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## SYSTEMS ENGINEERING NEW PLATINUM FRONTIERS

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### Abstract

South Africa has the world's largest *in situ* deposits of platinum group metals, but economically exploitable resources are shrinking due to escalating costs and technical challenges. The South African National Research and Development Strategy comments that an increase in the knowledge intensity of the resource-based sectors is required to turn these resources to account. Highly trained human resources, continuous improvement, technological innovation, and smart acquisition of know-how will become the major differentiators in the global mining market.

Mechanization and, ultimately, automation in mining have the potential to reverse the negative mining trend and resolve safety and other challenges. However, the adoption rate of mechanized mining in platinum (and hard-rock gold) has been slow for various reasons. Changing systems from conventional drill-and-blast to continuous mechanized mining is a big step-change endeavour. The problem of transformation is discussed, and the discipline of systems engineering is examined because of its successful application in aerospace and defence.

### Introduction

The traditional mining disciplines have often turned to management consultants to help bring about changes and improvements to their business. Hattingh and Keys<sup>1</sup> examined the applicability of industrial engineering to mining. They pointed to the growing acceptance of the discipline as a profession in mining and use of Toyota Production Systems (TPS), Lean, Six Sigma, and other practices.

The new frontier challenges of mechanized deep-level platinum and gold mining systems are similar to challenges faced by the aerospace and defence systems. The conversion from conventional people-coupled drill-and-blast mining to remotely operate mechanical miners is a big endeavour involving the alignment of many complex mining systems.

The authors believe that the new frontier of continuously mining more metal, more efficiently and more safely at greater depths, can also benefit from the systems engineering discipline. There are considerable overlaps between the disciplines and much debate on the differences<sup>2</sup>.

Systems engineering is practiced more in the aerospace, defence, and IT industries, whereas industrial engineering is practiced more in commercial manufacturing industries. Systems engineering tends to focus on the early life stages of systems design and development. Industrial engineering is perhaps more focussed on ongoing operations and improvement to meet customer needs for products and services.

The Centre for Mechanised Mining Systems (CMMS) is part of the School of Mechanical, Industrial and Aeronautical Engineering at the University of the Witwatersrand. The School includes specialized subjects in industrial and systems engineering. From our vantage point, industrial engineering has a stronger focus on the softer cognitive human factors (i.e. people in the system). Systems engineering is focussed more on analysis and design of technology and systems processes.

The CMMS is exposed to mining trends and issues through interaction with its sponsors, the University, and the mining industry. The authors believe there is a significant gap between the capabilities of mechanization technologies and their application in South African deep-level hard-rock mining.

Progress in hard-rock mining can be compared to civil engineering tunnelling in similar environments. For example, the Gotthard Base Tunnel through the Swiss Alps predominantly uses tunnel borers for over 150 km of tunnels, shafts, and passages, mostly in hard rock and at depth<sup>3</sup>).

There are limited mechanical mining examples in South African hard-rock mines – manganese and some chrome mines being the exceptions. Unsuccessful attempts were made to use tunnel boring machines (TBM) in deep-level gold mines in the late 1970s and early 1980s. Gold and platinum mines have experimented with a limited number of pick and disc-cutting mining machines since 2002. The authors believe that the gap in the application of mechanized technology presents an opportunity for mining to advance.

### **Mining, aerospace, defence, and manufacturing industries**

Industrial engineering has led to comparisons of mining with production plants, i.e. a 'rock factory' view. This view has led to performance improvements in mining<sup>1</sup>. The advancing frontiers of aerospace and military battlefronts offer a different perspective to the challenges of being able to mine safer and deeper, as follows:

- As distances increase and conditions become more hostile, there is a need to remove people from high-risk areas for safety reasons but still to keep them operating machines in highly variable operating conditions. Machines replace people in organized factory plants because machines can do standardized repetitive tasks better

