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Tunnels and Underground Spaces:
Sustainability and Innovations

Rapid Drill and Blast Tunnelling, through the Application of Systems Engineering Methods

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ABSTRACT

The net present value of many tunnelling projects depends on the time from capital development expenditure to revenue generation from production. The more rapid the tunnelling stages the higher the project NPV. This paper investigates the application of system engineering tools on safe rapid tunnelling and illustrates the benefits and limitations of such tools in real world.

Lean manufacturing, Six Sigma, Benchmarking and Simulation implementation case studies from mine tunnels in Canada and Australia, as well as from the construction of the Channel tunnel in UK are examined. These case studies demonstrate how the repetitive cyclic nature of underground development is well suited to systems engineering methods. And, explains how systems engineering methods have been used to improve advance rates across a variety of projects.

The paper concludes by identifying the availability of reliable and appropriate data as the most challenging aspect of applying these methods and suggests a number of opportunities for developing systems engineering methods by utilizing faster and more reliable reporting systems. This approach was identified as key to sustained implementation of systems engineering methods which offers the potential to continuously improve tunneling rates by incorporating systems engineering methods into the system itself.

RÉSUMÉ

La valeur actualisée nette des projets d'excavation de tunnel dépend du temps écoulé entre la dépense en immobilisations de développement et la génération de revenus issus de la production. La valeur actualisée nette croît en fonction de la rapidité à laquelle se succéderont les étapes de percement du tunnel. Cet article examine l'effet de l'utilisation de moyens technologiques sur le percement rapide et sécuritaire de tunnels et illustre les avantages ainsi que les limites de l'utilisation de ces équipements dans la réalité.

Cet article examine les études de cas, les analyses comparatives et simulations effectuées par Six Sigma sur la mise en œuvre de tunnel miniers réalisés en production allégée au Canada et en Australie, ainsi que dans la construction du tunnel sous la Manche, au Royaume-Uni. Ces études de cas démontrent comment la nature cyclique et répétitive du développement souterrain se prête aux méthodes d'ingénierie des systèmes. Elles révèlent aussi comment les méthodes d'ingénierie des systèmes ont permis d'accroître la vitesse d'exécution d'une variété de projets.

En conclusion, l'article révèle que l'aspect le plus intéressant dans l'application de ces méthodes demeure l'identification et l'accessibilité à des données fiables et pertinentes et indique un certain nombre d'occasions de contribuer au développement des méthodes d'ingénierie des systèmes par l'utilisation de systèmes de production de rapports plus rapides et plus fiables. Cette approche est présentée comme la clé pour la mise en œuvre soutenue des méthodes d'ingénierie des systèmes, offrant la possibilité d'accélérer le percement de tunnels par l'intégration continue des rapports dans le système lui-même.

1 Introduction

According to Atlas Copco (2005), hardrock tunnelling rates have increased on average by only 24 per cent over the last 25 years (Figure 1). This paper reviews the experience of the mining and civil tunnelling contractors in applying systems engineering concepts to advance tunnelling rates. Systems engineering involves the systematic analysis and improvement of processes through the development of process maps, measurement and simulation of cycle times and application of Lean production and Six Sigma concepts to improve cycle time and work quality.

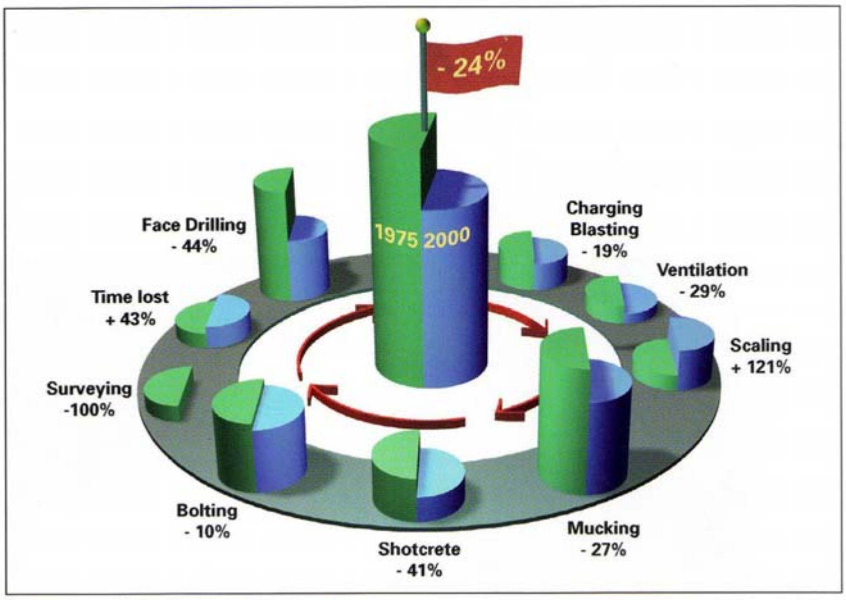

Figure 1 Atlas Copco Drill and Blast Diagram (AtlasCopco 2005)

2 Background

Quick tunnelling improves net present value (NPV). This is critical for big projects and mining industry where several kilometres of tunnelling is initially required at high capital cost(Suoreneni et al. 2008). This paper presents a review of system engineering applications for rapid tunnelling.

System engineering methods are the business improvement methods of choice for many manufacturing and processing industries around the world. Other systems engineering methods applied to rapid tunnelling and discussed in this paper include; lean manufacturing, six sigma, benchmarking, process mapping, simulation and standardised work.

