closed the year at a total EO level of 4.0Mt; marginally higher than the budget of 3.9Mt.

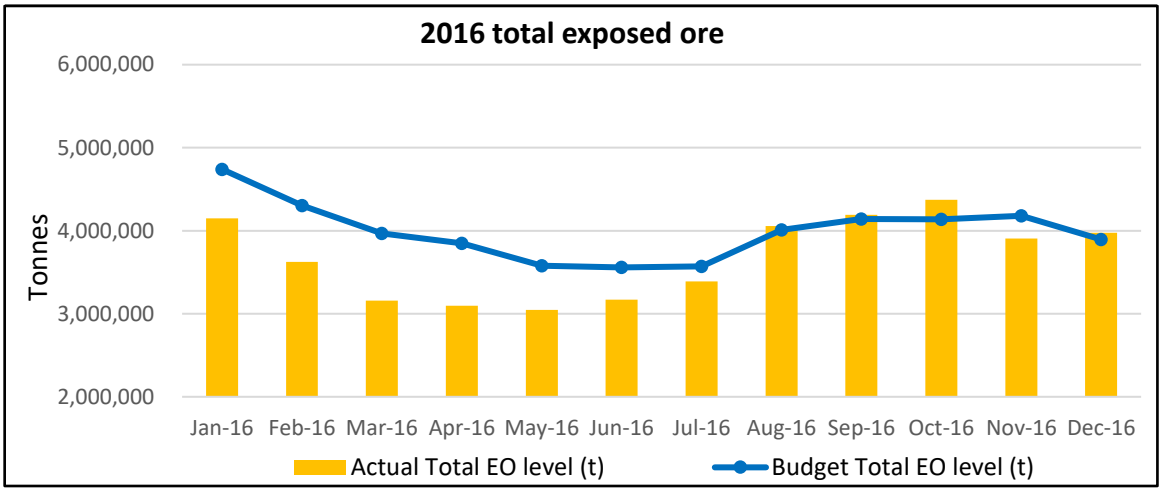


Figure 6.8. Total EO for 2016

The 2017 total EO performance for Kolomela is depicted in Figure 6.9. In general, the actual total EO tracks the monthly BP targets well. The lower than budgeted actual total EO during May and June 2017 is a direct result of an executive decision taken to reduce the high-grade ROM stockpile levels at Kolomela as part of a short-term initiative to increase iron ore sales from Kolomela during quarter 2 of 2017. Kolomela ended the year with 5.6Mt of total EO; this is 108% of the budgeted 5.2Mt.

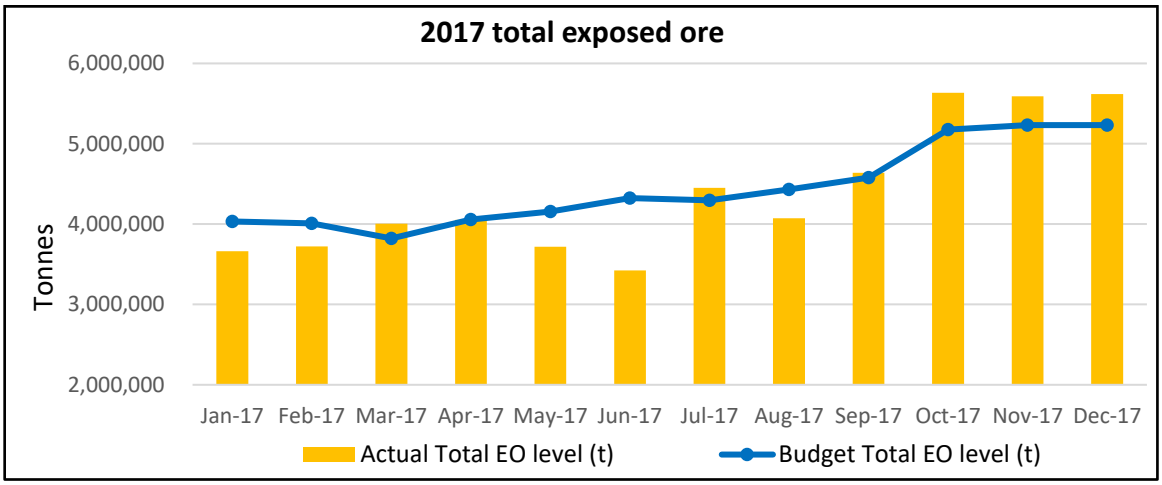


Figure 6.9. Total EO for 2017

6.6 Spatial mine-to-plan compliance results

The results of the measurement of spatial mine-to-plan compliance against the relevant BP for Kolomela are reported monthly. The reporting formats are in line with the guidelines discussed in Section 4.4 of this thesis.

The four metrics defined in Section 4.4.4 as part of the development of the spatial mine-to-plan compliance framework are practically used at Kolomela mine to describe the spatial mine-to-plan compliance performance monthly. An executive summary of the annual spatial mine-to-plan compliance reconciliation results achieved at Kolomela from 2015 to 2017 is presented in Table 6.1. The results represent the cumulative spatial mine-to-plan compliance at the end of each year. The two mine-to-plan indices are the same at the end of the year and therefore, only a single mine-to-plan index result is shown in the table.

Table 6.1. Cumulative mine-to-plan performance at Kolomela from 2015 to 2017

		2015	*2016*	*2017*
Ex-pit waste	Production compliance	106%	101%	106%
	Adherence index	79%	98%	93%
	Spatial mine-to-plan index	84%	99%	99%
Ex-pit ore	Production compliance	103%	100%	116%
	Adherence index	84%	99%	84%
	Spatial mine-to-plan index	89%	99%	98%
Total ex-pit mined	Production compliance	106%	101%	108%
	Adherence index	81%	98%	91%
	Spatial mine-to-plan index	85%	99%	99%

The production compliance results reflect the temporal ex-pit ore and waste results presented in Section 6.3. Even though the ex-pit mining activities exceeded the BP in the three-year period under discussion, the adherence index results illustrate that only 81% of the actual ex-pit mining activities in 2015 took place in areas planned in the relevant BP. This increased to 98% and 91% in 2016 and 2017, respectively as the implementation of the spatial mine-to-plan compliance framework matured at Kolomela. The low adherence index for ex-pit ore in 2017 reflects a significant exceedance of the BP ex-pit ore tonnage target in that year. The mine-to-plan index results quantify the spatial mine-to-plan compliance to the relevant BP. The spatial overlap between the actual areas mined in 2015 and the BP was 85% for the total ex-pit material mined. This represents a

significant improvement on the 74% achieved in 2013. The spatial compliance further improved to 99% in both 2016 and 2017.

Figures 6.10 to 6.12 are graphs where the 2015, 2016 and 2017 annual cumulative spatial mine-to-plan compliance reconciliation performance of Kolomela is presented in monthly increments using the two mine-to-plan indices and the four categories defined in Sections 4.4.3 and 4.4.4. The graphs represent the spatial mine-to-plan compliance for the total ex-pit mining activities (ex-pit waste plus ex-pit ore tonnes).

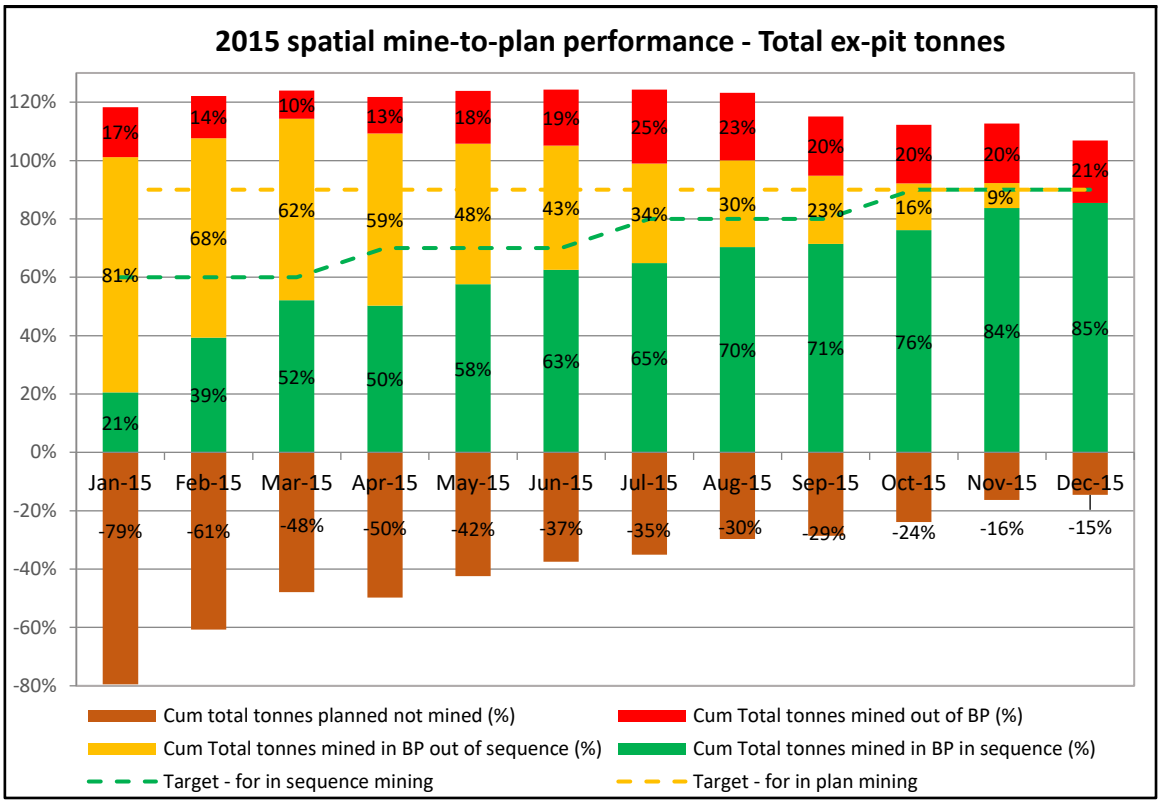


Figure 6.10. Spatial mine-to-plan compliance performance for 2015

Even though the monthly spatial mine-to-plan compliance reconciliation results did not yet achieve the set targets in 2015, the performance was a marked improvement on the 2013 results. The 2015 spatial mine-to-plan compliance results were supported by the fact that actual ex-pit mining activities exceeded the BP requirements by up to 24% on a cumulative basis throughout the year. This high production compliance (above 100%) could have a negative impact of increased mining cost leading to increased unit production cost when compared to the BP. During the first half of 2015 a significant amount of mining activities took place out of sequence indicating that some of the actual areas mined in the first half were planned for the second half of the year. By June 2015, the spatial mine-to-plan index 1 was 106% (63% mined in BP in sequence plus 43% mined in BP out of sequence),