- Mining, aerospace, and defence require rigorous command and control systems because they involve people controlling other people or machines, often in unpredictable and dangerous situations. Modern manufacturing philosophies engage and empower workers to creatively and continuously reduce waste, variability, and defects in production systems
- People-operated machines in mining and battle environments offer limited scope for automation. Manufacturing environments can be controlled to exacting tolerances. Computers systematically and tightly control material and component flows to production plants and their machines (much like the process plant at a mine)
- Owing to the limited control over mine, defence, and space environments, intelligent and cognitive human abilities and skills are critical for making decisions, solving problems, and controlling complex machines during unpredictable events and situations. People are engineered out of plant operations because they are the main cause of variance, unreliability, and uncertainty in a highly controllable environment
- Stretched supply lines and logistics call for ample supplies, storage, and backup-system capabilities. This is in contrast to 'just-enough' and 'just-in-time' supply strategies in fixed-location production plants
- Managing the risk and failure events arising from uncertainties in mining is more important than reducing the variability of repetitive processes and product defects in plants. People cannot readily repair a machine in an unsupported stope
- Significant personnel costs are incurred to create a safe people-friendly environment to transport, sustain, and protect lives in mines, space, and battlefields. People are removed from dangerous environments so that they can safely operate machines remotely. Manufacturing processes replace people because automation and robotics perform routine human tasks better, cheaper, and more reliably
- Machine systems in remote mine, space, and defence situations are subject to extremes of force, acceleration, and temperature. They need to be self-supporting, robust, durable, flexible, fail-safe, and connected with people to help deal with variable conditions. Manufacturing focus is on smooth flow and operation designed for easy replacement and switching of production lines.

The case has been made that the unpredictable and variable nature of mining, space, and defence operations require people-aided operations far more than automated manufacturing plants. There is also a greater need to move (but not separate) people from the greater dangers of operations in mines, in space, and enemy territory.

### ***Industrial and digital revolutions***

The industrial revolution coupled people directly to machines as this gave them more 'horsepower' and capabilities useful to industry. The digital revolution is now separating people from machines and connecting people more and more.

Smarter machines (includes computers) have relieved people of routine and tedious tasks, and often their jobs as well. Computers led to new jobs in IT departments required to operate and maintain computer and communication systems. Operation of machines used for less routine work, as in construction and mining, still requires significant operator time, even when remotely controlled.

Unmanned space missions and unmanned aerial vehicles (or drones), tele-remote and autonomous mining machines are examples of a growing trend towards remote control of machines.

Mines and workers stand to benefit from these technologies. Mines are generally in inconvenient locations, and there is a growing reluctance for skilled workers to work in mine locations for any length of time, and particularly in deep underground mines. Companies are reluctant to incur the costs of creating temporary people-friendly villages and underground environments.

Computer networks are providing greater global access between people, data storage, and processing (in the cloud). The trend is for larger amounts of data that can be sent faster and to more places than ever before.

The trend is also towards virtual control centres and virtual workers connected through internet and wireless communication to remote machines with sensors. Computers are embedded almost everywhere. Location of people matters less because large amounts of data and high transmission speed reduces the delay (latency) for people to interact with and control remote machines.

### **Mechanized mining systems - threat or opportunity to people?**

Mechanization and computerization naturally raise concern about jobs. There are many arguments that more jobs are created than lost. Machines will inevitably perform more intelligent robotic functions using various sensors to further assist and empower human operators at some level.

Urban surgeons are already performing delicate operations in rural hospitals using remote-controlled robots. It is envisaged that unskilled people in poor countries may soon be using home computers to clean more affluent homes in remote cities through the eyes of low-cost robots<sup>4</sup>).

## **People and machine roles in mining**

As discussed, the vagaries and variability of operating machines in mines require a far higher degree of people control than a lights-out production plant.

Any advances in mine machine intelligence will enable people to remotely control and manage machines more effectively or operate more machines. The benefits of eliminating fly-in fly-out and underground travel (and cooling) are considerable.

Economics will naturally find the best balance between the capabilities of people and machines. A remotely controlled machine on Mars needs to be fail-safe with a high level of intelligent autonomy, as a signal from Mars to Earth and back can take up to 40 minutes. Machines in mines can be operated remotely and accessed for repairs with negligible time delays.