3 Systems Engineering Methods

3.1 Lean Manufacturing

Lean manufacturing has its roots in the production systems developed by Toyota from the 1950's. The Production System has contributed to the rise of Toyota as one of the most successful automotive businesses in the world. "Problems" in the Toyota and Lean manufacturing view of the world, are sources of waste, where performance does not measure up to expectation. A formal definition of lean production techniques might be "the ceaseless elimination of waste" (Dunstan et al, 2006). Dunstan et al. (Dunstan et al. 2006) have done a comparison [Table 1] between resource/mineral businesses and Automotives and document a number of successful case studies of the application of lean manufacturing techniques by Rio Tinto Aluminium, The Northparkes mine and the Hunter Valley Coal Operations. In practice, Lean relies on:

- Engaging workplace leaders
- Asking employees to set agreed standards for their work
- Empowering employees to write their own standards and improve them
- The visual representation of key production performance data, empowering employees at the lowest level to make operational decisions based on the data
- Forming operations and maintenance employees into manufacturing teams
- Application of a suite of business improvement tools

Table 1 Comparison between resource/minerals businesses (after Dunstan et al. 2006).

Resource and Minerals Business	Automotive Business
A smelter or refinery cannot be stopped so there is inherent production push in the process	An automotive assembly line can be stopped so there is the ability to create pull systems
Production is in continuous units and around the clock	Production is in discrete units and often on less than one day cycles
Generates considerable dust	Little dust
Physically challenging environment	Ambient conditions
Inherently variable environment	Stable work environment
Remote locations	Large centres
Impact of weather	Indoor environment
Inherently variable raw materials	Controlled raw materials
Geographically spread output teams	Compact plants
Molten metal has a short shelf life before it solidifies	Long-life components suitable for supermarket-style storage

Lean manufacturing as a system engineering method for rapid tunnelling has limited applications because it does not consider the overall system nor does it consider interactions between processes. Because rapid tunnelling has complex interactions between processes it is unlikely that Lean manufacturing would be successful as a stand-alone method. That being said, Lean manufacturing’s focus on waste would be applicable to certain processes in the tunnelling cycle where waste is a problem. For example, Lean manufacturing would be well suited to reducing wastage in particular ground control process. For example, reducing excessive bolting and shotcreting by ensuring ground support designs are responsive to conditions. However, if applied to isolated waste issues without considering the overall system then eliminating waste could adversely affect tunnelling rates. For example, an attempt to reduce shotcrete wastage could make the shotcreting process take longer thereby increasing ground control times.

3.2 Six Sigma

"Six Sigma" was pioneered by Motorola and later popularized by Jack Welsh, CEO of General Electric Corporation. Its name derives from quality control principles relating to statistical process control.

If product quality is regarded as being normally distributed, a manufacturer will typically impose an upper control limit (UCL) and lower control limit (LCL) to define an acceptable quality range. In a three sigma system, the distribution is such that plus/minus three standard deviations lie within the upper and lower control limits. Thus, using standard normal tables, it can be seen that 2,700 defective products per million (0.27%) can be expected to fail both the upper and lower limit tests (see the blue zone on the left hand of Figure 2). Furthermore, if the process is such that the mean shifts by 1.5 sigma, then the proportion failing the upper control limit will increase to 67,000 per million.

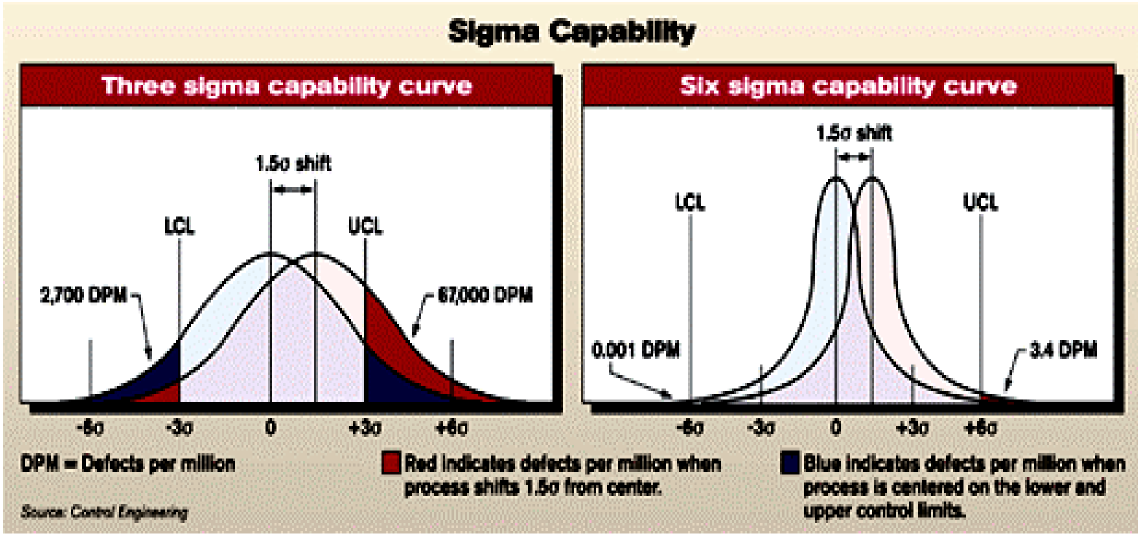

Figure 2 Six Sigma Product Defect Capability, source: (Harrold 1999)

To avoid such losses, Motorola defined their desirable product quality such that plus/minus six sigma fall between the upper and lower control limits. This means that only 3.4 defects per million are acceptable at each of the distribution cut-offs. The methods chosen to achieve this aim became known as the six sigma approach to continuous improvement.