spatial mine-to-plan index 2 was 63% and 5.5Mt of the actual ex-pit mining activities YTD were executed outside the areas planned in the BP (19% when expressed as a percentage of the planned tonnes). At the end of 2015, the spatial mine-to-plan index was at 85% (against a target of 90%).

Kolomela exceeded the 2015 BP ex-pit mining target by 3.1Mt (Production compliance of 106%). Only 48.9Mt of the 60.6Mt actual ex-pit mining activities in 2015 were executed inside the areas planned in the BP (Adherence index of 81%). The spatial mine-to-plan index of 85% represented the spatial overlap between the actual ex-pit mining activities and the BP areas. About 15% of the ex-pit tonnes planned for 2015 were not mined and 21% (or 11.7Mt) were mined out of plan.

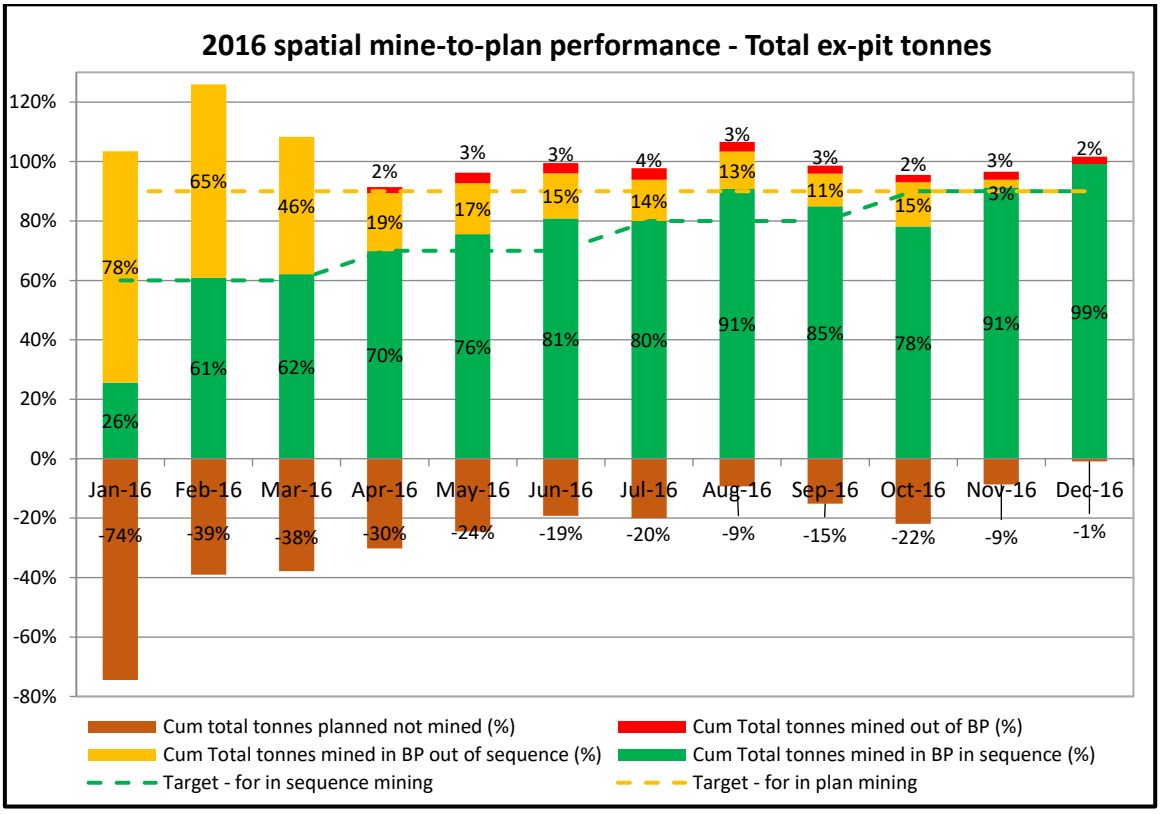


Figure 6.11. Spatial mine-to-plan compliance performance for 2016

The spatial mine-to-plan compliance results for 2016 did achieve the targets. Except for a less than ideal start in January 2016, both the spatial mine-to-plan indices were above the respective targets at the end of every month. The cumulative spatial mine-to-plan compliance reconciliation results at the end of 2016 can be summarised as follows:

- The actual ex-pit mining activities were slightly above the BP targets resulting in a production compliance of 101%;
- A total of 62.9Mt of the 63.9Mt actual ex-pit mining activities were executed inside the areas planned in the BP resulting in an adherence index of 98%; and

- The spatial compliance index was 99% and only 1.0Mt (2% of the planned ex-pit mining activities) were mined out of plan.

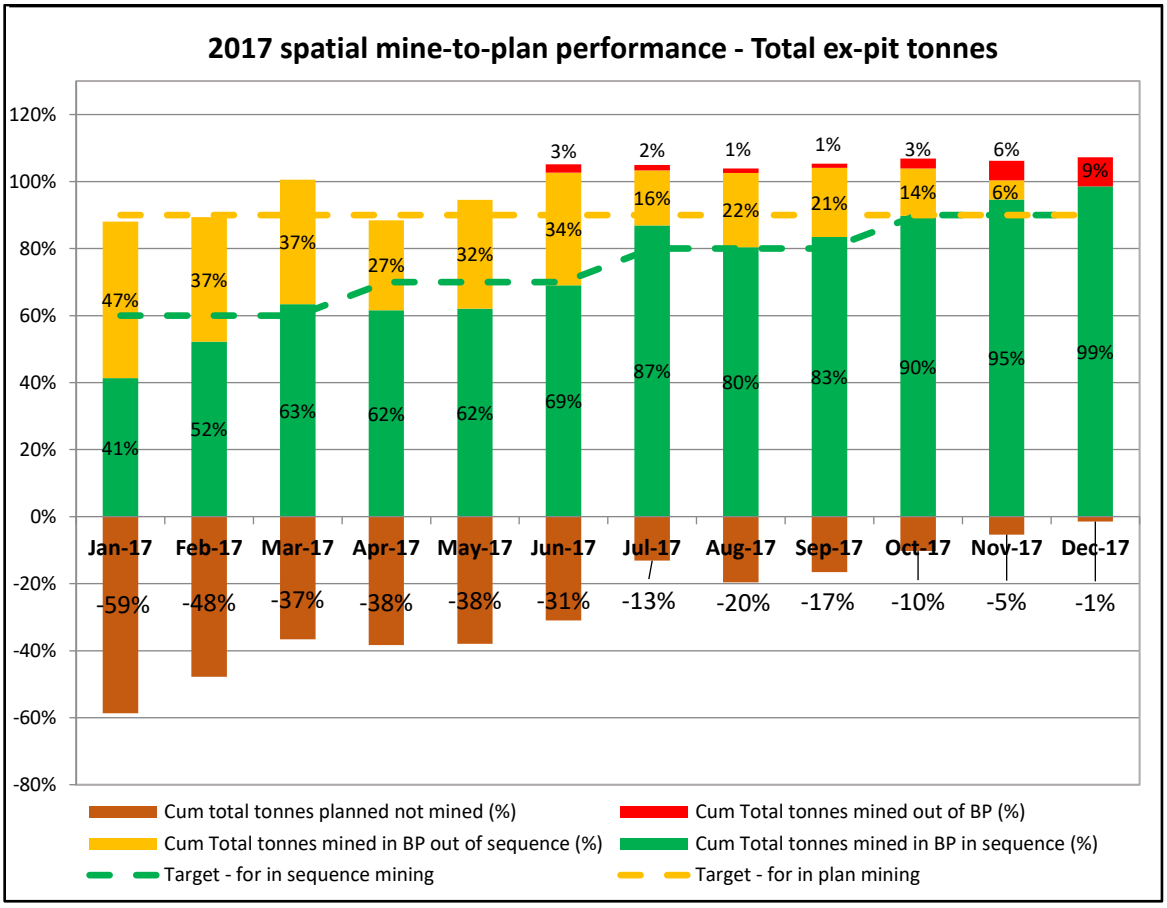


Figure 6.12. Spatial mine-to-plan compliance performance for 2017

The excellent spatial mine-to-plan compliance performance at Kolomela continued into 2017 and the spatial mine-to-plan compliance targets were again achieved for the full year. Figure 6.12 shows that Kolomela did not achieve its ex-pit production targets for the first 5 months of 2017. Due to out of sequence mining the spatial mine-to-plan index 2 results were also below target for this period. By the end of May 2017, the spatial mine-to-plan index 1 was at 62% against a target of 70%. Good ex-pit mining performance and a significant improvement in spatial compliance to the BP in the second half of 2017 led to improved spatial mine-to-plan compliance reconciliation results. The only negative aspect of the 2017 results was the relatively high percentage of out of plan mining (9%) because of actual ex-pit mining activities exceeding the BP targets (production compliance above 100%). The cumulative spatial mine-to-plan compliance reconciliation results at the end of 2017 can be summarised as follows:

- The actual ex-pit mining activities exceeded the BP targets resulting in a production compliance of 108%;

- A total of 65.6Mt of the 71.8Mt actual ex-pit mining activities were executed inside the areas planned in the BP resulting in an adherence index of 91%; and
- The spatial compliance index was 99% and 5.3Mt (9% of the planned ex-pit mining activities) were mined out of plan.

