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Application of systemic flow-based principles in mining

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Synopsis

Mining value chains are dynamic systems and should be managed according to systemic flow-based principles. This includes a detailed focus on the impact of variable geological conditions on material flow, product quality, and production cost, visibility of the total mining system to operators and managers, as well as the synchronization of resources and activities in downstream processes. Thirty mining operations across the African continent were studied to establish to what extent systemic flow-based principles are applied in day-to-day operations. The study indicated that although most mining operations have identified the relevant geo-processing variables, only a small number apply this information in a flow-based management approach. Most mining operators do not focus on developing a clear flow view of the mining value chain and on making it visible to operators and managers to enable them to optimally set and reset operations. Daily synchronization of geoprocessing variables is limited to a small number of variables, *e.g.* synchronizing ore hardness with drilling or milling requirements, in less than 30% of the operations evaluated. Operations where these principles have been adopted reported a noteworthy improvement in performance. The study indicates that notable potential exists in most of the operations evaluated to implement flow-based management principles, including geometallurgical principles. This can significantly improve value chain performance without exorbitant capital layouts and enhance ROCE.

Keywords

geological variables, mining value chain, mining systems, mining management, systems management, systemic, synchronization, geometallurgy.

Introduction

Objective of the study

The study seeks to establish to what extent systemic flow-based principles have been adopted in the southern African mining industry and the implications thereof. Specific attention is given to the importance of defining and managing geoprocessing dependencies (geological variables directly impacting mining and plant performance – the geometallurgical approach), establishing a flow view of the mining system, which typically includes a dashboard of the flow of ore/product quality and cost from the mining face to the customer, and limiting the impact of dependencies through synchronization of activities and resources, *e.g.* ensuring that a continuous miner does not wait for a roofbolter, or that reagent addition rates are matched with a specific ore/concentrate composition.

Research approach

On-site research was performed during the period 2009–2013 at 30 mining operations on the African continent (mostly from southern Africa), including small- to large-scale operations and different commodities. The research focused on the following areas:

- The impact of geology (ore and orebody morphology) on the performance of the mining system as a whole
- Development of orebody domaining logic for a mine and an indication of how this logic can be used to synchronize ore and orebody characteristics with downstream processes
- Managing geological and resource requirements to comply with a holistic and systemic approach towards mining
- Development of performance and throughput logic for selected geological variables at a mining operation
- The influence of two non-compatible material types (material types that behave differently during processing, *e.g.* soft ore and hard host rock) on mining and plant processing performance and product value.

Systemic flow-based principles were employed to study these areas and to compile the maturity matrix shown in Figure 1. The systemic flow-based principles considered included the following:

- Systems comprise elements and parts that are dependent on each other and on the environment; dependencies can be sequential or non-sequential
- Material, information, and money flow through the system in a specific direction
- Changing properties of material, information, and money as these flow through the system

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- ➤ Definition of the system by the interrelationship between the elements, parts, material/information; and its environment
- ➤ In the case of flow in a system, a capacity-constrained resource (resource with the least capacity) exists
- ➤ In the case of flow in a system, variability exists
- ➤ High levels of variability render system performance unstable and unpredictable.

The information obtained was evaluated against requirements defined for the optimal management of complex systems (discussed in ensuing sections). A maturity matrix (shown in Figure 1) was used to score the mining operations studied.

Figure 1 aims to summarize the elements required to establish and maintain a stable and predictable mining environment from a systemic flow-based perspective. The emphasis is on the synchronization of activities and resources, which is discussed in more detail in the following paragraphs.

In addition to this evaluation, a number of industry examples that support the arguments presented in the paper are also included.

Background

Mining chains as systems

The concepts of value chain and supply chain are well established in the mining industry, *e.g.* in the logistical systems and spares/consumable management environments. A supply chain typically consists of components that include people, organizations/departments, infrastructure, flows of material, information flow, and flows of intangible services. These components combine to improve flow from one area, department, or organization to another for the benefit of all participants (Skyttner, 2001). Similarly, systems are viewed as a composition of finite elements or components, which combine to form an integrated unit that supports a purpose. Skyttner (2001), Weiss (1971), Boulding (1985), and Churchman (1979) all indicated that supply chains (in this case mining chains) have similar characteristics to systems.

