SAIMM

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CAPACI OCCASIO

FOUNDED 1894

120 YEARS OF TECHNICAL EXCELLENCE 1894 - 2014

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As another successful and busy year comes to a close, we at

The Southern African Institute of Mining and Metallurgy

wish all of our members

and those who supported us throughout this year,

a heartfelt *Seasons greetings* to you and yours.

We point out to anyone who is interested in joining the SAIMM of the benefits of being a member:

- Receipt of a monthly professional *Journal* with informative technical content of a high standard which serves as a communication medium to keep members informed on matters relating to their professional interests.
- Attendance at conferences, symposia, colloquia, schools and discussion groups at competitive prices with discounted rates for members.
- Invitations to participate in technical excursions and social events which create further opportunities for inter-active professional association and networking.
- The SAIMM is registered with ECSA as a Voluntary Association and all SAIMM members qualify for discounted ECSA fees as a result of their SAIMM membership.
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The Southern African Institute of Mining and Metallurgy
Fifth Floor, Chamber of Mines Building
5 Hollard Street, Johannesburg 2001
P.O. Box 61127, Marshalltown 2107
Telephone (011) 834-1273/7
Fax (011) 838-5923 or (011) 833-8156
E-mail: journal@saimm.co.za

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Jacqui E′ Silva on Tel: (011) 834-1273 • email: jacqui@saimm.co.za or
Naomi Wernecke: Membership Administrator
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SAIMM
THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY
120 YEARS OF TECHNICAL EXCELLENCE

Journal Comment

A Southern African Silver Anniversary

2014 SOMP Annual Meeting

If it was not for the vision of the founder member of the Society of Mining Professors, Professor Günter Fettweis, the International Society of Mining Professors would not have been possible as it stands today. A group of mining professors under the guidance of Professor Fettweiss gathered on 21 October 1990 at the Montanuniversität in Leoben, Austria to establish the Society of Mining Professors. The first ever international scientific society had been the *Societät der Bergbaukunde* formed in 1762 in Schemnitz (Banska, Stiavnica, now Slovakia). In memory of this scientific society, it was agreed that the German name would be retained and that the English version, the Society of Mining Professors, would be used in conjunction with it. The first elected President of the Society was Professor Gunnar Almgren, of Luleå, Sweden, and the first Secretary General was Professor Tim Shaw of the then Royal School of Mines in London.

The mission of the Society of Mining Professors/Societät der Bergbaukunde is to be a vibrant society that represents the global academic mining community and is committed to making a significant contribution to the future of the minerals disciplines. The main goal of the Society is to guarantee the scientific, technical, academic, and professional knowledge that is required to ensure a sustainable supply of minerals for mankind. The Society facilitates information exchange, research and teaching partnerships, and other collaborative activities among its members and has been doing so for the last 25 years of its official existence. Today the Society is very well represented with more than 200 registered members from more than 70 universities in more than 40 countries and from all the continents of the world.

All lecturers in the Department of Mining Engineering at the University of Pretoria are currently members of the Society of Mining Professors and benefit from all the activities presented by the Society. The Department of Mining Engineering currently has 404 registered students, of which 337 are undergraduate students (77% Historically Disadvantaged South Africans (HDSAs), 23% white, and 29%women). It is our firm belief that our association with the Society of Mining Professors benefits our students as we are continuously comparing ourselves with acclaimed international mining institutions and their related activities. International mining education collaboration has never been more possible than at present.

A highlight of 2014 was the co-hosting of the annual International Society of Mining Professors conference in June, in conjunction with the School of Mining Engineering at the University of the Witwatersrand, with Head of Department Professor Fred Cawood. As President of the Society of Mining Professors for 2014, it was a great privilege for me to be part of this special occasion (the 25th silver anniversary celebrations of the Society), which was the first visit of the Society of Mining Professors to Africa. More than 100 delegates and their partners joined us at the end of June for a four-day event that was very well received by all our international visitors. Conferences of the Society have been held all over the world since its inception in 1990 – Europe, Australasia, the Americas, and now Africa. The South African conference was one of the biggest Society events to have been held outside of Europe. My acknowledgement and appreciation on behalf of the Society of Mining Professors to everyone that made this a great success, including all the sponsors (the Society of Mining Professors; Gold Fields; the Department of Mining, University of Johannesburg; the School of Mining Engineering at the University of the Witwatersrand; and the Department of Mining Engineering at the University of Pretoria)

The allocation of the December 2014 SAIMM Journal to the papers presented at the Society conference in 2014 is really a great step in the right direction for the Society, and I am very glad that this has been made possible. As a future initiative, all papers that are presented at the annual Society of Mining Professors conferences anywhere in the world will be used to make Society-related publications more available to the broader mining community. The cooperation of the SAIMM in this regard is hereby gratefully acknowledged.

Glückauf!

R.C.W. Webber-Youngman

Society of Mining Professors
Societät der Bergbaukunde

The Society of Mining Professors (SOMP) was established in 1990 during a special inaugural meeting hosted by the Montanuniversität in Leoben, Austria. The Society is considered the natural successor of the historic Societät der Bergbaukunde, which was formed in the early 18th century and is recognized as the world's first international scientific society. Since its inception, the Society has functioned primarily as a European entity representing senior academics in the mining engineering discipline.

At the 14th Annual General Meeting of the Society, in Milos, Greece, in 2003, a decision was taken to examine the role of the Society in global minerals education, to reassess its vision and membership guidelines, and to develop the future direction of the organization. This resulted in a plan of action to allow the Society to transform and position itself as the premier global voice of the academic minerals disciplines and to lead the effort of restructuring minerals education. These changes were adopted in 2005. Since 2005 the Society has continued to become a more international body, while not losing its European heritage and core values. In 2009 the Society met for the first time outside of Europe, travelling to Sydney, Australia for the annual meeting. Since that time, it has become standard practice to move the annual meetings regularly between Europe and elsewhere (including Peru in 2011 and South Africa in 2014). Further changes were made to the Society's Constitution and Strategic direction in 2012.

The Society is intended to be a vibrant global society, representing the majority of mining and mining-related academics. The purpose of the Society is to promote Mining Engineering as an engineering discipline, and to facilitate information exchange, research, and teaching collaboration and other collaborative activities among its members.

The vision is to be the leading international society for mining university professionals, recognized for:

- Effective networking
- Fostering collaboration and innovation in research, teaching, and learning practices
- Relevance and impact for the global mining sector and society at large.

The mission of the Society is to contribute towards a sustainable minerals supply for society through:

- Actively developing and supporting the mining engineering discipline
- Development of long-term professional relationships
- Exchanging innovative experience in teaching and learning practice
- Sharing research experience, capabilities, and future challenges
- Fostering professional career development and social awareness
- Providing timely, authoritative, and independent comments on relevant global issues

B. Hebblewhite

For this President's Corner, the Editor reminded me that this is the December edition of the *Journal*. For most of our members, December represents the time of year that celebrates the birth of Christ in the Christian calendar. Certainly, for many it is characterized by the opportunity to spend some quality time with family and friends in a spirit of comradeship and goodwill. Therefore, I would like to talk about two different things that this has brought to my mind.

Firstly, my thoughts turn to the families of the people that (hopefully) are reading these leading pages of the *Journal*. So, if you, the reader, happen to be the 'breadwinner' of the family, please make a point of passing on my words to your partners and children. It is with great sincerity that I wish to take this opportunity to acknowledge the sacrifices, commitment, and support that exists in the hearts of the families across the Southern African mining community. For their spouses and siblings, mothers and fathers, and friends and relatives who support their lives and careers in this fascinating industry. While many people say that work and home should never be mixed, I think that this is a very naive perspective on reality. The work environment and our family lives are inextricably linked at many levels. Successes and stresses at work are carried home in triumph or despair. Family milestones are celebrated at work with colleagues. This is brought into stark perspective when people are injured in the work environment or economic pressures result in mine closures and job losses.

One can look to any mining community anywhere in the world and see that it is the capacity, tenacity, and strength within the local community that fundamentally underpins the success of the mines (and in fact of all industry). So my thoughts and prayers, and those of Sandy my wife, are with you during December and January. We wish that you are able to enjoy that quality time without getting too caught up in the consumerism that tends to overtake more important values during these holidays. If you have to drive, please remember to take rest stops, be patient, and arrive at your destination safely.

My second thought is somewhat different. You are probably aware that there is a structure within the SAIMM called the Technical Programme Committees (TPCs – one for Mining and one for Metallurgy). Their function is the planning and organizing of the conferences, colloquia, and schools hosted under the banner of the Institute. Their membership changes over time, and occasionally senior members of the SAIMM are required to refresh the organizational memory within the TPCs, i.e. to explain their purpose and mandate. In addition to ongoing professional development, one critical purpose that the TPCs have is the generation of income that, in addition to membership fees, represents the leading source of funding that sustains the Institute. So, I was called upon to explain why conferences were expected to make a profit. Well, the simple answer to that question is that if they did not, (a) we would not be able to fund many of the developmental projects such as our regional branch offices or educational initiatives, and (b) all of our membership fees would increase substantially. However, some additional interesting information came out of my preparations to answer the above question for the TPCs.

Increase/decrease in conference fees over the past 5 years

Conference	Members	Non-Members
1-day	-32%	-23%
2-day	-11%	-15%
3-day	-1%	-14%

The table shows the cost of attending conferences over the past five years (2010 to 2014) for SAIMM Members and non-Members. The data represents the percentage change in cost relative to 2010. It is clear that in real terms, attendees at our one-, two-, and three-day conferences are in most cases paying substantially less in 2014 than in 2010! This is a remarkable achievement given that the quality of conferencing has improved, along with attendance, over the same period. Furthermore, on average our two-day conferences are one-third of the cost of the commercial, competitive market; and our three-day conferences are on average half the cost. This represents considerable value to our members and their employers through the ongoing professional development and networking opportunities that these events provide.

So, Happy Christmas to one and all, and enjoy your SAIMM Christmas present of many more high-value and low-cost conferences in 2015.

J.L. Porter
President, SAIMM

A NEW CHAIR IN OCCUPATIONAL HYGIENE AT WITS

The University of the Witwatersrand (Wits University) has received an investment of R15 million from Anglo American for a new research chair, to be known as the Anglo American Endowed Chair in Occupational Hygiene, in the Wits School of Public Health in the Faculty of Health Sciences.

The Chair will conduct research, and engage in other scholarly activities, with the aim of decreasing employee exposure to dust, noise, and other health hazards in mining and other industries, thereby contributing to employee wellbeing.

'The Wits School of Public Health has long been the forerunner in the country in research and postgraduate studies in occupational health. We are very proud to have been granted the funds by Anglo American for this Chair, and we are thankful that they are collaborating with us to strengthen our response to occupational hygiene, both in South Africa and Africa', said Professor Adam Habib, Wits Vice-Chancellor and Principal.

'The University's responsiveness in this important field will advance our vision as a globally competitive and locally relevant university located in the economic and social hub of Africa'.

Khanyisile Kweyama, Executive Director of Anglo American in South Africa said: 'This investment reinforces Anglo American's commitment to health and safety and to the well-being our people and communities, through partnerships with government, academia, and other stakeholders.

'Our occupational health strategy and management approach is governed by a series of standards, guidelines, and assurance processes aimed at preventing harm to our workforce. We are proud of our partnership with Wits University, which leverages the institution's leading research and teaching expertise across a wide spectrum of disciplines within the area of occupational health and hygiene. The partnership will further see a strengthening of the existing link between Anglo American and the University's mining engineering degree,' concluded Kweyama.

Occupational hygiene is the discipline of anticipation, recognition, evaluation, and control of health hazards in the workplace.

Dr Andrew Swanepoel, Senior Lecturer and Master of Public Health Occupational Hygiene Coordinator in the Wits School of Public Health, explains: 'Other examples of hazards that can be measured and controlled by occupational hygienists include airborne pollutants such as gases, fumes, noise, vibration, temperature extremes, and biological hazards such as Legionella bacteria.

'State-of-the-art equipment and systems, combined with high-level research and expert practitioners, are needed to identify, monitor, and control exposure to harmful dust, and all other mining industry-related health hazards,' said Swanepoel.

The University is well placed to conduct world-class research in occupational hygiene. For more than three decades, Wits academics from the School of Public Health, in partnership with the National Institute for Occupational Health (NIOH), have been conducting ground-breaking research on mining-related diseases.

'The new partnership with Anglo American is particularly important, as the University was founded on the School of Mining almost a century ago', said Swanepoel. 'Mining continues to play a central role in shaping the social, political, economic, and health landscape of South Africa and Africa today, where mining activities are rapidly expanding'.

'Mining and occupational hygiene and health are inseparable, and there is a severe shortage of occupational hygienists in South Africa and Africa. This, together with insufficient resources to support occupational hygiene, compromises the ability of the industry to protect and promote the health and well-being of employees', said Swanepoel.

The new Chair will build on the Wits School of Public Health's track record and strengthen occupational hygiene by increasing the number of Masters and PhD graduates, as well as postdoctoral fellows. Cutting-edge research will enhance the health and wellbeing of workers in various industries.

Over the next five years, the R15 million will:

- Establish and support a Chair in Occupational Hygiene to establish leadership in the University for this discipline. This will increase the research output for industry by developing a research programme, sourcing research funding, and enhancing curriculum development and teaching of occupational hygiene – appropriate for South Africa's and Africa's industries, with mining being prominent
- Jointly develop and present, in collaboration with Anglo American, short courses certified by Wits University to enhance the skills and knowledge of current occupational hygiene practitioners
- Further develop the Master of Public Health (MPH) in Occupational Hygiene and the training of professional occupational hygienists
- Strengthen occupational hygiene in South Africa and Africa by increasing the number of students graduating with MPH and PhD degrees, and post-doctoral students. Research supervisory capacity for occupational hygiene students will also be created
- Create African leaders in occupational hygiene through the PhD programme that will provide the leadership, knowledge, and skills to reduce hazards at the workplace and protect the health of employees
- Strengthen national and international links with occupational hygienists and related organizations, and recruit expert local and international teachers for occupational hygiene degree programmes and short courses
- Develop an integrated knowledge repository to service the occupational hygiene needs of Anglo American and the mining industry, over a wide range of parameters. Other industries will be embraced as well.

B. Zuma
Communications Officer, University of the Witwatersrand

PAPERS IN THIS EDITION

These papers have been refereed and edited according to internationally accepted standards and are accredited for rating purposes by the South African Department of Higher Education and Training

A Southern African Silver Anniversary Meeting, 2014 SOMP

These papers will be available on the SAIMM website
http://www.saimm.co.za

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Technical Note

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An evaluation of the effectiveness of teamwork, with an emphasis on peer assessment and peer review, in an introductory engineering course

by C. Daly*

Synopsis

The Faculty of Engineering at the University of New South Wales (UNSW) offers a core first-year engineering design and innovation course, ENGG1000, undertaken during the first and second semesters. This course is highly regarded in the sense that it provides an introduction to many concepts and activities that students will experience over the four-year minimum for which they are undergraduates at UNSW. Approximately 1400 students enrol in the semester 1 course across the Faculty, typically 80 of which undertake the Mining Engineering stream.

Students in teams of between six and eight design and construct a physical model to represent an aspect of their chosen discipline. For example, in 2013 the mining engineers designed and built a model dragline.

This paper concentrates a major aspect of the course – the involvement of team members in group activities and the development of the associated skills of peer assessment and peer review as the course progresses over a period of 12 weeks.

The term 'peer assessment' in this paper refers to the requirement for students to assess the design components of their peers. This course has a structured requirement in terms of how a successful design is a result of a sound design process rather than a 'try and see' approach. Each student must describe in detail the process they undertook to achieve their final design – hence the approach is independent of the discipline and/or project selected.

Peer review is a process whereby students review the contribution of their team members to the overall design. This activity encourages team involvement and interaction. The final assessment mark can be moderated by the outcome of this peer review, although it is run twice during the semester. The first 'run' is for feedback only during week six and hence no moderation is undertaken.

It was found through consultation with students and from questionnaires that both processes are well accepted and highly regarded by students, as they give them a degree of ownership of the assessment process. In addition, the processes provide rapid and relevant feedback on the progress of individual students.

Peer review and peer assessment are also considered to be very valuable tools for use in courses in succeeding years. For instance, many of the courses in mining engineering rely heavily on group assessment tasks.

Keywords

teamwork, peer assessment, peer review, Moodle, engineering design, first year.

Background

The Faculty of Engineering at the University of New South Wales (UNSW) in Sydney, the largest engineering faculty in Australia, comprises nine independent schools. These are the Graduate School of Biomedical Engineering, the School of Chemical Engineering, the School of Civil and Environmental Engineering, the School of Computer Science and Engineering, the School of Electrical Engineering and Telecommunications, the School of Mechanical and Manufacturing Engineering, the School of Mining Engineering, the School of Petroleum Engineering, and the School of Photovoltaic and Renewable Energy Engineering. The School of Materials Science and Engineering is based in the Faculty of Science but offers a similar first-year programme. Approximately 1800 undergraduate students join the Faculty each year to undertake an essentially common year comprising eight courses, including the core courses of Design, Mathematics, Physics, Computing, and Mechanics plus three electives. Most students join a discipline at the commencement of year 1; however, approximately 15% enrol in what is termed a 'Flexible First Year' where in addition the common core units, students can choose electives from any of the 10 school-based disciplines. At the completion of their first year, students must choose a discipline to commence in year 2. This approach caters for students who on entry have not decided their discipline. Dual degree programmes can also be selected, ranging in duration from 5 to 6 years but still based essentially on the common first year.

ENGG1000, Engineering Design and Innovation, is an introductory engineering design course offered twice a year. In semester 1 approximately 1400 students enrol, with around 400 in semester 2. I am currently course convenor of the faculty-wide semester 1 course. Each school provides a course co-

* *School of Mining Engineering, University of New South Wales, Sydney Australia.*

 This paper was first presented at, A Southern African Silver Anniversary, 2014 SOMP Annual Meeting, *26–30 June 2014, The Maslow Hotel, Sandton, Gauteng.*

ordinator for the design project they offer. Projects can range in size from 40 to 270 students. There are 14 projects offered by the 10 schools. The course runs centrally for the first 2 weeks and then for 10 weeks it moves to the school level.

What does ENGG1000 set out to achieve?

Many tertiary institutions offer a similar course in year 1. The value of such a course in introducing students to engineering design is well recognized. For example, the University of Queensland offers ENGG1100, which operates in a very similar manner but with slightly less numbers. However, the major difference is that the course is centrally managed for its duration rather than schools managing their own projects. This approach is advantageous from an administrative point of view, and also promotes more cross-disciplinary interaction. Students choose from a small number of projects managed centrally. In addition, students attend common lectures each week – a distinct advantage compared to UNSW where lecture theatre capacity limits this. Other examples of successes in this approach include the Multidisciplinary Design Project at the University of Twente (UT) Netherlands (Vos *et al.*, 2000) and in the USA at the University of Tennessee (Parsons and Klukken, 1995), where a similar course was developed to impart the core engineering values of being complete problem solvers, innovators, and the ability to collaborate with peers in solving a team-based problem.

The other major reason for ENGG1000 relates to personal development. The ability to function as a member of a team is today considered an almost essential requirement at university and in the workplace, especially in an engineering discipline. However students often enter year 1 of university with little or no experience of team membership (Dutson *et al.*, 1997) and can find the whole process quite daunting. However Dutson also comments that this inexperience can lead to poor leadership, poor communication and procrastination, internal conflicts *etc.* As I will show later, this does not appear to be the current case with ENGG1000. Maybe it is because the Australian high school system has changed over the past 20 years. From personal communications it appears that team and group work is quite common in Australian high schools. It could also relate to the structure of the ENGG1000 groups: a team leader is appointed who is committed to being a team leader. The appointment of senior undergraduate students as mentors, rather than academics, often means that a closer relationship develops between mentor and team members not only due to the similarity in age, but mentors are seen as colleagues rather than lecturers. However this does not mean that issues and conflicts do not arise. They do, but from my experience in limited numbers and often relating to group members having commitments that limit the time they can devote to their project. All team meetings are scheduled at mutually convenient times so that team members should be able to attend.

In addition, a very successful outcome of this approach to experiential learning is the wealth of feedback that is available from team interaction, from the peer assessment, and the peer review tasks (McAlpine and Reidsema, 2007). It has always been recognized that feedback to students is an essential aspect of the learning process, but is something we do not do well.

Learning outcomes and accomplishments

The learning outcomes of this course are quite extensive and include the requirement that students:

- Be familiar with the process of engineering design and the use of design methods for defining an open-ended design problem, generating alternative conceptual solutions, evaluating these solutions, and implementing them
- Understand the basic elements of project management and be able to plan and schedule work activities in accordance with standard practice
- Understand the dynamics of collaborative teams and how to work effectively within a team to accomplish tasks within given deadlines
- Be able to organize, conduct, and record engineering meetings
- Be able to effectively convey thoughts and ideas in an engineering design report
- Be able to understand the issues of quality, safety, diversity, and equal opportunity as they apply to university and professional life
- Understand the roles and responsibilities of a professional engineer.

Learning outcomes and the assessment framework

ENGG1000 has been designed to ensure there is equivalence and alignment between the implementation of the course by the various schools. Each school operates within an agreed framework of learning outcomes as indicated in Table I. The

Table I

Flexibility of learning outcomes within schools

Learning outcomes	Weighting
Development of engineering design skills for creative solutions to open-ended problems	30%–50%
Communication skills in technical report writing, graphical communications, and experience in public presentations.	30%–50%
The development of teamwork and project management skills.	10%–30%
Information gathering and evaluation skills to support the design process	10%–30%
School-selected discipline knowledge component	0–20%

course convenor provides administrative support to each school, which is able to modify its offering up to a maximum of 20% in line with the school's own preferences or expertise.

After completing one week of introductory classes, students select one of 14 projects offered across the Faculty. Students are encouraged to choose a project outside their selected discipline. For example, a Civil Engineering student could choose the mining project and a Mining Engineering student the civil project. A cross-discipline approach is quite appropriate to this type of course and also provides a basic experience of another discipline, which is particularly important for students enrolled in the flexible first year and who are required to make a discipline selection at the end of year 1.

From the above it is clear that this course emphasizes teamwork, communication skills, and an introduction to what engineering is all about. Irrespective of the project chosen, these skills are developed and each student is able to easily change disciplines at the completion of year 1.

Structure of the course

It is a challenge to provide an introductory or welcoming lecture to 1400 students on their first day at university. Our largest lecture theatre holds 1000 students. We have experimented with a few ways of lecturing to all students at one time. One attempt involved the video distribution of the main live lecture to other locations on campus. This entailed many challenges, including technical issues, and was used only once. Such an approach distances the student from the presenter.

As a potential solution in 2013, two theatres that hold 1000 and 500 students at the same time were used. This approach meant the duplicating of the material presented. For example, I would take the larger lecture and a colleague would take the other using exactly same Powerpoint slides. Students were required to enrol in one of two classes with associated locations to ensuring not all arrived at the same venue. Overall, this was quite a satisfactory approach and will be used again.

The first challenge – impromptu design

The overall philosophy of Engineering Design and Innovation is to generate scenarios in which students must work together in small teams with the ultimate aim of not only producing quality group submissions, but also to gain experience in working together and becoming comfortable with assessing the quality of their peers' work and contributions to a task.

The initiation into the basics of teamwork to achieve a common goal commences in week 1 with an impromptu design exercise. This task requires all 1400 students to be involved. A three-hour period is set aside and 30 classrooms booked. There are 700 places available for one hour to create a design and then to demonstrate the design to a judging panel. Students work in groups of eight. The groups form spontaneously as they enter the classroom. Each classroom has two or three staff to supervise the process and present the design brief for the first time.

The design brief for semester 1, 2013 – water tower challenge

You are a team of design engineers and have been appointed by your engineering firm to prepare a bid for tender of a new multi-million dollar development being put up by 'Sydney Power'. The development is to design a fully sustainable water tower/reservoir capable of holding a large volume of water at a high elevation, which is pumped up during day using a solar powered pump. It can be used as a back-up power source during peak energy usage times or power outages by releasing water into a lower reservoir and past a turbine. The mechanical energy from the flowing water is transferred into electrical energy and diverted back into the main power grid. This is important as a coal-fired power station requires around a week's notice to adjust its power output to meet demand.

To design and build a scale model (1:100) of the water tower structure capable of supporting/holding 100 marbles (water) for 10 seconds. Your aim is to build the tallest structure in order to produce the most potential power from your design. Emphasis will be placed on an innovative design, the aesthetics of the design and the overall performance of the structure under loading. Be aware that your tower must have some way to hold the marbles. The tallest tower to support the most marbles for the specified time wins!!'

Figures 1 and 2 represent a typical group working on building the tower from a range of 'materials' provided. Figure 1 shows the materials provided including paper cups, drinking straws, 'paddle pop' sticks *etc*. Each team is provided with the same materials and project specification.