Figures 6.13 to 6.15 show how the spatial mine-to-plan compliance reporting at Kolomela was enhanced with visualisations of mine plans. To illustrate the implementation of these visualisations as part of the spatial mine-to-plan reporting process, the figures depict the spatial mine-to-plan reconciliation results for the LF pit for a month in the third quarter of 2016. Actual ex-pit mining activities is compared to the relevant BP using the categories defined in Section 4.4.3. Comments are provided to explain the spatial deviations from the BP.

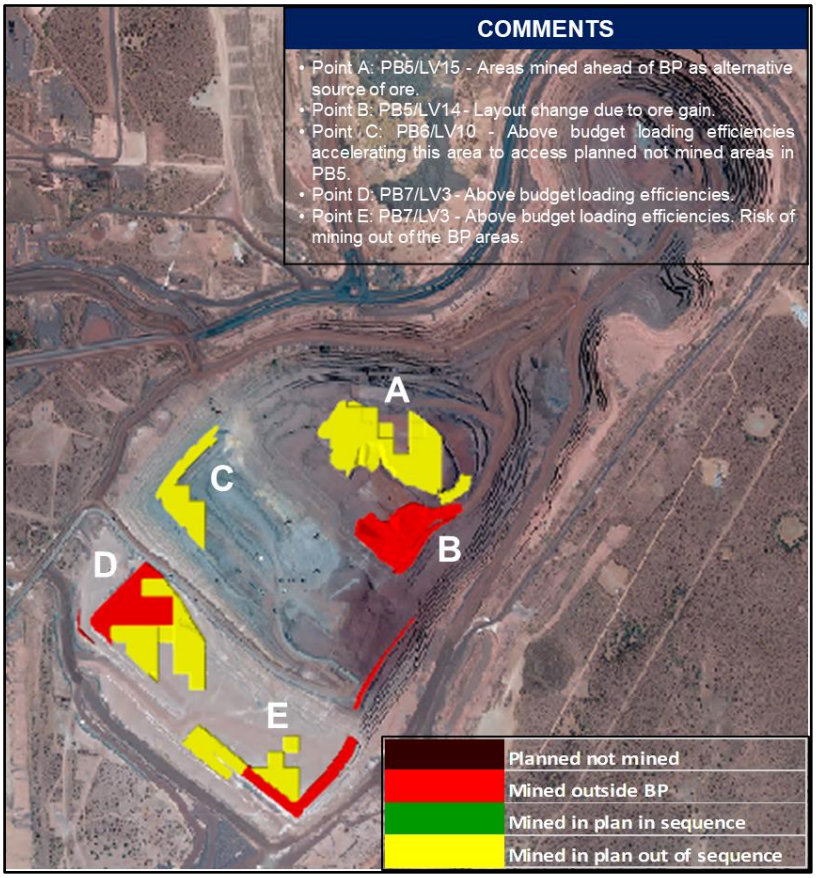


Figure 6.13. LF pit spatial mine-to-plan compliance visualisation – areas mined out of sequence and out of plan

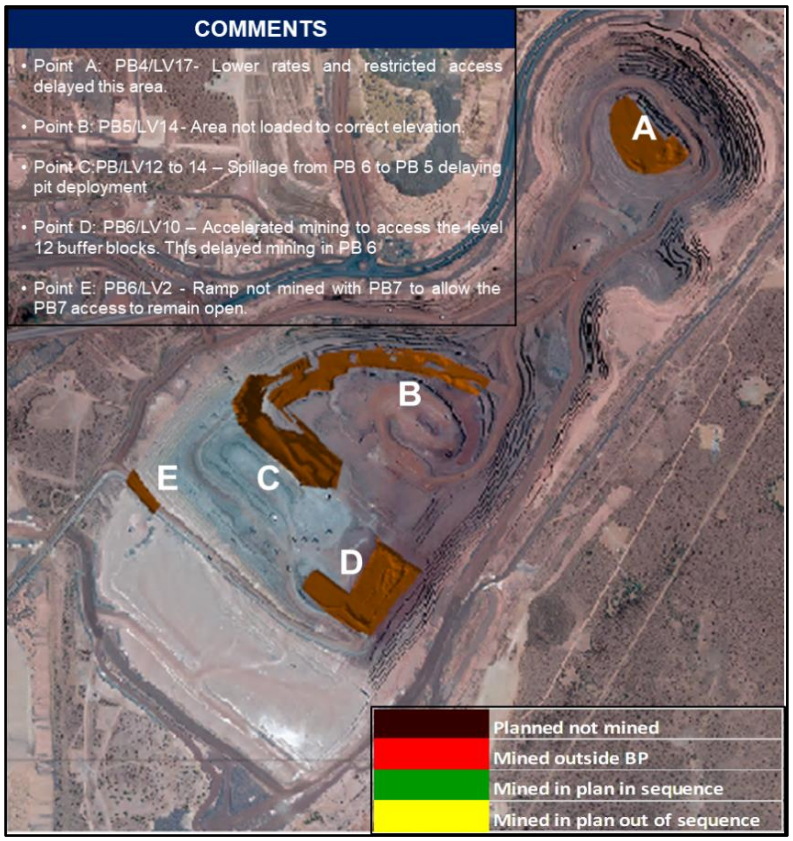


Figure 6.14. LF pit spatial mine-to-plan compliance visualisation – areas planned and not mined

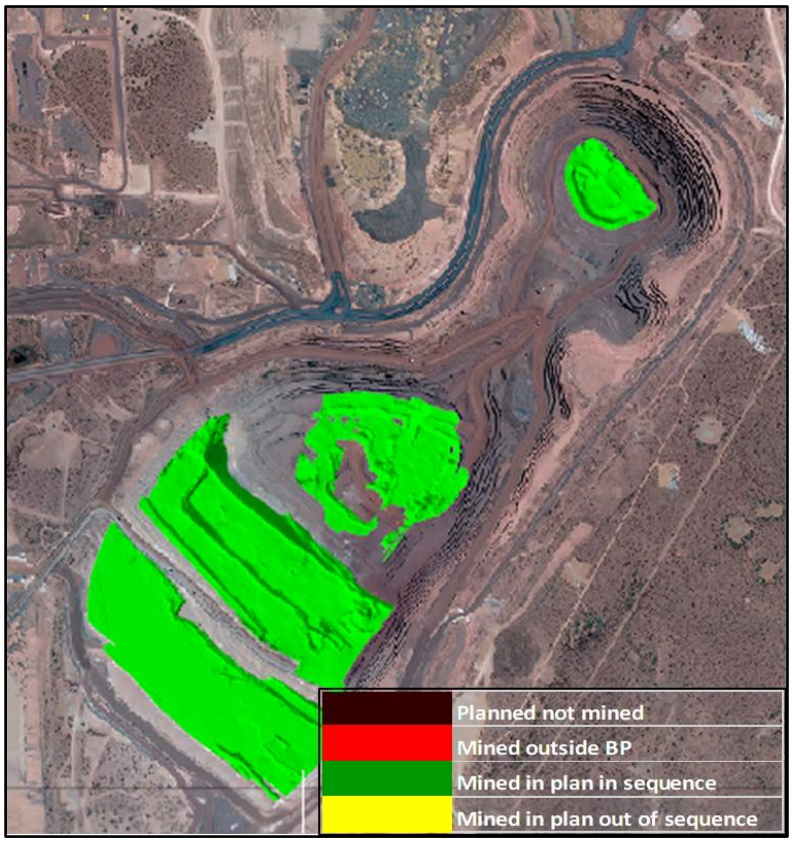


Figure 6.15. LF pit spatial mine-to-plan compliance visualisation – areas mined in plan and in sequence

The significant improvement in spatial compliance from 74% in 2013 to 99% in 2017 is a clear indication that the implementation of the spatial mine-to-plan compliance framework, developed by this thesis, improved the spatial compliance to the BP at Kolomela. The contribution that the implementation of the CDT, developed by this thesis, had on enhancing the measurement of spatial mine-to-plan compliance and ultimately contributing to the improvements in the spatial mine-to-plan compliance performance at Kolomela will be discussed in the next section.

6.7 Results from the application of the CDT

The CDT developed by this thesis, was implemented at Kolomela and provided the capability to drill-down into the various pits, pushbacks and mining benches. This tool was applied, firstly, to gain a more detailed understanding of where actual mining took place relative to the areas planned in the relevant BP. Secondly, the application of the CDT enabled RCA to be conducted on the spatial mine-to-plan reconciliation results. This provided insights to the management team at Kolomela into the major reasons for poor mine-to-plan compliance and thus provided focus to improvement initiatives.