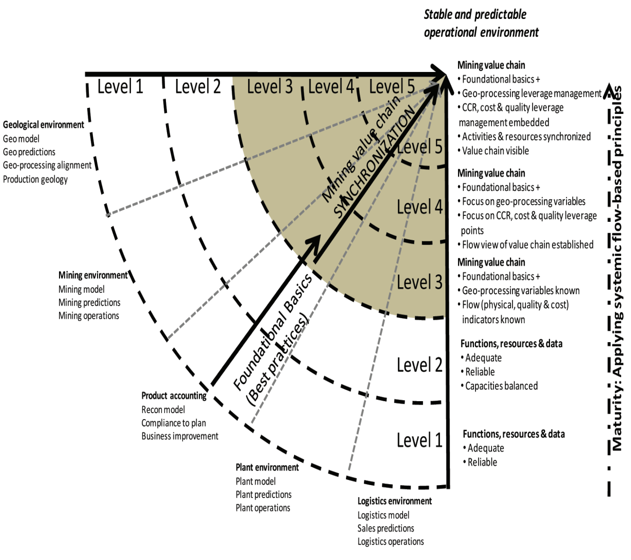

Figure 1 – Maturity matrix used for the application of systemic flow-based principles in mining (Laurens, 2013)

This conclusion has far-reaching implications for the management of mining systems when these characteristics are contemplated. These characteristics include (Ackoff, 1981; Backlund, 2000; Carbone, 1999):

- ➤ *Systems are influenced by their environment* and other systems. Systems are dynamic, with the interaction of sub-systems across boundaries
- ➤ Each system component has an effect on how the *system functions as a whole*
- ➤ The operation of *each system component is interdependent*. A network of dependencies and interdependencies exists across system boundaries, which can enhance or ruin system performance.

The implications of each of these points on managing complex mining chains are discussed later in more detail.

Benefits of taking a systems approach

The literature elaborates on the benefits of viewing and managing supply chains (mining chains in this case) as dynamic systems, *i.e.* managing flow in the system as a whole. Cooper *et al.* (1997) and Stonebraker and Afifi (2004) explain how valuable resources are wasted if supply chains are not adequately streamlined and managed. This situation stems from a lack of integration and knowing which flow constraints determine the system's output. This in turn directly impacts the allocation of capital and the productivity of resources, which are some of the main concerns of mining at present. Mentzer *et al.* (2001) also explain how supply chain management can lower costs, improve customer satisfaction (internal and external), and create a competitive advantage for the business. Here the authors emphasize the contribution of understanding and managing all dependencies (variables impacting flow), behaviours, and flows (material/products, information, financial resources, demands and forecasts) at different levels in the organization.

Another important issue in mining systems management is the alleviation of the impact of up– and downstream variability on performance. Since all resources, activities, equipment, and processes are dependent on each other, disturbances ripple downstream and upstream through the production chain if not effectively dampened by buffers. Forrester (1958), Fowler (1999), Towill (1996), and Wikner *et al.* (1991) reported that this ripple effect is amplified as it moves away from the source up or down the supply chain, with a significant impact on the performance of the system as a whole due to its destabilizing effect, *i.e.* increased variability hampers synchronization in the system. Understanding which factors cause these ripple effects from a flow perspective can limit the impact on supply chains as it assists to optimally set and reset equipment and processes as well as to optimally allocate resources to where they are needed most in the production system. Changes in the geological environment and mining and plant conditions impact not only production, but often also product quality. Variability in product quality in turn has a serious impact on the performance of customer processes, and every effort should be made to produce a consistent product quality (Everett, 2001).

Furthermore, the number of dependencies and interdependencies (a complex network of dependencies and interdependencies exists) in supply chains is increasing with changes in the internal and external environment and organizational growth. Funk (1995), Mughal and Osborne (1995), Osborne (1993), and Simatupang and Sridharan (2002) all report that increased supply chain complexity is associated with poor performance. Approaching/managing supply chains and systems from a flow perspective can significantly simplify these complex networks and improve business performance.