A brief online survey was held after the completion of the task, in which students were asked to rate their experience. The responses (Figures 3 and 4) are quite positive. The day is hectic and there are always challenges. One of the main issues is that despite considerable reinforcement, students still do not know where to go on the day. This means that some students are often late, and timing is very important as they only have 50 minutes to complete the task. Another issue has been congestion at the testing 'station' due to the number of teams arriving simultaneously to be assessed. Next time we will arrange for more assessors.

Team Builder

Once all students have selected their project, most schools then require access to a Moodle application – Team Builder. This application is basically a very brief survey – it asks questions relating to an individual's experience with hand tools, teamwork experience, interest in being team leader, writing ability *etc*. The resulting data is used to create groups that have an appropriate mix of skills. This approach is regarded an improvement over the more common random assignment of students to groups. Hence by the second class of week 2 all students are assigned to groups and are asked to meet. When students arrive at this class they are moved into their groups and a mentor is assigned. A mentor is typically a senior undergraduate student who is paid an hourly rate and meets with their group for an hour or two each week.

Figure 1—The design phase

Figure 2—The winners

Mentors are appointed to act as guides during the design process. They are not meant to give suggestions or assist in the construction of the model, but provide support from their previous experience, and are able to comment on the path that the team may wish to follow and provide guidance if the group is not working well together.

A structured overview of the design process

It is widely accepted that engineering design is a systematic process of analysing the problem, creatively considering a range of potential solutions, then evaluating the solutions in relation to the requirements of the task until a final solution is reached (McAlpine and Reidsema, 2007). In ENGG1000 the design process is completed in a series of phases throughout the semester (Figure 5):

- Phase 1 Formulating the problem to identify the range of aspects of the task that may be investigated further. This leads to a statement of the design problem
- Phase 2 Conceptual design – generating a range of design concepts for solving the problem
- Phase 3 Evaluation – critique and evaluate the proposed concepts to select the best solution
- Phase 4 Detailed design – refine the solution and consider implementation issues
- Phase 5 Implementation – building and testing the design prototype.

The first three phases involve peer assessment where a student submits their own contribution to each phase. The student then self-assesses their assignment. In addition,

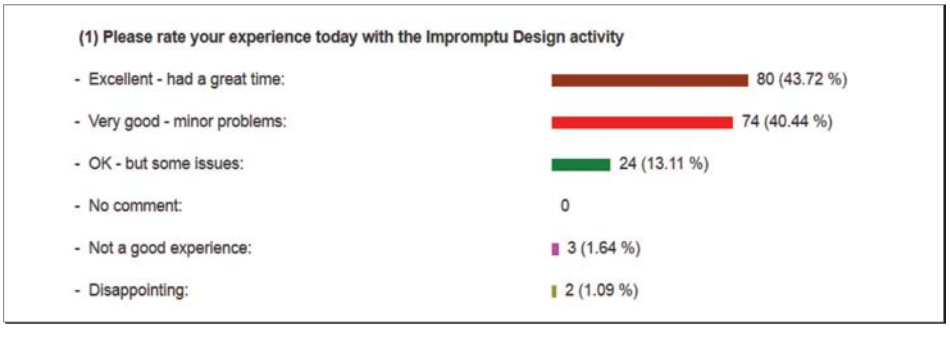

Figure 3—Feedback on the impromptu design activity

chosen feedback response
Response number: 8 (Anonymous)
(1) Please rate your experience today with the Impromptu Design activity
Excellent - had a great time
(2) What was best about the activity?
Meeting new people, interacting to solve a common problem.
(3) What didn't work very well?
Not much really.
(4) What could we do better next time?
Nothing.

Figure 4—Typical feedback from the exercise

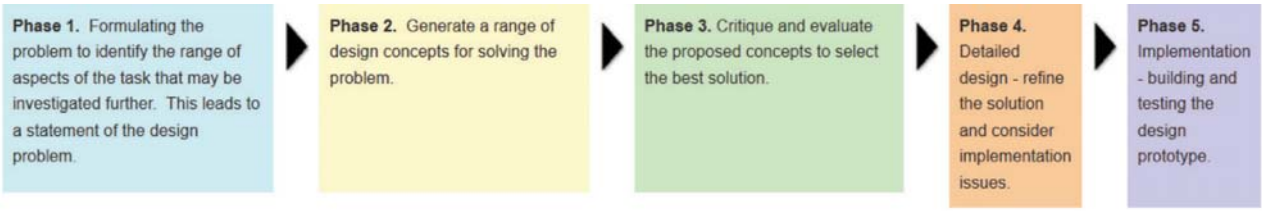

Figure 5—The phases of design – the learning portfolio

three randomly selected students assess the submission. Each phase has an assessment value of 7%, 80% of which comes from the averaged assessment of the three peer assessors and 20% from the 'effort' a student puts into the peer assessment – including feedback *etc*. The assessment stage of each phase takes approximately one week. This means that quality feedback is received quite rapidly.

Why peer assessment?

As this course progresses the active involvement of the students in the assessment increases. It becomes a very student-centred approach to design, which in many cases is quite appropriate as the course is all about exploring potential designs as well as how to achieve the selection of a final design. It is experiential learning. There is no pre-determined answer – students will reach a conclusion at the end of week 12. They will have presented a final design and gained from the experience of developing this final design. The process can be chaotic at times – individuals have their own ideas on what is a good design but it is the team's responsibility to put forward a methodically evaluated design that will have the best chance of success. The process is also staged in a way that each student must contribute to the team and to the team's project each week. There is no easy way to avoid responsibilities. The success of the project depends on the contribution of all team members. In addition, each week a student must complete a reflective diary entry via a Wiki to document their contribution for all team members to see.

This course was originally developed to provide a unique learning opportunity for students entering into the first semester of year 1 engineering. Besides this course, students enrol in more traditional courses including mathematics, physics, and an introduction to discipline course. The latter courses essentially operate by requiring individual assessment tasks to be completed. However, it was felt that more realistically, students will be required to operate in teams or groups in the later years of their studies and in their eventual workplace. ENGG1000 was planned not only to provide an introduction to the design process, but also to introduce students to teamwork and give them an understanding of the assessment process. Along with this, of course, is the added advantage of a unique opportunity for peer feedback. Lack of meaningful or timely feedback is considered one of the major concerns of students. Time-challenged academics often do not return adequate feedback to students. Often a student will gain, say, 8/10 for an assignment without any comments on why (Race, 2001).

There is considerable literature available on peer involvement in the design process – most of which is quite positive in terms of the students' and the teachers' experience. Phil Race is regarded as one of the experts in this field. Towards the end of this paper I present data gained from a recent survey of students. It is important to state that assessment is according to a rubric. A rubric is made available to all students very early in the process, allowing them to prepare their assignment along the lines of the rubric with clear knowledge that it will be self- and peer-assessed. This removes any concern or confusion over how an assignment will be assessed and at least provides the basic feedback that students will receive.

What are the advantages of peer involvement?

There are many advantages of this approach discussed in the literature, but I consider the most important being the fact that it involves the students in the whole process of completing, submitting, and reviewing an assignment. It gives them more ownership of their learning. It promotes the concept of deep learning as opposed to surface learning – reflection is basically forced on the student. It appears that students are more concerned that another student will see their work compared to their lecturer seeing it, and they undertake more effort so as not to be potentially embarrassed (Kennedy, 2005)

I feel that a major component of the peer assessment process is the associated self-assessment task that I include in all similar assessment tasks. This really requires a student to focus on their own contribution before assessing what their peers have submitted. This activity further involves students in the assessment process and hence the learning process (Gibbs and Simpson, 2004).

In addition, a student can undertake the peer assessment process in their own convenient time, in a suitable place where they can essentially spend as much time (within reason) as they wish completing the assessment task. Hence I really see the advantage of the online assessment process as opposed to a more public class-based environment. From my experience, students in an online environment give thoughtful and detailed feedback because it is what they would like to receive themselves. This is of course, not always the case as there are those that resist this form of participation.

The following comments highlight the strength of this approach.

From a current student:
Please give me good marks I need this omg I'm failing please help me please
And this response from a peer:
'Nice title. Unlikely to work for actual examiners, but as this is peer-assessed it's easy to see how you thought it was worth a shot. Rather than just giving you good marks though, I thought I'd be honest but fair and help explain why you might be "failing", which is probably more useful for you in the long run anyway. Results section was good. Individual work bit covered how you discerned between design ideas, however you didn't mention your design goals and how you decided which goals were the most important. Without that it's hard to tell what criteria you used to judge which designs were better than others.'

However, the detractors will say that assessment is a lecturer's responsibility, they know best and are able to assess all students independently. Students will also say that they are not able to assess. However, as I have often discovered, if the process is explained carefully and the support to undertake the assessment is provided via a rubric, students are more accepting, especially when they realize that the feedback they will receive is rapid and beneficial. It is important that the contribution towards the final assessment for the course is reasonable. I recommended and use 21% for the three phases in this course, and this is probably a maximum for this type of course.

Phase 1 as an example

The following is the information provided to the students regarding phase 1.

For this module, individually and in teams, you will develop a working problem statement that will guide your decision as you progress through the design process. There are many structured approaches to formulating the problem – a number of these approaches are described in Chapter 3 of Dym's Engineering Design textbook. In preparation for the first Learning Portfolio exercise, you will use one or more of the techniques outlined in Chapter 3. These include questioning the client (ie the authors of the project brief or their representatives) and brainstorming.
Individuals will develop problem statements along with objectives (goals) and constraints. Then teams will use techniques described in Chapter 3 to refine the tentative problem statements, resulting in one working problem statement for the team. In the Learning Portfolio entry, you will reflect on this activity.

Individual task

Read the relevant sections of the text (Section 3.1 as well as Chapter 1 and 2 if you haven't read them already). Develop your own tentative problem statement, including objectives and constraints.

Group work

1. *Present your refined problem statement to your team. Note their feedback or suggestions.*
2. *Break into a few subgroups of 2-3 and select a problem statement that was not written by a member of the subgroup. Use brainstorming or another method to refine the problem statement.*
3. *As a team, write a working problem statement. Note the date and time and put a big red box around your problem statement. Later, you can reflect on your first attempt at a problem statement.*

Be sure to note the date and time, as well as the names of the participants, for your entries.

Follow up assignment

When your team has finished the above activity you are ready to do the Phase 1 Portfolio submission detailed in the Project Plan.

- *Learning Portfolio Phase 1 submission—Length: 500 to a maximum of 800 words.*
- *Results—Write the team's problem statement.*
- *Reflection—Consider how your thoughts and ideas about the project have developed during the problem statement phase of the design project. Include the following headings in your reflection of the process.*
- *My original problem statement—Include under this heading your original statement, what you understood about the problem statement process and how effective was the way you developed your statement.*
- *Team problem statement refinement process—Include how your team went about this process and how effective the process was in helping the team members develop their ideas.*
- *What I learned about design and teamwork?—Include in your reflection:*
  - *how you think the team will approach the design problem and*
  - *what experience and ability to learn do you have that will help you to make a positive contribution to design and teamwork*

How is the student assessed?

- *Criterion 1*—Does the student clearly show a good understanding of the techniques available and explain how the technique was used to generate a problem statement?
  - No
  - Yes
- *Criterion 2*—Does the student include a description of the group's application of a recognized approach to the development of a problem statement?
  - None
  - One
  - More than one
- *Criterion 3*—How clearly does this student demonstrate an understanding of the problem statement process and the techniques as applied by the student and the group?
  - Limited understanding and application
  - Reasonable understanding and application
  - Clear understanding and application

- *Criterion 4*—Does the student appear to have learned how to contribute to the team process and how to help the team to be effective?
  - Limited understanding and application
  - Reasonable understanding and application
  - Clear understanding and application
- *Criterion 5*—Rate this text from 1 to 10. (With hindsight this could have more detail).

Typical feedback

'Overall this was an excellent portfolio as all sections were answered clearly and were direct to the point. You demonstrated a deep understanding of the problem statement, however it was too specific rather than having an 'outline' like you mentioned'.

A great advantage of this approach is that students receive very rapid feedback (usually within a few days of submission). A student's final mark is determined by the average of three assessments. The total mark for this task is 80% of the final average assessment plus a 20% component for assessing three other students. This 20% is determined by how well the assessor assessors a peer's submission compared to how well they assess three exemplar submissions previously assessed by the lecturer.

Student opinion on peer assessment

Even though 1400 students were enrolled, not all schools agreed to make use of peer assessment in this course. Of all the schools involved, only one school did not. This meant that approximately 1000 students undertook the peer review task. This was the first year it was run as a Moodle module. There were a number of technical issues as our installation of Moodle had problems handling 1000 student submissions. Technical issues always produce a bit of a negative response to an otherwise good idea. Overall I am happy how it went – I did, however, have to intervene and assess a few submissions myself. A very few students unfortunately did not take the task seriously. In addition, each school was responsible for introducing the task and presenting essentially the same introduction to the task. This did not necessarily happen as I had planned.

I received a number of responses to a brief questionnaire. Some of the more favourable responses are as follows:

*(Q7) Please provide some feedback on what you thought was good about the peer assessment exercise.**

It gave me a very good assessment of my own marking standards, allowing me to be more objective about the tasks requirements in the future.

*(Q8) Please provide some feedback on what you think we can do better next time.**

Clearer instructions; I thought that the problem statements i was reading for my exemplars were for a completely different task, and this led to confusion.

*(Q10) I am really enjoying the group work component of this course.**

Agree

There were other similar comments regarding the lack of clear explanations.

*Q7) Please provide some feedback on what you thought was good about the peer assessment exercise.**

It allowed me to gain an idea of how others approached an objective in comparison to one another and myself.

*(Q8) Please provide some feedback on what you think we can do better next time.**

Explain the purpose of peer assessment clearly.

*(Q10) I am really enjoying the group work component of this course.**

Agree

However, the group work is almost universally supported by students.

A further two responses are summarized in Figures 6 and 7.

Some more of the comments regarding the value of peer assessment need reviewing, but I feel that the response relates to a lack of information provided on this. The 'Agree' response is quite encouraging.

The final stage – peer review of student contribution

One of the major challenges with group work is in assigning individual grades from a group project. In general, not everyone contributes to the group project at the same level, or even in the same way. Trying to decide what marks to assign to individuals can be difficult – giving all the students the same mark is also not always fair. I believe that the group members are the best judges of this.

To counter the argument that 'group projects are not fair', as the course progresses to approximately halfway through the semester an exercise is undertaken to provide feedback on how group members are contributing to the task. The term

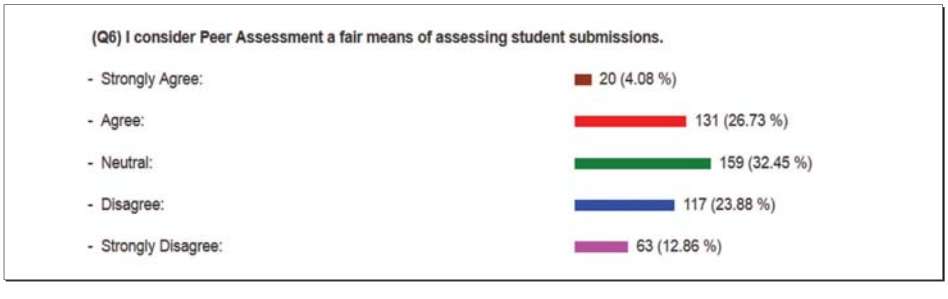

Figure 6—Student comments on peer assessment

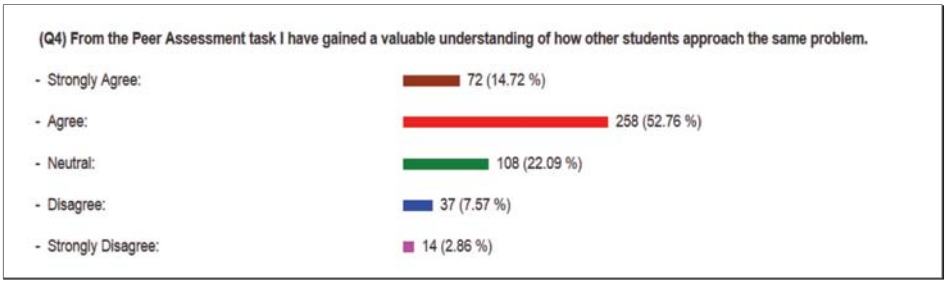

Figure 7—Student reflections on value of peer assessment

'peer review' is generally used to describe this task. The task is a formative task – it generally provides a very positive outcome for all involved, andcan be quite a morale booster. In this course I use a commercial site that promotes a specific peer review approach. SPARK^{PLUS} is a web-based self- and peer-review approach that enables students to confidentially rate their own and their peers' contributions to a team task or individual submissions (Willey and Freeman, 2006)

Students are required to rate their peers on a scale from NC (no contribution) to AA (above average) as shown in Table II.

Based on the following criteria, students use a slider scale from 0-100 to input their assessment based on the following criteria.

Rating criteria

- Efficient functioning of group – how does the team member rate in:
  - Helping the group to function well as a team?
  - Level of enthusiasm and participation ?
- Contribution to design groups
  - Did the team member attend and participate in team meetings and complete assigned tasks on schedule?
  - Was the team member dependable and reliable in doing their share of the work?
  - Was the team member effective and valuable in accomplishing tasks and assignments?
  - Did the team member take initiative to seek out tasks and responsibilities?
  - Did the team member facilitate the team process, provide valuable direction, and motivate others?
  - Did the team member help to create a positive team experience and contribute to team morale?

Once the assessment has been completed by all team members, individuals receive a score called an SPA.

SPA = SQRT(Total ratings for individual member/Average of total ratings for all team members)

An SPA of 1.0 would indicate that the team member's contribution was rated as being equal to the average contribution of the team. A major divergence from 1.0 would indicate a need for further investigation to determine if there were issues within the group.

The main use of the SPA is as an assessment moderator for a group submission. For instance, with some pre-set conditions, an individual's mark = the team mark × the individual's SPA.

In addition, the student is asked to self-assess their contribution to the project. This second score or factor that is generated is termed an SAPA. It is calculated as:

SAPA = SQRT(Self-assessment value/Average rating of all team members)

This is a powerful feedback option as it compares what the student 'thinks' their contribution is with their team members' views. Again, the ideal score is 1.0.

Once the task is completed by all students the results are released. Students are aware of the implications of the SPA and SAPA scores. Table III and Table IV indicate the results for a group of eight students. Results are not returned to students if less than four students complete the task. Table III indicates that Student 2 is performing extremely well although they may be somewhat reserved in the assessment of their own input. Table III also indicates that all students except the fourth student are contributing strongly to the task. An SPA of 0.83 is quite low and indicates that the student is not performing. However, the SAPA of 1.48 indicates that they consider they are contributing far and above what the other group members believe. Such a high

Table II

Rating options

NC	No contribution	0–4
WB	Well below average	4–28
BA	Below average	28–52
AV	Average	52–76
AA	Above average	76–100

Table III

Sample SPA and SAPA scores undertaken in week 6

SPA	SAPA
0.98	0.98
1.17	0.9
1.1	1.03
0.83	1.48
0.96	1
0.96	1.05
1.01	1
0.96	-

Table IV

Sample SPA and SAPA scores undertaken in week 12 for same group

SPA	SAPA
1.02	0.97
1.05	0.94
1.01	1.05
1	1.04
0.99	1.07
0.97	1.1
0.99	0.9
0.97	1.17

score could also indicate the student has just selected 100% in all categories. This student would be interviewed if the SPA was to be used as a moderator.

The feedback given by team members may also help to explain the SPA of 0.83. The team is concerned regarding the lack of involvement in the project.

- Good team member, although a higher attendance rate to meetings would be appreciated.
- Has made some solid contributions to the project and the design. plenty of experience
- Whilst not present at meetings, he still provided valuable insight and experience to the team environment.
- Did not come to many of the meetings.
- Seldom attends to the group meeting due to personal reason and hardly hear any valuable information from him.
- Gave effective suggestions on the project.

In addition the last line of Table III indicates that the student has not undertaken the SPARK assessment. The score of 0.96 is a result of their peers' review only.

As previously mentioned, all students see their own scores and feedback. It is expected that students will consider all comments and modify their contribution a little where needed. It is very rare that I need to talk to the group member.

Table IV represents same process undertaken in week 12 after all assessments had been completed. In comparison to the results published after week 6, the indication is that the group contributions have improved, although only slightly in some cases. It is interesting to note that student 4 has improved greatly, with their SPA increasing from 0.83 to 1.0 and their SAPA dropping to a more acceptable level of 1.04. This illustrates how the peer review process is received by students. The comments below on the same student also show the change in effort that appears to have been made. All feedback is released unedited, and I believe is well accepted and obviously can be a great morale booster or an early 'wake-up call'.

- Good team member, great to work with.
- Great bloke to work with, plenty of innovative ideas and experience
- Provided a wealth of experience and advice for the team.
- Provided fantastic contributions to the group.
- Contributed a lot in building of the dragline.
- Good team member, enthusiastic and dedicated.
- Great team member always sparing much time for group given his tight schedule

Summary

The data in Table III and Table IV is taken from the 2013 offering of this course. The total cohort was 79 students in 10 groups. After week 12, 77 student SPA results were compared to those obtained after week 6. Two students had been removed as their scores were incomplete. Of the remaining 77, 24 students (31%) had a lower SPA in week 12 compared to week 6. However, the average decrease in SPA averaged only 0.05 points. I am not too concerned regarding this value as 43 (56%) students showed an increase in SPA, with 10 remaining the same. The average overall improvement in SPA was 0.035. Although it cannot be formally confirmed, I believe that the increase in student involvement is a result of the feedback gained at the end of week 6. Peer review is a powerful tool and can be a great morale builder rather than a punishment tool.

Not all courses require this process to be undertaken twice in a semester. However, in ENGG1000 it is run in week 6 as a formative exercise, and again in week 12. The SPA value from week 12 is used as a moderator of a student's mark. This generally works quite well. However, situations have arisen where a student receives a very low score, or very high score that could return a final mark of greater than 100%. Typically, in each course outline made available to students before commencement of the course a limit is advised. For example SPAs are limited to between 0.90 and 1.10 in the case of ENGG1000. If a score is outside these limits I would meet with the student to discuss the issues and determine if there were any extenuating circumstances. In cases where the SPA is very low I find that other individual assessments are often completed poorly and receiving similar SPAs from other group work. This is a good indicator that the student is not coping well with the workload, and the student is encouraged to discuss their progress with a staff member.

Peer review of group work contributions has been a major component of UNSW mining courses for a number of years. Overall, I feel that peer review overcomes some of the traditional issues with group work, particularly being able to determine the contribution of an individual to an assessment task. So often group members receive the group mark, which is not always appropriate. This often promotes discontent within the group and engenders a clear reluctance to undertake further group work assignments.

A clear advantage of introducing peer review and peer assessment in a year 1 course is that students become accustomed to using both approaches in later years, when they become more important.

Conclusions

This paper set out to describe initiatives trialled and present some of the challenges of continually developing and managing a course for 1400 students with a strong emphasis

on group work and peer interaction, which is uncommon in a typical year 1 course. The main challenges included the process of working together as a team. Many, if not most, students would have had little experience with working in a team and hence the transition to this type of non-individual study can be quite confusing, challenging, and even confronting when students have to work together in a small team to produce an outcome. In addition, the members of the team are required to provide feedback to their team colleagues on the quality of assessable material submitted as well as on commitment to the process of completing it.

I have shown that, overall, the process is a success. Students gain a lot from the experience. However, there are issues that need to be addressed. We need to ensure that students understand the reasons for peer assessment, that they are comfortable with the process, know how to give feedback, are comfortable with assessing another students' submission, and know how to comment on the level of involvement of colleagues in the process. We need to work at showing students that group projects are fair and are a common approach across many courses in engineering.

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The Sasol Engineering Leadership Academy

(Part of the Sasol Chair in Safety Health and Environment initiative in the Department of Mining Engineering, University of Pretoria)

by C. Knobbs*, E. Gerryts*, T. Kagogo*, and M. Neser*

Synopsis

Contrary to the way it is often portrayed, the average organization or company is far from being a cold, calculating machine. It is actually a highly emotive place where interaction with people is a fundamental part of its ability to perform satisfactorily.

The company, through its employers, expects employees, including new graduates, to have the ability to cope adequately with this emotive environment. The graduate is frequently unable to meet this expectation because he/she has not been developed to do so. Technical knowledge is his only asset. This deficiency manifests itself in leadership shortcomings, both intrapersonal and interpersonal. Further analysis reveals a deficiency in three elements of leadership – self-awareness, oral communication, and an ability to work cooperatively in teams.

To address these three elements of leadership, Sasol Coal, a subsidiary of the big petrochemical company in South Africa, sponsored a leadership programme at the University of Pretoria for their final-year bursary students in the faculty of Engineering. This programme, the Sasol Engineering and Leadership Academy (SELA), consisted of a number of interventions designed to address the three areas of self-awareness, oral communication, and cooperative behaviour in teams. These interventions varied from an intrapersonal nature to interpersonal aspects. Psychometric assessments were followed by experiential modules dealing with the three constructs.