The diagnostic capabilities of the CDT are illustrated using the spatial mine-to-plan compliance reconciliation results of the KB pit. Figure 6.16 represents the main CDT analysis report for the pit for the 2017 year up to September 2017.

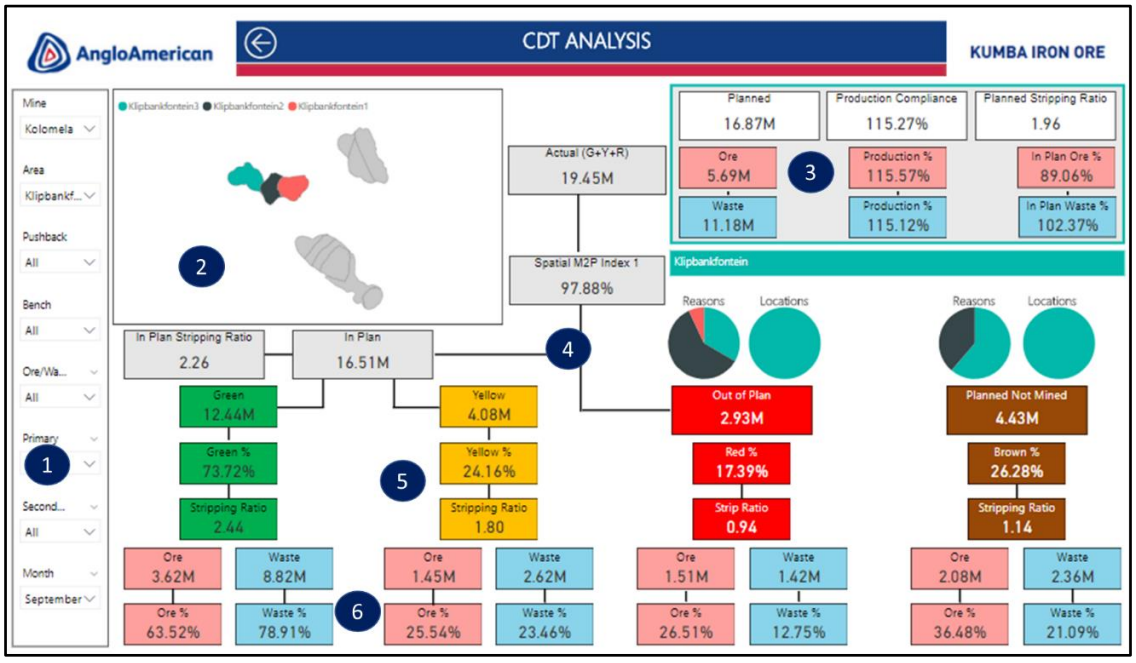


Figure 6.16. Main CDT analysis report – Kolomela, KB pit, September 2017

The following results from the main CDT analysis report for the KB pit are highlighted below:

- Point 1: The drill-down part of the report indicates the selection of KB pit and September month. Here numerous selections can be made through the drop-down menus to further drill-down into spatial mine-to-plan performance in the other pits at Kolomela, into a specific pushback within a pit and also considering waste and ore mining activities.
- Point 2: The KB pit is highlighted in the plan visualisation view.
- Point 3: The production compliance was 115% against a BP target of 16.9Mt, spatial mine-to-plan index 1 for ore was 89% and for waste 102%.
- Point 4: The spatial mine-to-plan index 1 for total ex-pit mining was 98% and 16.5Mt were mined in plan at a stripping ratio of 2.26.
- Point 5: More detail is provided on the cumulative spatial mine-to-plan compliance results for the KB pit. For example, the spatial mine-to-plan index 2 was 74% and the out of sequence mining result was 24%, 2.9Mt were mined out of the BP areas and 4.4Mt of the KB pit plan was not mined.
- Point 6: The spatial mine-to-plan compliance for ore mining activities was lower than the compliance for waste mining. The spatial mine-to-plan index 1 for ore was 64% and as a result 2.1Mt of planned ore had not been mined yet. Also, 1.5Mt (or 27%) of the YTD ore mining execution took place outside of the BP.

The application of the main CDT analysis report at Kolomela ensured that the management team could drill-down into the various pits and pushbacks as well as into waste and ore mining activities to improve the understanding and interpretation of the overall spatial mine-to-plan reconciliation results for the entire Kolomela mine.

The ability of the CDT to provide further detail on the spatial mine-to-plan compliance performance in the three pushbacks of the KB pit, the mining benches within these pushbacks and the ore and waste mining activities is illustrated in Figures 6.17. The spatial mine-to-plan report in Figure 6.17 shows how the drill-down capabilities of the CDT was used at Kolomela. Figure 6.17 shows that the CDT was used to drill down into the waste mining activities on the three active mining benches of pushback 3 of the KB pit at Kolomela mine. The spatial mine-to-plan compliance of waste mining on benches 2 and 3 is acceptable, while out of plan and out of sequence waste mining occurred on bench 4.

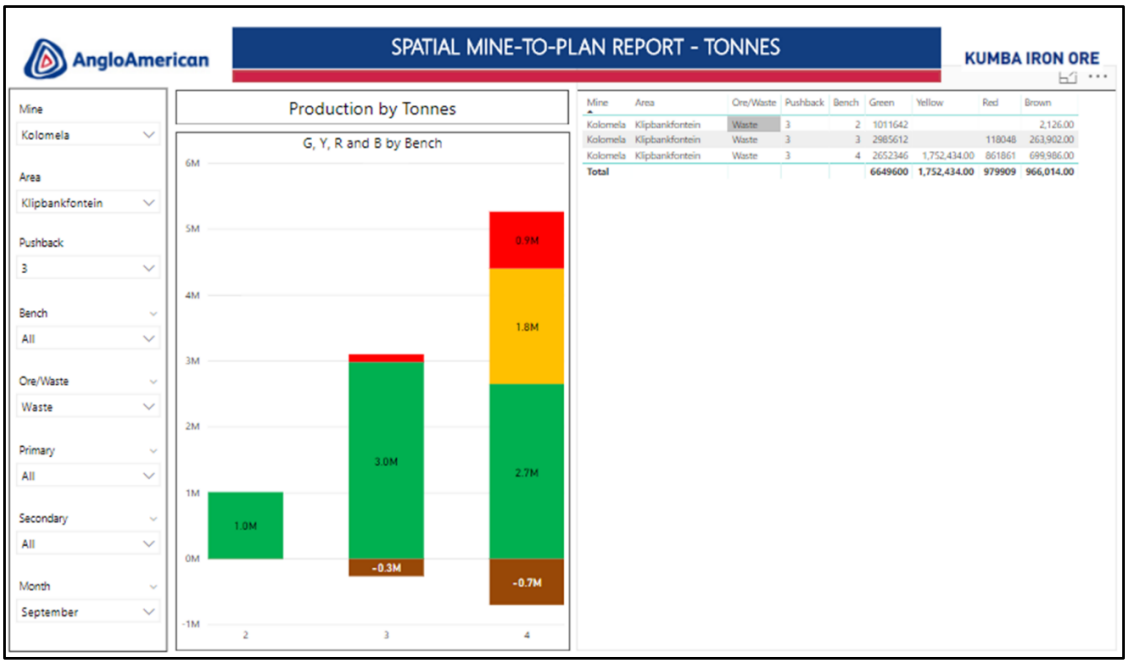


Figure 6.17. Spatial mine-to-plan report (waste tonnes) – Kolomela, KB pit, PB 3, September 2017.

Figure 6.18 illustrates the results obtained from the application of the RCA capability of the CDT at Kolomela. The root cause report for the KB pit provides insights into the major reasons for ex-pit mining activities occurring outside of the BP, out of sequence in the BP and the resultant areas that were planned and not mined.

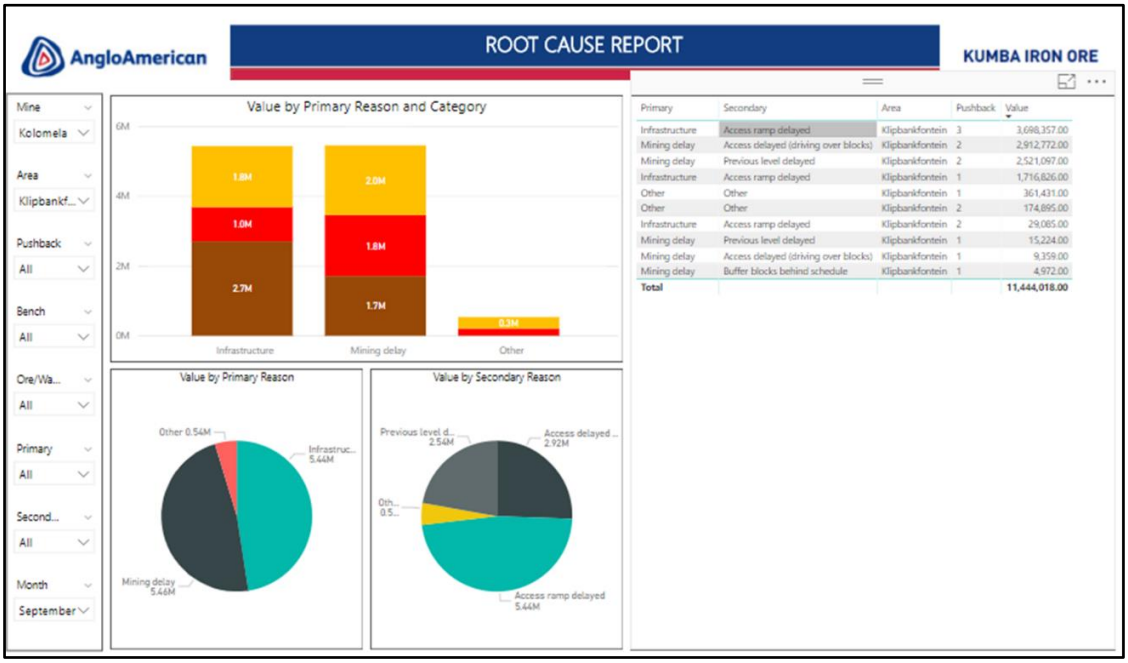


Figure 6.18. Root case report – Kolomela, KB pit, September 2017

Figure 6.18 shows that infrastructure related reasons and reasons associated with delays in mining activities were the major reasons for mining execution not spatially complying to the BP in the KB pit. Secondary reasons are also described in the report and included delays in access ramps and buffer blocks being behind schedule.