Finally, managing a supply chain from a flow perspective develops an understanding of the key business drivers of an organization at all levels. This aligns performance expectations by executives and managers with actual supply chain performance. Underperformance issues can then be effectively dealt with at all levels (Skyttner, 2001).

Management of mining systems

With the abovementioned system characteristics in mind, some elements of a mining management approach based on flow principles should be highlighted.

Management of the geological environment

Most mining operators are acutely aware of the negative impact that changes in the internal and external environment can have on their performance. In the medium to longer term this is typically dealt with by becoming leaner (limiting waste in all parts of the business), employing risk/weight factors to adjust plans and forecasts to make them more 'realistic', and developing internal/external relationships that can benefit the organization. On the other side of the spectrum, management of a changing/variable mining environment on a day-to-day basis also poses many challenges. For example, variability in the ore morphology (mineralogy, texture, weathering effects, *etc.*) and orebody morphology (seam thickness, roof and floor conditions, dip, *etc.*) from one mining block/area to the next can have a significant ripple/destabilizing effect on downstream processes, as alluded to earlier.

When the management of variability in specifically the geological environment is contemplated from a systemic flow-based perspective, the following requirements should be highlighted:

- All the ore and orebody characteristics that impact the flow and quality of the ore, as well as the cost of production per mining area (per block for complex orebodies and per pit/shaft for less complex ores), must be determined. Capacities, efficiencies, recoveries, and costs are then linked to the most important ore and orebody characteristics per area, which are then used in models, mine plans, and forecasts. This is typically the so-called geometallurgical approach (currently focusing mainly on the impact of variable ore characteristics on plant performance and not that much on the impact of variable orebody properties). For example, if variability in ore hardness is a key driver of production performance (production rate, recovery, and cost), then the orebody is classified according to ore hardness categories and mined in a manner that does not compromise the performance of the system as a whole. With this approach there is a definite move away from considering only average ore grades (Schouwstra, 2010), ore volumes, and averaged correction factors to a more condition-based approach, *i.e.* the specific environment dictates production performance
- Designing and setting up a system at a strategic and tactical level does not suffice to optimize supply chain performance, as unexpected events can occur during operations. In order to counter the impact of these events, an ability to identify and exploit the system constraint(s) and key dependencies in the system on a day-to-day basis is required, *i.e.* managing system dynamics (ever-changing geological and mining environments, HR dynamics, *etc.*) on an ongoing basis. Exploitation of the resource(s) that determines the performance of the system as a whole requires timeous identification and management of all factors, in this case variable geological factors, that impact system performance. Mouritus and Evers (1995) indicated that the most important component in a flow chain is the human component. It can therefore be argued that operators and their managers must have the skills to identify the dynamics in a system (Skyttner, 1996) and set/reset the system to give optimal performance in terms of production rate, ore/product quality, and cost. This requires an ability to develop a systemic flow view (compared to a functional and process view) of the mining environment, manage the system as a whole, and synchronize activities/cycles, among other things, as illustrated in Figure 1 and discussed in more detail in the following paragraphs.

Management of the system as a whole

Figure 2 illustrates that mining personnel can adopt different views of how a system can be viewed and managed. Figures 2a and 2b depict a functional and an activity-based view, respectively. Here the emphasis is on optimizing each part of the system, *i.e.* a fragmented approach. Figure 2c illustrates the process dependencies in a continuous miner – roofbolter – shuttle car system, each with its inherent performance variability. Operation of this system within an ever-changing geological, mining, and business environment is also shown. Figure 2 demonstrates that management of a system as a whole not only implies managing the entire system comprising the different functional departments or processes. It actually implies managing all key dependencies and interdependencies among resources, as well as resources and the environment in order to maintain synchronization in the system (Ackoff, 1981; Backlund, 2000; Carbone, 1999). This requires a *detailed systemic flow-based understanding of the operation* (refer to Figure 1c), visibility of the entire production chain (in terms of ore/product flow, quality, and costs through the different steps), visibility of the constraint(s), and visibility of triggers/factors (*e.g.* geological factors) that impact the performance of the constraint(s). This enables operators, managers, and individuals responsible for the management of the end-to-end process to optimally operate a complex mining system (Mouritus and Evers, 1995).