Central to the six sigma approach is the use of a structured, disciplined, rigorous approach to process improvement based on DMAIC (see Figure 3). DMAIC is an acronym meaning Define, Measure, Analyse, Improve and Control. The following explanation of the DMAIC cycle is drawn from Rath and Strong (2000):

The first phase is *Define*. The project's purpose and scope are defined. Background information on the process and customer is collected. The output of this phase is:

- A clear statement of the intended improvement (the business case and team charter)
- A high level map of the process (this uses an input-output map called SIPOC, considering Suppliers, Inputs, Process, Outputs, and Customers)
- A list of what is important to the customer (Critical-to-Quality or CTQ factors)

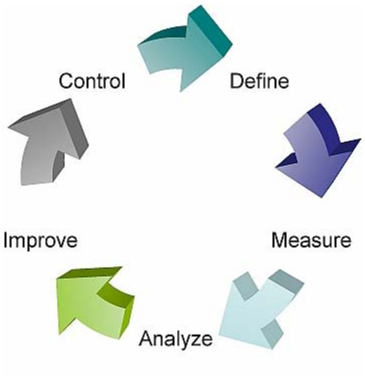

Figure 3 Six Sigma DMAIC Improvement Cycle (after Rath and Strong 2000)

The second phase is *Measure*. The goal of Measure is to focus the improvement effort by gathering information on the current situation. The output of Measure is:

- Baseline data on the current process performance
- Data that pinpoints problem location or occurrence
- A more focused problem statement

These outputs provide the basis for the *Analyse* phase. The goal of this phase is to identify the root cause(s) and confirm them with data. The output is a theory that has been tested and confirmed. The verified cause(s) forms the basis for the next phase.

The goal of the *Improve* phase is to try out and implement solutions that address root causes. The outputs are planned, tested actions that should eliminate or reduce the impact of the identified root cause(s). Additionally, a plan is created for how the results will be evaluated in the next phase.

The goal of the *Control* phase is to evaluate the solutions and the plan, maintain the gains by standardising the process and outline steps for on-going improvements including opportunities for replication. The output is:

- Before and after analysis
- A monitoring system
- Completed documentation of results, learning and recommendations

Like Lean Production techniques, Six Sigma draws upon a suite of business improvement tools for each of the DMAIC phases. Six Sigma relies on training a number of high level business improvement specialists within an organisation. Using martial arts terminology, these specialists are referred to as green, yellow and black belt Six Sigma practitioners.

Companies such as BHP Billiton and Caterpillar have successfully implemented six sigma business improvement programs throughout their operational units.

3.3 Benchmarking

According to Hall and Harper (2005) Benchmarking is a practical and effective method of measuring operational performance, identifying performance gaps and providing and prioritizing performance targets. Furthermore for benchmarking (or any performance improvement process) to add value, it must consider the complexities of underground mining and work within the framework of the strategic plan. Most benefit is derived from having the right plan; however the plan cannot provide value if it is not implemented in an effective and sustainable way to be successful benchmarking must adhere to a rigorous and structured process. The benchmarking process comprises the following main components. (Hall and Harper 2005): Data Collection, Data Entry and Report Production, Evaluation report preparation, Discussion of findings, Improvement action plan and on-going monitoring.

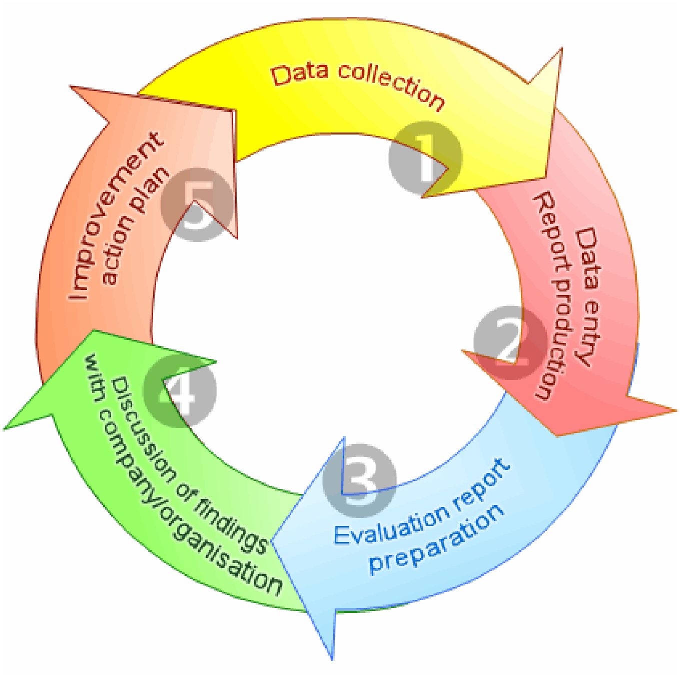

Figure 4 Benchmarking process

To add value, benchmarking must incorporate the strategic goals of the organisation into the process (Hall, AJ & Harper 2005). These goals should be linked to the underlying cost and physical drivers of operation performance. Hall (2005) argues that it will ensure that the implemented solutions will add value to the operation. Undertaking a benchmarking project is a significant commitment and it is essential that sufficient resources are allocated to the process to ensure the maximum benefit is derived (Hall and Harper 2005). The benefits derived from a properly conducted benchmarking project will often far outweigh the costs.

Hall(2005) states that benchmarking is often used by site mining personnel to assess how well mining systems and processes are operating relative to comparable sites. At this stage benchmarking emphasises processes that appear to be performing less than predictions and picks out processes where improvements could be achieved by other system engineering methods. On the other hand, benchmarking outcomes can be employed more directly as part of the solution to processes that perform less well than expected by providing samples of best practice and focusing on processes where improvements are most likely to be made.