SELA was evaluated at the end of the year. The results showed a positive shift in the main constructs of self-awareness, communications, and cooperation. This was measured quantitatively and qualitatively. Conclusions were drawn and recommendations for improving the programme were proposed.

Keywords

leadership, self-awareness, communication, group work.

Introduction–the problem

Most engineering schools have been reluctant to get involved in developing soft/leadership skills in undergraduates, in spite of the fact that it is not possible to neatly and clinically separate technical skills from leadership skills.

Graduates leave university with an abundance of solid technical knowledge, but with low leadership indicators (as shown on psychometric assessments conducted at the beginning of their final year of study) to support this knowledge. It is not possible to function optimally as an engineer with only the technical knowledge, no matter how hard-won and vitally important it is.

As an example of these shortcomings, the Department of Mining Engineering at the University of Pretoria has assessed emotional intelligence levels and other behavioural attributes in final-year students over the past few years. The results show marked deficiencies in certain important intrapersonal and interpersonal constructs. These constructs or skills are vitally necessary in complementing technical knowledge in view of how much time an engineer spends in association with people and in forging effective working relationships. This association with people takes place from day one. The new graduate is immediately put to the test on 'people' issues, having received meagre instruction or practice in applying basic leadership skills.

Graduates go through a type of identity transition when they enter the workplace, despite having worked during their vacations at various companies. Those experiences are ephemeral – entering the workplace as a permanent employee is different. This transition from student to employee can and does cause all sorts of anxieties, justified or otherwise. According to the psychometric assessments for final-year students in the Department of Mining Engineering for the last three years, many students are not well equipped to cope with the exigencies of the real world. In particular they are confronted with people/soft issues, either in themselves or in others, that require leadership skills to resolve.

Literature survey

Griesel and Parker (2009) highlight the different positions taken by employers and the role of higher education in meeting the skills'

* *University of Pretoria, Pretoria, South Africa.*

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needs of graduates. Employers cite gaps between 'what they get' and 'what they expect' in graduates. Communications (written and oral), openness and flexibility, self-motivation and initiative, leadership ability, ability to relate to people, and teamwork are among the attributes showing the largest gaps. In an empirical study of young graduates conducted by the first author, the absence of soft (leadership) skills or poorly developed soft skills were frequently mentioned as something they would have wanted to learn at university (Knobbs, 2012).

Both employers and young engineering graduates arriving at the workplace for the first time have identified 'gaps' or 'deficiencies' in the graduates' knowledge and skills. Scott and Yates (2002) asked engineers to rate those attributes most important for success and to what extent these attributes were taught or developed at university. Principally, the gap is in 'people' skills and is a consequence of poorly developed leadership attributes, of both an intrapersonal and interpersonal nature.

Male *et al.* (2010) refer to a 'skills gap' when comparing what employees want from engineering graduates with what graduates bring to the work place They identify in their survey that the soft skills missing in undergraduate education are communications, self-management, attitude, problem solving, and teamwork. Nair *et al.* (2009) confirm this and showed that communications and interpersonal skills are the two most significant deficiencies in graduates.

Communications, responsibility, and self-confidence are the three main challenges that graduate engineers face when entering the workplace according to Baytiyeh and Naja (2012). The importance of people management skills and oral communication skills for success as an engineering manager is demonstrated by Saunders-Smits and De Graaff (2012). Their research shows that 'technical' comes last on the list of 12 attributes. For engineering specialists the reverse was the case, although communication skills featured prominently.

In their sample of early-stage chemical engineering graduates Martin *et al.* (2005) identify, through a questionnaire and interviews, several gaps, not the least of which are practical knowledge, interpersonal skills, and management/leadership. A survey of skills required for effective project management singled out six skills, four of which were soft skills – interpersonal communications, people management, team management, and problem solving; leadership skills followed close behind (Tong, 2003).

Martin *et al.* (2005) investigated non-technical competencies such as communications, teamwork, life-long learning, and attitude among chemical engineering graduates. The graduates stated that they had acquired good general communications skills from their undergraduate education. Interpersonal skills were highlighted and seen as the vital link between communications and teamwork. On the matter of teamwork they were divided as to whether the university had prepared them well. The graduates in the survey declared that the university had not prepared them adequately for leadership roles. In another report from the aerospace industry, communications and the ability to function in teams were highlighted as part of what the broad engineering education should include (McMasters, 2003).

Sageev and Romanowski (2001) concentrated on technical communications among graduates who had attended a course on this subject as undergraduates. They recommended that communications should be made an integral part of the engineering degree. The graduates said that communication skills had helped to advance their careers. Oral presentations, group discussions, and persuasive language were all stressed as important elements in their technical communications programme. The programme was roundly endorsed by the workplace, which gave its input into promoting, advancing, and improving the course.

Oral communications are recognized as a major attribute for practicing engineers, who spend much time in discussion and conversation (Darling and Dannels, 2003). This study of practising engineers reported on the types of communication and the audiences that engineers have to deal with. The environment was succinctly described as an 'oral culture'. A programme to teach communication, leadership, and teamwork was instituted at the University of Tennessee in response to calls from industry employers and engineering educators. Assessment of the efficacy is done by means of a peer evaluation survey, with plans to introduce a longitudinal study measuring behavioural changes (Seat *et al.*, 2001). This is another example of where teaching skills (as opposed to inculcating knowledge) and improving self-awareness is a precursor to developing or influencing leadership capabilities.

A major survey conducted by the National Academy of Engineers (2005) refers to a number of attributes that engineers should display to be truly successful. These attributes are accredited by the Engineering Council of South Africa and are listed as follows:

1. Strong analytical skills
2. Practical ingenuity
3. Creativity
4. Communication
5. Business and management principles
6. Leadership
7. High ethical standards and a strong sense of professionalism
8. Dynamism, agility, resilience, and flexibility
9. Life-long learners.

Motivation

The workplace can be a harsh environment when requirements for assimilation and success, as seen by employers, are not fully met by the knowledge and skills that young graduates bring to the company straight from university. Apart from a dearth of practical engineering experience, students lack soft skills/leadership acumen and the ability to deal with the people issues that arise in the workplace. This can lead to unhappiness and frustration affecting their incorporation into the culture of the company and their ability to make meaningful contributions and to advance their careers. It is postulated that this lack of leadership skills, principally self-awareness, communications, and cooperation (working in groups) is a gap in their toolbox and its significance is recognized by employers and graduates alike.

These identified deficiencies or gaps hamper the graduates' ability to assimilate and to adapt to life in the 'real world'. Furthermore, they can cause anxiety and frustration, and even thwart their career advancement. The ability to

adapt successfully affects retention and motivation, and can be a serious problem in some sectors of the industry. Sometimes, traumatic entry into the workplace causes young graduates to seek their fortune elsewhere. And if they are fortunate enough to be appointed or considered for an appointment as a supervisor early in their careers, they are often ill-equipped to take the position. Early intervention to develop leadership skills is needed.

In the opinion of the first author it seems reasonable, if not essential, to equip these young engineers with the necessary fundamentals of leadership to make their entry into the workplace less traumatic and equip them to perform adequately. It is postulated that these fundamentals of leadership, be they intrapersonal or interpersonal skills, can be developed by concentrating on the three leadership constructs of self-awareness, oral communication skills, and group co-operation skills.

According to Yorke and Knight (2006) employability is influenced by four interrelated components, namely: skills (communications, management of time and self, problem-solving, and life-long learning); a field of knowledge; identity and self-worth; and meta-cognition (self-awareness and reflection).

Objectives

SELA's main objective is to instil enhanced leadership skills into a group of final-year engineering undergraduates. Self-awareness, oral communications, and working co-operatively in groups were selected as the main 'drivers' of this leadership development programme. Changes in these three elements were measured qualitatively and quantitatively.

The model in Figure 1 illustrates the structure of the leadership problem and how SELA addressed this:

Methodology

Data was collected at the beginning of the programme in February by means of three psychometric instruments – *Shadowmatch* (habits and behaviour), *EQi* (emotional intelligence), and *HBDI* (thinking styles). SELA consisted of 32 students, mostly final-year undergraduates with SASOL bursaries. They came from a number of different departments in the Engineering (EBIT) faculty, with the largest group from chemical and mining engineering. This multidisciplinary composition of the participants proved to be one of the real boons of the course.

To measure the possible change in self-awareness, communications, and working cooperatively within small groups, a mixed method approach was employed. The *Shadowmatch* assessment measuring the behavioural habits of the group was administered at the beginning of the programme and again after the programme to map possible changes in the behaviour of the students. A qualitative-quantitative questionnaire was used after the course to detect the changes in perception from the students about themselves. The other two instruments, *EQi and HBDI*, were not repeated due to cost constraints.

Intervention

The philosophy adopted for the interventions in the leadership programme was driven by the Harvard model derived from the US Army officers' course of *knowing-doing-being* (see Figure 2). The *knowing* part emphasizes the cognitive domain or knowledge about leadership (least addressed in SELA). The *doing* part emphasizes behavioural aspects and essential skills leaders need – it is about learning by experience. The *being* part concentrates on the identity, character, and values of leaders. It is essentially about who they are (self-awareness).

The course was presented in eight contact modules within the full group and held on Saturdays (this was the only arrangement that could cater for the multidisciplinary

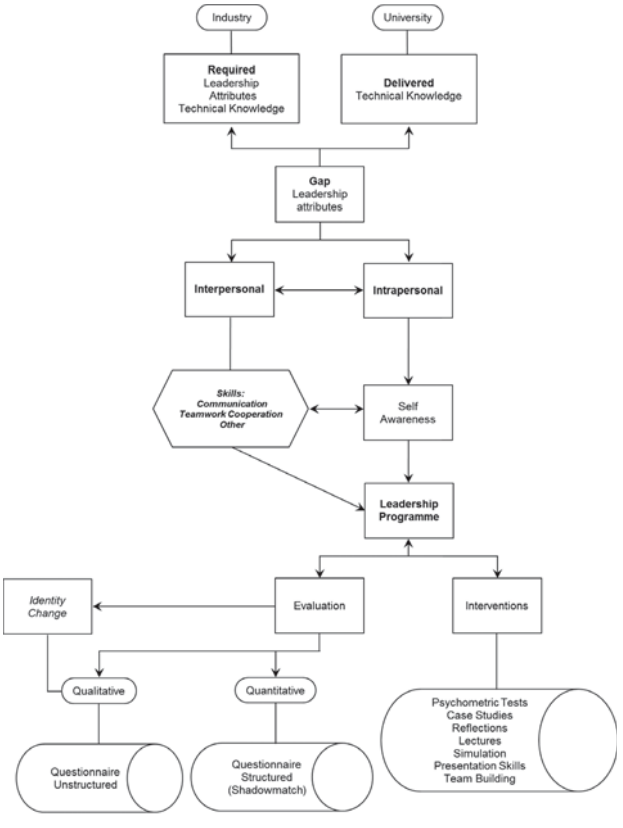

Figure 1—Bridging the gap

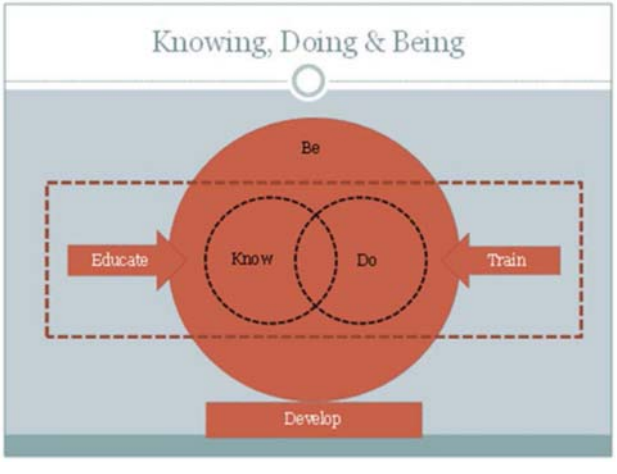

Figure 2—The Harvard Model (Snook *et al.*, 2012)

composition of the group). Appendix 1 shows the programme of modules with the various interventions. Between modules, which were approximately one month apart, case studies were examined. Smaller groups of four students were formed. These groups discussed the cases among themselves and then met with the first two authors in a coaching session. Oral communications and group collaboration were emphasized.

At these sessions, the group presented its findings and through discussion and debate students were prompted to further tease out hidden issues in the case studies that may have been overlooked. Not only were students exposed to real-life situations of human behaviour, which was instructive in itself, they were interacting as a group and experiencing all the issues associated with group performance like conflict and communications. An hour was allocated for the small group discussion and an hour for the coaching sessions.

Groups were changed after every two modules to give everyone an opportunity to interact with as many of their fellow students as possible. This practice mimics the situation in real life, where an individual will probably be a member of more than one group and may find himself moved from one team to another frequently.

Module 1 concentrated on the completion of three assessments, which were done in a computer laboratory on campus. The assessments used were the Herrmann Brain Dominance Instrument (*HBDI*) (Herrmann, 1996), *Shadowmatch*™(2009), and the *EQ-i* (Bar-On, 1996). These assessments were selected to assess and develop the main three constructs of focus in the leadership programme, namely self-awareness, communications, and co-operation (teamwork). *HBDI* measures individual thinking styles and lends itself to illustrating all three constructs in a useful way. *Shadowmatch* measures behavioural habits and calculates the similarity or differences in habits of people in a certain environment. *Shadowmatch* also has a team assessment functionality, which enriches teamwork in the smaller groups. *Shadowmatch* has the ability to generate individual performance programmes, which some students embraced with the help of a mentor. *EQi* was used mainly for detecting emotional self-awareness and to enhance the appreciation of emotional concepts, which students are not used to dealing with in an engineering curriculum.

Modules 2, 3, and 4 dwelt on the results of these assessments. The results were discussed with the participants, who not only learned about themselves (self-awareness) but also about their fellow students with whom they were interacting on a regular basis, and particularly when sitting in the same small groups together. By the end of module 4, students had an overview of the intrapersonal matters that made up the foundation of the self-awareness part of leadership.

The second four modules concentrated on the interpersonal aspects of leadership, starting with presentation skills, where two members of the Department of Speech and Drama were brought in as facilitators. Module 5 was spent mainly on communications and watching a case study where a jury needs to decide on the outcome of a murder case. The last module was a simulation exercise covering the controversial 'fracking' process. The small groups represented different stakeholders negotiating fracking in the South African context.

Reflection

Writing reflections is an integral part of leadership development, and commentary on the facets of self-awareness, oral communication, and cooperation in the programme was encouraged. The connection between leadership and personal reflection is intended 'to maximise individual potential by allowing students to evaluate the significance of their experiences from a leadership perspective' (Densten and Gray, 2001). Students were encouraged to reflect on how they felt about the programme after each module and to critically explore their feelings and thoughts in a confidential written document of no more than one page. The facilitators made comments and suggestions before returning the reflection paper to each student.

Some students wrote reflection papers regularly, expressing discovery or anxieties aroused by the programme. Some students wrote sporadically, a few never wrote at all. The multidisciplinary composition of the participants proved to be one of the real virtues of the course according to participants.

Results

SELA's objectives of improving, understanding, and developing skills in the main three tenets of leadership were measured qualitatively and quantitatively through a questionnaire. The questionnaire was used to evaluate the students' perceptions of the changes in self-awareness, communication skills, and their skill in working in small groups. Participants completed a comprehensive questionnaire and the *Shadowmatch* assessment was repeated at the end of SELA.

Qualitative: unstructured questions in questionnaire

Students rated the enjoyment and efficacy of each intervention. Clearly some interventions were not as highly regarded as others. The case studies proved to be difficult for many of the participants, who as engineering students were seeking more structure and solid solutions to the problems unveiled in the case. There seemed to be a measure of discomfort in examining 'messy' human behaviour issues. This probably accounts for the low rating given to case studies as an intervention.

The unstructured questions solicited many comments, too numerous to mention in total. The following comments are samples of some of the questions and statements made by the participants:

Question 2. What aspects of the course did you enjoy?

Students answered this question in favour of group work, being able to learn about and practice presentations, and the opportunity to meet and interact with people they did not know. Quoted samples of some of the reactions were:

'Being forced to work in groups and presenting part of a case study'

'Meeting and learning about new people'.

Question 3. What aspects of the course did you not enjoy?

In some cases, students found it challenging to balance time for studies with the contact time to attend monthly meeting, especially at the end of the year as final-year projects had to be handed in. Quoted examples of their feedback regarding this question were:

'Occasional inability to contact and meet with group members'

'Time-consuming in relation to studies and projects that need to be done for the University'.

Question 4. What topics should be added to the course?

Students mentioned that they wanted more theory on the subject of leadership. Several students also mentioned aspirations to reach out into the community to apply what they had learnt on the programme. Some examples of their feedback were:

'More role-play to practise handling conflict and workplace meetings'

'Community group work to learn how to interact with engineers in a public environment and not only on campus'.

Question 5. What topics should be removed (or modified) from the course?

No strong trend could be detected, except for a request to change the selection of case studies. Some of the feedback from students was:

'The selection of case studies'

'Have more debates than presentations'

'Reduce reading material'.

Question 6. What else can be done to improve the course?

Several comments were received from individuals on this question, but the only repeated suggestion for improving the course was to involve more people from other engineering disciplines.

'Encourage more people to attend the course who are not necessarily Sasol bursars'.

Question 14. What else do you want to tell us about the course or yourself?

Students indicated that they enjoyed the programme, that they found it helpful personally, and that they would recommend the programme to other students. Some commented on the fact that the course was recommendable especially to engineering students because of the skills and views presented. It was also mentioned that the course influenced the way they interacted with others.

'Extremely useful and many engineering students would benefit from the skills and perspectives presented'

'I found out things about my personality which I did not previously know'.

Quantitative: Structured questions in questionnaire

Appendix 2 shows the responses to the structured part of the questionnaire that the students completed after the course. From those responses it is clear that students' perceptions and skills were changed by their involvement in SELA. Communications, self-awareness, and group work were the constructs in focus and the course was designed to improve knowledge and skills in these constructs.

- *Communications*—Questions 1, 2, 4, and 5 dealt with communications. Students indicated that their confidence to communicate in small and larger groups changed a lot. They perceived that their ability to effectively communicate by sharing ideas had changed significantly. Students collectively agreed that their presentation skills were enhanced through the SELA programme
- *Self-awareness*—Questions 3, 7, and 10 dealt with self-awareness. Students indicated that their self-awareness changed a lot and that the assessments done in the SELA programme helped them to understand themselves better. Students also indicated that their personal sense of self was enhanced through the interaction with fellow students and the facilitators in SELA
- *Group work*—Questions 6, 8, and 9 dealt with groups and teamwork. Students specified that their perceptions of interpersonal skills were enhanced through the intervention. The assessments proved to be helpful to students in understanding other people and fellow students. Most students indicated that even as engineering students they enjoyed working in small groups.

Shadowmatch results

As mentioned previously, students completed the *Shadowmatch* worksheet before the SELA interventions started in February 2013 and again after the interventions in October 2013. The average of the full group on each habit was calculated on both occasions and compared in order to calculate the biggest differences on each habit (see Appendix 3). *Shadowmatch* measures 25 different habits. The group showed significant changes in the following habits (see Figure 3).

Responsiveness is the individual's reaction speed, in other words the habit of acting immediately if and when necessary (De Villiers, 2009). The average profile of students showed a 10% increase in responsiveness. *To simplify* is the habit of breaking complex scenarios down to linear challenges that can easily be resolved (De Villiers, 2009). Students showed an 11% increase in the habit of simplification.

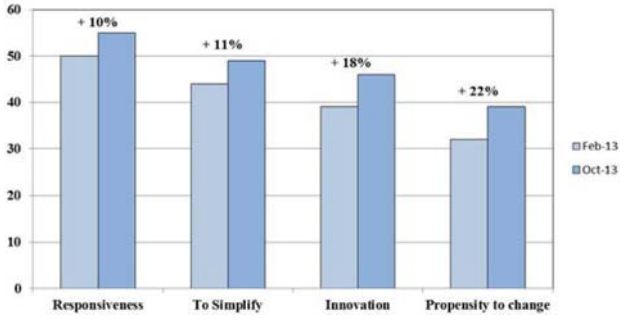

Figure 3—Most significant changes in habits according to *Shadowmatch*

The most significant shift in the habits of SELA students were on *propensity to change* and *innovation. Shadowmatch* (De Villiers, 2009) defines *propensity to change* as the habit of being comfortable with change and the ease with which an individual adapts to new and different things and environments. Students showed a 22% improvement in being comfortable with change after the interventions of SELA. *Innovation* is defined as the habit of finding new ways and identifying better processes and methods to improve on current methods of working (De Villiers, 2009). An 18% improvement in attitude towards innovation was seen in the average profiles between February and October 2013.

How do these relate to the primary objective of improving the leadership elements of self-awareness, oral communication, and cooperative group work? *Shadowmatch* constructs correlate well with some of the National Academy of Engineers (2005) attributes, as mentioned earlier, but the connection with the three elements of leadership under study is tenuous.

Conclusion

For the graduate, a smooth entry into the workplace and confidence to perform built on fundamental leadership skills and capabilities is invaluable; for the employer the graduate is likely to make a more meaningful contribution to improving the company's performance. Employers will reap the profits and individuals will boost their standing in the company. In brief:

- The responses to the questionnaire showed the strong extent to which skills associated with the three targeted facets had been enhanced by the SELA interventions
- The positive changes in the *Shadowmatch* profiles on average, particularly in respect of certain habits associated with leadership, are encouraging. The fact that so many individuals showed marked positive changes in habits/behaviour on the *Shadowmatch* results is gratifying
- Some interventions, like case studies, need to be revisited. Cases with more technical bias might engender more interest and involvement, bearing in mind that the main idea of the case is to stimulate a process of vigorous interaction in the group more than address the knowledge or content aspect of the case
- The speech and drama intervention to help with self-confidence and making presentations was highly applauded, but probably consumed too much time that could have been allocated to other interventions
- The fracking simulation was a rip-roaring success and more time needs to be found to do the intervention full justice
- Too few reflection papers were submitted and more effort needs to be put into persuading participants of the enormous value that can be gleaned from this practice.

SELA, as a pilot study, achieved the objective of showing a measurable change in the three main elements of leadership chosen for the programme. Undoubtedly, these changes can be amplified by giving careful consideration to the composition of the interventions. Shortcomings have been identified in certain interventions that could result in modifications or, indeed, replacement. Spreading SELA's wings to accommodate more students must be considered. It is abundantly apparent from surveys that there is a healthy demand from students to participate in SELA, although its continuation and expansion is dependent on time, availability of funds, and the capacity of the facilitators.