It should also be noted that mapping out processes (Figure 1b) and creating an understanding of the key processes in an organization should be followed by putting measures in place to manage flow in these processes. Without the latter, management of the mining system is for

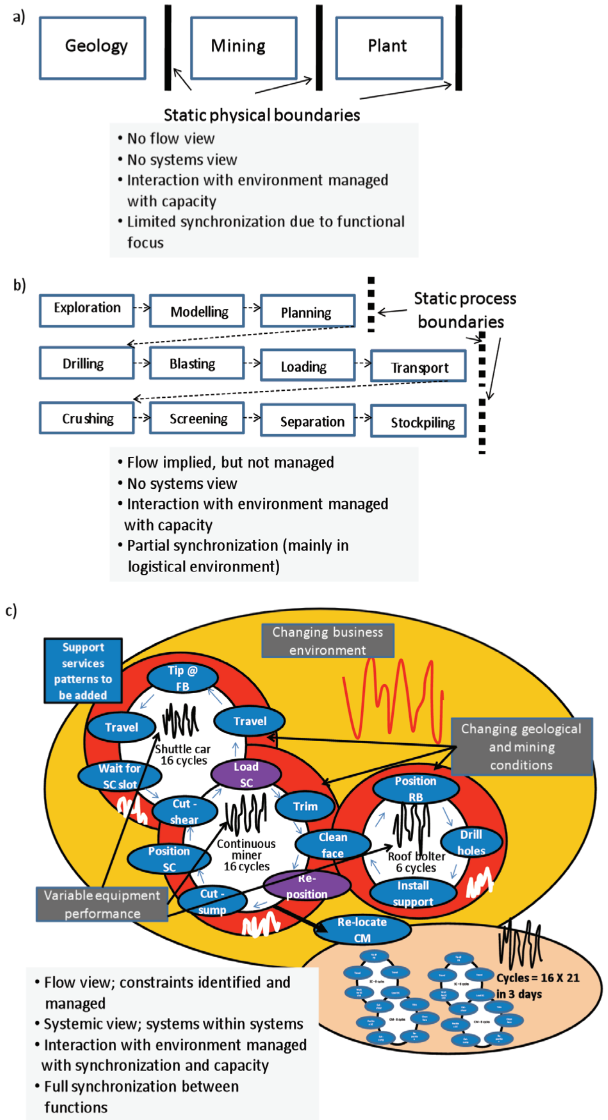

Figure 2 – Views of primary mining value chains: (a) functional view, (b) process view, and (c) systemic flow view (continuous miner–shuttle car–roofbolter system in its respective and combined environments)

all practical purposes left to chance, which in turn can create more dependencies and thus increase the complexity in mining systems.

Management of (inter)dependency

Figure 2c illustrates a simplified view of some (inter)dependencies between underground coal mining equipment, between the equipment and its environment, and the mining system and the macro environment. In addition to the relatively obvious dependencies illustrated here, a number of less obvious dependencies related to the geological environment also exist. These can include the following geo-processing dependencies:

➤ The link between ore/waste morphology and equipment/plant settings, *e.g.* mineralogical composition of the feed influences the hardness of the feed, which directly impacts the crusher settings, mill loads, and feed rates in the comminution circuit. Another example is the link between reagent dosage rate and the amount of a competing species in the feed to a flotation circuit
➤ The link between variable orebody morphology, *e.g.* undulating roof and floor conditions, and equipment set-points has a detrimental impact on mining rates and the amount of dilution in the plant feed. Steep-dipping ore zones, faulted areas, changing seam thicknesses, and the presence of dykes have a similar impact on the performance of the mining value chain
➤ The link between different mineralogical entities (*e.g.* ore *vs* ore and ore *vs* waste) and its behaviour through the downstream processes, *e.g.* a mixture of hard host rock and soft ore or a mixture of fine- and coarse-grained ore. These factors have different influences on downstream processes – the concept is referred to as the compatibility of material. If entities have poor compatibility, the process performance as a whole will be adversely impacted
➤ The dependencies created through compounding effects (different variables impacting a resource simultaneously) are seldom considered. A case in point is when the feed to a dense medium cyclone contains high levels of ultra-fines, a high percentage of near-dense material (NDM), and a lower ore to waste ratio than planned. The ultra-fines can typically impact the rheology of the medium, as this changes the apparent viscosity of the dense medium. NDM in the ore results in the so-called cut-point shift, where separation takes place at a higher density than the medium density; and when one of the outlets also becomes a physical flow constraint due to higher waste levels in the feed, the output of the system becomes uncontrollable and unpredictable.

Dependencies are typically managed using time, space, volume, or capacity buffers. A well-placed and managed buffer (Goldratt and Cox, 1998) can limit the impact of dependencies and simplify complex mining systems. The impact of geoprocessing dependencies on the performance of the system as a whole, however, can be reduced only if specific 'flow properties' of the ore are synchronized with downstream processing activities and set-points, *e.g.* the mining of compatible material types from different areas should be synchronized and plant settings must match the plant feed flow and quality properties to ensure optimal throughput, product recovery, quality, and cost.

Results and discussion

In the previous paragraphs the main characteristics of a system were highlighted, namely that systems are sensitive to changes in their environment, system components impact the functioning of the system as a whole, and system components are interdependent. The implications of this for the management of dynamic mining systems were also briefly highlighted, *i.e.* the necessity to:

➤ Identify and manage the impact of variable ore and orebody characteristics (geological environment) on production rates, product quality, and cost
➤ Manage the mining system as a whole by introducing visible flow and decision-making triggers in the system
➤ Synchronize and maintain synchronization in the system, which can include the synchronization of

Table I

Identification of geoprocessing variables and their use in a flow management approach

Commodity	Number of operations	Identification of geo-processing variables		Geo-processing information used in a daily flow management approach*	Maturity ranking (level)
		Ore/waste morphology	Orebody morphology		
Iron ore	4	Some variables identified in some of the operations	All variables identified in most of the operations	Limited in most operations	2-3
Coal	6	Some variables identified in most of the operations	All variables identified in most of the operations	Limited in most operations	3-4
Zn/Pb	2	Some variables identified in both the operations	Most variables identified in both the operations	Limited in all operations	3
Diamonds	4	Some variables identified in some of the operations	Some variables identified in some of the operations	Limited in all operations	2
Gold	5	Some variables identified in most of the operations	All variables identified in all the operations	Limited in all operations	3
Platinum	3	Some variables identified in some of the operations	All variables identified in all the operations	Limited in all operations	3
Chromium	2	Some variables identified in both the operations	Some variables identified in both the operations	Limited in both operations	2-4
Manganese	3	Some variables identified in some of the operations	Most variables identified in all the operations	Limited in some operations	2-4
Vanadium	2	Some variables identified in both the operations	Most variables identified in both the operations	Limited in both operation	3
Mineral sands	1	Some variables identified	Some variables identified	Limited	3

* Measures and targets exist for geoprocessing variables and are managed in-time based on area-specific conditions (condition-based standards)

activities, ore flow properties with equipment settings, *etc.*, in order to limit the potential negative impacts of (inter)dependencies in the system and across system boundaries.

Different mining operations were evaluated to specifically establish whether geological variables that impact flow in the mining system have been identified and used in a holistic end-to-end management approach that supports synchronization between the characteristics of the ore and equipment settings. The results obtained are discussed in the following section.

Influence of the geological environment

Table I indicates (using the maturity matrix depicted in Figure 1) to what extent ore and orebody characteristics/morphology have been identified and used in a flow management approach in the different mining operations evaluated.