3.4 Process Mapping

An underground mine can be considered as a process which transfers a mineral resource from the ground into a product, concentrate or metal(Hall and Harper 2005). Hall argues that the process is made up of a number of sequential process steps which transfer ore from one stock type to another. Each consecutive ore stock has a greater worth than the previous caused by less time and labour being necessary to transform the ore into a product. Hall (2005) states that to achieve the performance targets set during the planning process it is important that sufficient ore stocks are maintained to allow for the uncertainties encountered during the normal course of the underground mining process. Ore stocks need to be conserved at adequate levels for a mine to deliver the specified ore requirements in a sustainable and efficient manner to the processing plant.

3.5 Standardised work

Variability in operating procedures within and between crews is often an accepted part of mining operations. However, this variability is the enemy of high performance(Winchester 2006). Standardised work is a rigorous procedure to standardise, document and progressively improve the way work is done and is applicable to all the other Lean tools. It is implemented through discussing existing practices for a particular work process and documenting a baseline procedure. Through 'kaizen' or brainstorming sessions or through suggestions made by employees at regular meetings, the procedure is incrementally improved Standardised procedures and adherence to them is important if a mine is to remain competitive with international best practice (Dunstan et al. 2006).

3.6 Simulation

Simulation is an efficient and cost-effective tool for decision-making and analysing real-world systems and repetitive construction processes. It models the behaviour or properties of processes to predict behaviour. Simulation is especially useful where there are complex interactions between processes making analytical solutions too complex to calculate.

Tunnelling and trenchless construction processes are excellent candidates for the utilization of computer simulation due to their repetitive nature. Management of infrastructure, underground, or pipeline projects is challenging because of inherent uncertainties. The most effective way to deal with uncertainty is to collect supplementary information and knowledge. When expensive or infeasible, quantification of uncertainty may be performed using analytical or simulation techniques.

In mining operations simulations have been carried out for many years (Hall, 2000).Hall (2000) comments that simulation is well suited to evaluating the effect of changes in complex dynamic and interrelated systems. Engineering processes can be simulated using a vast array of commercially available computer programs

4 Rapid Tunnelling Applications

4.1 Lean Production

The North-Parkes Mines Experience (Rio Tinto Practice)

Barry Lavin (Managing Director Northparkes Mines) reports:

> *"Northparkes Mines, an underground block-caving copper mining operation in central New South Wales, recently began developing first stage of a new underground mine at its E48 project. This involves excavating 10000 meters of tunnels using conventional drill and blast mining methods. Reintroduction of underground development presented challenges to project team. The majority of issues were associated with mine services, equipment and work procedures and many of them were recurring."*

Development of underground excavations follows a cyclical process that is repeated every 12 to 24 hours(Dunstan et al. 2006). The tunnelling cycle, undertaken by a crew of five or six miners, consists of:

- Drilling a pattern of blast holes into the rock face;
- Charging blast holes with explosives and firing;
- Ventilation (Cleaning blasting fumes)
- Mucking out broken rock; and
- Supporting the new section of tunnel with ground support elements including meshing, rock bolts and spray-on concrete

Advance rates vary between three and five metres per cycle. This was the task that Lean was called in to control and improve. A key feature of Lean is its ability to manage a large number and variety of issues simultaneously using visual prompts to assist the communication of issues. A Lean Information Centre was established in the project's shift change centre (Figure 5). The metrics that the tunnelling teams chose to track were safety, environment, employee availability, cycle completion times, weekly tunnelling targets and utilisation of resources.(Dunstan et al. 2006)

Figure 5 Lean Information Centre (after Dunstan, Lavin & Sanford 2006)

Lean has proved to be a flexible and adaptive management tool. It is currently being used to track more than 100 issues simultaneously (Dunstan et al. 2006). It also allows for communication of tunnelling rates and metrics. This could improve communication with team leaders and crew members and let them see where issues are occurring. As a result, crew members are more willing to contribute to identifying and solving issues that cause delays in the production cycle.

The Lean process facilitates a structured response to productivity issues, which has improved the efficiency and effectiveness of shift changes. Overall, the benefits derived from implementing Lean Information Centres at Northparkes have been significant (Dunstan et al. 2006), with the process contributing to a 56 per cent improvement in the cycle time within the first 30 days of adoption (Figure 6). They have provided a structured approach to improving productivity. The main benefits are that tunnelling targets and performance against those targets are visible. Tunnelling teams are actively involved in identifying and solving causes of delay.