Modern mining machines are already equipped with various sensors and computer connectivity to remote technicians. Mechanical miners with image sensors are likely to be operated by skilled operators in convenient urban environments, and diagnosed remotely by the equipment supplier. Indeed, large items of plant such as winders and draglines are already serviced in this manner. Remote-controlled search-and-rescue machines are already in use, with video and other sensors.

It is not science fiction to envisage geologists and other professions directing machines to gather image and sensor information, or workers guiding the robotic arms on worker machines installing piping or maintaining a mining machine.

## **Contributing to sustainable life on Earth**

Lower costs and greater depth range will unlock vast resources that are currently uneconomical or too high-risk to exploit. Mining largely supplies the material and energy sources required to create and sustain the global built environment. Some research indicates that world population could peak and stabilize at around 9 billion by 2050, directly as a result of urbanization<sup>5</sup>.

The migration from rural to urban environments is currently taking place through 'arrival cities' (informal settlements, townships, slums, migrant suburbs, ghettos etc.) that are on the fringes of established cities today. What is generally seen as a problem ignores its great success at creating a new middle class, ending the horrors of rural poverty and inequality. South Africa's new government has built over 1.4 million houses, and China is building the equivalent of a city every few weeks to accommodate migrants from the countryside.

Significantly, urbanization leads to smaller families and reduced population growth rates. The money, knowledge, and education flowing from urban migrants to propel the next wave of arrivals have the effect of also reducing birth rates in rural areas. As urbanization increases and family sizes reduce below the replacement level (2.1 children per couple), the problem of overcrowding and competition for resources is replaced with the much more sustainable problem of a non-growing population.

Where does mining come into the picture? The creation of urban environments to accommodate around 5 billion more people in cities before 2050 is largely dependent on mining for materials and energy. South Africa has the largest reserves of non-energy mineral wealth (\$2.5 trillion)<sup>6</sup>. Platinum group metals, valued at nearly \$2.3 trillion, play a significant role in many industries, technologies, and products. Mechanized mining could, in a roundabout way, be a key enabler of sustainable life on Earth.

### **Dealing with disruptive mechanization technologies**

There are various reasons why South African mining is in decline relative to global trends<sup>4</sup>. Politics, economics, power supply, and workforce skills play a role. The authors believe the reluctance to invest in mechanization is largely due to the disruptive technology phenomenon (of mechanical versus conventional drill-and-blast mining).

Managers are naturally inclined to keep doing what has worked in the past. It is extremely difficult for mining companies to funnel resources into disruptive programmes that existing mining structures, explicitly don't want, are not yet proven, and which do not currently work as well as conventional systems. This is compounded when implementation challenges arise or short-term costs rise during the change-over to advanced systems, and shareholders grow dissatisfied at reduced dividend yields, usually measured in quarterly reports, against programmes that may take many years to yield full results.

A well-known Harvard Review article discusses how best to ride the wave of disruptive technologies<sup>7</sup>. One of the most consistent patterns in business is the failure of leading companies to stay at the top of their industries when technologies or markets change. Mining (customers in general) are reliably accurate at assessing the potential of current (conventional drill-and-blast) technologies, but they are reliably inaccurate at assessing the potential of disruptive (mechanical mining) technologies.

When and how does platinum commit to a disruptive technology that won't initially outperform drill-and-blast mining?

The advice given is to ride the wave of disruptive technology when it is apparent that it will disrupt conventional technology. This is the case when the projected trajectory of performance improvement of the disruptive (mechanical) technology will cross above the current (conventional) mining technology. Is it time for the hard-rock precious metals sector to ride the mechanical mining wave?

Drill-and-blast, and various mechanical excavation rates have been benchmarked and compared<sup>8</sup>. The performance rate for TBM-type machines, for example, has been trending exponentially upwards since 1980. The advance rate of drill-and-blast mining is handicapped by other sequential processes (drill, charge, evacuate, blast, ventilate, remove rock, loosen, support etc.).

Furthermore, the effective labour cost component of drill-and-blast is escalating exponentially with time, depth of mining, cooling energy, and safety consequences.