From Table I it is evident that most mining operators have identified at least some geoprocessing variables, *i.e.* geological variables that directly impact mining and plant performance. In fact, some mining houses are actively focusing on geometallurgy to enhance their knowledge of the processing potential of their deposits.

The use of geoprocessing information for the daily management of operations is, however, limited to mining plans – in some cases it is not used at all. In these operations, the focus is mainly on maintaining average grades, volumes, qualities, and process efficiencies, *i.e.* system dynamics caused by the presence of constraints and dependencies in the system and across system boundaries receive little attention. This approach is in most cases supported by a fragmented or functional approach to all aspects of mining (Figure 1a). However, when an integrated approach is employed in mining and an emphasis is placed on the correctly identified geoprocessing variables, significant financial benefits can be obtained as discussed in the case study below.

Case study: management of geoprocessing variables at a mid-sized coal mine

Claassen (2013) stressed the importance of identifying and managing geoprocessing variables at a mid-sized coal mine operating in the Witbank coalfields, South Africa. It was shown that blending non-compatible coal and the treatment of ROM material containing high and variable levels of ultra-fines, near-dense material, and dilution had a detrimental impact on the performance of the dense media separation (DMS) plant operations. The ability to link geological properties of the ore and orebody such as weathering, undulating floor conditions, and ore texture with downstream processing requirements resulted in the development of condition-based planning standards and improved synchronization of the total system. This in turn improved system stability and rendered operations more predictable. Figure 3 illustrates an almost 30% improvement in DMS plant production performance subsequent to the implementation of flow-based principles at the mine.

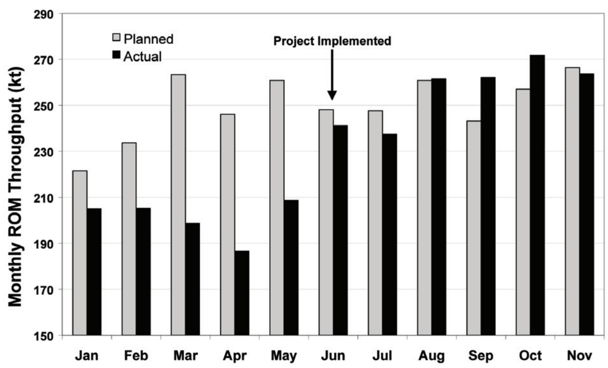

Figure 3 – Improvement in DMS plant performance subsequent to the implementation of flow-based principles at an Mpumalanga coal mine

Management of the system as a whole

The visibility of the primary mining value chain, including key secondary chains (*e.g.* spares and consumable supply chains), at the different mines selected was evaluated. More specifically, the study aimed to establish to what extent a detailed flow view is created by the mines to assist their operators and managers to manage flow in the system. Table II summarizes the findings of this part of the study (using the maturity matrix depicted in Figure 1).

Some mining operators have developed a detailed flow view (refer to Table II) of parts of their mining systems to assist mainly with the management of logistics, *i.e.* ore flow to plant or product to market flows. Apart from this, very few mining operators attempt to create a flow view of the end-to-end mining system to assist operators and managers to better operate and manage these systems. One of the chrome mines reviewed, however, developed a simplified flow view of mining operations that yielded a notable improvement in overall performance as discussed in the following paragraph.

Case study: establishing visibility of ore flow at an underground chrome mine

A flow view was established and constraints determined for an underground chrome mine consisting of five sections, as illustrated in Figure 4. Prior to a study and implementation of subsequent corrective actions, the system was unstable with constraints frequently moving from one section to another and/or one resource to the next in a specific section. Making the overall mining system visible to operators and managers assisted them to identify the flow constraints, put corrective actions in place, and actively manage the system as a whole. The intervention implemented resulted in a sustainable increase in production from about 3500 t/d to 4500 t/d (Kloppers, 2013).

Synchronization in mining systems

Synchronization of activities, cycles, and the characteristics of the ore with equipment and process settings can be employed to limit the impact of (inter)dependencies in complex supply chain systems such as mining systems. *It could be argued that synchronization should be a key component of a flow-based management approach towards these systems. A focus on synchronization should also be an indicator of whether a mining operator understands mining system flow dynamics and has the ability to apply flow-based management principles*. Table III indicates whether the mining operations studied focus on the use of synchronization to limit the impact that (inter)dependencies, specifically geoprocessing dependencies, can have on operational performance.