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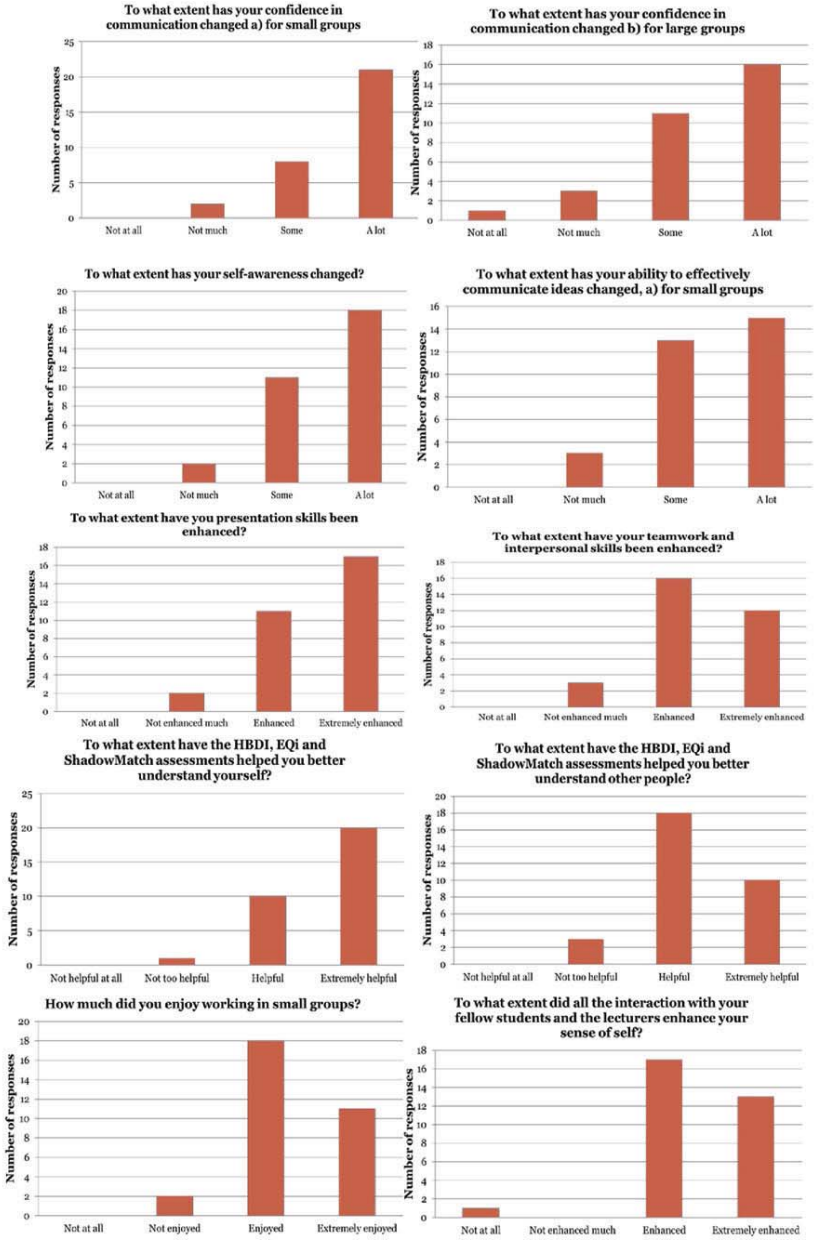
Appendix 1

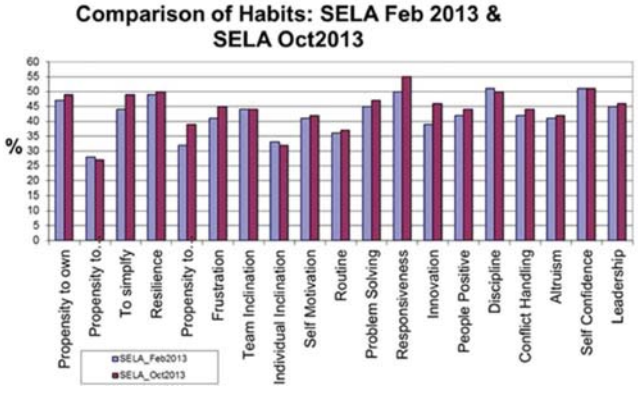
Programme of modules and interventions

SELA PROGRAMME 2013		
	Contact Times	**In between modules**
Introduction	**Module 1** Three psychometric assessments; discussion on need for non-technical skills. Groups formed.	Group work case study discussion session and coaching session.
Intrapersonal	**Module 2** Thinking preferences. Full day at Team Building Institute (TBI) Outcomes: Understanding the four quadrants of thinking preferences, your own and others (HBDI).	Group work case study discussion session and coaching session.
	Individual reflection	
	Module 3 Habits for success. Visiting lecturer (P. de Villiers). Outcomes: Understanding the significance of habits/behaviour (Shadowmatch).	Group work case study discussion session and coaching session. *Holiday in the Alps.*
	Individual reflection	
	Module 4 Emotional and social intelligence (Eli). Visiting lecturer (Prof. Maree). Outcomes: Understanding the role that emotions play in your associates' lives.	Group work: New groups case study discussion session and coaching session. *Through the Looking Glass A*
	Individual reflection	
Interpersonal	**Module 5** Presentation skills. Visiting facilitators from Speech and Drama. Outcomes: Improving your presentation and other oral skills.	Group work case study discussion session and coaching session. *Through the Looking Glass B&C* Prepare group presentation on *The Fashion Shoe Company.*
	Individual reflection	
	Module 6 Presentation skills and exercises. Visiting facilitators from Speech and Drama. Outcomes: Improving your presentation and other oral skills.	Prepare for case studies on *Twelve Angry Men* and the *Fracking* simulation
	Individual reflection	
	Module 7 Discussion on group functioning. Visiting lecturer. Outcomes: How effective groups function, particularly their handling of conflict.	Group work: New groups case study discussion session and coaching session.
	Individual reflection	
	Module 8 A simulation exercise on 'FRACKING'. Outcomes: Hands-on experience of debating and negotiating in multifarious topical issues.	
Farewell brunch gifts and Certificates		

Appendix 2
Responses to structures questions



Appendix 3
Shadowmatch results



Mine disaster and mine rescue training courses in modern academic mining engineering programmes

by H. Mischo*, J.F. Brune*, J. Weyer*, and N. Henderson*

Synopsis

The mining industry worldwide is currently facing a significant restructuring process. In most underground mines, widespread mechanization of the mining processes increases production while reducing staff numbers. At the same time, mining depths as well as the lateral spread of the mine workings are increasing. This ever-changing mining environment requires sophisticated solutions for the design and operation of underground mines. In fact, a reduced number of mining engineers is taking responsibility for ever-increasing mine operations. This applies not only to the excavation of the minerals, but also to all other aspects of the mining operation, including health and safety, disaster management, and mine rescue organization.

Most mining engineering graduates entering the industry lack experience in mine emergency management. Young engineer trainees must learn mine emergency management and rescue work in addition to their normal training experience on the job. Often, and unfortunately, emergency and rescue training at different mining companies is not carried out to the highest level and standard and with the best possible training outcomes. The tasks and challenges a young engineer faces while being trained in a new position do not leave much room for additional training in mine rescue and emergency management. At the same time, experienced, 'old hands' are retiring and cannot easily be replaced due to limited graduation numbers.

Strategies are being developed at mining universities worldwide to train mining engineering students in handling mine emergency situations and to provide hands-on experience for managing potential accident and disaster scenarios underground. Two of these strategies, from the USA and from Central Europe, are presented in this paper. These specific strategies have to be seen under special consideration of the local and regional boundary conditions, but might serve as case studies for mining schools and universities in other countries.

Keywords

mine disaster and emergency management, education and training, mine rescue training, underground education and training, student education and training, internationalization.

University mine rescue training courses at Colorado School of Mines

Industrial background

The mining industry in the USA is still a major contributor to the primary sector of the economy. In 2010, there were a total of 819 underground mines actively operating in the USA (CDC-NIOSH, 2010).

Well-established mine regulations at the federal and state levels and specialized enforcement authorities provide a high-quality legislative and organizational environment for the implementation and organization of mine rescue and emergency management. Federal regulations require each underground mine to have two mine rescue teams available while miners work underground. Small and isolated mines may share rescue teams by entering into agreements with neighbouring mines or the States. These primary rescue teams must be available on-site within 'reasonable time' following notification (US Code of Federal Regulations. 2014.

The mine rescue training programme at Colorado School of Mines

In the early 1980s, Missouri University of Science and Technology (MST) was the first to institute a university mine rescue team to prepare mining engineering students to handle mine emergency response and rescue situations. In 2009, the Colorado School of Mines (CSM) followed with its own programme. Currently (2014), eight North American mining universities operate mine rescue programmes fielding one or more mine rescue teams.

CSM currently trains three student mine rescue teams: an experienced men's team, an experienced women's team, and a co-ed team made up of first- and second-year students to allow new members to gain exposure and to be trained for the experienced teams. The first CSM team was formed in 2009, the second in 2010, and the third team in 2011. Membership in the CSM mine rescue programme is voluntary and open to students of all majors at CSM. The programme is organized and run by students, and the participating students do not

* *Technical University Bergakademie Freiberg, Freiberg, Germany.*

† *Colorado School of Mines.*

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receive school credit for their participation. Currently, the teams are made up of engineering students from nearly all major engineering courses at CSM. The only condition of membership is that the students are able to meet basic physical requirements in order to ensure the personal health and safety of the team members and of the entire team during programme activities. The student team captains design training plans together with the faculty programme coordinator. The programme's faculty advisor assists with the logistics of the trainings and helps organize practices, practice sites, equipment, tools, and supplies. Mine rescue specialists from the mining industry are often called in to help at these practices and to teach specific subjects ranging from equipment maintenance to mine ventilation, first aid, communication, and map work. The teams are organized in the same way as professional North American mine rescue teams, with each team composed of a minimum of seven members: five members in the underground team and two at the fresh air base. All team members must be trained to wear breathing apparatus and in first aid, and many members are trained as emergency medical technicians. Generally, two or more members of each team are designated technicians with expertise in equipment maintenance, while at least three members specialize in first aid. Teams are also trained in the operation of an incident command centre.

Training objectives are established at the beginning of each academic year. Practices may include full mine rescue problems, post-disaster exploration exercises in artificial smoke, technical rescue training, and specialty practices. In total, at CSM the teams practice more than 2000 man-hours per year. The overarching goal is that each rescue team and every team member can demonstrate proficiency and understand mine rescue procedures, regulations, and mine rescue rules. Training is often carried out in a two-stage approach. In the first stage, rescue teams practice in simulated mine environments installed at a surface facility. Training objectives are to execute mine rescue tasks in a simplified mine layout on surface without the obstacles and environmental conditions that rescuers would face in real underground emergencies. The surface facilities are open so that teams can see each other and instructors can observe each team member individually. Mine rescue contests (Figure 1) have been established in many locations and at various levels of competence as a way to train teams to think through specific situations and to prepare for real underground exploration exercises.

In the second stage, CSM mine rescue teams train in a real underground mine environment. These underground exercises allow teams to develop advanced team communication skills and to practice realistic mine rescue scenarios. These exercises are held at the Edgar Experimental Mine, which is operated by CSM in Idaho Springs, Colorado (Figures 2 and 3). A typical example of such underground exercise is an exploration-focused practice such as a scavenger hunt in a smoke-filled section of the mine. With limited visibility created by theatre smoke, the teams work under breathing apparatus to find and map a specified number of objects and report their exact location to the fresh air base (FAB). Teams also record air quality and damage to ventilation control equipment, roof falls, and other evidence of a fire or explosion. Team members stationed at the FAB record all observations and report them to the incident command centre (ICC). Such exercises not only test the team's ability to move and co-operate in smoke, but they are also a great tool to practice communication between the map man, the co-captain, and the FAB. Other types of mine rescue practices

Figure 1—Surface mine rescue contest at CSM

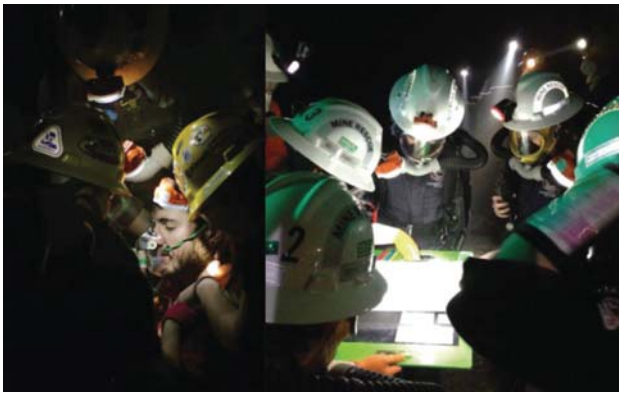

Figure 2—Student underground mine rescue exercises at CSM / Edgar Mine

Figure 3—Underground exercises at CSM

may include high- and low-angle technical rope rescue, confined space training, and firefighting both underground and at surface locations. The Edgar Mine is equipped with a confined space maze that is currently being upgraded to provide a realistic experience for navigating complex, tight spaces in smoke and for carrying out rescue missions where an injured person must be extracted. The CSM teams are also given access to a large variety of additional firefighting and medical rescue training courses held at the Edgar Experimental Mine for professional firefighters and emergency management teams from nearby cities and towns. CSM mine rescue teams also develop valuable skills in special interest areas that include first aid, mine ventilation management, and rescue equipment maintenance.

Each year, all three CSM mine rescue teams compete in professional mine rescue contests. These contests are a great opportunity for the student teams to test their skills against professional mine rescue teams and to expand their network. The contests evaluate the competitors on their knowledge of mine rescue rules and regulations, their ability to work as a team, technical understanding of their equipment, and first aid abilities. The contests are split into four sections: written test, field competition, technician competition, and first aid competition. Each section challenges a different aspect of the team's mine rescue knowledge and enables judges and trainers to easily identify areas needing improvement. All CSM teams compete in state-wide and regional mine rescue contests, and often attain top placements in competitions with professional mine rescue teams.

Every other year, the CSM mine rescue programme hosts the Biennial Intercollegiate Mine Emergency Response Development Exercise (MERD) at the Edgar Mine in Idaho Springs, Colorado (Figure 4). This competition is for student mine rescue teams only. At the most recent MERD in the spring of 2013, five rescue teams participated; three from CSM, one from the University of British Columbia in Vancouver, Canada, and one from the Missouri University of Science and Technology at Rolla, Missouri (Figure 5).

These student MERDs are a great opportunity for mining engineering students to network and learn from each other, while also obtaining advice from professional mine safety and rescue specialists. Each team is assigned a mentor, an expert in the mine rescue field, who follows the team throughout the competition and provides advice, allowing the students to learn as much from the competition as possible.

Figure 4—Student Mine Rescue Teams at MERD 2013

Professional mine rescuers bring a wealth of helpful suggestions and advice for the student teams, teaching from their real-life experiences. There are also several professional mine rescue trainers, with years of experience in the field of mine safety, who attend the student practices and competitions, mentor students, and teach classes in their areas of specialty. These experts serve as role models for the students and are a great resource throughout their collegiate career and often into their professional lives as well.

Mine rescue and mine disaster management training at the Technical University Bergakademie Freiberg

Industrial background

Due to the ongoing restructuring and simultaneous decline of the number of large underground mining operations, the mining industry in Central Europe is experiencing a steady reduction of staff numbers in the remaining mines. It is feared that the well-established, centralized mine rescue organizations may collapse within the next decade. With this, a large number of small mines and underground operations may face a lack of skilled and capable mine rescue support. New strategies and organizational efforts for sustainable mine rescue operations in Germany are currently being discussed. German federal mining law requires companies to provide suitable mine rescue coverage for their underground operations. Mines must either establish their own rescue teams or join and support centralized mine rescue organizations or rescue teams. Based on the size and number of the active underground mining operations in Germany, five central main mine rescue centres are maintained nationwide. Two of these centres are operated by the German hard coal mining industry, while the other three centres are run by the BG RCI, the employers' workman's compensation insurance association for the minerals and chemical industries. These central mine rescue centres are responsible for the education and certification of mine rescue team members and the ongoing education and training of teams and team leaders. The rescue centres are equipped with sophisticated testing equipment for maintaining and calibrating mine rescue equipment. The centres also establish guidelines and recommendations for the use of the personal protection and rescue equipment, as well as for the execution and coordination of rescue operations, and set the standards and write content for mine rescue training courses.

Figure 5—All student teams at the second MERD at Edgar Mine, 2013

In Germany, every active member of a mine rescue team must be a minimum of 18 years old and should not be older than 40. All members are volunteers, and individuals may serve as a team member, a team captain, or a chief. All members must be fully cross-trained, experienced miners who are familiar with a variety of situations underground. All rescue team members must have medical clearance under German medical standard G26/3, a specially designed, extensive medical examination under physical stress for people working under breathing apparatus. This clearance must be obtained before a rescue team member may be permitted to wear a breathing apparatus in a mine rescue operation. This thorough medical examination must be passed every second year and must also be renewed after recovering from illness or accident. The content and duration of the training for rescue team members, team captains, chiefs of rescue teams, and equipment attendants (bench technicians) are prescribed in the guidelines of the central mine rescue stations. These guidelines also govern education and training for mine rescue teams, organization and preparation of rescue operations, the minimum number of rescue teams that must be present on site before a rescue operation can commence, and a list of equipment required in order to start the rescue operation. An apprentice may become a mine rescue team member after attending a one-week basic training course and passing additional theoretical and practical examinations.

Due to the ongoing restructuring in the mining industry, some changes in the basic structures of mine rescue operations must be implemented. Generally, a minimum of three fully operational mine rescue teams must be on site to start a mine rescue operation in a non-coal mine, while ten teams must be present at a hard coal mine. Under the new structure, smaller, three-man teams maybe formed under certain circumstances at small mines to enter the mine for life-saving operations only, with a second team on standby. The new regulations, together with other restructuring elements, adapted laws, as well as modified operating schemes have been presented to the public and are expected to be implemented during the year 2014. The mining engineering department of the Technische Universität Bergakademie Freiberg (TU BAF) has been part of the restructuring programme for several years and has hosted a number of scientific conferences and workshops on the reorganization and restructuring of the mine rescue scheme in central Germany.

Mine rescue and disaster management courses at Technische Universität Bergakademie Freiberg

Occupational health and safety is a core competence for mining engineering graduates. This led to the incorporation of related course content into the mining engineering curriculum almost a century ago. Today, a specific course covers the subject not only for mining engineering students, but also for all other raw-material majors. For several decades, mining engineering students have been trained in a supplementary course in mine rescue provided by the central mine rescue station of BG RCI in Leipzig (Figure 6). During this block course, students are introduced to the structure, tasks, and responsibilities of mine rescue as well as the organization of a mine rescue operation.

The course ends with a 'hot' emergency practice under breathing apparatus in the BG RCI exercise and training centre, which resembles the confined spaces and obstacles of an underground mine (Figure 7). Like every other mine rescue team member, the students also must obtain the medical certificate G26/3 before being admitted to this course. The course was formerly a mandatory part of mining engineering education, but owing to the constraints of the European harmonization in engineering education, the legal situation now is that it can be offered on a voluntary basis only. Nevertheless, the vast majority of students participate in the training.

During a mine emergency, mining engineers often play a leading role in the organization and the technical management of the disaster instead of going underground with the mine rescue teams. To prepare engineering students for this role, a new course on incident control and

Figure 6—TU BAF mining students at BG RCI central mine rescue station

Figure 7—Confined spaces training at BGRCI central mine rescue station

management was added at TU BAF in 2012. This course is taught primarily by guest lecturers, who are also working as expert consultants in mine emergency management for the German mining industry. The course content includes incident command structures (adapted from military command structures – Figure 8), incident management, use of control and software tools, communication, organization of incident control, as well as public relations in cases with serious and fatal injuries. Students perform several practical exercises where they assume different roles managing an emergency. The role-playing exercises are designed following real incidents and include the necessary internal and external communication as well as public relations management, including press releases and press conferences. This course is mandatory for all mining engineering majors.

In 2013, staff of the mining engineering department of TU BAF had the chance to participate in the second MERD at the Colorado School of Mines as external observers. Following this exercise and close interaction and discussions with their American colleagues, a similar student mine rescue team structure has been implemented at TU BAF, making use of the 'FLB Reiche Zeche' research and experimental mine on campus (Figure 9). A member of the CSM student mine rescue team was invited to Germany and worked on an implementation project at TU BAF in the summer of 2013. The Freiberg student mine rescue team will be trained like all other professional mine rescue teams in the region and will also be outfitted with the standardized breathing and technical rescue equipment. The goal is to not only operate this mine rescue team for the training of the students, but also to support the existing mine rescue structure of the FLB experimental mine with additional forces. An extensive training space at the FLB is being modified to be used as an underground mine rescue training centre not only for mine rescuers, but also for underground and confined space training for firefighters, the federal agency for technical relief (THW), and other special rescue teams. Currently, the legal requirements for the large scale integration of a student mine rescue team into the safety and rescue structure of the mine as well as into the overall disaster control structures of the region are being discussed with the local mining authorities.

Figure 9—Mine rescue exercise at FLB Reiche Zeche research and experimental mine

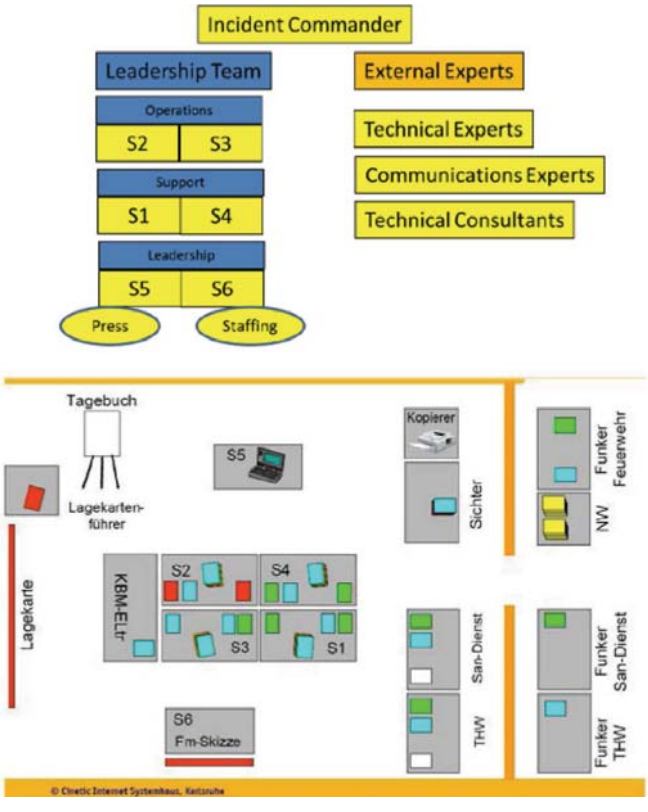

Figure 8—Incident command structure and set-up in Germany

Support and equipment for mine rescue teams

The CSM mine rescue programme receives technical and financial support from many corporate sponsors in the mining industry. Companies support the collegiate mine rescue system by providing funding for travel, donating equipment, and volunteering their time as experts and trainers. CSM mine rescue teams also frequently borrow equipment from Freeport-McMoRan's Henderson Mine Rescue Team and from the State of Colorado Front Range Mine Rescue Team. From the inception of the CSM mine rescue programme, these two organizations have provided strong support by permitting the students to use their equipment. The CSM teams are working toward acquiring all necessary gear to become independent and fully equipped mine rescue teams. During the 2012-2013 school year, the programme was successful in expanding its equipment inventory, with the donation of five new Sentinel BG-4 rebreathing apparatus sets from Dräger and a Mine ARC permanent mine refuge chamber installed in the Edgar Mine. Currently, CSM is rebuilding and expanding the training maze with a section of belt conveyor, a sound system to produce realistic sounds of equipment starting up, and sensors to monitor the rescue team operation in thick smoke.

The professional mine rescue teams from local Colorado mining companies and local fire departments are also major supporters of the CSM mine rescue programme. They volunteer their time to assist with practices and help advance the students' learning.

At TU BAF, the established annual mine rescue block course at the central mine rescue station in Leipzig is sponsored by the BGRCI. The incident management course is run by lecturers from CKK Company and sponsored by the RWE Group. The on-site mine rescue training is executed by the foremen of the Wismut GmbH mine rescue station, which still represents the core of the new Saxonian mine rescue structure. Training is supervised by their chief advisors and the CEO of the Leipzig Mine rescue station.

For mine rescue education at TU BAF and for the training of the new student mine rescue team, the Drägerwerk AG & Co. KGaA has donated a number of brand-new Dräger PSS® BG4 Plus breathing apparatus sets as well as latest-generation gas detection devices. The MSA Auer GmbH, a subsidiary of the MSA group, has donated several latest-generation gas detection devices as well as two sets of AirElite 4h breathing apparatus. These AirElite 4h units provide the same standard as all the other regional mine rescue units in Saxony, thus allowing the student mine rescue teams to be trained together with the professional mine rescue teams (Figure 10).

Figure 10—MSA Auer AirElite 4h and Dräger PSS® BG4 Plus (MSA, Dräger)

Conclusions

Student mine rescue and emergency training is a unique way to emphasize the importance of mine safety and mine emergency management to young engineers. It allows students to enter the industry with valuable skills, including recognition of safety and health hazards in mining, while providing an opportunity for professional networking. Participation in student mine rescue also benefits students from majors other than mining engineering by developing skills that lead to responsible performance under pressure, while emphasizing the importance of working as a team in the challenging environment of an underground mine rescue. Different legal and industry standards and boundary conditions in different mining regions may require specialized curricula for student mine rescue training courses.

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New systems for geological modelling—black box or best practice?

by C. Birch*

Synopsis

A 'geologically constrained' orebody model has long been hailed as vital for a Mineral Resource statement that is compliant with the South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves (SAMREC Code). In this paper, the requirements for geological modelling as contained in the outline for the SAMREC Code are considered, and whether the new modelling software available on the market is a 'black box' or is better for modelling than traditional methods of wireframe creation.

Implicit geological modelling is a technique that uses a radial basis function to establish and update geological models relatively quickly and efficiently from borehole data, outcrop data, manually interpreted vertical or horizontal sections, and structural data. Assays and any coded drill-hole data, such as lithology and alteration, can be interpolated.

Leapfrog Geo software is an example of this new approach to geological modelling. A case study of a short training course in geological modelling for non-geologists at the University of Witwatersrand, as part of the Higher Certificate in Mineral Resource Management, is presented. The benefits of this type of geological modelling software are considered for this type of assignment as well as for mining industry applications.

The use of geological models in mine planning is reviewed and a case study is presented comparing the variations in mine plan design and financial output of 13 final-year Mine Design projects from the University of the Witwatersrand School of Mining Engineering. These designs were all based on the same geological model created in the traditional way, and yet the resultant mine designs were significantly different, with very different resulting financial outlooks for the project. This raises questions as to how significant a very detailed model in the pre-feasibility and feasibility phases of projects really is, considering the huge costs involved in gathering the required data to build a SAMREC-compliant geological model.