The logical conclusion is that the performance improvement trajectory of mechanical cutter-based mining will inevitably cross over the drill-and-blast trajectory. The platinum sector and original equipment manufacturers (OEM) should therefore start to ride the wave of mechanical mining.

The disruptive technology study results were directed at the technology-driven OEM companies. The authors argue that the advice applies equally if not more so to the mining companies. Mechanical mining is not a simple matter of waiting for OEM companies to develop the right machines.

Despite increasing rates of change, new technologies still take decades to fully develop and achieve market penetration. Earlier commitment to the evolution of mechanical mining systems will accelerate delivery of greater speeds, depths, scale, range, capacities, and efficiencies that will ultimately drive costs down.

Mechanization affects the core value chain and all its support systems. The greater disruption is not in the engineering design of the technology, but because it will take the most time, money, energy, and leadership to re-engineer the affected people, technologies, and system processes in much of the enterprise.

The question now is: How does the platinum industry engineer new systems around disruptive mechanized technology in the least disruptive way?

### **Systems engineering of new mining frontiers**

Would hard-rock mining be different today if the gold mining industry had persevered with R&D work on TBM and other machines started in the late 1970s? The rusty mine graveyards testify of many failures to introduce, manage, and learn from disruptive technologies. Often trials were conducted with the idea that if a machine can work in the most difficult area it can work everywhere. Failure did not mean it could never work anywhere. Clearly the key to success lies in the process it will follow.

Many promising technologies and products have failed to cross the chasm (technology gap). How do aerospace and defence manage to successfully accomplish ever more challenging missions and endeavours and remain at the cutting edge of technology? The authors suggest that their systems engineering approach appears to give them an edge.

People form many links in the conventional underground value chain. People with tools are incredibly resourceful and can fix most broken links in that chain. Replacing people links with technology has both advantages and disadvantages.

Systems then become more dependent on technological links, and therefore need rigorous systems engineering to ensure that the value chain is strong.

### ***How to engineer a better System***

The difficulties of adopting a new but currently imperfect disruptive technology have been discussed. Mechanization will affect most enterprise systems, including the conventional mindset and culture. Re-engineering of platinum systems to mine continuously and mechanically, faster, deeper, safely, and profitably is a mission not unlike a space mission in many respects. How does a company go about this?

The International Council on Systems Engineering (INCOSE) defines systems engineering as an interdisciplinary approach and means to enable the realization of successful systems.

Systems engineering was formally recognized as a discipline only in 2002, with the introduction of the international standard ISO/IEC 15288 for the creation of products and services. The University of the Witwatersrand, with the assistance of CSIR expertise, has adopted the INCOSE systems engineering body of knowledge (SEBOK) as the foundation for its new School of Systems Engineering. The INCOSE handbook formally documents its process-oriented approach, much like the Project Management Body of Knowledge (PMBOK) familiar to many in the mining and engineering profession.

### ***The art and science of systems engineering***

Systems engineering is both an art and science and a critical core competency for successful NASA missions<sup>9</sup>.

Much like a system itself, systems engineering as a whole is greater than its parts, making it difficult to identify the unique systems engineering components that have contributed to aerospace and defence system successes.

The art of systems engineering is described as technical leadership that balances broad domain knowledge, engineering instinct, problem solving, leadership, and communication to address the complexities of systems and the severity of constraints on developing new missions and systems.

The science of systems engineering is systems management requiring organizational skills, processes, and persistence. Systems engineers ideally need both technical leadership and systems management skills, with some role overlap with project managers.

The art and science characteristics provide some principles for a successful approach to mining mechanization:



- Provide a systems-oriented environment with streamlined controls and minimum management encumbrances, and which promotes communication and creativity
- Apply rigorous processes and procedures throughout the project life cycle to ensure a design meets its mission within cost and budget
- Maintain the big-picture perspective through each life cycle phase (concept, development, operations); what has been done, needs to be done, and remains to be done
- Understand and communicate the architectural organization, engineering details, and system-wide connections
- Manage inevitable change, incomplete requirements, uncertainties, and probabilities of risks
- Leadership requires confidence, decisiveness, proper paranoia (expecting the best and planning for the worst), and awareness of what is not known
- Ensure diverse technical competencies, and encourage curiosity and learning of new things
- Apply efforts equally to ensure systems with capability margins for error, and to prevent insurmountable problems, gaps, and overlaps.