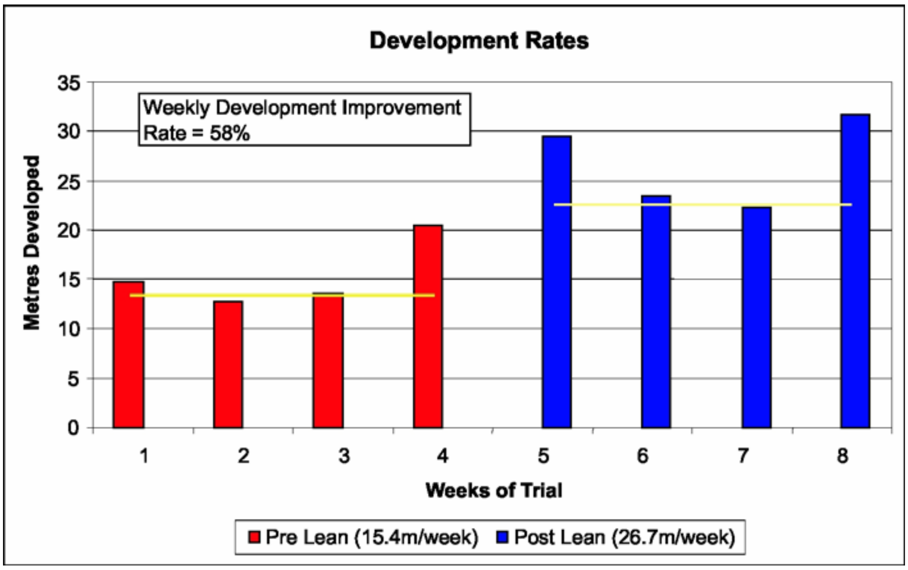

Figure 6 Northparkes Tunnelling Rates (after Dunstan, Lavin & Sanford 2006)

4.2 Six Sigma Application

Cadia East Rapid Tunnelling Technologies

Willcox (2008) Reports on a pre-feasibility study being undertaken by Newcrest Mining Limited, the Cadia East implementation team has developed an access decline to the proposed underground operation. Willcox (2008) discuss the components of Six Sigma methodology were applied to support the systematic changes and demonstrated that tunnelling rates improved 60 per cent above the comparable single heading benchmark. The initial step involved breaking down the tunnelling cycle into the elements. The initial forecast of cycle time is 12 hours based on these elements (Table 2).

Table 2 Tunnelling cycle time (after Willcox 2008)

Element	Time
Fumes clearance	30 mins
Water and inspect	30 mins
Bog # 1 (300 t)	90 mins
Hydroscale and shotcrete	100 mins
Bolt (27 bolts)	120 mins
Bog # 2 (200 t), clean up	90 mins
Drill face (70 holes)	150 mins
Charge and fire	90 mins
Total time	12 hrs
Advance (assume 85%)	269 m/rn

Willcox (Willcox 2008) found a number of improvements through lateral thinking exercises, by breaking down face utilisation and face efficiencies and their contribution to the advance rate. The potential improvements were then ranked using impact, likelihood and `Pareto' rankings. Cycle times and the individual components were analysed for each month with comparison to expectations. Common cause events such as pumping issues (Figure 7) were identified, with positive and negative contributions to cycle times discussed and actioned.

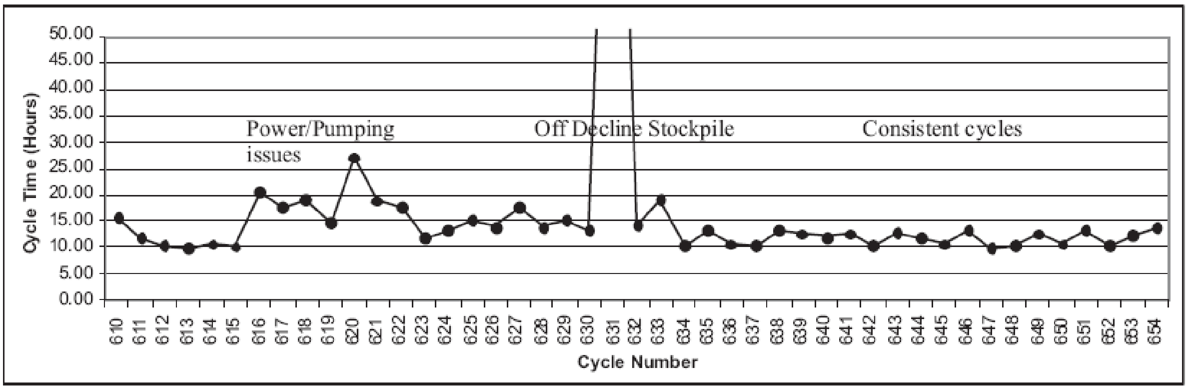

Figure 7 Cycle times – December 2006 (after Wilcox 2008)

Box plots (Figure 8) were used as an additional graphical method to present cycle components, essentially showing the distribution of the data by using the median, quartiles and the extremes. The box shows the middle 50 per cent of the data.

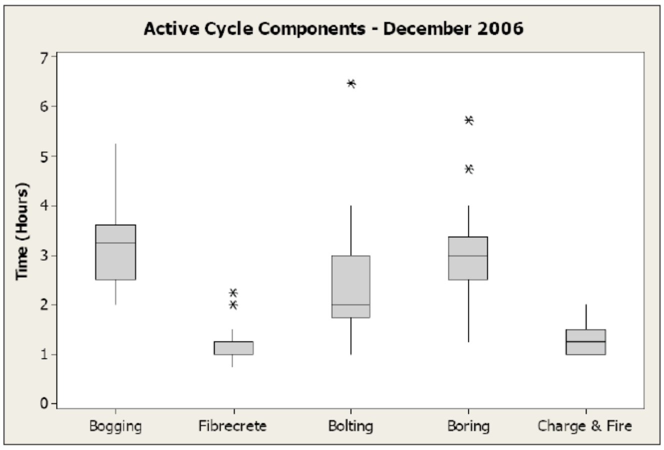

Figure 8 Box plot for cycle components – December 2006 (after Wilcox 2008)

Overall Willcox (2008) found Six Sigma improvement processes have supported the adoption of emerging technologies at Cadia East. Accurate long round, high performance drills coupled with emulsion explosives and high-capacity materials handling have demonstrated single heading tunnelling rates over 8 m/d (50 per cent above the current Australian benchmark of 5.25 m/d) are now practically possible (Figure 9).