Keywords

implicit geological modelling, mine design, software.

Introduction

This paper examines geological modelling from the perspective of a lecturer from the School of Mining Engineering with a background in Resource Geology as well as Mineral Resource Management. The questions that are raised look primarily at how geological modelling has changed recently and whether the new methods are acceptable for creating resource statements that comply with the South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves (SAMREC Code) or other international reporting codes.

The ease with which a student can be taught to do geological modelling is considered, as well as how the models that are created using implicit geological modelling software compare to those created in traditional ways. This is to answer the broad question whether the new modelling methods are just 'black boxes' or if they should be considered to be the best practice.

The paper then continues to look at mine designs and their production schedule-based discounted cash flows with the resultant net present value (NPV) and internal rate of returns (IRR). These two figures are often the numbers on which the investment decision is based, or by which projects are ranked in times of limited capital. This portion of the study was also conducted in the academic environment but was based on a real-world mine. The question was to consider how important the geological model is in the mine design, because so many other factors can also influence the final investment decision.

The School of Mining Engineering, at the University of the Witwatersrand in Johannesburg, South Africa is recognized as one of the top mining engineering schools and departments throughout the world. Mining engineers play a key role in the planning and exploitation of mineral resources. The School's programme is designed to provide the graduate with the engineering expertise that he or she will require as a mining engineer. The 4-year BSc Mining Engineering programme is the school's flagship programme and includes

* *School of Mining Engineering, University of the Witwatersrand.*

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individual and group project work. The final project is a mine design project completed during the final months of the students' undergraduate year (University of the Witwatersrand, 2013). The School also has postgraduate programmes (MSc and PhD), as well as certificate programmes in Mine Planning and Mineral Resource Management for people currently in the mining industry. This study has been conducted considering students in both their final year of the BSc Mining Engineering programme as well as students on the Mineral Resource Management Certificate programme.

Geological modelling

Geological modelling is a computerized representation of lithological, structural, geochemical, geophysical, and diamond drill-hole data on and below the Earth's surface (Fallara, *et al.*, 2006).

Geological models are based on limited data for sub-surface interpretation. They simplify the complexity found in nature. Traditionally, accuracy of the resultant models depended on the experience and training of the modeller. In mining, geological models are used to predict the presence of economic quantities of minerals, and then quantify the amount of material available. Models are nowadays a fundamental part of mine planning. Prediction has an extrapolative rather than interpolative character, and thus involves risk and leads to decision-making (Hodkiewicz, 2013).

Resource geologists traditionally favoured the use of sectionally hand-digitized wireframe models for resource estimation (*e.g.* those created with Datamine, Gemcom, or other mining software packages). Automated methods were generally not considered appropriate by those traditionally doing modelling for estimation purposes. They were looked on as 'black boxes' that allowed the computer to do the interpretation, rather than the geologist. Advances in the software available for the automatic creation of geological models (implicit geological modelling) have led to the challenging of the traditional methods. This paper considers the advantages of these new methods, and asks if they are not actually the best practice.

The modelling challenge

Traditionally, 3D models are built from isolated borehole intersections as well as other sources of information (sections, surface mapping *etc.*). Interpretation is required to fill in the gaps between the areas of certainty. The models often simplify real-world complexity due to the lack of information. Owing to the degree of interpretation required, the model builder's skill, training, as well as personality all affect the resultant model, making verification of the model very difficult. Auditing the results presented in a resource statement could thus be exceedingly difficult as the model can never be replicated exactly. The production of these models is very time-consuming, as well as costly, considering the labour costs of a skilled geologist required for this task.

The challenges in geological modelling are thus to reduce the time it takes to build these models, to represent real-world complexity, and have models that anyone can replicate for auditing purposes. As new information becomes available, the models should be easily updated to reflect the new data accurately.

The benefits to the individual scientist of improving the method of building geological models are that the hours spent doing the boring wireframing are reduced. Due to the repetitive nature of this task it is often left to junior staff. There is then more time to verify the models and interpret specific aspects which the model has not represented adequately. The throughput of models increases and thus there is more job satisfaction for staff, more publications, and increased promotional opportunities. Updating models with new information can be done as soon as it becomes available, as the model can be linked to the database and thus automatically updated as the database is amended.

The benefits to the 'client' organizations are that the models are more consistent. There is less variation between their own in-house models and those created by independent consultants. This will allow models to be easily audited for inconsistencies and errors and thus give credibility to the resource statements published. The models are created efficiently and thus are easily updated as the new data is loaded without requiring expensive and time-consuming editing of the current model. This will aid decision-making as all the data available is utilized and the model uses the latest data.

Traditional wireframing

Traditional models are created using wireframes based on geological logging of boreholes. This type of modelling is time-consuming and a good understanding of the geology is needed to make it effective. To create this type of model, the orebody is sliced into sections and the orebody intersections of the boreholes are linked by strings (Figure 1).

The method is time-consuming, and very repetitive, and relies on a fair amount of interpretation by the modeller while linking the strings. After the entire orebody has been interpreted, the strings are linked together to form the wireframes. This process must then be carefully checked to ensure there are no cross-over strings or openings as this will prevent the modelling software (*e.g.* Datamine) from filling the wireframe volumes with blocks that are needed for the evaluation, as shown in Figure 2.

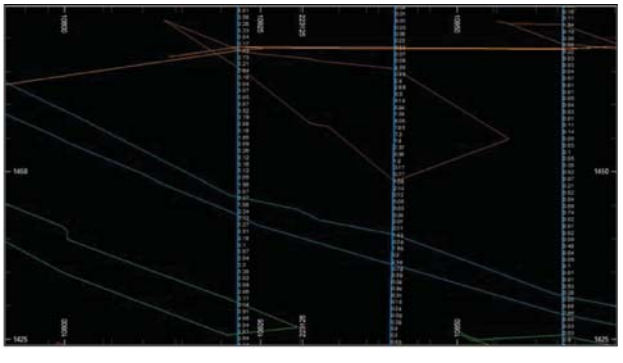

Figure 1—Section showing drill-holes with strings linking the orebodies (hand wireframing) (Birch, 2011)

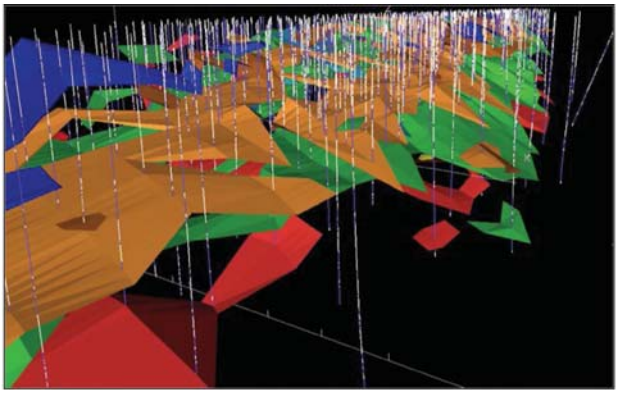

Figure 2—Datamine wireframes manually created from borehole intersections (Birch, 2011)

If the initial borehole logging was done by inexperienced geologists who interpret the geology incorrectly, the computer modelling and orebody evaluation will not be effective.

Implicit geological modelling

Implicit geological modelling is a technique that uses a radial basis function to establish and update geological models relatively quickly and efficiently from borehole data, outcrop data, manually interpreted vertical or horizontal sections, and structural data.

The radial basis function allows scattered 3D data points to be described by a single mathematical function. Models can be isotropic, meaning without any trends or directional bias, or anisotropic, based on planar, linear, or more complex structural trends. Assays and any coded drill-hole data, such as lithology and alteration, can be interpolated (Hodkiewicz, 2013).

A commonly used software package for implicit geological modelling is Leapfrog Geo (Leapfrog, 2010).

Benefits of implicit geological modelling over traditional wireframing

A comparison of implicit geological modelling and the traditional method of hand digitization is shown in Table I.

This simple comparison of the two methods illustrates that there is no basis to the claim that traditional digitization is superior to implicit geological modelling for the generation of geological models. Table II shows that implicit geological modelling methods are in fact superior to hand digitization.

In modelling of true 3D objects, such as orebodies, interpolation methods in implicit geological modelling do not rely on sectional information to produce a 3D model. This is one of the major weaknesses of traditional modelling where the 3D model is built up from a series of sectional interpretations (Cowan, 2010).

International reporting codes

Investors have become far more circumspect in investing in mineral projects following scandals like Bre-X (Cawood, 2004). This has led to the introduction of various reporting codes, which are essentially aimed at protecting investors and holding professionals responsible for the figures that they release in the public domain. Compliance with these codes is considered a prerequisite for public listing on various international stock markets like Toronto (TSX), Australia (ASX), and the Johannesburg Securities Exchange (JSE). Codes, as opposed to laws, allow for professional judgment, and a good guide as to what is acceptable is doing what a reasonable person would do. To ensure compliance with this principle, mineral resource practitioners try to follow best-practice principles as far as practically possible, because this makes it easier to justify the decisions to professional peers if called upon to do so.

There are several classification schemes worldwide, including:

- Canadian CIM classification (NI 43-101)
- Australasian Joint Ore Reserves Committee Code (JORC Code)
- South African Code for the Reporting of Mineral Resources and Mineral Reserves (SAMREC Code).

In this paper, the SAMREC Code has been used for illustration purposes, but the other codes share the same definitions and broadly follow the same requirements for compliance. Figure 3 shows the relationship between mineral occurrences, Inferred, Indicated, and Measured resources, as well as the modifying factors required to convert Resources into Reserves.

Table I

Traditional wireframing compared with implicit geological modelling

Aspect	Hand wireframing	Implicit modelling
DH contact honouring	Yes (manual)	Yes (automated)
Minimum curvature fit between points	No. Only straight lines. Curvatures are manually digitized	Yes
Modelling speed	Slow	Very fast
True 3D modelling, *i.e.* drill-hole sectional fences are not needed	No. Limited to sectional digitization	Yes. Not limited to sectional interpretation
Models can be replicated	No. Manual digitization cannot be replicated	Yes, given the same variables
Can multiple models be generated from the same data?	Yes, but not very practical as it is very time-consuming	Yes

Compliance with the SAMREC Code regarding the declaration of resources and reserves requires various aspects to be recorded and documented in a series of tables. Figure 4 is an extract from SAMREC Code Table 4, which deals with interpretation/modelling and thus is relevant for this discussion on geological modelling techniques.

Before implicit geological modelling can be accepted as a viable technique and be considered compliant with the SAMREC Code, the issue whether an automated modelling method can be considered to comply with the provisions laid out for modelling techniques as described in the SAMREC Code needs to be determined.

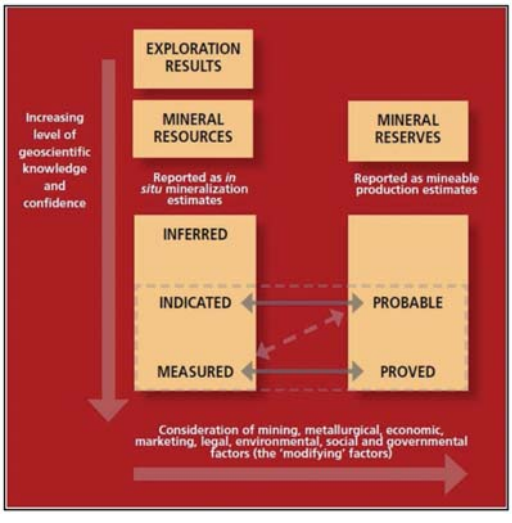

Figure 3—Relationship between Exploration Results, Mineral Resources, and Mineral Reserves (SAMREC, 2009)

Table 4 in the SAMREC Code does not prescribe what modelling technique must be used. The Code does not specify what specific methods should be used for resource estimation process, provided that the geological assumptions are clearly stated and that these assumptions are reasonably consistent with the data. It is therefore inappropriate to suggest that a certain method (e.g. sectional digitization) is more suitable than other methods of modelling (Cowan, 2010).

Modelling summary

It is felt that the benefits of implicit geological modelling include faster modelling results, allowing for quicker response to new information becoming available. This will allow the exploration team to change their exploration strategy faster and focus exploration efforts on the areas with the highest possible returns. Furthermore, compliance with SAMREC has been demonstrated using the implicit geological modelling method. Focused exploration will have an upside in the tonnage available for mining, which will benefit the client when it comes to finding investors to progress the project.

Leapfrog Geo (a well-known example of implicit geological modelling software) is, however, considered with suspicion by traditional resource geologists, who still feel more comfortable with creating wireframes manually. A method that models the orebody automatically is perceived as

T 4. INTERPRETATION/MODELLING

ASSESSMENT CRITERION: *T 4.1 Geological model and interpretation*

EXPLORATION RESULTS (A)

(i) Briefly describe the regional geology.
(ii) Describe the geological model, level of investigation (e.g. conceptual, pre-feasibility etc.) and inferences made from this model.
(iii) Discuss data density, distribution and reliability and whether the quality and quantity of information are sufficient to support statements, made or inferred, concerning the exploration target or deposit.
(iv) Reliable geological models and/or maps and cross sections that support interpretations should exist.

MINERAL RESOURCES (B)

See 4.1 B (i) to (iv).
(i) Describe the geological model, construction technique and assumptions. Discuss the sufficiency of data density to assure continuity of mineralization and geology and provide an adequate basis for the estimation and classification procedures applied.
(ii) Describe the thoroughness (precision and accuracy) with which lithological, structural, mineralogical, alteration or other geological, geotechnical and geo-metallurgical characteristics were recorded.
(iii) Discuss whether consideration was given to alternative interpretations or models and their possible effect (or potential risk) if any, on the Mineral Resource estimate.
(iv) Discuss geological discounts (e.g. magnitude, per reef, domain, etc.), applied in the model, whether applied to mineralized and/or un-mineralized material (e.g. potholes, faults, dykes, etc).

MINERAL RESERVES (C)

See 4.1 B (i) to (iv).

ASSESSMENT CRITERION: *T 4.2 Estimation and modelling techniques*

EXPLORATION RESULTS (A)

(i) If an exploration target or deposit is reported, then the estimation techniques used to determine the grade and tonnage ranges should be described in detail.

MINERAL RESOURCES (B)

(i) Describe the determination of and estimation techniques applied to volume, density, grade, size distribution, value, geotechnical, geo-hydrological, geo-metallurgical or other appropriate models (e.g. section, polygon, inverse distance, geo-statistical or other method) should be stated and justified, together with key assumptions and implications thereof, including any adjustments made to data (i.e. compositing, grade cutting / capping), sample spacing, estimation unit size (block size), selective mining units, reconciliation, domaining and maximum distance of extrapolation from data points.
(ii) Describe assumptions and justification of correlations made between variables.
(iii) Discuss the block or grid cell size in relation to the average sample spacing and any assumptions behind modelling of selective mining units (and non-linear estimation techniques if used).
(iv) Any relevant specialized computer program (software) used should be named (with the version number) together with a reference to where all the original files are stored for this specific model.
(v) State the processes of checking and validation, the comparison of model information to sample data and use of reconciliation data, and whether the Mineral Resource estimate takes account of such information.
(vi) Describe the assumptions made regarding the estimation of any by-products or deleterious elements.

MINERAL RESERVES (C)

See 4.2 B (i) to (vi).

Figure 4—Table 4 from the Samrec Code regarding interpretation/modelling (SAMREC, 2009)

a 'black box', and errors in data capturing and input will not be picked up. It is felt, however, that similar input errors can compromise the current method also, especially where the person doing the initial core logging is not skilled. Ultimately, any method must be checked, double-checked, and then independently verified.

Case study – can a non-geologist produce a valid geological model?

The School of Mining Engineering at the University of the Witwatersrand offers a Certificate in Mineral Resource Management (MRM). The MRM programme is a 2-year modular programme that was developed in close collaboration with industry and is aimed at filling a competency gap in the field of MRM. Delegates who successfully complete the programme obtain a certificate of competency in Mineral Resource Management. The programme is also a stepping stone to a postgraduate qualification at the School of Mining Engineering. Delegates may also register for specific individual modules and receive a certificate of competence in the module (University of the Witwatersrand, 2013). Not all the delegates on the programme are from a mining technical background.

Geological modelling module

The MRM 5 module is an introduction to geological modelling and students are evaluated via examination and a practical assignment using Leapfrog Geo software. The practical assignment was based on a borehole data-set from the Merensky Reef supplied by Leapfrog South Africa. Leapfrog South Africa personnel modified the data-set to include some obvious and not-so-obvious errors. The students had to validate the data and produce a geological model. They were given strict instructions regarding the colour coding and how the output was to be presented. This module was presented in September 2013 by the author.

The focus of the assessment was ascertaining that the data errors were all identified and rectified. A detailed report on these errors was required. The model also had to be compliant to the 'client' requirements regarding colours and the format of the final output files. The models created by the students were furthermore compared to the model created by the author for accuracy. Figure 5 shows the author's model.

Figure 6 shows one of the models created by a student on the MRM 5 programme. This student had no previous geological modelling experience prior to attending MRM 5, and is an employee in the legal department one of the large mining companies.

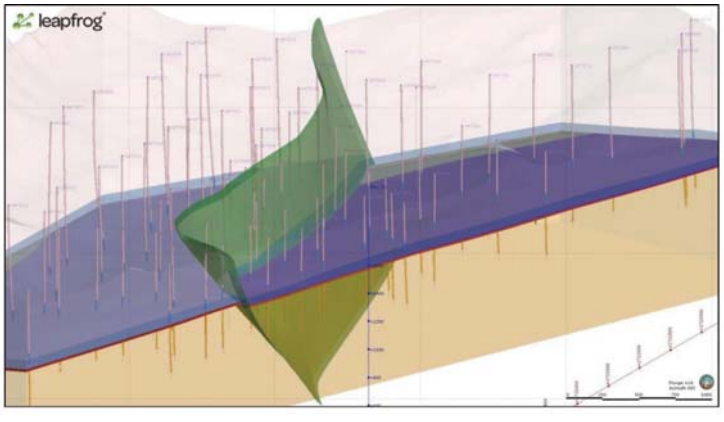

Figure 5—Model answer for MRM 5 assignment exercise (University of the Witwatersrand, 2013)

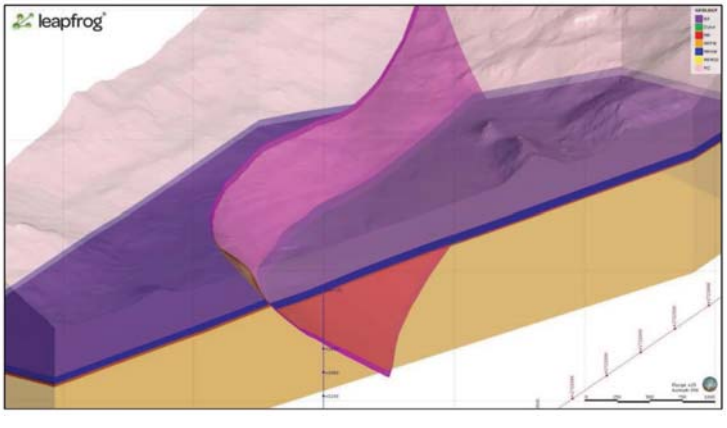

Figure 6—Answer for MRM 5 assignment by a student with no technical experience (University of the Witwatersrand, 2013)

As can be observed, all the major data errors were identified and rectified and the resultant model is visually similar to the model created by the module presenter. This type of deposit is traditionally difficult to model using traditional wireframe methods due to the very thin nature of the economic horizon. Leapfrog Geo allows the modeller to identify the age relationships between the various lithologies, and then creates the stratigraphic sequence automatically from the borehole intersections. The fault is digitized from the surface mapping and when activated, the displacement is automatically determined.

For an experienced modeller, this assignment could be completed in a very short period of time. The process followed for an entire deposit, would be the same as for this assignment, but just on a larger scale. As new data is loaded into the database, the model would be updated automatically. The most important component of the modelling process is data verification and ensuring the database is accurate. Most errors are easily identified in the model and thus the ability to quickly create a model goes a long way towards ensuring that the final model is accurate.

How important is the geological model in the mine design?

The international reporting codes require extensive documentation and compliance regarding the quality of the sample data and how it is collected, stored, and processed. This leads into the modelling and evaluation techniques used until the output of the classified resource statement is obtained. The SAMREC Code in South Africa is the guide to what is an acceptable level of detail for this statement (SAMREC, 2009). For the conversion of Mineral Resources to Mineral Reserves, the modifying factors must be stated and justified. These include the following:

- Mining methods
- Minimum mining dimensions
- Mining dilution mining method
- Mine design criteria
- Infrastructure
- Capacities
- Production schedule
- Mining efficiencies
- Grade control
- Geotechnical and hydrological considerations
- Closure plans
- Personnel requirements.

The whole scheduling aspect of a mine design is critical in converting the Mineral Resource into a monetary value due to the considerations of the time value of money (and resultant net present value, NPV, and internal rate of return, IRR).

This paper considers how assumptions made during the mine design and scheduling process can affect the financial outlook of a project at the pre-feasibility study (PFS) stage, using the School of Mining Engineering Final Mine Design Project as a case study. Thirteen groups of students were given the same geological model as a starting point for their mine designs. This model can be considered a perfect representation of the orebody for the purposes of this project, as they were not required to recreate or verify this model as part of their project. In reality, when a group of consultants do pre-feasibility studies on an orebody, each consultant would create their own geological model, which adds a whole layer of variation when comparing the results. The mine design exercise presents a fairly unique opportunity to compare 13 interpretations of the same geological model taken to PFS level. In the corporate world, due to the costs involved, a company would never commission 13 different mine designs.

Final Mine Design Project

Seventy final-year students were split into 13 groups with 5 or 6 members in each group. According to the brief given at the start of the project, the students had to carry out a mine design exercise to the level of a PFS based on the mineral deposit block model supplied to them. They were to utilize the knowledge gained over their previous coursework, as well as experience gained during vacation work, to complete the project. They then had to make a substantiated recommendation regarding the viability of mining the deposit. The financial aspects of the project were thus critical, as well as the technical aspects. For 2013, the final mine design project was the Lily Gold Mine, close to Barberton in the eastern part of South Africa.

The students were supplied with a high-quality geological block model of the deposit created by the mine geological team (Figure 7). For purposes of this study, this block model can be considered to be perfect, as they all were given the same model and accepted it as a true representation of the deposit.

Lily Gold Mine

The Lily Mine began as an open pit operation in 2000. The open pit closed down in 2008 after producing more than 100 000 ounces of gold. The orebody extends for at least 2000 m along strike and has been drilled to a depth of approximately 700 m. A detailed geological model was created by the mine and was presented to the students for their mine plan (Figure 7). The current underground mine design has been constrained due to available capital, and the students were expected to take this into account and thus come up with designs significantly different due to the removal of this constraint.

Mine Design report

The students were instructed to start their designs at the stage where the mine began underground operations and the plant had a maximum capacity of 37 000 t/month. If they wished to increase the plant capacity, they would have to budget for this increase in their mine design. The students were given the geological model as generated prior to the underground development; based on the sampling in the pit as well as the surface diamond drill-holes (Figure 7). The final report presented to the School of Mining was to cover all the aspects of a mine design and was expected to be at a level of detail that would be acceptable as a PFS. Most of the staff

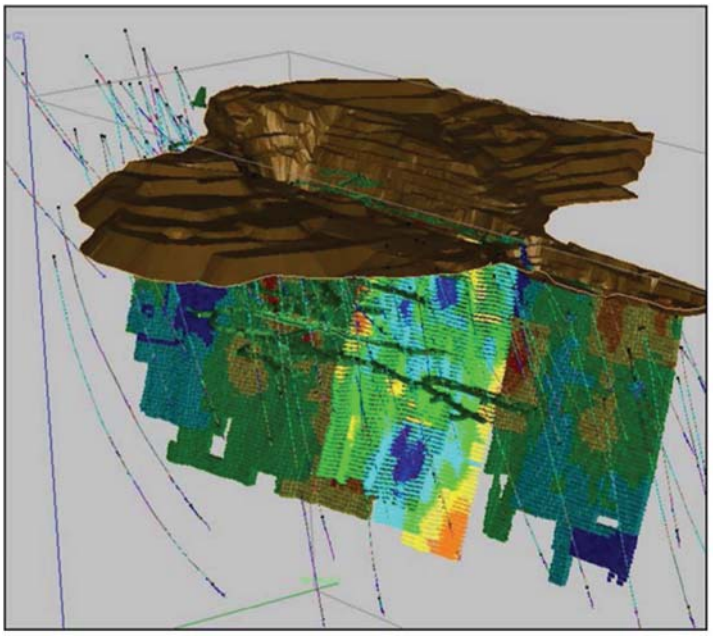

Figure 7—Lily gold mine geological model (Vantage Goldfields, 2013)

in the School were allocated specific chapters in the report and mentored the students as to what was expected to complete their chapters. They then graded those chapters as part of the final mark. The students also presented their final designs to a panel of staff members, as well as external examiners from industry. In 2013, the external examiners were staff from Lily Gold Mine.