In line with the intent of the spatial mine-to-plan compliance framework described in Chapter 4 of this thesis, the insight gained at Kolomela through the application of the CDT was used to continuously improve the spatial mine-to-plan compliance performance. Kolomela successfully applied technology solutions to enhance the improvement process. The technology solutions applied at Kolomela as part of the spatial mine-to-plan compliance reconciliation process are discussed in the next section.

6.8 Results from technology applications

Technology solutions were implemented at Kolomela to enhance the effectiveness of the first feedback loop of the spatial mine-to-plan compliance framework. Visibility of the spatial location of actual loading activities relative to the planned mining blocks and visibility of the progress with PTs were achieved through the application of RPAS technology and HP-GPS technology.

RPAS technology was practically applied at Kolomela to monitor the progress of critical mining blocks and to track progress with PTs. Kolomela deployed DJI Matrice M600 and DJI Matrice M210 rotor wing RPAS units as part of the implementation of the first feedback loop of the spatial mine-to-plan compliance framework at the mine. The sensors used typically included YellowScan LiDAR scanners, 30X zoom video cameras and digital cameras.

Figure 6.19 shows an example of the typical results from the application of RPAS technology to monitor the progress of loading activities against the STMP as part of the execution of the agreed NBA.

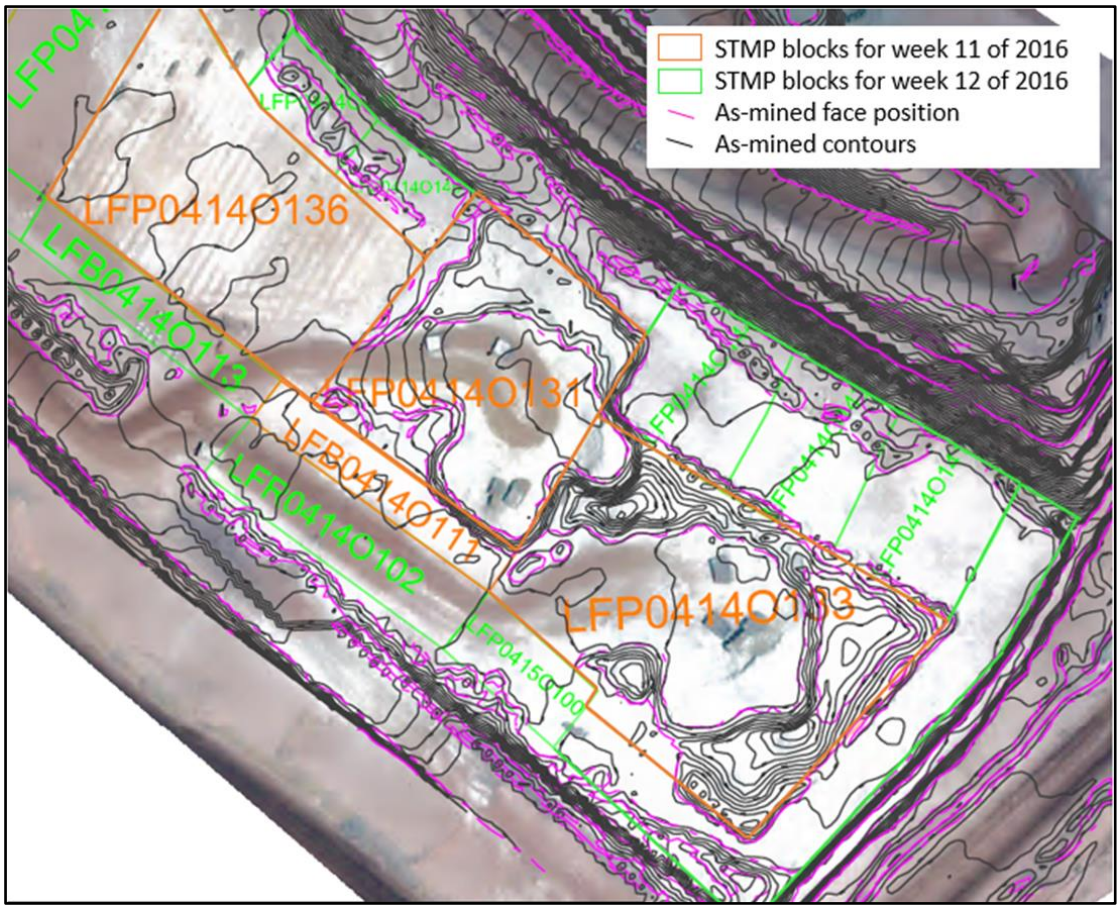


Figure 6.19. As-mined face position visually reconciled with STMP blocks at Kolomela LF pit

Figure 6.20 provides an example of the application of RPAS technology to enhance the mine-to-plan compliance reconciliation process by monitoring the progress of PTs against the agreed timelines for completion. The results show the weekly monitoring of the establishment of a critical access ramp in the KB pit. The establishment of the access ramp was critical to the spatial execution of the BP as it provided a new link between pushbacks 1 and 2 of the KB pit, thus enabling mining activities to commence in line with the BP within the current access ramp. Ultimately, the new access ramp was executed safety and on the STMP schedule. The RPAS monitoring positively contributed to the safe and timely establishment of a quality access ramp.

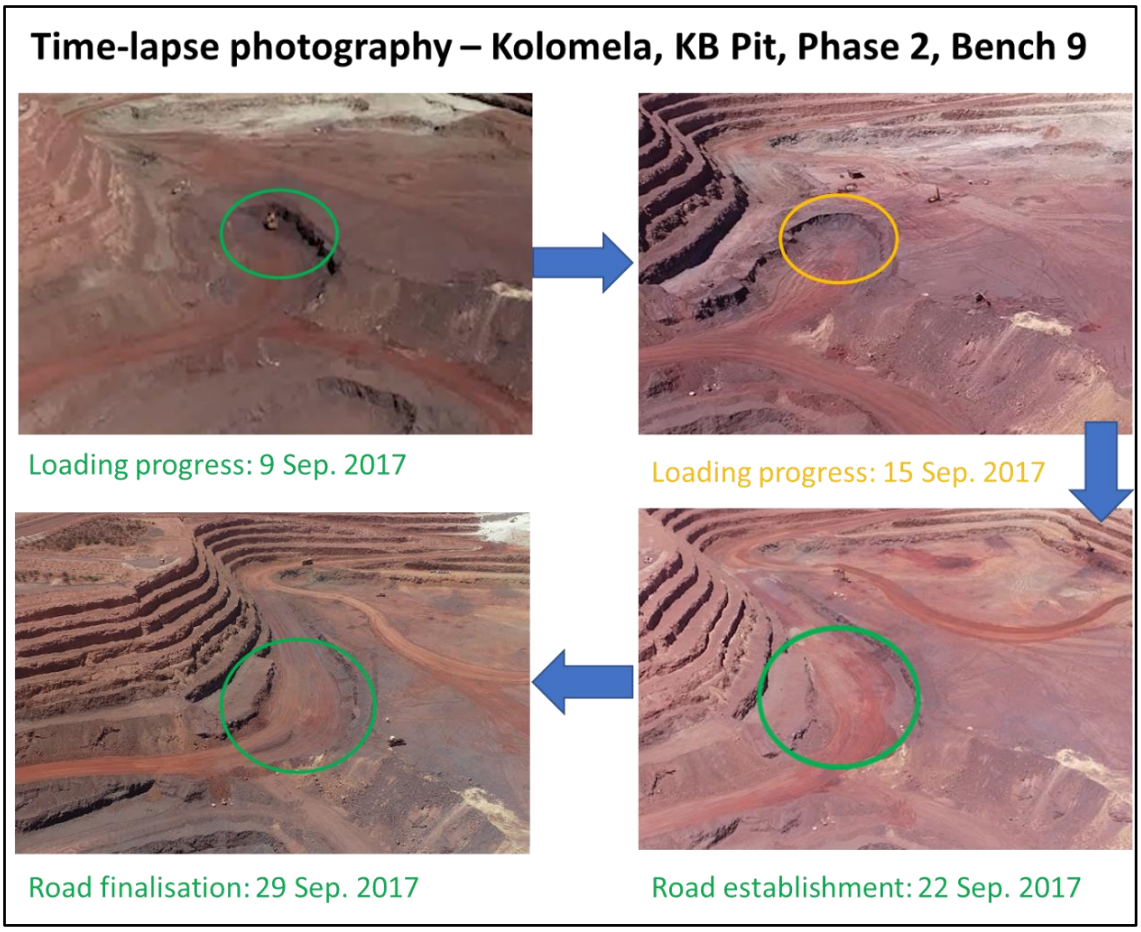


Figure 6.20. RPAS monitoring of the access ramp in KB pit

As part of the Modular Mining FMS, ProVision HP-GPS units were installed on all the major loading units at Kolomela. This allowed for real-time and accurate tracking of the 3D position of the loading units in the various pits relative to the loading blocks from the STMP. This supported the implementation of the agreed NBA through tracking of the spatial loading compliance against the STMP. Figures 6.21 and 6.22 provide examples of the application of loader HP-GPS technology as part of the integrated process of tracking and managing spatial mine-to-plan compliance at Kolomela. Figure 6.21 shows the on-board display of the ProVision HP-GPS system in a Komatsu PC3000 loading unit at Kolomela loading in the LF pit. The display is actively used by the operator to ensure loading takes place in compliance with the STMP. The use of ProVision as a tool to improve spatial compliance to the STMP also forms part of the training of loader operators at Kolomela.