Table III suggests that only a small number of mining operations, namely 8 out of 30 mines (27%) in this case, focus partially on synchronization in daily operations to limit the impact of (inter)dependencies between geoprocessing variables. This could imply that only a small percentage of mining operators have developed a flow-based understanding of mining systems and are therefore able to optimally exploit their resources, which include the mineral resource(s), equipment, people, and capital (Cooper *et al.*, 1997; Stonebraker and Afifi, 2004).

If it is argued that the mining value chain can be viewed as a dynamic system and its performance is highly dependent on system stability and predictability, it follows that a focus on synchronization of geoprocessing variables can result in significant improvements in business performance, as discussed in the following paragraph.

Case study: synchronizing ore flow characteristics with smelter requirements at a steel producer

A steel production value chain comprising coal and iron mines, the respective washing plants, and the smelter was evaluated and solutions implemented to improve synchronization in the system (Laurens, 2007). The aim of the exercise was to improve overall (total value chain) business performance with an emphasis on improvements in net profit and return on investment.

Synchronization between smelter feed material and the operational requirements of the smelter was achieved through the production of coal and iron ore at a consistent quality and rate in the respective washing plants. Consistency in raw material quality and volume at the washing plants, which

Table II

Total mining value chain visibility to operators and managers

Commodity	Number of operations	Mining system visibility to operators and managers	Maturity ranking (level)
Iron ore	4	• Detailed flow view created for parts of the value chain in most operations • Visibility fragmented mostly along functional boundaries in most cases	3-4
Coal	6	• Detailed flow view created for some mining equipment in some operations • Visibility fragmented mostly along functional boundaries in all cases	3-4
Zn/Pb	2	• Detailed flow view not created • Visibility fragmented mostly along functional boundaries in both cases	2-3
Diamonds	4	• Detailed flow view not created	3
Gold	5	• Detailed flow view not created	3
Platinum	3	• Detailed flow view not created	3
Chromium	2	• Detailed flow view established in one of the operations • Visibility fragmented at one of the operations	2-4
Manganese	3	• Detailed flow view established at one of the operations • Visibility fragmented mostly along functional boundaries at two of the operations	2-4
Vanadium	2	• Detailed flow view not created	2
Mineral sands	1	• Detailed flow view created for parts of the operation • Visibility fragmented along functional boundaries	4