Mine financial valuation

For this study, the variations between the mine designs and their impact on the financial valuation chapter of the report were considered. For this chapter, the students had to determine the construction/establishment times and costs, as well as operating costs for the life-of-mine. They had to determine appropriate levels and methods of beneficiation and apply the correct royalty and income tax rates. They then had to do a full cost-benefit assessment of the project, including a discounted cash flow (DCF) analysis and calculate the resultant net present value (NPV) and internal rate of return (IRR). Based on these figures, they had to make appropriate recommendations regarding investment in the project.

Results

The final financial results from the groups were very different. Only two of the groups chose to increase their planned tonnages from the mine above the current plant's maximum of 37 000 t/month. With these two groups, the capital costs for construction of the mine varied primarily with the plant costs and building extra mining capacity. The lower resultant mining costs allowed for lower cut-off grades and higher extraction rates. Some of the groups were very conservative as to how much of the measured reserve they putt into their life-of-mine plan, and all the groups restricted their designs to only the Measured portion of the Mineral Resource statement.

The mining profiles (production ramp-up and grade) were very different between the groups. The capital spending scheduling was also very different. The relationship between higher initial capital spend and a lower mining cost would be expected, but this is not always apparent when looking at the relationship between capital and working costs in these designs.

The tons mined, life-of-mine, capital costs, working costs, NPV, and IRR are shown in Table II.

The life-of-mine tonnage profiles vary from 1.7 Mt to 6.7 Mt. The life-of-mine varies from 6 to 17 years. The capital costs vary from R286 million to R1 045 million. The working costs vary from R455 to R900 per ton. The resultant NPVs range from R45 million to R581 million, and the IRR varies from 20% to 61%.

There is thus a three-fold increase from the lowest IRR to the highest, and an order of magnitude difference between the lowest and highest NPV.

Investors in mining projects often use the NPV and IRR as their primary decision-making tools. Based on the results of the exercise, potential investors would either reject this project as being too marginal (IRR of 20%) considering the current financial risks associated with mining gold in South Africa, or be very enthusiastic about the project and willing to invest (IRR greater than about 40%).

It must be noted that all the groups made errors in their projects, but they all produced designs of sufficiently high quality to pass the course. For the chapter on financial valuation, the lowest mark given was 50% and the highest was 90%. This chapter counted for 8% of the final Mine Design report mark.

Table II

Financial valuation results of the mine design project (University of the Witwatersrand, 2013)

Tons	Life of mine	Capital	Working cost (R/t)	NPV	IRR
2.7 Mt	8 years	R460 million	R600	R511 million	43%
6.2 Mt	**17 years**	R350 million	R600	R193 million	**61%**
1.7 Mt	**6 years**	R347 million	R535	R81 million	29%
6.1 Mt	12 years	R435 million	R481	R153 million	27%
4.1 Mt	11 years	R440 million	R600	R210 million	31%
5.4 Mt	13 years	R720 million	R684	R50 million	**20%**
3.9 Mt	11 years	R400 million	R492	**R581 million**	**61%**
2.6 Mt	7 years	R375 million	R595	R103 million	28%
4.6 Mt	12 years	R430 million	**R900**	R190 million	26%
6.7 Mt	11 years	**R1 045 million**	**R455**	R190 million	25%
3.8 Mt	8 years	**R268 million**	R736	R184 million	43%
4.3 Mt	10 years	R851 million	R550	**R45 million**	23%
3.7 Mt	8 years	R411 million	R695	R100 million	30%

Conclusions

New software is speeding up the geological modelling process and giving more consistent results. This allows more time to focus on interpretation and allows for faster revisions to the model. The learning curve is far quicker than for traditional modelling techniques and the skills set required to produce successful models is greatly reduced. This paper presents a case study demonstrating that a student with no previous geological experience can produce a simple model from a borehole data-set that broadly matches that produced by the lecturer, identifying a range of errors and correcting them. It has been shown that the SAMREC Code does not dictate the method that has to be used to create the model, being more focused on the correct recording and validation of the data used in the estimation of the mineral resource. It is thus felt that implicit geological modelling software like Leapfrog Geo is superior to traditional methods and should be considered best practice for geological modelling.

The SAMREC Code is very limited when it comes to specifying how the mine design is created and scheduled, which can have a major impact in the resultant NPV and IRR. All that the Code requires is that the modifying factors are documented and justified. Even a single geological model is open to huge variations in, and interpretations of, the mine design/scheduling phase, which can make or break the project's success. It has been shown that groups of student mining engineers, using the same geological model, can produce mine designs that result in significant variations in the financial outlook of the project.

Investors are often not experienced in mine design and scheduling. Even if they are satisfied with the capital and working cost stated in the design, the differences in when the capital is spent and the revenue obtained from the mining of the orebody are hard to verify. They are thus totally reliant on the experience of the mining engineer to optimize the design to ensure the highest return on the investment.

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Modelling and determining the technical efficiency of a surface coal mine supply chain

by M.D. Budeba*, J.W. Joubert*, and R.C.W. Webber-Youngman*

Synopsis

Determining the efficiency of a surface coal mine operation is an essential activity, which can help in deciding on the optimal use of input resources, including effective capital allocation, in generating a desired quantity of coal of a specific quality.

Mines operate today in challenging conditions, with diminishing reserves of high-quality coal, remote location of new coal deposits, infrastructure problems, environmental legislation, and the effects of climate. All these have an impact on the performance of a mine. Given such challenges, a company has to be technically efficient compared to other existing coal producers in order to generate profits. It can use the measurement of its efficiency to evaluate its productivity, benchmarking this against the best-performing mines and determining optimal variables in order to minimize slack and achieve the desired outputs.

This paper discusses the use of Data Envelopment Analysis (DEA) in evaluating the efficiency of a surface coal mine supply chain for the coal export market. The supply chain is considered to be composed of sub-processes that are modelled as a multistage system. Numeric examples will be used to illustrate the application of DEA.

Keywords

DEA, technical efficiency, surface coal mine.

Introduction

Coal is a fossil fuel mineral that has a variety of uses, including the generation of electricity, metallurgical applications such as steelmaking, cement manufacture, and petroleum fuel production. It contributes 25% of the world's primary energy needs, after fuel oil which contributes 35%. Thermal coal contributes about 40% of electrical energy, and it is anticipated that this will increase to 46% by 2030. The world energy demand, estimated for the period from 1990 to 2030, is growing at a cumulative annual growth rate (CAGR) of 1.7% (Schernikau, 2010). This reaffirms the need for enhanced production from existing mines, and the opening of new mines to increase the supply of coal and to meet increasing demand.

However, the demand for coal in the short term, estimated for the period from 2010 to 2016, is projected to increase by 2.8% per annum. This demand is driven mainly by the countries outside the Organisation for Economic Cooperation and Development (OECD), largely dominated by China and India. The demand for coal by China in the same period, for example, is estimated to be escalating at 5.2% per annum (IEA, 2011).

Despite the increasing demand for coal, Höök *et al.* (2010) emphasize that while coal resources are vast in many countries, the supply is affected by geology. The depletion of the more easily accessed coal could have an effect similar to the end of abundant and cheap oil. Once the more attractive coal has been depleted, extraction will become more expensive and complicated. In addition, the authors argue that coal reserves in the world are unevenly distributed. A few countries control the majority of the world's supplies, among them the USA, China, Russia, India, Indonesia, Australia, South Africa, Germany, Poland, and Kazakhstan. Together, these countries account for 93% of the world's hard coal reserves.

Coal is extracted using either surface or underground mining methods. The mine is required to be efficient and cost-effective in order to be competitive and profitable. The efficient mine is the one that uses a minimum of resources to deliver maximum output, or at least uses the same resources to produce a maximum output. Effective cost in particular is the hallmark of efficient mines. Such mines form the envelope of best practice, and can be used as a benchmark for the improvement of inefficient mines.

New and currently producing coal mines are subject to challenges that can affect their

* *Department of Mining Engineering, University of Pretoria, Pretoria, South Africa.*

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efficiency and cause uncertainties. Some of these challenges are related to the specific features of a deposit, for example coal seam thickness, and others such as remoteness, climate, environmental legislation, and the exchange rate. Shafiee, Nehring and Topal (2009) and Shafiee and Topal (2012) highlight factors such as a high stripping ratio, seams with complex metallurgical characteristics, mines located in isolated regions, lack of access roads, inadequate electricity and water supplies, unfavourable climate, and the challenges of mountain topography, all of which may cause project uncertainties. Major factors upon which management has to decide include the stripping ratio, capital allocation, choice of production rate, and the washing rate or crushing rate. All these can be divided into controllable (discretionary) or non-controllable (non-discretionary) variables. Thus mines need to be efficient and cost-effective in order to remain competitive relative to other producing mines.

Previous research in measuring the efficiency and competitiveness of surface coal mines has not considered the challenges highlighted in this paper. The available models can be considered as 'black boxes' because they do not incorporate details of supply chain sub-processes of coal for the export market. There is a need for a model that uses multiple inputs to generate multiple outputs of the whole supply chain while considering these challenges that affect the efficiency of the mine. The model will provide an insight into the competitiveness of the mine relative to other producers of coal for export

This paper applies Data Envelopment Analysis (DEA) methodology, which is a linear programming technique that is used to determine the envelope of the best practice decision-making units (DMUs). DEA was used to develop a model that can be utilized to determine the envelope of the best-practice surface coal mine, using discretionary variables and applying linear regression to determining the influence of non-discretionary variables on the efficiency score.

The numerical example of eight DMUs that were used for illustration indicated that one DMU is technically efficient, while the remaining seven are technically inefficient. These are surface mines that need improvement in order to be efficient. It was also found that distance from the port (Dist-port) and precipitation influence the efficiency score of surface coal mines.

The contribution of this work includes development and demonstration of the application of the DEA model for measuring the relative efficiency of surface coal mines supplying coal for the export market only. In addition, the paper develops an understanding of the influence of the non-discretionary variables on efficiency score for a surface coal mine, which can help the mine to determine the set of controllable variables that will increase its competitiveness relative to other producers. For example, coal mining projects can select optimum technical variables such as capital to increase their competitiveness.

A literature review on efficiency measurement is first discussed. This is followed by an explanation of the research methodology and model formulation, and the application of the models is illustrated. Finally, conclusions are drawn and suggestions offered for further research.

Literature review

The concept of efficiency has been defined by various authors. In general, it involves the relationship between the inputs and outputs of an organization or a firm. In the work of Markovits-Somogyi (2012), efficiency is defined as the capacity of a company to realize its stated objectives and to use its available resources cost-effectively. According to Joubert (2010), efficiency analysis offers guidelines and benchmarks for both public and private enterprises to achieve maximum outputs with minimum inputs.

Figure 1 shows a diagram of a producing unit that could apply to both a profitable and a non-profitable organization. Referred to as a decision-making unit (DMU), it consumes inputs and transforms them into outputs.

Efficiency can be evaluated using parametric methods, those requiring the use of production functions such as regression and stochastic frontier; and non-parametric methods, which do not require a predefined function such as DEA. Most of these are used, but DEA in particular is a robust approach compared to the other methods, for the following reasons:

- It does not require a predefined function to be specified; hence it avoids error due to mis-specification of the function
- It can be used even when there is insufficient data
- It is used to measure efficiency of a unit involving multiple inputs and outputs.

The major shortcoming of DEA is that it is sensitive to outliers, which means that the data used needs to be free from measurement errors (Kumar and Gulati, 2008). In contrast, parametric methods need more data and also require a predefined function to be specified (Markovits-Somogyi, 2012). These factors make DEA preferable to other methods for measuring the efficiency of DMUs that use similar multiple inputs to generate similar outputs.

DEA was first introduced by Charnes and Cooper in 1978 (Cooper *et al.*, 2007). It is a non-parametric method for

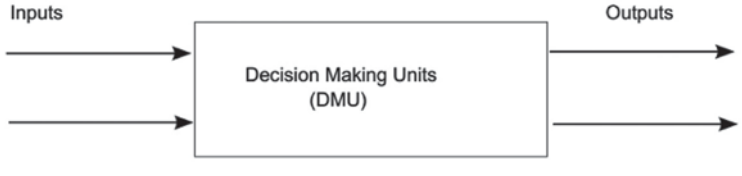

Figure 1—Decision-making unit transforming inputs into outputs (after Emmanuel, 2011)

measuring the efficiency of a DMU. DEA has been successfully applied since its introduction. For example, it has been used to evaluate the performance of various operations, including production planning, research and development, agricultural economics, airport performance, and other applications (Li *et al.*, 2012). In particular, DEA has been used in evaluating the technical efficiency of coal mines, the growth in productivity in both opencast and underground mines, and in assessing the efficiency of coal mine safety measures (Kulshreshtha and Parikh, 2002; Shu-Ming, 2011; Tong and jia Ding, 2008). All these studies, however, consider DEA as a black box. They do not indicate those details of a mine operation that could decide either the efficiency or inefficiency of the mine.

The focus of the applications of DEA in coal mines has been on the general discretionary inputs and outputs; the influences of non-discretionary inputs have not been considered. Thus most of the applications consider the inputs and outputs of a mining company without detailing the components of the production system. It is difficult to assess the required technical levels of inputs in each sub-process of the coal supply chain; hence the evaluation views the coal mine as a black box.

Data envelopment analysis for efficiency measurement

DEA is based on a linear programming method that is used to determine a set of best practices regarded as being efficient (Li *et al.*, 2012). The method is used to construct an envelope of the best-practice DMUs using similar inputs and outputs; the envelope is therefore determined by the pareto-efficient DMUs (Joubert, 2010).

The basic DEA models are those of Charnes-Cooper-Rhodes (CCR) and Banker-Charnes-Cooper (BCC) (Martić *et al.*, 2009). CCR models assume a constant return to scale (CRS), and are based on the assumption that an increase in inputs results in a proportional increase in outputs. The CCR model is used to determine the overall efficiency of a DMU. The BCC model assumes a variable return to scale (VRS), which means that the increase in inputs may result in either a lesser or greater proportional increase in outputs. The BCC model is therefore used for determining the pure technical efficiency of DMUs.

The pure technical efficiency approach measures the ability of management to utilize resources in producing outputs. CCR efficiency can be decomposed into scale efficiency and pure technical efficiency. Scale efficiency helps management to choose the optimal size of the DMU (Kumar and Gulati, 2008).

To illustrate the concept of DEA, consider a set of DMUs A, B, C, Q, and D, using a single input of resource to produce a single output (Figure 2). The DMUs A, B, C, and Q are efficient on VRS, thus forming an envelope of best-practice DMUs, while DMU D is inefficient. Based on CCR, only B is efficient, while the others are inefficient. A DMU is considered to be efficient if it has an efficiency score of 1.

Mathematical representation of basic DEA models

Consider a set $\mathbf{J} = \{1...n\}$, each member of which is considered to be a DMU using m inputs of x_{ij} for $i \in \mathbf{I}$ and generating s outputs y_{rj} for $r \in \mathbf{R}$. The weights assigned to inputs and outputs are v_i and u_r respectively. The efficiency score can therefore be defined by Equation [1] (Talluri, 2000). The efficiency of each DMU expressed in a fractional program is then transformed and solved using the linear programming method (Cooper *et al.*, 2007). The DMU under evaluation will be DMUj = o and its efficiency score is denoted by h_o.

$$\text{Efficiency} = \frac{\text{Weighted sum of outputs}}{\text{Weighted sum of inputs}} \qquad [1]$$

$$Max\ h_o = \frac{\sum_{r \in \mathbf{R}} u_r y_{ro}}{\sum_{i \in \mathbf{I}} v_i x_{io}} \qquad [2]$$

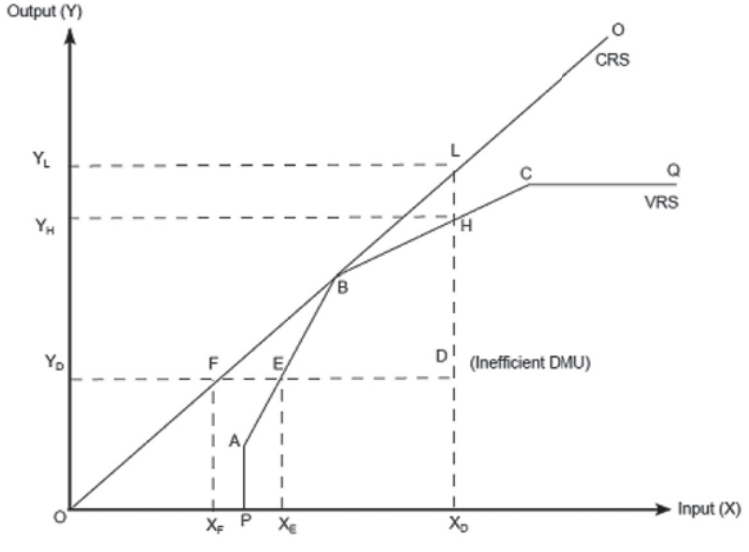

Figure 2—Illustration of CRS- and VRS-efficient DMUs (Kumar and Gulati, 2008)

Subject to

$$\frac{\sum_{r\in\mathbf{R}} u_r y_{rj}}{\sum_{i\in\mathbf{I}} v_i x_{ij}} \le 1 \quad \forall j \in \mathbf{J}$$

$$u_r v_i \ge 0 \qquad \forall i \in \mathbf{I}, \forall r \in \mathbf{R}$$

Equation [2] is a fractional program that can be transformed by Charnes-Cooper transformation into a linear program (LP):

$$Max\ g_o = \sum_{r\in\mathbf{R}} \mu_r y_{ro} \qquad [3]$$

subject to

$$\sum_{r\in\mathbf{R}} \mu_r y_{rj} - \sum_{r\in\mathbf{R}} \omega_i x_{ij} \le 0 \quad \forall i \in \mathbf{I}, \forall r \in \mathbf{R}$$

$$\sum_{r\in\mathbf{R}} \omega_i x_{io} = 1$$

$$\mu_r, \omega_i \ge 0$$

where

$$\omega_i = t v_i \qquad \forall i \in \mathbf{I}$$

$$\mu_r = t u_r \qquad \forall r \in \mathbf{R}$$

$$t = \frac{1}{\sum_{i\in\mathbf{I}} v_i x_{io}}$$

The dual of Equation [3] is given by the following linear program:

$$\min\ \theta \qquad [4]$$

subject to

$$\theta x_{io} - \sum_{j\in\mathbf{J}} \lambda x_{ij} \ge 0 \quad \forall i \in \mathbf{I}$$

$$\sum_{j\in\mathbf{J}} \lambda y_{rj} \ge y_{ro} \qquad \forall r \in \mathbf{R}$$

$$\lambda \ge \mathbf{0}$$

θ is the efficiency score

Equation [4] is solved n times, with n equal to the number of DMU_S. If a variable return to scale is considered, the condition $\sum \lambda = 1$ is added in Equation [4]. Taking into account the presence of slack, the dual of Equation [3] is given in Equation [5].

$$\min\ \theta \qquad [5]$$

subject to

$$\theta x_{io} - s^- = \sum_{j\in\mathbf{J}} \lambda x_{ij} \quad \forall i \in \mathbf{I}$$

$$y_{ro} + s^+ = \sum_{j\in\mathbf{J}} \lambda y_{rj} \qquad \forall r \in \mathbf{R}$$

$$\lambda \ge 0$$

where s^- and s^+ are slacks for the input and output respectively.

Research methodology and model formulation

The model consists of two stages. The first stage is the formulation of the overall DEA model, comprising the mining operation, the washing operation, and transport to the port, using discretionary variables. The second stage is the regression of the non-discretionary variables on the efficiency score to assess the influence of non-discretionary variables. The resulting efficiency scores are dependent on one another, which violates the assumption of the regression models that the response and predictor variables should be independent. Xue *et al.* (1999) suggest that resampling by replacement (bootstrapping) of the efficiency scores to create other samples of the same size as the original sample will eliminate this dependency. The formulation approach is indicated in Figure 3.

- Discretionary and non-discretionary data were obtained through the Raw Material Group (IntierraRMG) database for coal. Other sources of data included technical articles, reports, and mining company annual reports
- Illustration was carried out through solving the models using General Algebra Modelling System (GAMS) software, a free demonstration system with limited application. Regression and bootstrap was carried out in R, which is free and open-source software.

Model formulation

The formulation of the model involved examining the sub-process of surface coal mines that supply coal to the export

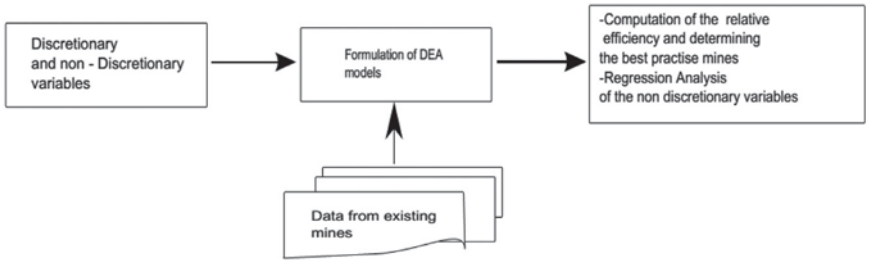

Figure 3—Modelling approach

market. The chain of the process includes mining, the washing process, and transportation to the port for export. The structure considered for this research is shown in Figure 4.

According to Cook *et al.* (2010), the overall efficiency of the multistage process is the convex linear combination of stage-level measures. This can be interpreted as the weighted efficiency of each subsystem of the whole multistage system. The weight assigned for the efficiency of each subsystem of the whole chain is the ratio of the input resources used by the subsystem under evaluation to the total input resource used by the whole system.

Chen *et al.* (2009) show that the weight assigned to the efficiency of each sub-process to obtain the overall efficiency should be greater than a parameter α which is chosen to avoid one or two of the weights being zero, and the rest being equal to 1 upon optimization. These concepts together were applied in the formulation of the DEA model for this research.

To formulate the model, we considered a set of surface coal mines $\mathbf{J} = \{1...n\}$producing coal and supplying it to the export market. Each mine is considered as a DMU. Assuming that input to the mining operation denoted by m is $i\in\{1,...,\}$ inputs at the beginning of the washing operation denoted by b is $k\in\{1,...,\mathbf{K}\}$ inputs at the beginning of port denoted by p is $f\in\{,...,\mathbf{F}\}$, intermediate output from mining and as an input into the washing operation is $g\in\{1,...,\mathbf{G}\}$, and the output from the washing operation, which is also an input to the port, is $t\in\{1,...,\mathbf{T}\}$.

The following definitions for the symbols were used:

x_{ij}^m = the given amount of input $i\in\mathbf{I}$ to the mining operation m of DMU $j\in\mathbf{J}$

x_{kj}^b = the given amount of input $k\in\mathbf{K}$ to the washing plant b of DMU $j\in\mathbf{J}$

x_{fj}^p = the given amount of input $f\in\mathbf{F}$ to the port p of DMU $j\in\mathbf{J}$

z_{gi}^m = the amount of intermediate output from the mining operation and is an input to the washing plant of the DMU $j\in\mathbf{J}$

z_{tj}^b = the amount of intermediate output from the washing plant and is an input to the port of the DMU $j\in\mathbf{J}$

y_{rj}^p = the given amount of output $r\in\mathbf{R}$ from the port p of DMU $j\in\mathbf{J}$

v_r^p = weight given to the outputs $r\in\mathbf{R}$ from the port p of DMU $j\in\mathbf{J}$

u_f^p = weight given to the inputs $f\in\mathbf{F}$ in the port p of DMU $j\in\mathbf{J}$

η_t^b = weight given to the outputs $t\in\mathbf{T}$ from the washing plant b of DMU $j\in\mathbf{J}$

u_k^b = weight given to the inputs $k\in\mathbf{K}$ to the washing plant b of DMU $j\in\mathbf{J}$

u_i^m = weight given to the inputs $i\in\mathbf{I}$ to the washing plant b of DMU $j\in\mathbf{J}$

η_g^m = weight given to the outputs $g\in\mathbf{G}$ from mining and is an input to washing plant

ω_i^m = weight for the inputs $i\in\mathbf{I}$ to the mining operation m after transformation to linear program (LP)

ω_f^p = weight for the inputs $f\in\mathbf{F}$ to the port p after transformation to LP

ω_k^b = weight for the inputs $k\in\mathbf{K}$ to the washing plant b after transformation to LP

γ_g^m = weight for the outputs $g\in\mathbf{G}$ from the mining operation m after transformation to LP

γ_t^b = weight for the outputs $t\in\mathbf{T}$ from the washing operation b after transformation to LP

μ_r^p = weight for the outputs $r\in\mathbf{R}$ from the port p after transformation to LP

ε = an infinitesimal positive number that ensures the weights are positive.