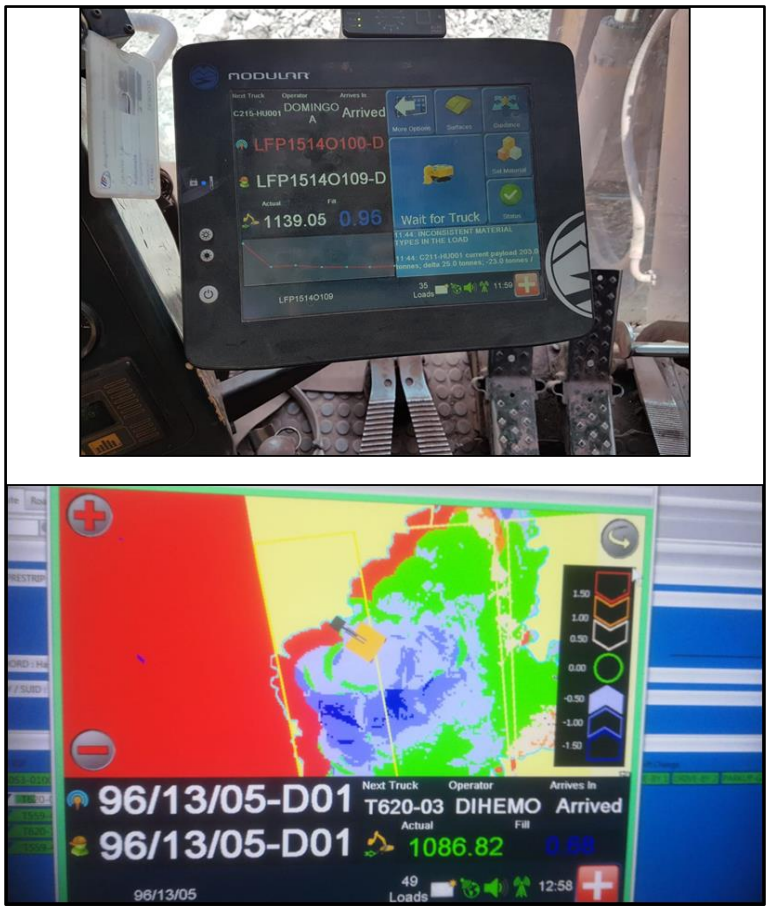


Figure 6.21. Loader in-cab display at Kolomela

The ProVision view that is available in the Kolomela mining control room is shown in Figure 6.22. The actual loading position for a PC300 loader in pushback 4 of the LF pit is displayed in relation to the STMP blocks and any spatial deviation can be visually identified and managed.

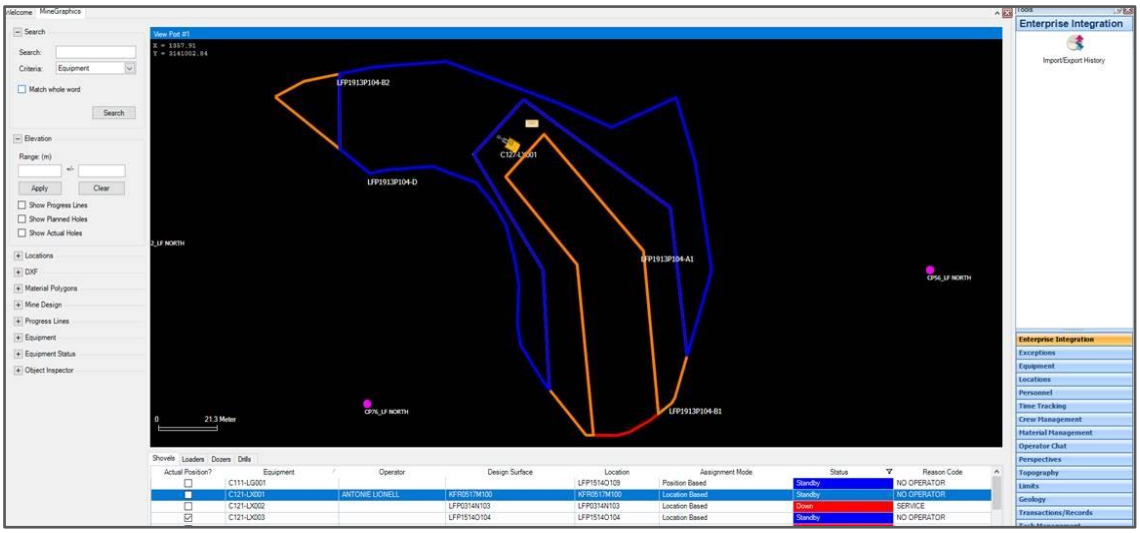


Figure 6.22. ProVision control room display – loader position vs. planned blocks

This section illustrated how RPAS and HP-GPS technology was implemented at Kolomela to enhance the effectiveness of the spatial mine-to-plan compliance reconciliation process. These technology applications provided tools to accurately track the actual spatial mining progress in near real-time and compare that to the spatial aspects of the STMP. An evaluation of the impact of spatial mine-to-plan compliance performance on exposed ore at Kolomela mine will be discussed in the next section of the thesis.

6.9 Consequence of spatial mine-to-plan compliance on operational flexibility at Kolomela

During the discussion of the consequence assessment in Section 4.6 of this thesis, the following question was posed: "*What consequence does the level of spatial mine-to-plan compliance to the BP have for the mine's ability to maintain mining flexibility?"* The answer to this question lies in the relationship between the spatial mine-to-plan compliance reconciliation results and the actual EO levels achieved.

The validation of the spatial mine-to-plan compliance framework at Kolomela over a three-year period provided a unique opportunity to conduct an evaluation of this relationship. The actual mine-to-plan compliance reconciliation results (described in Section 6.6) could be compared to the actual total EO results (described in Section 6.5). For the purposes of this comparison the difference between the actual total EO at Kolomela at the end of each month and the relevant BP estimated EO is expressed as a percentage of the BP estimate for total EO for that period; this percentage is referred to as the EO factor. The formula for calculating the EO factor is provided in Equation 6.1.

$$EO\ Factor = \frac{(Total\ actual\ EO - Total\ BP\ EO\ estimate)}{Total\ BP\ EO\ estimate} \quad (6.1)$$

Figures 6.23 to 6.25 illustrate the relationship between the spatial mine-to-plan compliance reconciliation results and the EO factor at Kolomela monthly for the three years over which the framework was validated.