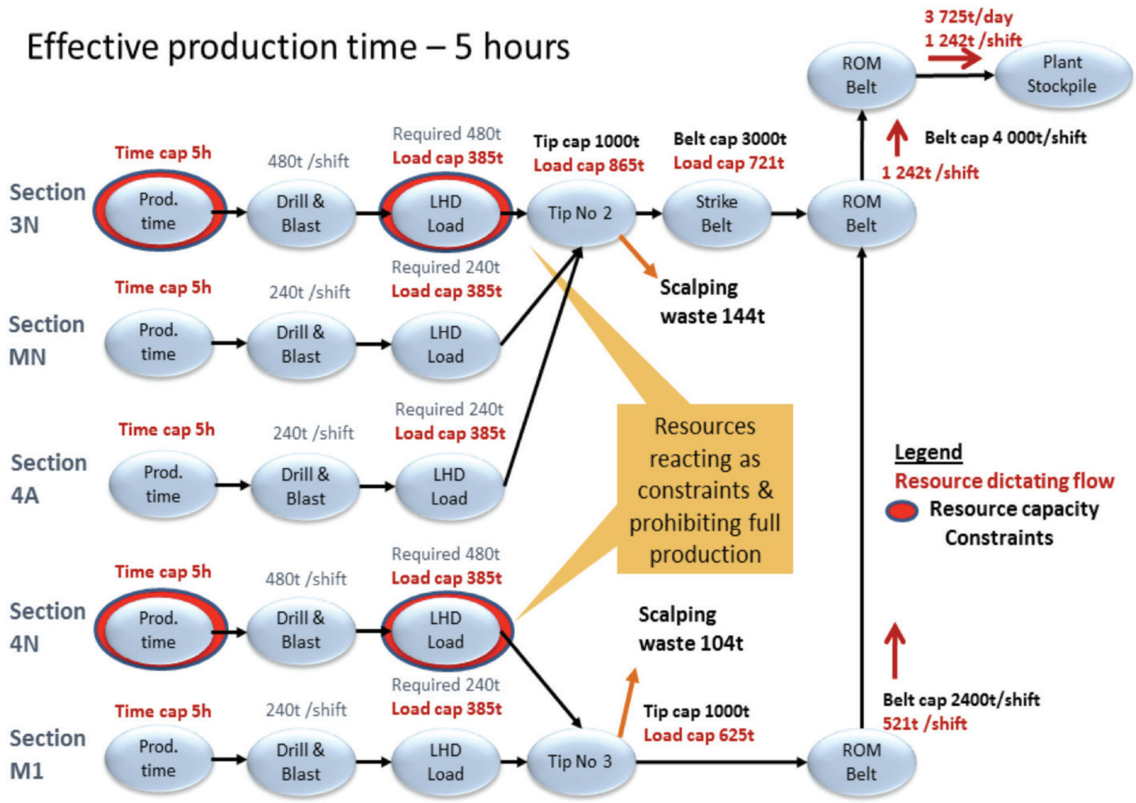

Figure 4 – Simplified flow view of five underground sections at a chrome mine (Kloppers, 2013)

Table III

The use of synchronization to minimize the impact of (inter)dependencies between geological variables and processing capabilities in daily operations

Commodity	Number of operations	Geo-processing dependencies synchronized in daily operations*	Maturity ranking (level)
Iron ore	4	Limited to some dependencies in one of the operations	2-3
Coal	6	Limited to some dependencies in some of the operations	2-4
Zn/Pb	2	Limited to some dependencies in one of the operations	2-3
Diamonds	4	None	2
Gold	5	None	2
Platinum	3	None	2
Chromium	2	Limited to some dependencies in one of the operations	2-4
Manganese	3	Limited to some dependencies in one of the operations	2-4
Vanadium	2	None	2
Mineral sands	1	Limited to some dependencies	3

* Does not include synchronization in logistical activities such as ore/product transport

were managed as the constraints in the system, was in turn achieved through optimal synchronization of plant settings and ore (coal and iron ore) characteristics. The latter was achieved through classification (domaining) of the respective orebodies based on *physical and chemical ore flow characteristics* and batch-washing the different domains through the respective plants. A significant improvement in system stability followed, which resulted in financials gains 'beyond expectations'.

Conclusions

Research into the application of systemic flow-based principles at 30 mining operations on the African continent indicated that:

- Even though geoprocessing variables are identified in a number of operations, they are not actively used in a daily flow management approach at most of the operations
- The development of a detailed flow view of operations is mostly limited to areas where logistics forms a key component of mining systems
- Visibility of the mining system is mostly fragmented along functional/departmental boundaries; highly fragmented operations do not support flow in the system
- Daily synchronization, a key indicator of the application of systemic flow-based principles, is employed at a small number of operations to limit the impact of (inter)dependencies in variable mining systems
- A focus on geoprocessing variables, visibility of mining value chains, and the synchronization of mining activities can yield notable improvements in performance as indicated through a number of case studies

A thorough understanding of mining system dynamics and an ability to implement systemic flow-based principles at all organizational levels should enable operators and managers to optimally set and reset operations to achieve optimal flow of material, ore/product quality, and costs. Furthermore, prioritization and allocation of resources (equipment, people, and capital) should be based on flow requirements in the systems. A focus on these factors will enhance synchronization and therefore product production at the required quality and lowest possible cost.

The study indicates that significant potential exist in some of the operations evaluated to implement flow-based management principles, including geometallurgical principles. This can significantly improve value chain performance without exorbitant capital layouts and enhance ROCE.

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