Convex linear combination of the efficiency of each sub-process was used to generate the overall efficiency of the supply chain. The resulting mathematical model of the surface coal mine supply chain for the export market represented by Figure 4 is presented in Equation [6].

$$Max\ h_o = \frac{\sum_{r\in\mathbf{R}} v_r^p y_{ro}^p + \sum_{g\in\mathbf{G}} \eta_g^m z_{go}^m + \sum_{t\in\mathbf{T}} \eta_t^b z_{to}^b}{\sum_{i\in\mathbf{I}} u_i^m x_{io}^m + \sum_{k\in\mathbf{K}} u_k^b x_{ko}^b + \sum_{f\in\mathbf{F}} u_f^p x_{fo}^p + \sum_{g\in\mathbf{G}} \eta_g^m z_{go}^m + \sum_{t\in\mathbf{T}} \eta_t^b z_{to}^b} \quad [6]$$

subject to

$$\frac{\sum_{r\in\mathbf{R}} v_r^p y_{rj}^p}{\sum_{f\in\mathbf{F}} u_f^p x_{fj}^p + \sum_{t\in\mathbf{T}} \eta_t^b z_{tj}^b} \le 1$$

$$\frac{\sum_{t\in\mathbf{T}} \eta_t^b z_{tj}^b}{\sum_{k\in\mathbf{K}} u_k^b x_{kj}^b + \sum_{g\in\mathbf{G}} \eta_g^m z_{gi}^m} \le 1$$

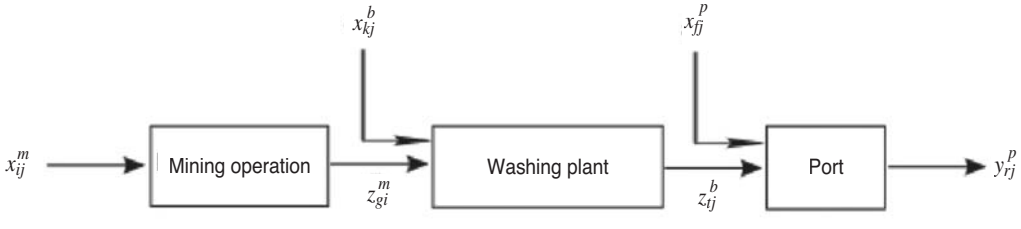

Figure 4—Surface coal mine supply structure for the export market

$$\frac{\sum_{g\in\mathbf{G}} \eta_g^m z_{go}^m}{\sum_{i\in\mathbf{I}} v_i^m x_j^m} \le 1$$

$$u, \eta \ge \varepsilon$$

The above linear programming was transformed by the Charnes-Cooper transformation approach in Equation[3] to yield:

$$\text{Maximize} \sum_{r\in\mathbf{R}} \mu_r^p y_m^p + \sum_{t\in\mathbf{T}} \gamma_t^b z_{to}^b + \sum_{g\in\mathbf{G}} \gamma_g^m z_{go}^m + u_1 + u_2 + u_3 \quad [7]$$

subject to

$$\sum_{i\in\mathbf{I}} \omega_i^m x_{io}^m + \sum_{k\in\mathbf{K}} \omega_k^b x_{ko}^b + \sum_{f\in\mathbf{F}} \omega_f^p x_{fo}^p + \sum_{g\in\mathbf{G}} \gamma_g^m z_{go}^m + \sum_{t\in\mathbf{T}} \gamma_t^b z_{to}^b = 1$$

$$\sum_{g\in\mathbf{G}} \gamma_g^m z_{gi}^m - \sum_{i\in\mathbf{I}} \omega_i^m x_{ij}^m + u_1 \le 0$$

$$\sum_{t\in\mathbf{T}} \gamma_t^b z_{tj}^b - \sum_{k\in\mathbf{K}} \omega_k^b x_{kj}^b - \sum_{g\in\mathbf{G}} \gamma_g^m z_{gi}^m + u_2 \le 0$$

$$\sum_{r\in\mathbf{R}} \mu_r^p y_{rj}^p - \sum_{f\in\mathbf{F}} \omega_f^p x_{fj}^p - \sum_{t\in\mathbf{T}} y_t^b z_{tj}^b + u_3 \le 0$$

$$\sum_{i\in\mathbf{I}} \omega_i^m x_{ij}^m \ge \beta$$

$$\sum_{k\in\mathbf{K}} \omega_k^b x_{kj}^b + \sum_{g\in\mathbf{G}} \gamma_g^m z_{gj}^m \ge \beta$$

$$\sum_{f\in\mathbf{F}} \omega_f^p x_{fj}^p + \sum_{t\in\mathbf{T}} y_t^b z_{tj}^b \ge \beta$$

$$\omega, \gamma, \mu \ge \varepsilon$$

$$u_1, u_2, u_3 \text{ are free in sign}$$

where:

u_1, u_2, u_3 are added to account for variable return to scale for the mining operation, washing operation, and port respectively

ε is an infinitesimal number whose value is 10^{-6}. It is used in ensuring that the optimal weights are positive

β is a parameter that is chosen to avoids the weights assigned to efficiency score in convex linear combination being zero upon optimization of efficiency, and also to ensure that there is a minimum weighted input for each DMU in each sub-process. In this research optimal value of $\beta = 0.2$

Considering the influence of non-discretionary variables on the resulting efficiency score, the linear regression was applied, using the efficiency score as a dependent variable and non-discretionary variables as independent variables (thickness, distance to the port, precipitation, life of mine (LOM), and calorific value (CV)). The regression model that was applied in this research is shown in Equation [8].

$$\theta = \alpha_0 + \alpha_1 \text{ Thickness} + \alpha_2 \text{ Distance} - \text{port} + \alpha_2 \text{Precipitation} + \text{LOM} + \text{CV} + \text{error} \quad [8]$$

where θ is the efficiency score and α is the coefficient of regression.

Illustration of the application

To illustrate the application of the model, data from eight surface coal mines producing coal for export were extracted from RMG database, while the supplementary information such as standards for export tons, number of employees and others were obtained from media reports, company websites, and mining company annual reports.

Data-sets for selected discretionary and non-discretionary variables are presented in Table I and Table II respectively. In Table I the revenue is secondary data that was calculated from the product of price and export tonnages. For illustration purposes, surface coal mines for this research were given DMU numbers.

Table I

Discretionary input variables and output variables

DMU	Reserve (Mt)	CAPEX US$M	No. Employees	Moisture (%)	SR	Ash (%)	ROM (Mt)	Carbon tax $/t)	Recovery (%	Export (Mt)	CV Export MJ/Kg	FOB Price $/t	Revenue US$M
DMU1	61.40	750.00	448	2.0	3.00	14.5	3.197	23	0.9	2.09	27.21	103.25	215.79
DMU2	25.20	177.00	250	3.5	7.00	6	2.800	23	0.9	2.8	27.21	103.25	289.10
DMU3	29.10	45.30	70	6.0	4.60	12	7.640	23	0.9	7.18	23.02	103.25	741.34
DMU4	21.30	144.00	400	9.0	5.50	10	2.800	23	0.9	1.4	25.12	03.25	144.55
DMU5	172.60	1300.00	170	14.5	3.70	9.5	8.210	23	0.9	27.9	25.12	103.25	2880.68
DMU6	66.00	330.00	330	2.2	7.00	10.35	2.612	23	0.9	2.612	25.12	103.25	269.69
DMU7	26.31	275.00	300	2	10	8.75	2.900	23	0.9	2.9	25.12	103.25	299.43
DMU8	100.00	122.90	400	3.5	10	9	3.779	23	0.9	3.779	23.02	103.25	390.18

Source: RGM, annual mining reports, media and company websites

Table II

Non-discretionary input variables

DM	Thickness (m)	Precipitation (mm)	Dist-port (Km)	LOM (Yrs)	CV (MJ/kg)
1	4.0	600	286	20	29.31
2	3.2	568	407	12	31
3	3.0	685	250	20	27.2
4	11.0	789	105	10	28.26
5	38.0	655	278	17	27.9
6	5.0	674	164	17	30
7	0.6	674	161	9	29.3
8	2.9	568	360	10	28.01

The model in Equation [7] was solved using General Algebraic Modelling system software (GAMS), a free demonstration system considering discretionary variables only. In the second step, multiple regressions were applied on non-discretionary variables. The regression of the efficiency score on non-discretionary variables was done using the R open-source software.

The inputs for the sub-processes of the DEA model were:

- Mining operation: CAPEX (capital expenditure), stripping ratio (SR), number of employees, and moisture (%)
- Washing plant ROM, ash, and recovery
- Port: carbon tax.

The overall outputs of the model were revenue and CV-export.

Results

The results of the efficiency scores after solving the model (Equation [7]) using GAMS for each DMU using the data in Table I are presented in Figure 5. DMU 6 is technically efficient, with an efficiency score of 1; this DMU define the envelope of the best practice of all surface mines used in the illustration for the application. DMUs 1–5, 7, and 8) are inefficient surface coal mines with efficiency scores less than 1. This implies that in order to be efficient, DMU 1 has to improve by 4.5%, DMU 2 by 11.2%, DMU 3 by 18.0%, DMU 4 by 25.9%, DMU 5 by 1.7%, DMU 7 by 1.2%, and DMU 8 by 6.9% in relation to the best-practice mines through reduction of controllable inputs.

The influence of non-discretionary variables (Table II) on efficiency score for each DMU was determined using R software. The results are summarized in Table III. The summary statistics tests in Table III show that the probabilities (p-value) for t-value for coefficient of Dist-port, precipitation, and thickness variables are lower than the 0.05 significance level, while that of LOM is greater than 0.05. This suggests that the Dist-port, precipitation, and thickness variables have an influence on the efficiency scores, while LOM has no influence on the efficiency scores of the mines. The inclusion of the CV variable in the regression together with the other discretionary variables in Table II shows no relationship with the efficiency score. This is due to the relationship between the CV and the other predictor variables, which affects the regression results.

Bootstrap technique was applied to the efficiency scores obtained for each DMU to avoid dependence among them, so as to generate a random set of efficiency scores. For illustration purpose the data was resampled with replacement of 1000 samples, with each having eight DMUs, on the variables indicated in Table II, and then regression was applied to each sample. The results of the bootstrap regression are presented in Table IV.

Through observation of the confidence interval 95% (CI) in Table IV, distance to the port (Dist-port) and precipitation affect the efficiency of a surface coal mine. This is because the confidence interval for coefficients of these variables does not include zero. This statistical test suggests that these variables have influence on the efficiency score. The CIs for the coefficient of the thickness and LOM include zero value, which indicates that thickness and LOM do not affect the efficiency score.

The major differences between the results presented in Table III and Table IV are in the values of the standard errors. The results in Table III have standard errors obtained from efficiency scores that are dependent on each other, and those

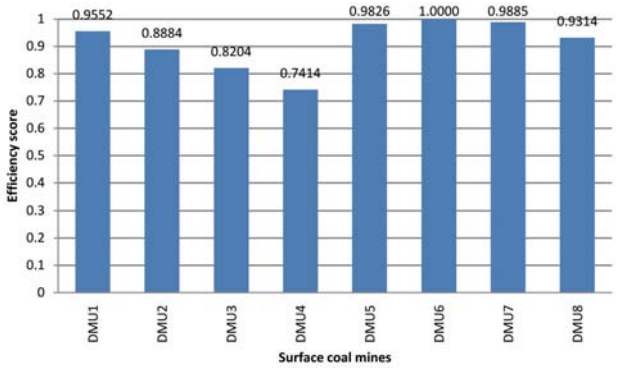

Figure 5—Variable return–to-scale technical efficiency of DMUs for illustration

Table III

Regression results for the discretionary variables

Variables	Estimate	Std. Error	t value	Pr(>|t|)
Precipitation	-0.00293	0.00046	-6.41200	0.00769
Thickness	0.00390	0.00120	3.23500	0.04805
Dist-port	-0.00170	0.00032	-5.35900	0.01272
LOM	0.00066	0.00297	0.22300	0.83784

Table IV

Regression results for 1000 bootstrap samples

Variables	Estimate	Bias	Std. Error	CI (95%)
Precipitation	-0.00293	0.00050	0.00199	(-0.0128, -0.0012)
Thickness	0.00390	-0.00187	0.01870	(-0.0062, 0.0885)
Dist-port	-0.00170	0.00022	0.00126	(-0.0063, -0.0008)
LOM	0.00066	-0.00051	0.00835	(-0.0067, 0.0307)

in Table IV are obtained from resampling technique that eliminates dependence among the efficiency scores.

In addition, it is observed that the results from both ordinary regression and bootstrap regression are not sufficiently conclusive to confirm that the selected non-discretionary variables for illustration do affect the efficiency score of a surface coal mine. More data and more variables can help to draw conclusions and identify extra non-discretionary variables that influence the efficiency of surface coal mines. For example, the ordinary linear regression indicates that the thickness of the coal seam has an influence on the efficiency score, while the regression for the bootstrap (resampling) technique indicates that the thickness does not influence the efficiency score. This apparent contradiction can be clarified by including more observations in the study.

Conclusions

Determining the relative efficiency of a surface coal mine helps management to identify inefficient mines and select the optimal level of the variables that can be used in order to improve the company's efficiency and thus its competitiveness. It can help the mine to determine the effective cost of achieving the desired outputs.

At any given producer, the relative technical efficiency of the mine can be determined by comparing it with the best-practice mines. New mines can also determine their position or can choose the best discretionary variables to help them to increase their competitiveness in the market.

This study suggests that future research should be focused on creating models to predict the efficiency of new surface mines, taking into account both the discretionary and non-discretionary variables from the results of the efficiency score. This would help new mines to evaluate their operational variables before spending more capital, making them competitive in any given business environment.

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Can artificial intelligence and fuzzy logic be integrated into virtual reality applications in mining?

by R. Mitra* and S. Saydam*

Synopsis

The University of New South Wales (UNSW Australia) has been a world leader in the development of innovative virtual reality technologies over the last 15 years. AVIE (Advanced Visualisation and Interactive Environment) was developed by iCinema as a collaborative venture between UNSW's Faculties of Engineering and the College of Fine Arts. This is the world's first 360°-surround, virtual reality (VR) stereo projection theatre system.

The School of Mining Engineering at UNSW Australia has developed 18 different virtual reality modules aimed at mine safety training and mining engineering education. These modules are being regularly used in both the mining industry and the university. The School of Mining Engineering is continuously involved in the development of different modules. Research is also currently being conducted on the implementation of other technologies into this environment. Artificial intelligence (AI) and fuzzy logic are tools that the authors would like to consider implementing in future module development. This paper will review current research in both these areas and consider options for applying these technologies.

Keywords

mining, virtual reality, artificial intelligence, fuzzy logic.

Introduction

The School of Mining Engineering at the University of New South Wales (UNSW) Australia has progressively built simulators for the mining industry in collaboration with the industry. A project was commenced in 1999 with seed funding from UNSW and Coal Services Pty Ltd. Subsequently, funding was provided from industry in 2002 through the Australian Coal Association Research Program (ACARP). A flat screen 'proof of concept' system was deployed at Newcastle Mines Rescue Station (NMRS) in Argenton, New South Wales (NSW), Australia.

Stothard *et al.* (2004) described the development, deployment, and implementation of a virtual reality (VR) simulation capability by the School to address the specific needs of the Australian coal mining industry. The simulation capability developed is a hybrid system designed to provide simulation technology to both large and small operators. The system was deployed at mine rescue stations in NSW and is currently in daily use for training in areas such as unaided self-escape, rib and roof stability, hazard awareness, and isolation. The objective is to simultaneously train groups of miners in an environment where they are exposed to high-resolution, 'one-to-one' scale visualization of the underground environment in which they will operate.

From an educator's point of view, the effects of simulation and role-playing on students '*involves the whole person - intellect, feeling and bodily senses – it tends to be experienced more deeply and remembered longer*' (Brookfield, 1990). According to Meyers and Jones (1993), students who use simulations are '*forced to think on their feet, question their own values and responses to situations, and consider new ways of thinking*'. The main objectives are to make trainees feel as though they are located in the mine and provide them with a fully immersive experience (Stothard *et al.*, 2008).

Furthermore, the School has been involved in UNSW's award-winning iCinema Advanced Visualisation and Interaction Environment (AVIE) project – a 3D 360-degree VR facility and iDOME (proprietary hardware / software platform developed by the iCinema Centre) (Hebblewhite *et al.*, 2013; Mitra and Saydam 2011; Saydam *et al.*, 2011). The School has constructed an AVIE and an iDOME (a 2D version of the AVIE), funded partly by a Federal Capital Development grant in 2007, for developing mine safety training simulations. Figure 1 shows the AVIE and iDOME facilities at the School of Mining Engineering.

* *School of Mining Engineering, University of New South Wales, Australia.*

(a) (b)

Figure 1—(a) AVIE and (b) iDOME at the School of Mining Engineering, UNSW Australia

Advances in computing power have enabled great progress in artificial intelligence (AI) and fuzzy logic. These technological breakthroughs can best be utilized with a greater awareness of this technology and what it can achieve. This study will investigate if there is any potential for integrating fuzzy logic and AI into the VR technology that is currently used at the School.

Mining-related virtual reality modules developed at UNSW

Apart from developing modules aimed at improving the health and safety standards for the mining industry, the School has also developed numerous modules using the same technology for improving teaching and learning for mining engineering education at UNSW Australia. These modules are used in majority of the courses in both undergraduate and postgraduate teaching. All the modules are capable of running in the AVIE at the School and also on a standalone PC. Some of these modules are currently being adapted to run on the Internet so that students can access them at their leisure (Mitra and Saydam, 2011). The following is a list of the various modules that have been or are currently being developed for both the industry and learning and teaching (Hebblewhite *et al.*, 2013; Mitra and Saydam 2011; Saydam *et al.*, 2011):

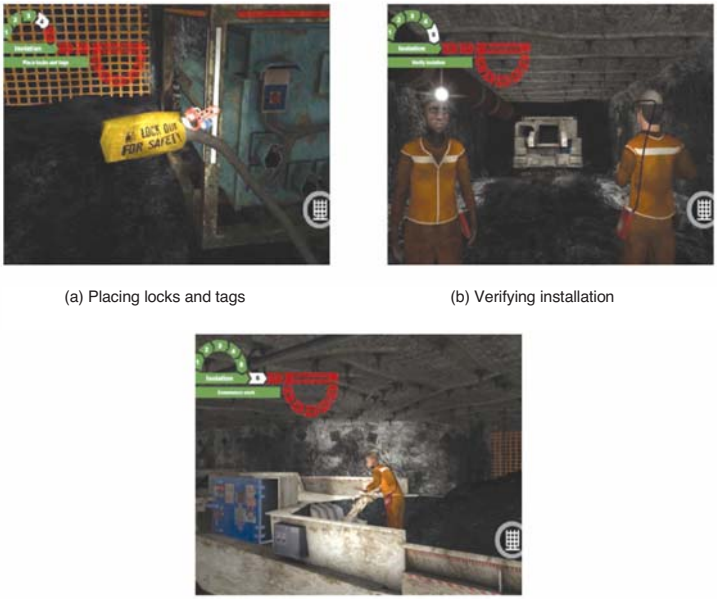
1. Hazard awareness
2. Isolation (Figure 2)
3. Outburst
4. Spontaneous combustion
5. Deputies inspection
6. Self-escape
7. Rib stability
8. Truck inspection (Figure 3)
9. Working at heights
10. Laboratory rock testing
11. Mining in a global environment (Figure 4)
12. Block caving (Figure 5)
13. Truck and shovel (Figure 6)
14. Longwall top coal caving (Figure 7)
15. ViMINE 1 (Figure 8) and ViMINE 2 (Figure 9)
16. NorthParkes community awareness
17. Coal geology (under development)
18. Caving geomechanics data visualization (under development).

Artificial intelligence

Artificial intelligence (AI) is defined as '*the study and design of intelligent agents where an intelligent agent is a system that perceives its environment and takes actions which maximizes its chances of success*'. This term was created by McCarthy (1956), and was defined as *the science and engineering of making intelligent machines* (ScienceDaily, 2014).

Russell and Norvig (1995) define four different categories for AI. These categories include systems that:

- Think like humans



(a) Placing locks and tags

(b) Verifying installation

(c) Commencing work after completion of isolation

Figure 2—Screenshots from the Isolation module

Figure 3—Screenshot of the truck used in the Truck Pre-shift Inspection module

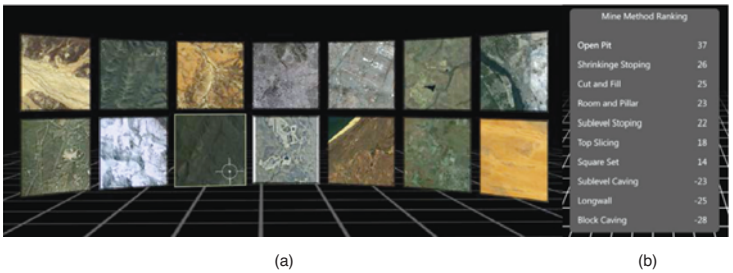
Figure 4—Students doing the assignment in the Mining in a Global Environment module

Figure 5—Drawpoint in the virtual block cave mine

Figure 6—Equipment selection simulation observed in the Truck and Shovel module

Figure 7—Screenshot from the Longwall Top Coal Caving module

Figure 9—ViMINE 2 open pit design



(a) (b)

Figure 8—ViMINE 1. (a) Selected terrain scenarios; (b) mining method ranking

- Think rationally
- Act like humans
- Act rationally.

According to Shapiro and Eckroth (1987), the first AI programs were developed during the 1950s. These programs could perform tasks such as playing chess. None of the programs developed in the 1960s were able to solve complex problems, although they did further the understanding of the intelligent problem-solving process. Gaming programs became popular for testing AI as this was the easiest way to compare two programs and investigate whether simple rules would be able to overcome limited memory problems. It became evident, however, that this was not the case due to the large number of move sequences to be considered.

During the 1970s, AI systems were used mainly in laboratories and incorporated specific knowledge based on the area they were assigned to. Commercial systems that were cost-effective became available during the 1980s for both government and industry purposes (Shapiro and Eckroth, 1987). With increasing use of these new systems, a lot of errors became apparent. However, in spite of these flaws, the systems continued to be used by both companies and the government. The 1990s and 2000s saw a variety of major developments in AI technology.

Applications of artificial intelligence in various fields

AI technology is applied in numerous fields, including planning and scheduling, gaming, vehicle control, medicine, robotics, language understanding and problem-solving, and speech recognition. This section will provide examples of some of these areas.

In regard to planning and scheduling, the system consists of a search engine, which uses a planned database and knowledge base to construct a plan. An example of such a system was used by the National Aeronautics and Space Administration (NASA) on board its Deep Space One spacecraft in 1999 (Jonsson *et al.*, 2000). The system was used to detect, diagnose, and recover from any problems occurring on the spacecraft. Plans were generated by the system considering limitations in time, resources, and flight safety rules. Spyropoulos (2000) discusses the application of AI planning and scheduling for therapy planning and hospital management.

As mentioned previously, one of the most popular applications of AI technology is in the area of gaming. Russell and Norvig (2003) discuss Deep Blue, a chess-playing computer built by IBM that in 1997 defeated Garry Kasparov, the then world chess champion. Another game, WarCraft, was the first game to employ pathfinding algorithms at such a grand scale, for hundreds of units in the game engaged in massive battles (Grzyb, 2005). SimCity is another example where AI has been successfully used.

AI can be used to control a vehicle without much human intervention. The Robotics Institute at Carnegie Mellon University (USA) designed the Autonomous Land Vehicle in a Neural Network (ALVINN) with the task of following roads. Successful trials with the test vehicle have indicated that the network can effectively follow real roads under certain field conditions (Pomerleau, 1989).

In the field of medicine, AI has the potential to exploit meaningful relationships within a data-set for use in the diagnosis, treatment, and predicting outcomes in many clinical scenarios (Ramesh *et al.*, 2004). 'Pathfinder' is an example of an expert system that helps surgical pathologists in diagnosing lymph-node diseases. It is one of a growing number of normative expert systems that use probability and decision theory to acquire, represent, manipulate, and explain uncertainty in medical knowledge (Heckerman *et al.*, 1992).

AI technology can expand the capabilities of robots. HipNav is an example which uses AI to create a three-dimensional model of a patient's internal anatomy. Robotic controls are then used to guide the insertion of the patient's new hip replacement (Russell and Norvig, 2003).

In the field of linguistics and problem solving, Littman *et al.* (1999) discuss PROVERB, a computer program that uses filters, an archive, and other information sources to solve crossword puzzles. A solver chooses the best candidate from solutions generated by 30 different modules. These modules can be split into five categories – word list modules, crossword database-specific modules, information retrieval modules, database modules, and syntactic modules. Word list modules ignore the clue and run every word from a dictionary that has the correct length. Crossword database modules search for similar clues from a database of previous crosswords. Information retrieval modules search online full-text sources such as encyclopaedias. Domain modules search specific domains for solutions based on specific parameters such as authors, songwriters, or actors. Syntactic modules are used to solve specific clues where it is required to fill in a blank.