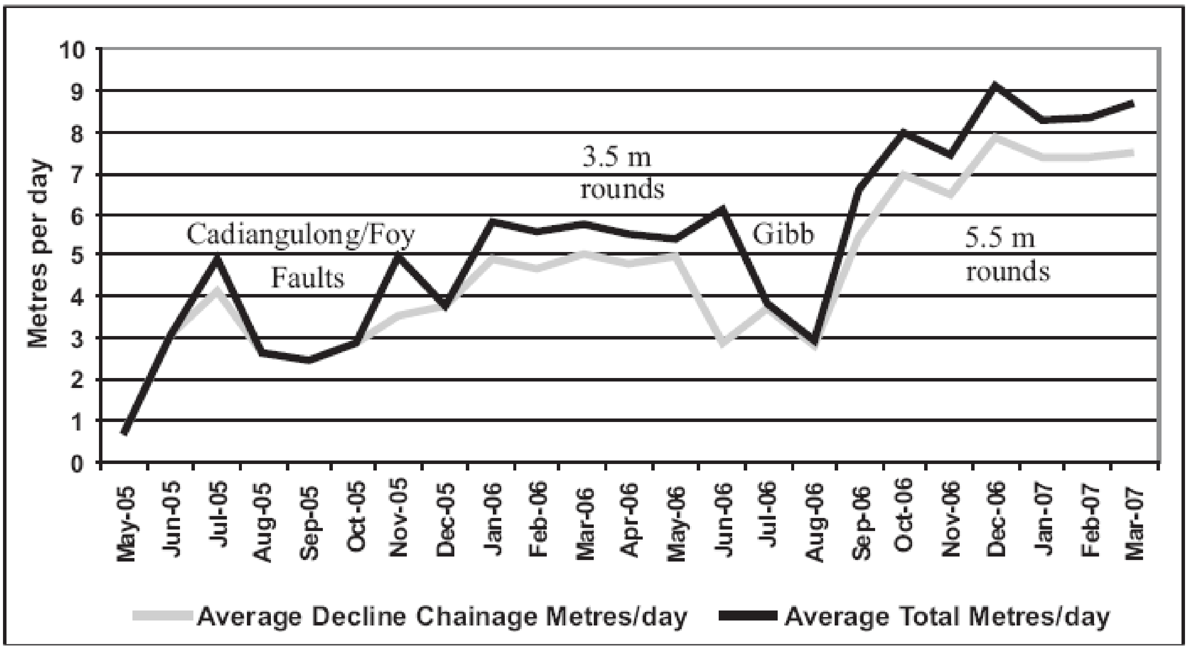

Figure 9 Cadia East single heading tunnelling rates 2005 - 2007 (after Wilcox 2008)

4.3 Benchmarking

Table 3 contains 8 drill and blast tunnelling case studies used to estimate underground development benchmarks. (Neumann 2001) collated the majority of the case studies presented in Table 3. The median advance rate for the 8 case studies was 7.0 m/day and the average was 6.8 m/day. It is important to note that Table 3 contains both single and multiple heading tunnelling case studies. Multiple heading developments have faster average advance rates because of better equipment utilisation. Differences between mines can also be attributed to differing operational, productivity and cost priorities (Neumann 2001).

Table 3 Drill and blast benchmark case studies (Nuemann 2001; Stewart et al, 2006)

Case Study	Country	Average Advance Rate
PT Freeport(Barber et al. 2005)	Indonesia	9.0 m/day (63m/week)
Craviale Tunnel(Kalamaras et al. 2005)	Italy	5.5 m/day (38.5/week)
Kidd Creek mine(Neumann 2001)	Canada	5.3 m/day (37 m/week)
Holt McDermott mine(Neumann 2001)	Canada	7.2 m/day (50 m/week)
Creighton mine (Neumann 2001)	Canada	5.0 m/day (35 m/week)
Brunswick mine (Neumann 2001)	Canada	5.8 m/day (40.6 m/week)
Dome mine (Neumann 2001)	Canada	7.4 m/day (51.8 m/week)
Musselwhite mine (Neumann 2001)	Canada	8.9 m/day (62.3 m/week)

Benchmarking of not just the overall system performance, but also the individual processes across numerous operations has identified ground support as the process with the most potential to increase tunnelling rates. A survey by Laurentian University Mining Automation Laboratory (LUMAL, 1997) Figure 10 shows that the greatest amount of tunnelling cycle time (36–46%) is spent on support installation. This observation is supported by evidence presented (Peake and Rupprecht 2002) from the South African underground mines. For 30 years the Norwegian University of Science and Technology (formerly known as University of Trondheim, The Norwegian Institute of technology) has been collated, analysed and reported on tunnelling design, performance and cost data for both drill and blast and TBM tunnelling. These studies indicate that for a 6m by 5m face ground control comprises 32% of the tunnelling cycle time (Figure 11) (Johannesson 1995).