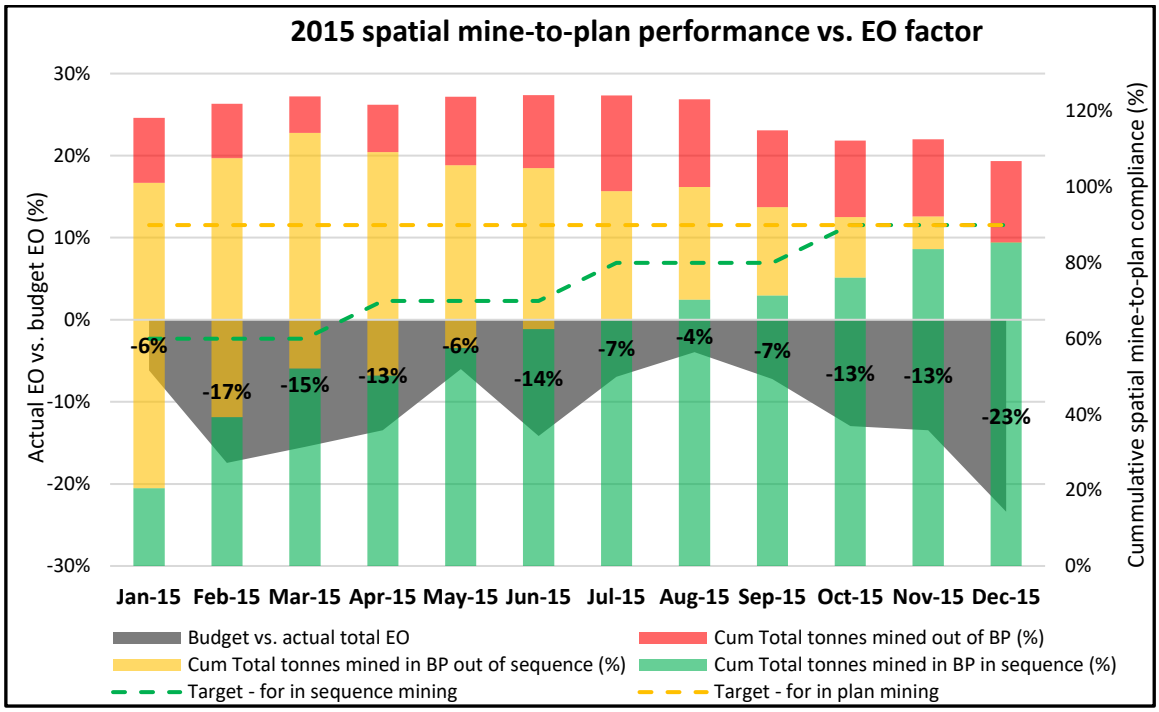


Figure 6.23. Spatial mine-to-plan compliance vs. EO factor for 2015

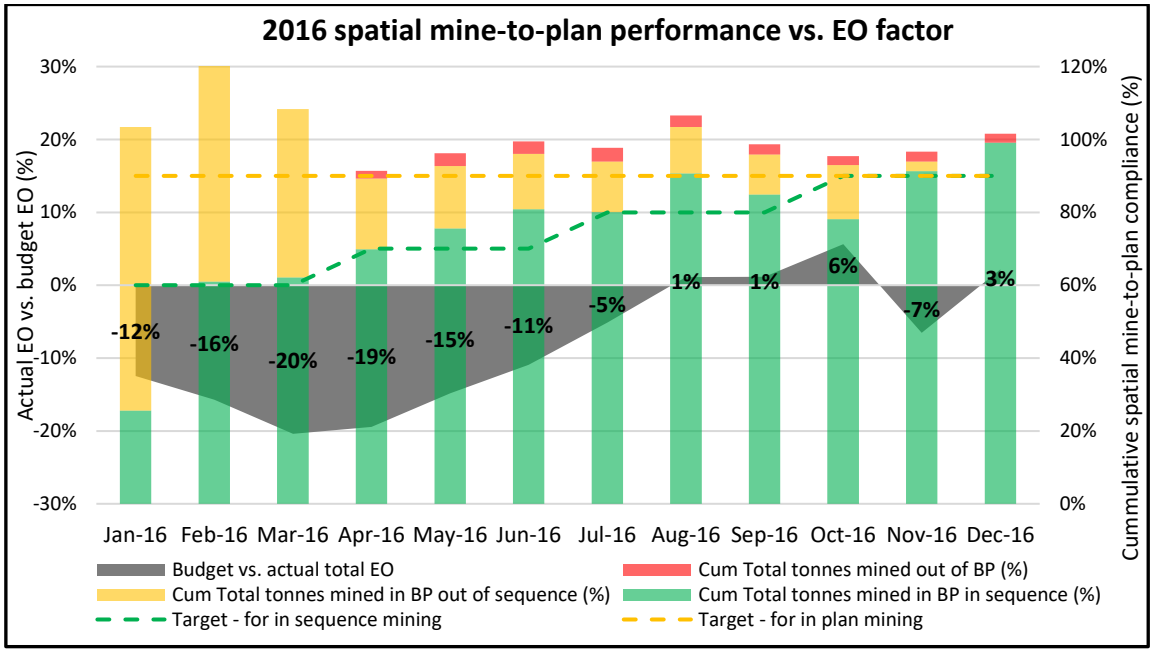


Figure 6.24. Spatial mine-to-plan compliance vs. EO factor for 2016

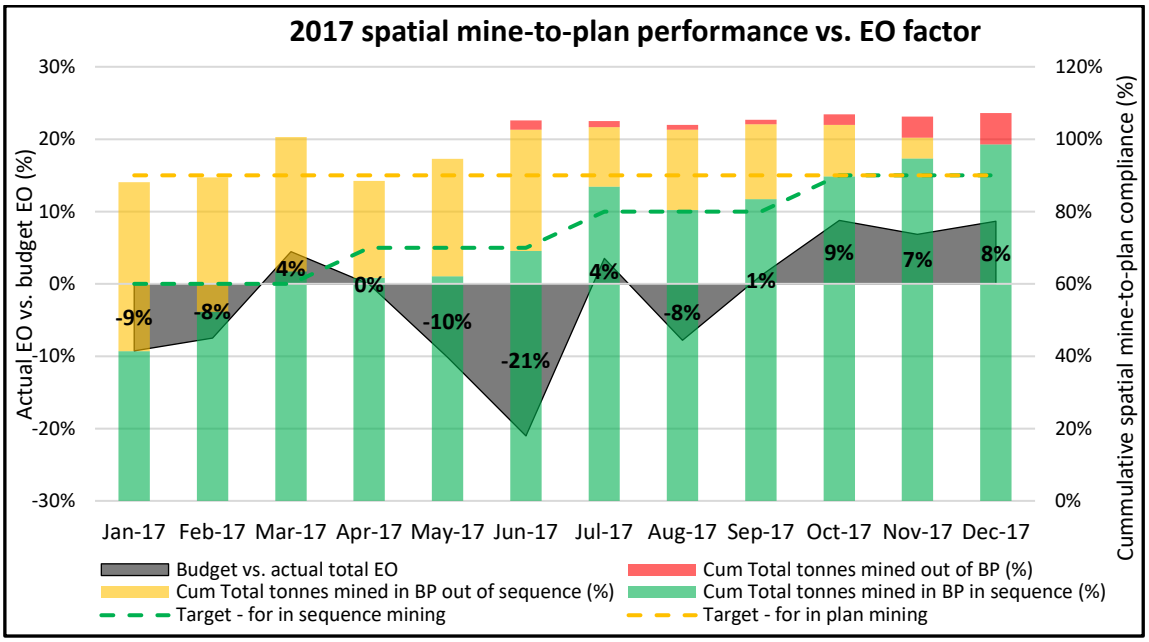


Figure 6.25. Spatial mine-to-plan compliance vs. EO factor for 2017

During 2015, the perennial underperformance of spatial mine-to-plan compliance against the targets coincided with consistently lower than budgeted EO levels (negative EO factors). Although the spatial mine-to-plan compliance reconciliation results for 2016 was an improvement on the 2015 performance the EO factor only improved in the second half of that year. In 2017 the EO factor was between -10% and 10% monthly except for May and June 2016 (the reason for the lower than budgeted actual EO in these months was explained in Section 6.5).

An evaluation of the historical relationship between the spatial mine-to-plan compliance performance and the EO factor at Kolomela indicate:

1. A positive relationship between spatial mine-to-plan compliance reconciliation results and the EO factor; i.e. when spatial mine-to-plan compliance achieved the set targets total EO was generally on par or above the budgeted EO levels; and
2. A lagging effect where an improvement in spatial mine-to-plan compliance performance does not immediately translate into improved EO levels (this is evident in the first half of 2016).

The results obtained during the validation of the spatial mine-to-plan compliance framework at Kolomela illustrated that the positive consequence of achieving targeted spatial mine-to-plan reconciliation results was the achievement of budgeted total EO levels. Therefore, above target spatial mine-to-plan compliance performance ensured the sustainability of the mining operation in the longer-term as the planned level of mining flexibility was maintained.

6.10 Summary of results

A summary of the Kolomela mining performance for the 2015 to 2017 (inclusive) period is provided in Table 6.2. The aim of the summarised matrix is to provide a concise view of the Kolomela temporal and spatial mining performance before, during and after the implementation of the spatial mine-to-plan compliance framework developed by this thesis.

Table 6.2. Summary of the Kolomela mining performance from 2015 to 2017

	2015			2016			2017		
	Budget	Actual	Variance	Budget	Actual	Variance	Budget	Actual	Variance
Ex-pit waste (Mt)	43.0	45.7	6.3%	49.8	50.2	0.8%	52.6	55.6	5.7%
Ex-pit Ore (Mt)	14.5	14.9	2.8%	13.7	13.7	0.0%	14.0	16.2	15.7%
Total ex-pit mined (Mt)	57.5	60.6	5.4%	63.5	63.9	0.6%	66.6	71.8	7.8%
Ex-pit Fe quality (%)	64.2	62.7	-2.3%	63.7	63.9	0.3%	63.5	63.7	0.3%
Total Exposed ore (Mt)	5.3	4.1	-22.6%	3.9	4.0	2.6%	5.2	5.6	7.7%
Spatial mine-to-plan index for total ex-pit mined (%)	90.0	**85.0**	-5.6%	90.0	**99.0**	10.0%	90.0	**99.0**	10.0%
Exposed ore factor (%)	-23%			3%			8%		

Table 6.2 shows that Kolomela achieved the budgeted temporal KPIs consistently throughout the three-year period. In 2015 the spatial mine-to-plan compliance performance was below target associated with below budget performance for ex-pit Fe quality and total EO; the EO factor was -23% in 2015. The improved spatial mine-to-plan compliance in 2016 and 2017 (spatial mine-to-plan index of 99%) positively supported ex-pit ore Fe quality and total EO performance resulting in an EO factor of 8% at the end of 2017.

6.11 Summary of Chapter 6

The results of the validation of the spatial mine-to-plan compliance framework at Kolomela were presented in Chapter 6. The framework developed by this thesis was implemented at Kolomela from 2015. The temporal ex-pit mining performance and the EO results over the three-year period from 2015 to 2017 indicated the following:

- the ex-pit ore and waste targets were generally achieved monthly and exceeded on a cumulative annual basis; and
- the ex-pit Fe quality and EO targets were not achieved during 2015 and the first half of 2016 (for EO specifically).