Aerospace and defence consort and collaborate with leading suppliers of technology and sources of specialist domain knowledge to better engineer their systems. Mining companies need to do the same, as they do not have the resources in-house. The AngloGold Ashanti Technology and Innovation Consortium is an example.<sup>10</sup>

### **Cost benefits of systems engineering**

INCOSE research on defence systems indicate that when 20 per cent actual costs have been accrued, then 80 per cent of the total life-cycle cost (LCC) has already been determined. Changes after the initial phase become progressively more costly. Systems engineering processes ensure a rigorous focus on early concept exploration and design to reduce the risk of hasty commitments without adequate study.

All engineering costs time and money. INCOSE research has shown significant reductions in project cost, schedule overruns, and schedule variance, as a direct result of systems engineering effort. Excessive systems engineering effort results in diminished returns and wasteful effort. The Systems Engineering Handbook<sup>11</sup> processes provide a framework for tailoring effort to specific project circumstances. It cannot be used as a recipe book or a substitute for competent leadership.

INCOSE provides its handbook, standards, and body of knowledge to its members. The NASA handbook (SP-1605) is available on the internet<sup>12</sup>.

### ***Risks and Opportunity management***

Systems engineering is strongly focussed on the risk and opportunity management process. This provides a balance between cost, schedule, and technical risks and opportunities. Continuous resolution is required before baselines are set for future approvals at decision gates. This provides confidence that the business case remains sound and solutions are achievable.

The concept of operations (CONOPS) process used in defence is applicable to mining operations (not to be confused with the term 'continuous operations'). Creating possible scenarios helps team communication, creative thinking, and discovery of risks and opportunities.

Traceability is a process that ensures that risks, for example, can be traced to needs, requirements, specifications, and to specific life-cycle projects (prototype/simulator testing, maintenance, and support systems).

The information management processes are used through life-cycle design stages, milestones, and decision gates to ensure system integrity.

Strong focus is placed on system interfaces. Conventional mining relies on interfaces between human sensing ability underground, and intelligence to detect and respond with conventional drilling machines and equipment.

In a scenario where people are removed from danger areas, sensors tracking geology on a machine detect a fault/throw and transmit information and notification to the geological department; a geologist re-interprets the reef with modelling software and transmits the information to planning; a mine planner adjusts tunnel layout and transmits the changes to the machine operator, who changes course to re-intercept the probable reef horizon. Successful interfacing of technology (soft and hard IT and machines), processes, and people is a critical success factor.

Project programmes to develop a new disruptive mechanized mining system entail risk. Requirements are approximate, and the technology performance and impact of existing systems uncertain. Systems engineering processes encourage business, budget, and technical project baselines. The baselines are verified and validated at decision gates. Verifications ensure that systems are being developed right (according to baselines). Validations with stakeholders ensure that the right systems are being developed. Gates determine readiness to move to the next life-cycle stages (concept, development, production, utilization, support, retirement). This ensures stakeholder needs are met in an orderly and efficient manner.

Requirements and technology options are often unclear. Incremental and iterative development (IID) processes were used on the NASA Space Shuttle. Large- and small-cycle IID provide rapid value and responsiveness on small projects.

## **The need for modelling systems**

Systems engineering places a strong emphasis on mathematical, simulation, and other modelling as a means to manage and understand systems complexity. The Centre for Mechanised Mining Systems (CMMS) is conducting research into better ways to describe, communicate, understand, and improve complex mechanized mining systems through the development of:

- A simpler descriptive language that all domain stakeholders can easily understand
- A simulation-based risk and planning tool that can predict the effects of operational risk and uncertainty on a plan.

## **Describing complex systems**

The plethora of descriptive languages for describing and communicating systems poses the same problem as the Biblical Tower of Babel story. Language confusion affects projects. The various engineering disciplines each use several preferred language standards for describing what systems look like and how they work.