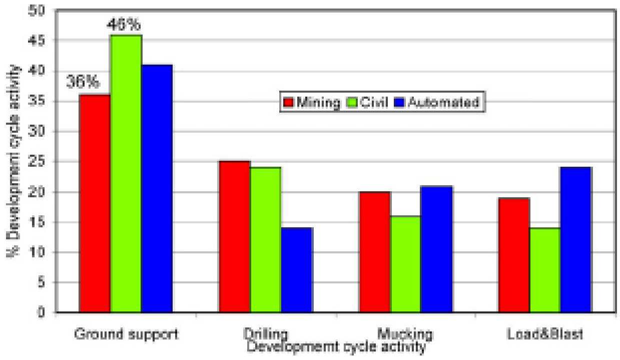

Figure 10 Comparison of tunnelling cycle activity times in drill and blast [source (Peake & Rupprecht 2002)]

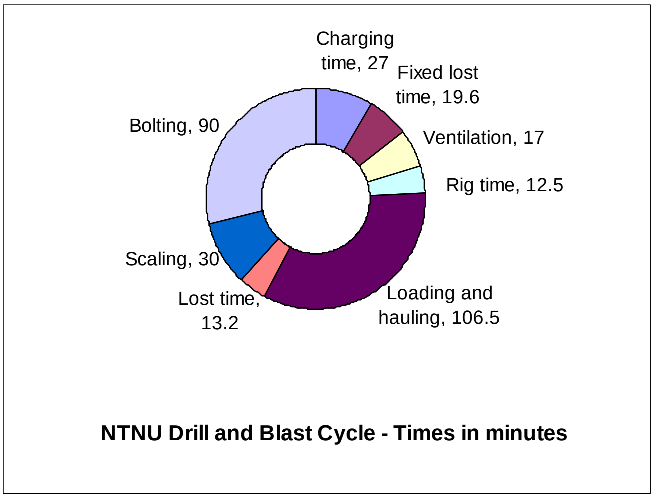

Figure 11 Cycle time times for drill and blast tunnelling for a 6m by 5m face based on NTNU Prognosis for $30m^2$ prognosis. Total cycle time=375 minutes. Ground control (scaling and bolting) represents 32% of cycle time.

4.4 Process Mapping Application

Channel Tunnel

At the Channel Tunnel Rail Link project located in the United Kingdom, contractors responsible for rebuilding St. Pancras Station are integrating Lean Construction and Six Sigma in order to achieve critical construction milestones (Koerckel and Ballard 2005). These include distributed real-time production planning and control; tunnelling, use and continuous improvement of standard processes; active measurements of the planning system performance and action on root causes of failures; and cross-functional collaboration

Strategic Project Solutions (SPS) has developed production control software for implementing the Last Planner System, (Ballard 2000) along with other "lean" and modern business principles and theories. The SPS software, SPS Production Manager, is a web resident database, allowing coordination across all specialists, those on site and off site, and enabling data collection and analysis.

According to Koerckel, Ballard and Espanad (2005), all work groups met daily to review and commit to a production plan for the day and to record completions and non-completions for the previous day. The "work flow reliability" for the project, shown in Figure 12, has improved from 70% to 80% over an 18 month period. Notable also is the reduction in variation.

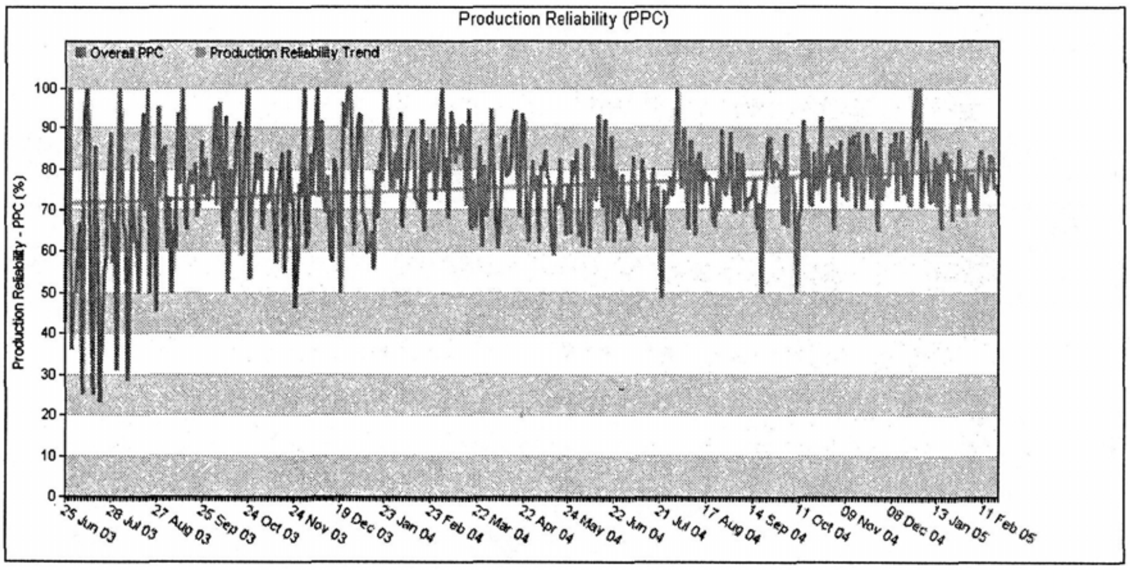

Figure 12 CTRL Production reliability graph to 22 Dec 2004(Koerckel & Ballard 2005)

On top of these individual items, by using SPS Production Manager & 3D prototyping to improve their control of the works and their short term planning, the West Deck team has targeted a 10% productivity improvement over the East Deck.

4.5 Simulations

CAMIRO Drill and Blast Cycle Simulations

Stewart et al used benchmarking in combination with simulation results to estimate a theoretical limit for underground development rates of 19m/day. This theoretical limit assumes that it is theoretically possible to achieve the following technical developments and advances while also assuming that the simulated 178% increase can be directly translated to the 6.8 m/day benchmark average.(Stewart et al. 2006):

- Shielding to eliminate ground support time
- Successful long round drilling in all ground conditions.
- Halve set-up times
- 3 boom jumbo can be configured to operate effectively at cross-sectional area of $35m^2$ to $40m^2$.
- Container truck
- Reduce explosive loading time by 30 minutes.