The spatial mine-to-plan compliance performance at Kolomela improved significantly following the implementation of the framework. The 2015 results were a significant improvement from the initial results in 2013, but the mine missed the 90% spatial mine-to-plan compliance target by 5% in that year. In 2016 and 2017 the spatial mine-to-plan compliance reconciliation targets were exceeded. The introduction of the framework at Kolomela was enhanced by the practical application of the CDT, RPAS technology and HP-GPS on loaders. The implementation of the framework led to an improvement in the spatial mine-to-plan compliance at Kolomela and positively contributed to the achievement and exceedance of the spatial mine-to-plan compliance reconciliation targets.

The relationship between the spatial mine-to-plan compliance reconciliation results and the EO levels were explored in Section 6.9. The results of the evaluation indicated that good spatial mine-to-plan compliance performance led to improved EO levels at Kolomela. This confirms that the implementation of the framework ultimately contributed to the improvement in the longer-term operational flexibility of the Kolomela mining operation.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Overview of Chapter 7

The conclusions and recommendations of the thesis are presented in this chapter. Section 7.2 provides a summary of the major findings of the thesis and highlights the knowledge gaps that were addressed. The contribution that the thesis makes to the current knowledge base is summarised in Section 7.3. Section 7.4 lists recommendations for future research.

7.2 Major findings of the thesis

LOM plans typically form the foundation for the estimation of the value of a mining operation. The LOM plans are further refined trough the various planning horizons with the aim of guiding mining execution to deliver on the estimated or expected value. The actual value realised by a mine is dependent on the quality and integrity of the mine plans as well as on the level of execution against these mine plans.

When evaluating the level of execution against a mine plan, **temporal and spatial aspects should be considered**. Performance against shorter-term temporal KPIs could be positive, while mining activities are not occurring in the correct spatial areas to the detriment of longer-term KPIs such as timely exposure of future ore. An unbalanced drive for short-term performance could result in mining of unplanned areas, thus, achieving short-term targets at the expense of the mine plan with a negative impact on the long-term sustainability of the mine. The risk lies in achieving efficiency in mining at the expense of effectiveness.

The actual value realised from the mining operation is significantly impacted by the quality of spatial execution against the mine plan. Spatial mine-to-plan reconciliation is a direct measure of adherence to the mine plan in terms of areas mined. This reconciliation adds value and reduces risk by tracking the spatial execution of the latest approved BP. This in turn ensures long-term sustainable ore supply and the identification of key issues negatively impacting on production and achievement of planned EO.

The importance and value of spatial mine-to-plan compliance is recognised in existing literature and this KPI is identified as one of the worst performing metrics on any mine (Morley and Arvidson, 2017). Compliance with mine plans are described as fundamental to the mine management process (Angelov and Naidoo, 2010) and Kear (2006) proposed the development of metrics such as a spatial mine-to-plan compliance index. Despite this,

there has been **limited research focus directed to measuring and managing the spatial aspects of mine-to-plan compliance at open-pit mines**. When facing the challenge of improving spatial mine-to-plan compliance, exiting literature defaults to a singular focus on improving the mine plans. This approach implies that the only way to improve compliance to the mine plan is by improving the mine plan itself.

The knowledge gaps identified in existing literature indicated that the problem of managing spatial mine-to-plan compliance in open-pit iron ore mines has not been studied thoroughly and there is a great need to improve spatial mine-to-plan compliance methodologies. This created an opportunity for focussed research into the development of a spatial mine-to-plan compliance framework for open-pit iron ore mines. This thesis took steps towards filling the identified knowledge gaps.

To ensure consistent, predictable and sustainable delivery against the agreed mine plan, it is important that the development of a high-quality mine plan is followed up and supported by a framework that ensures spatial compliance against the plan. This thesis **developed, implemented and validated a spatial mine-to-plan compliance framework for open-pit iron ore mines** to ensure that the expected value is actively targeted and ultimately achieved during the execution of the mine plan.

The thesis succeeded in developing a comprehensive and integrated framework that can be used by the open-pit iron ore mining industry to effectively measure and manage spatial mine-to-plan compliance. Various definitions, categories and mathematical expressions were defined. Planned and actual open-pit mining surfaces were used to quantitatively express spatial mine-to-plan compliance reconciliation results. From this basis, **a CDT was developed and employed** to provide the ability to drill-down into selected mining areas and to accurately determine the major drivers or root causes of deviations. The impact and consequence of spatial mine-to-plan compliance deviations on the achievement of operational targets as well as on the operational flexibility of the open-pit mining operation was determined. The **NBA concept** was used to improve the spatial mine-to-plan compliance by addressing the root causes of non-compliance and providing guidance and direction to the operational mine planning horizon. The thesis also illustrated the benefits of the **application of technology** to enhance the proactive management of spatial mine-to-plan compliance.

The **framework addressed various knowledge gaps identified in existing literature** thereby extending the breadth and depth of the knowledge base on spatial mine-to-plan compliance. The knowledge gaps were addressed through:

- defining the BP as the mine plan against which spatial mine-to-plan compliance is primarily reconciled;

- using ex-pit tonnes as the basis for the reconciliation calculations;
- defining a comprehensive set of reconciliation categories included definitions for mining in plan “in sequence” and mining in plan “out of sequence”;
- defining a comprehensive set of spatial mine-to-plan compliance metrics including the spatial mine-to-plan indexes;
- developing and implementing the CDT;
- introducing the concept of spatial plan-to-plan reconciliation;
- applying the NBA concept to drive effective decision making with the aim of improving future spatial mine-to-plan compliance; and
- illustrating the implementation readiness, practical application and maturity of RPAS and HP-GPS technology solutions to enhance the effectiveness of the framework.

Kolomela was presented as the open-pit iron ore mine on which the **spatial mine-to-plan compliance framework was validated.** In 2013 only 66% of the ex-pit mining activities spatially complied to the relevant BP and the spatial mine-to-plan index was 74%. The undesirable spatial mine-to-plan compliance results presented a significant risk to the sustainability of the mining operation. Kolomela mine was a suitable case study as it was having noticeable deviations from the agreed upon mine plan. The deviations were negatively impacting the sustainability of the long-term production profile. From a business case point of view, any mine in a similar position could be an ideal case study mine. In addition, the significant scale of the mine, geographical complexity, relatively high stripping ratio, DSO processing, high cost of mining activities and the mine’s contribution to Kumba’s performance made Kolomela an ideal case study mine and presented an excellent opportunity to apply the spatial mine-to-plan compliance framework developed by this thesis.

The roll out of the spatial mine-to-plan compliance framework, developed by this thesis, at Kolomela facilitated the effective management of the spatial mine-to-plan compliance reconciliation process. The **significant improvement in the spatial mine-to-plan index from 74% in 2013 to 99% in 2017** is a clear indication that the implementation of the framework improved the spatial mine-to-plan compliance to the BP at Kolomela. Insights gained through the application of the CDT contributed to the improvements in the spatial mine-to-plan compliance performance against the BP. Applying the NBA concept targeted areas that were planned, but not mined at the time of the assessment and addressed the root causes of adverse spatial mine-to-plan reconciliation performance. The RPAS and HP-GPS technology that were implemented at Kolomela enhanced the effectiveness of the spatial mine-to-plan compliance reconciliation process.

The results obtained during the validation of the spatial mine-to-plan compliance framework at Kolomela illustrated that the positive consequence of achieving targeted spatial mine-to-plan reconciliation results was the achievement of budgeted total EO levels. Therefore, above target spatial mine-to-plan compliance performance ensured the sustainability of the mining operation in the longer-term as the planned level of mining flexibility was maintained.

The findings from the validation process positively answered the research question posed by this thesis: *The development and implementation of the spatial mine-to-plan compliance framework, complemented by the application of CDTs and appropriate technology, does improve the compliance to the mine plan of an open-pit iron ore mining operation.*

7.3 Contribution to knowledge

The thesis contributes to knowledge as a reference based on empirical research validated at Kolomela. The research represents applied knowledge with a significant value contribution potential to fundamentally improve open-pit iron ore mining reconciliation practices. In summary, this thesis **contributes to knowledge** in the following key areas:

1. Providing a practical, comprehensive and integrated spatial mine-to-plan compliance framework that defines the components and relationships that determine the level of spatial compliance against the tactical mine plan, thus enabling the open-pit iron ore mining industry to measure and manage spatial mine-to-plan compliance effectively;
2. Developing and applying spatial mine-to-plan CDTs that create the ability to drill-down into selected spatial areas within the bigger iron ore mine and enable understanding of the root causes of deviations to inform the NBA; and
3. Employing appropriate technology in a novel way to enhance the effectiveness of the framework.

Although, the thesis focussed on open-pit iron ore mining in South Africa the application can transcend the iron ore mining industry and the South African context to find application in open-pit mines globally.

7.4 Recommendations for future work

During the research, development and implementation phases of this thesis some unanswered questions arose. These led to the following recommendations for future research:

- Application of the spatial mine-to-plan compliance framework on open pit mines where other commodities are extracted (not iron ore);
- Development and application of a similar framework to manage spatial compliance to planned waste dumping locations (dump-to-plan);
- Development of a more comprehensive set of reasons for spatial mine-to-plan deviations as part of the CDT;
- Application of additional technology solutions such as dynamic terrain modelling and digital twins;
- The quantitative and statistical analysis of the relationship between spatial mine-to-plan compliance reconciliation results and EO and ore quality;
- Expansion of the evaluation of the consequence of spatial mine-to-plan compliance performance to include financial aspects; and
- Possibility to evaluate the impact of low spatial mine-to-plan compliance on the overall cost of production.

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