The CMMS is conducting research around a computer-aided tool to describe large systems. The tool holds promise as it employs a simple, easy-to-learn descriptive language, and computer-aided graphics can generate desired system views from a single source of truth.

## **Simulating complex systems**

There are many advanced mine planning and scheduling software systems on the market. Plans are generated based on average (monthly/daily) mining rates, and ignore the effects of variation. Removal of variation from schedules sometimes results in large discrepancies between predicted schedules and actual performance.

This phenomenon can be illustrated with a simple example. Assume a TBM roof bolter takes 55 minutes to drill and bolt a set of ring holes every hour (i.e. 5 minutes waiting, 92 per cent equipment utilization). Shotcrete is applied 2 hours after drilling starts (i.e. 65 minutes wait after drilling and bolting is complete). Clearly there are no problems with the deterministic plan.

Assume variation is introduced to both starting (every 1 hour on average) and operation time (55 minutes), according to an exponential distribution (using the same averages). This would account for geology-dependent TBM advance rates, cutter breakages, and drilling and bolting logistic problems.

Basic queuing theory predicts the long-term schedule effects: drilling now has to wait an average of 10 hours for sections to become available, and only 16 per cent of supported sections are ready on time for the shotcreting cycle. What appears to be a feasible (good) plan based on deterministic (averages) values becomes infeasible (terrible) when variation is introduced.

Variability in systems is associated with reliability, survivability, maintainability, repairability, and supportability. Failure Modes Effects and Criticality Analysis (FMECA) is an extension of the familiar FMEA analysis. It is used in space and defence applications because it includes a probability element. The shortcoming of all failure mode analysis methods is that they cannot address failure combinations without simulation modelling.

CMMS is developing simulation and risk-based planning applications. A benefit of simulating complex mechanized systems is the ability to predict the scenario effects and sensitivities of risk and uncertainty, and ore flow surge and availability, for example. Designs and solutions can be tested before machines are purchased and systems are changed.

## **Conclusion**

Although mechanical mining systems are largely untested in the platinum industry, there is potential opportunity to utilize them to mine faster, deeper, safer, and more economically:

- The South African platinum industry possesses the greatest share of mineral wealth in the world, and therefore has the greatest opportunity to prosper even from marginal mechanization benefits
- Mechanization is a disruptive technology that will initially underperform current conventional drill-and-blast mining. The performance trajectories of mechanical mining clearly predict an imminent crossover to the superiority of mechanical systems
- The platinum industry should engage sooner rather than later, as a significant level of adoption of new technology in mining (and other industries) typically takes decades and has a high impact on systems. Such endeavours are best achieved through a collaborative approach
- The discipline of systems engineering has contributed to aerospace and defence successes and has potential to contribute to the successful engineering of mechanized systems for platinum mining
- The replacement of people with lights-off automated production plants is unlikely in mining. People-machine/tool partnerships are indispensable for many mining processes. The digital revolution is enabling remote operation of machines and advances in machine intelligence that will enable people to control more machines and systems more productively
- In the greater scheme of things, mechanized mining is likely to have its greatest impact by supplying materials (and energy) in support of the greatest human migration from rural to sustainable urban environments.

Systems engineering is a complementary approach to industrial engineering, particularly during the development and implementation stages of future mechanized mining systems. These disciplines rely extensively on modelling to help discover unforeseen risks and opportunities before acquisitions and system changes. The CMMS is developing tools to help describe systems for communication and understanding purposes, and for simulation of risk-based planning to predict the effects of failure modes, variability, and design scenarios.

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Mark worked as a research officer and lecturer at Wits University researching the application of computers and operations research methods to mining problems. He started a company to develop a suite of geology and mine planning solutions called CADSmine. He later co-founded Graphic Mining Solutions International (GMSI) with AngloGold Ashanti and served as technical director through its growth phase. GMSI, recently renamed MineRP, is a leading international company with many unique offerings. MineRP supports over 500 seats of CADSmine which is recognised as the leading enterprise mine planning system. Mark is currently a visiting fellow to the Wits Centre for Mechanised Mining Systems advising on computer modelling of complex systems. He is currently involved with PhD research for the Centre, and with the development of a computer aided framework for systems knowledge management.