Simulation results for an idealised scenario including; halved set-up times, elimination of ground support time, reduced drilling preparation time, using a 3-boom jumbo, independent firing and reduced explosive charging time has the potential to increase development rates by 90% to 10.2m/day (from the simulation base case 5.4m/day). If the 90% improvement directly translates to the average advance rate for the drill and blast case studies from report by Stewart et al (7.0 m/day), this scenario would increase advance rates to a theoretical limit of 13.3 m/day.

5 Discussion

5.1 Benefits

The case studies presented in this paper demonstrate how systems engineering methods have been used to improve underground tunnelling rates across a variety of projects and using a variety of methods. In summary, systems engineering methods have been attributed with the following improvements or benefits:

- North Parkes achieved a 58% improvement in cycle time using Lean.

- Application of Lean software for the Channel Tunnel Rail Link project increased production reliability from 70% to 80%.

- Six sigma supported application of emergent technologies that resulted in single heading tunnel rates over 8 m/day (60% above the Australian benchmark of 5.3 m/day).

- Simulation has been used to prioritise rapid tunnelling research areas to those with the most potential to improve tunnelling rates.

- At Kidston mine, tunnelling m/Manshift increased by 25% from 0.31 to 0.39 m/manshift.

- Use of simulation software to predict advance rates enables better tunnelling design and planning.

5.2 Implementation

Implementation strategies are keys to obtaining benefits from system engineering methods. Based on the case studies presented in this paper, both Lean and Six Sigma appear most advanced in terms of implementation strategies, while benchmarking and simulation are less developed in this regard. Both benchmarking and simulation appear to be primarily undertaken by specialist outside consultants for the purpose of decision making and mine planning. Hall (2000) reports how simulations have been used by mine planning engineers to analyse truck and loader fleet requirements for different mining scenarios, while CAMIRO (2002) used simulation to prioritise research areas. Hall and Harper (2005) recognised the importance of bringing together a site benchmarking team including a "site champion responsible for coordinating different departments" who was considered key to successful implementation (Hall and Harper, 2005). The "site champion" role is key and yet, implementation strategies are not defined for this role. Implementation of benchmarking outcomes depends upon the leadership, authority and ability of the "site champion". This contrasts with Lean which has detailed strategies for operational implementation of improvement recommendations.

Six sigma process mapping steps have been shown to be an effective method for identifying processes where lack of quality control results in delays to the tunnelling cycle. That being said, the complexity of the rapid tunnelling cycle processes and process interaction is such that it relies considerably on experience and understanding to identify critical to quality factors. Hughes (2001) experienced difficulty applying Six Sigma with the level of rigour usually associated with the method. The issue of system complexity could be overcome by combining Six Sigma with a higher level analytical method such as benchmarking or simulation.

A common feature of all systems engineering methods is their reliance on reliable process information upon which to base analysis and improvement. Hall (2000), Hall and Harper (2005) and Hughes (2001) all discuss problems with data reliability and availability. Automated data acquisition/capture systems require much data checking and validation. The possibility exists to incorporate automated data validation and checking algorithms/programs which would enable more timely response to process issues, in much the same way that minerals processing plants use real-time data for process control 24 hours a day 7 days a week.

5.3 Sustainability

Sustaining the benefits of system engineering into the future offers long-term benefits as opposed to one-off improvements. Communicating benefits, performance and results of analysis both to management and operators are factors mentioned by Spears (Spears 2001), Dunstan (2006), Hughes (2001), Hall and Harper (2005) and Hall (2000) as being integral to ongoing or sustained implementation.

Implementation of Lean manufacturing boosted tunnelling rates by providing highly visible targets, performance monitoring, as well as, actively involving tunnelling teams in identifying and solving the causes of delay. Lean's use of boards to display performance metrics in tables uses a style of communication familiar to underground employees and was shown to work well. In addition, employees involved in different processes are invited to participate in the process, and the system engineering method becomes part of the system. By contrast, six sigma's performance graphs are more abstract, and therefore more difficult to communicate.

While Lean has demonstrated benefits in terms of ongoing implementation, ideally it should not be seen as a stand-alone systems engineering solution for improving rapid tunnelling. It is conceivable, or even likely that over time a different set of performance metrics should be used. For example, as tunnelling becomes deeper truck availability may become a new limit on tunnelling rates.

It is clear that all system engineering methods discussed use a project or study team, often using consultants from off-site. A limitation of using one-off project or studies is that systems engineering is implemented in a static way often to a situation that may no longer exist. As technology to capture data in real-time advances the possibility exists to create real-time dynamic system engineering methods that can respond quickly and potentially make system engineering part of the system. It is realistic to suggest that developing automated data validation algorithms would capitalise on system engineering benefits by making sustained implementation easier. In minerals processing plants this has been the case of decades. While there are practical challenges to developing a dynamic system engineering solution for rapid tunnelling, the benefits in terms of improved advance rates are well worth the expenditure.

6 Conclusions

Application of systems engineering methods in tunnelling and mine tunnelling has been shown to improve tunnelling rates. And, the repetitive cyclic nature of underground development was well suited to systems engineering methods.

Combining higher level analytical system engineering method such as, simulation and benchmarking, with a method with well defined implementation strategies such as, Lean or Six Sigma, offers the potential to deal with the complexity of tunnelling process interactions while also offering practical and proven methods for implementation.

More reliable and faster data capture and reporting was identified as key to sustained implementation of system engineering methods. Faster and more reliable data also offers the potential to continually improve tunnelling rates by incorporating systems engineering methods into the system itself.

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