According to Sharples (1996), many tasks could be made easier by controlling through speech rather than typing. Modern systems can recognize speech with little or no training compared to older interfaces, which were limited in regard to input. Stolcke (1997) lists a variety of technological areas in which speech recognition is available such as dictation software, medical equipment, and stock trading over the telephone. Speech recognition technology development is measured by the ratio of incorrectly recognized words to the number of words spoken, known as the word error rate. While the word error rate can be affected by a number of factors such as the size of the vocabulary, the speaking style of the user, whether the query is open or task-oriented, whether the system is trained for more than one user, the channel quality of the system, and background noise, the rate is not affected by the language chosen.

Applications of artificial intelligence in mining

For many years, AI tools have been in use in various mining-related applications. Bandopadhyay and Venkatasubramanian (1986) developed a fault diagnostic expert system for the longwall shearer. Altman *et al.* (1988) developed an expert system, Mine Ventilation Manager, to control the operation of a mine ventilation network system. Schofield (1992) developed MINDER, a decision support system capable of assisting the mine planner in the complex task of selecting the optimum surface mining equipment. One of the major objectives of this program was to enable integration with other mining software packages.

Denby and Kizil (1991) describe the development of an advanced computer system for the assessment of geotechnical risk in surface coal mines. The authors review the ESDS, an expert system for slope stability assessment. The paper concludes by presenting an example that illustrates how ESDS may be utilized as a decision support system at the design stage of a UK surface coal mine. Faure *et al.* (1991) developed an expert system, XPENT, for slope stability analysis.

There are numerous examples of work done in the area of mapping minerals. Kruse *et al.* (1993) used a knowledge-based expert system to automatically produce image maps showing the principal surface mineralogy developed from Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data. Moore and Sattar (1993) developed a knowledge-based system to assist in the modelling and economic assessment of potential mineral deposits in Queensland, Australia. The system was able to be readily tailored to address specific mineral commodities and environments.

Bearman and Milne (1992) reviewed the opportunities for expert systems in the minerals industry, and explored potential future developments and applications for the industry. Romans (1993) provides examples of application of knowledge-based systems in the minerals industry leading to substantial savings. Kizil *et al.* (1995) also summarized the use of AI applications in mining. They mentioned Waller and Rowsell's (1993) work on the development of a system named '*Intelligent Drilling Control*' using AI in petroleum industry. The system aimed to optimize the drilling process, and measure the real-time pick consumption and calculate the drilling costs.

Deliormanli *et al.* (1995) developed an expert system software named EMQDS (*Expert Marble Quarry Design System*) to select appropriate equipment, assess the work-force, and conduct a financial analysis for marble production.

Toll (1996) discusses the application of AI systems for geotechnical applications. According to the author, a significant number of systems have been developed for site characterization, classification of soils and rocks, foundations, earth retaining structures, slopes, tunnels and underground openings, mining, liquefaction, ground improvement, geotextiles, groundwater/dams, roads, and earthworks.

Morin (2001) discusses the integration of support elements such as expert systems, numerical models, data analysis and visualization tools, and simulation to bring added functionality and intelligence to the mine design and planning system. According to the author, the integration of these elements, if feasible, would form an intelligent design system with decision-support capabilities that exceed anything currently available on the market.

'*Expert and knowledge based systems, probably the most popular AI tools, have found their way into a number of computer-based applications supporting everyday mining operations as well as production of mining equipment*' (Kapageridis, 2002). This study mentions the use of AI tools for exploration and reserve estimation, geophysics, rock engineering, mineral processing, remote sensing, process control and optimization, and equipment selection. Foloronso *et al.* (2012) developed an expert-based mineral identification system to teach undergraduate students. They were able to promote effective and meaningful learning of scientific observation in the area of Earth Science. According to Knobloch *et al.* (2013), mineral predictive maps can be created with the help of artificial neural networks (ANNs) which use a comprehensive data-driven modelling approach. Based on a '*self-learning' process, this AI technology can be used to interpret almost any geoscientific data for generation of both qualitative (prediction of locations) and quantitative (prediction of locations, grades, tonnages) mineral predictive maps. By analysing the footprints of known mineralization in the framework of available geoscientific data, the approach generates trained ANNs that are further used to generate predictive maps*.

Fuzzy logic

Traditional science is centred on the binary status view that a statement is either entirely true, or entirely false. However, according to Kosko (1999), '*fuzz*' includes statements that are only partially true in order to define vague terms that have entered human language. This way of thinking has generally not been accepted by modern science. A set is a binary structure to which objects belong. An object either belongs to a set or it does not; sets do not allow for partial membership. Depending on whether or not they belong to a set, objects are represented by a 1 or 0. However, a fuzzy set allows for partial membership. Fuzzy logic systems use fuzzy sets to convert inputs into the correct outputs. Like a human expert, a fuzzy logic system uses rules of thumb to determine what action must be taken in a certain situation. These are called *Fuzzy If-Then* rules and they follow the form *if x is A then y* is *B* where A and B are linguistic values defined by the fuzzy sets on the universe of disclosure X and Y (Castillo and Melin, 2008). In the above rule, x is A is defined as the antecedent or premise while y is B is called the consequent or conclusion. An example of such a rule in our everyday life can be *if service is great then tip is greater than 15%*. The curse of dimensionality says that there will always be a limit to the number of rules that can be used due to the memory limits of computer chips. A membership function maps the object values within a set and can take a number of forms. Bezdek (1996) lists the following five basic operations that are used to manipulate fuzzy sets:

- Equality
- Containment
- Complement
- Intersection
- Union.

Fuzzy logic began in Ancient Greece with the philosopher Zeno. According to Kosko (1999), Zeno posed the question: *if we remove the grains from a pile of sand one at a time, at what point does it cease to be a pile*? The fuzzy answer is that the pile leaves the set of piles of sand as smoothly as the individual grains are taken away from it. At the turn of the 20th century, Bertrand Russell stated that '*everything is vague to a degree you do not realise it until you try to make it precise*'. Russell said that during the transition phase,

objects would spend the majority of their time in a mix of the two states. In the 1920s Jan Lukasiwicz looked at these theories as an extension of binary logic. He stated that all statements are either true or false to some degree, but that the 'true' and 'false' scores must add up to 100%. In 1937, Max Black drew the first graph of a fuzzy set. However, the philosophical community largely ignored these views due to their attitude towards logic at the time. The term '*Fuzzy*' was introduced by a paper by Lofti Zadeh, the chairman of the electrical engineering department at the University of California, in 1965. However, it was decades before his work received recognition in the form of a medal of honour from the Institute of Electrical Engineers in 1995.

According to Kosko (1999), one of the first devices to use fuzzy logic was a kiln for F.L. Schmidt and Co. in Copenhagen, in 1980. The coal feed rate was reduced if both temperature and oxygen levels were high within the kiln. One of the most notable developments in the use of this technology was the Sendai subway railway system developed by Hitachi in 1988. The system replaced train drivers along the 13.6 km long, 16-station track. The introduction of the system has led to a smoother ride for passengers, with a 10% reduction in energy consumption compared to human drivers (Kisko, 2005).

Many of the earliest applications of fuzzy logic were designed to be used by organizations. The first home appliance to use fuzzy logic was a washing machine developed in 1990 (Wakami *et al.*, 1996). The optimum washing time was determined through outputs from a washing sensor and fuzzy logic technology. The washing sensor used a light-emitting diode and a phototransistor to measure the transmittance of the water. The rate at which the light transmittance decreased indicated whether the dirt in the machine is muddy or oily, which in turn indicated whether there was a light or heavy amount of dirt in the washing machine. Fuzzy logic used these inputs to determine the optimal washing time.

Fuzzy logic technology has also been used to stabilize videos shot with amateur video cameras. As video cameras became smaller and lighter, the effect of hand jitters became more noticeable. The image stabilizing system consists of a motion detection chip, interpolation processing chip, field memory, and microprocessor to hold the fuzzy interference. The image is sent to the field memory while also being processed by the motion detection chip. The motion detection chip looks for correlation between images to detect the amount and direction of movement. The field memory then repositions the image and uses the electronic zoom function of the camera to enlarge the compensated image. Fuzzy logic is used to distinguish between a shaking video and a moving subject. This is determined by whether all objects within the image are moving in the same direction or if they are moving in different directions.

Fuzzy logic technology, when combined with an infrared ray detector, can be used to assist an air conditioner in efficiently cooling the occupants of a room through knowledge of the current temperature and the number of occupants and their positions. The rotating infrared ray detector creates a two-dimensional thermal image with each element given a temperature value. The fuzzy logic algorithm then performs three tasks – removing the background, identifying each occupant, and expanding the region of each occupant. In order to isolate the occupants from the background, the algorithm identifies areas where the average temperature for that group of elements is higher than a set value. Given that a peak temperature would represent each occupant, the algorithm identifies elements whose temperature is higher than the eight elements surrounding it and assigns each of these peaks a number to identify the number of occupants. The algorithm then expands the area covered by each occupant by lowering the threshold temperature in order to expand the area covered without increasing the number of peaks.

Fairhurst and Lin (1985) discuss the application of fuzzy methodology in tunnel support design. According to the authors, '*a decision system for tunnel support design allows questions to be posed and answered in relation to the information stored in a rafael design knowledge base*.' Such systems will be successful depending on their ability to extract information from geology, rock mechanics, and tunnel technology and translate it into a form or forms that help the user to make a more intelligent decision for tunnel design. The study presents a preliminary discussion of approaches to the development of such systems.

Fuzzy logic technology can be used to compensate for friction in machinery. Friction is based on both the position and the velocity of an object and is difficult to predict with an accurate model (Liu *et al.*, 2006). However, due to the large impact of friction at low velocities, developing such a model is important. Experts designed a fuzzy logic control to approximate such phenomena. A fuzzy logic system has also been used to identify suitable advisors for call centre customers. According to Shah *et al.* (2006), companies are aware that a happy customer can lead to repeated business. It is therefore important to match the correct advisor to each customer. There are five behaviour dimensions of the advisor that can influence customer satisfaction; these include mutual understanding, authenticity, extra attention, competence, and meeting minimum standards. Different customers would react in different ways to each of these, so it is important to know which will work best for each demographic of customer. Fuzzy logic can be used to infer the goals of the users. To develop such a system, the company must collect data, cluster and analyse the data, identify the separate categories, categorize both consumers and advisors, identify the critical factors and derive their membership functions, develop if-then rules, implement the fuzzy interference process, test the system in a real-world environment, and validate the system from feedback received.

Beynon (2008) discusses the use of fuzzy logic in decision trees. Decision trees allow for greater interpretation of an analysis by humans. The root node of each tree is split into leaf nodes to further classify objects. Each leaf node is created using fuzzy if-then rules. Decision trees increase the understanding of complicated situations and can be applied to a variety of scenarios. Beynon (2008) applies a fuzzy decision tree to the complex situation of company audit fee evaluation.

Conclusions

The School of Mining Engineering at UNSW Australia employs a VR simulator that is used to replicate mining situations in a comfortable, safe, and forgiving environment. The VR system offers many benefits to its users, including flexibility in time and place, and the rate and privacy of the learning experience. The system has a variety of uses, including the development of understanding and the retention of learning, customized on-the-job training, fault finding, easy communication of complex data, evaluation of the consequences of poor decision-making, trainee assessment, identification of flaws in training programmes, and accident identification and reconstruction.

The modules developed at the School can immensely benefit from the use of both AI and fuzzy logic technologies. In order to improve the interactive feature of the system, the user must be able to control the system in a more natural way. Currently, all the modules are operated in the AVIE through an iPad environment. However, speech and gesture are the most natural way in which humans interact with others. According to iCinema (2012), a motion capture function that can recognize the gestures of up to five people at once is currently offered by the AVIE system. However, the current mining simulations do not utilize this feature. Integrating this feature will definitely improve the interaction in the AVIE facility and will add more realism required specifically for training effectiveness in this environment. To reduce the word error rate for this new function, the control could be initially limited to a number of key phrases.

Using a similar technology as in air conditioners, infrared detectors can track the movement of people in this environment and then through the use of AI make changes to the way the module operates. As an example, different actions by a group of trainees can lead to different outcomes. Another application of this technology is in the ViMINE module. This module involves decision-making based on input from the user.

An overview of the historical and current uses of AI and fuzzy logic technologies, as well as how each form of computing works, has been conducted, and some applications of both AI and fuzzy logic provided. From this study, it can be seen that there is a lot of opportunity for applying AI and fuzzy logic technologies to the current VR technology used at the School in order to benefit learning and teaching. Further detailed studies will look into the specifics of how these technologies could be integrated into the current system. A pilot study will initially be conducted on one of the modules to test the feasibility of this integrated technology.

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Key performance indicators — a tool to assess ICT applications in underground coal mines

by C. Dauber* and M. Bendrat*

Synopsis

Implementing new technologies in industrial operations entails the challenge of measuring the improvements gained by the applied technology. Nevertheless, it is absolutely essential to assess the technical and economic benefits in objective and comprehensible numbers to create a platform for further management decisions. Underground coal mines are characterized by numerous, quite complex procedures which make it difficult to determine the specific economic benefit of a new machine, technique, or method. In the OPTI-MINE Project funded by the European Union's RFCS programme, five underground coal mines applied the latest information and communication technologies (ICTs) to improve efficiency, mine safety, occupational health, and environmental impacts. An integral part of the project is the assessment of these technologies by using key performance indicators (KPIs). The paper will describe some examples of the selected KPIs and the preliminary findings.

Keywords

key performance indicators, information and communication technology, ICT-applications, network infrastructure, material tracking, wireless communication.

Introduction

The key performance indicators (KPIs) described below are established within the framework of the project 'Demonstration of Process Optimization for Increasing the Efficiency and Safety by Integrating Leading Edge Electronic Information and Communication Technologies (ICT) in Coal Mines'. The EU Project OPTI-MINE, with a duration from July 2011 until June 2014, is subsidized by the European Union within the framework of 'Research Fund for Coal and Steel (RFCS)'.

'*OPTI-MINE is a demonstration project, which aims at integrating, installing and operating the newest Information and Communication Technologies (ICT) applications at an industrial-scale and bringing together all the technical and economic data in order to make their European-wide implementation in the mining industry possible but at a minimum risk. Not only the new ICT applications themselves are being demonstrated, but by integrating the ICT systems into one common Ethernet (TCP-IP) based open network platform of high bandwidth and standardized configuration (internet technology), information can be exchanged between all applications and processes. Thus the processes as a whole can be optimised and the efficiency and safety of mines will increase considerably.*

'*The project covers leading edge ICT for underground mining processes including logistics, transport, personnel communication and information by voice and data, machine communication, staff localisation, guidance etc. Individual components developed within the project will be integrated into a comprehensive system where possible. The benefits demonstrated by this comprehensive optimisation of mining processes are related to considerable improvements of efficiency, mine safety, occupational safety and health and environmental impacts.*' (OPTI-MINE, n.d.)

The participants are:

- Project coordinator:
  - Evonik Degussa GmbH (EVD) on behalf of RAG-A, Germany
- Academic partners:
  - Silesian University of Technology (SUT), Poland
  - Georg Agricola University of Applied Sciences (DMT-TFH), Germany
- Underground coal mines:
  - RAG Anthrazit Ibbenbüren GmbH (RAG-A), Germany
  - Premogovnik Velenje d.d. (PRV), Slovenia
  - Hulleras del Norte S.A. (HUNOSA), Spain
  - OKD a. s. (OKD), Czechia
  - Kompania Weglowa S.A. (KWSA), Poland
- Suppliers of the new technical equipment:
  - Minetronics GmbH (MT), Germany
  - Asoc. Inv. y Des. Ind. Rec. Nat. (AITEMIN), Spain.

* *Georg Agricola University of Applied Science, Germany.*

The proposed activities of the participating mines have been allocated to different clusters. Table I presents a map of the activity clusters with names of companies participating in each kind of activity. Because the backbone for any application is an adequate network infrastructure, a common field of interest for all mining companies is the development of modern network infrastructure (cluster c1). The other fields of interest are generally site-specific and reflect the areas that require improvement from the point of the view of management. These fields of interests have been gathered and identified in a group of activity clusters.

Key performance indicators

As stated in the Grant Agreement of the project, the introduction of KPIs is essential to evaluate the improvements created by new ICTs. KPIs are a set of selected parameters, designated to facilitate the ongoing assessment of an activity and its results. Due to the complex nature of an operational process, the parameters have to be selective. It is essential to select the most important factors to obtain a reliable and clear view of the operational process.

Implementing new ICT underground covers a multi-layered process and depends on many parameters with a dynamic behaviour. Additionally, the operational setting varies as coal mining is not always a steady, well-defined production process. Therefore the assessment of ICT implemented underground is quite a complex task and requires some simplifications.

Prior to the selection of the KPIs, the academic partners SUT and DMT-TFH had to determine the general requirements that suitable KPIs have to fulfil. These requirements are not limited to the coal mining sector; they are commonly agreed upon in the industry.

- Key performance indicators must reflect the operational goals
- Key performance indicators must be quantifiable by numbers
- Key performance indicators must be free of authoritative judgements
- Key performance indicators must depend on data that is reasonably easy to obtain.

With regard to their scientific and industrial experience, the academic partners designed a number of KPIs applicable for the new ICTs and fulfilling the above requirements. These KPIs covered technical issues of the technology, parameters of the monitored machinery, data concerning the logistics underground, and process-related figures. Due to the specific ICT installations, the varying operational objectives, and the local conditions for each mine, individual KPIs have been designed. After an intensive discussion with project partners, some of the drafted KPIs were altered in accordance with the recommendations of the mining companies. There was a general commitment that the selected KPIs should describe the status before and after implementing the new technology. At the end, it was commonly agreed that each mine should adopt at least three indicators that should cover the essential process improvements gained by the new ICTs.

The determination of KPIs requires a number of operational data. The basic requirements for data collection were set as follows:

- In general, data collection consists of two measuring periods, one before and one after implementing ICT
- Between the two periods, a sufficient testing and troubleshooting time for implementing the technology has to be considered
- With regard to the time frame of the project, a third period of data collection should take place six month after the second period. The sustainability of the improvements will be the focus of this activity
- A minimum number of 10 data-sets are required for each KPI
- The data-sets must cover at least one month
- The partners must check whether operational deviations regarding the KPIs have occurred. If so, a differential treatment of the raised data and the calculation of concerned KPIs must be carried out.

Table I

Activities of the mining companies in the OPTI-MINE Project

Cluster	RAG-A	HUN	PRV	OKD	KWSA
c1: network infrastructure	x	x	x	x	x
c2: material logistic	x	x		x	
c3: personnel communication & information	x	x	x		
c4: personal tracking		x	x	x	x
c5: environment monitoring		x	x		
c6: machine communication				x	
c7: conveyor monitoring	x	x			

KPIs applied by RAG Anthrazit Ibbenbüren GmbH (RAG-A), Germany

Figure 1 outlines the system structure that RAG-A has applied in the cluster 'Material logistics'.

The technology in this cluster consists of a network structure expansion with fibre optic cables (FOCs) in the production area 'Beustfeld'. In addition to 5000 m of FOC and 20 FOC distributers, 15 industrial-grade PCs (IPCs) and 9 mining infrastructure computers (MICs) have been installed. (Mueller, C. and Hübner, R.) The MICs equipped with RFID

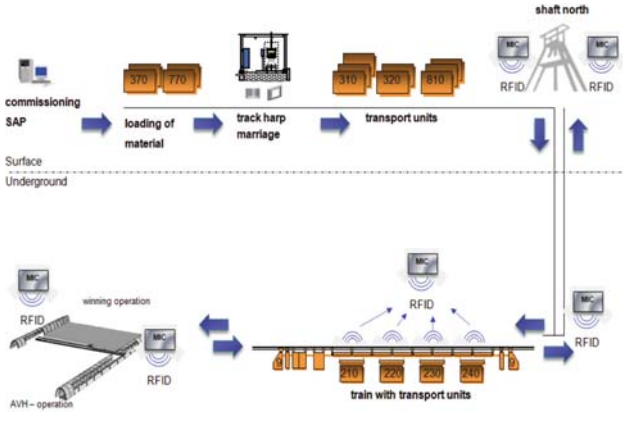

Figure 1—Process for tracking transport units and attached material at RAG-A (Kuschel and Misz, 2013)

readers are able to detect and utilize the passive tags. The RFID tags are affixed to the transport units to enable their location to be tracked.

The informative link between the transport unit, for example the number '370', and the loaded material is executed with an additional barcode label attached to the transport unit. The information from these two different labels is interconnected (marriage) before the transport unit arrives at the shaft.

One KPI is called 'Specific transport performance indicator (TPI)' and is aimed at indicating the productivity of the workforce engaged in the transport of the material units.

KPI: '*TPI*' Specific transport performance indicator in 1/MS (Man Shift)

$$TPI = \frac{n_{TU}}{n_{MS}} \quad [1]$$

TPI: Specific Transport Performance Indicator [-]
n_{TU}: Number of delivered Transport-Units per month [-]
n_{MS}: Number of required Man-Shifts per month [-]

Preliminary findings

The objective of the improved process is increased productivity, *i.e.* the maximization of *TPI*. The coal mine RAG-A Ibbenbüren has collected the relevant data for the new mining area, the 'Beustfeld' (Figure 2), which has been equipped with the new ICT system. Additionally, this data has been recorded for the mine in total (Figure 3).

As shown in Figure 3, the specific transport performance indicator for the mine in total comes to about 2.3, *i.e.* each worker employed for transport (monorail driver, handling people *etc.*) moves 2.3 transport units per shift. In the Beustfeld area (Figure 2), which is completely equipped with the new technology, this indicator ranges around 3. The performance in the Beustfeld is thus about 30% higher than in general. Despite some other parameters that may have an influence, this is a clear indication that the new ICT system makes a valuable contribution to the productivity of the workforce underground.

Another applied KPI refers to the amount of information the new technology is providing to the operator. The parameter for this KPI is the location of the transport unit, and the aim is to know the actual position of each unit at every time.

KPI: 'I_{ITU}' Average Increase of the level of information about locations of Transport-Units in percent:

$$I_{ITU} = \frac{n_{TUa} - n_{TUb}}{n_{TUb}} .100\% \quad [2]$$

I_{ITU}: Average Increase of the level of Information about the locations of Transport Units underground [%]
n_{TUa}: Mean Number of known locations of Transport Units, referred to the specific mining area, **a**fter implementation of new ICT
n_{TUb}: Mean Number of known locations of Transport-Units, referred to the specific mining area, **b**efore implementation of new ICT

Preliminary findings

The objective of optimization is a positive I_{ITU} as this indicates an improved level of information about the location of the transport units underground. Table II represents the recorded data, starting in May 2012 when the new technology was not yet in place. In this month the operator received in average of 2.17 known locations of a transport unit underground. After implementing the new ICT technology in the Beustfeld area, this figure ranged between 3.01 in February 2013 and 5.14 in August 2013.

The I_{ITU} (column 5 of Table II) shows the operator receives on average 60% more information about the location of the transport units. This is a very welcome improvement. A widely branched coal mine is often called a 'black hole' due to the fact that knowledge about numbers of units, their location, and content is often very limited. Less information leads to failed, missed, or dispensable transports. Furthermore, it will reduce the productivity of monorails and operators, as their capacity is not properly matched by the dispatching system.

The recorded increase in the level of information is very well in line with the findings of the previously described KPI 'TPI' (Specific Transport Performance Indicator). It is a strong indication that the new technology leads to significant improvements to the operational process of material logistics.

Cost saving, not a KPI, but most important for mining companies

Another parameter, which was not selected initially, should be mentioned. Owing to the new ICT, it is possible to locate the IPC necessary for the control of the longwall faces on surface. In consequence a flame-proof version is not required and maintenance *etc.* is less complex. The Ibbenbüren coal mine started in 2010 with four IPCs under-ground at an expenditure of 159.124 Euro (Table III). In 2013 all these underground IPCs were replaced by IPCs on surface. These

Figure 2—Specific transport performance indicator TPI for the Beustfeld area (Kuschel and Misz, 2013)

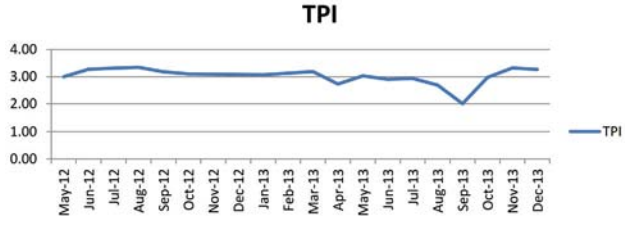

Figure 3—Specific transport performance indicator TPI for the mine in total (Kuschel and Misz, 2013)

Table II

Number of known locations of transport units in the Beustfeld area (Kuschel and Misz, 2013)

	Reference value 2012 May				
	Sum Locations AP 13/12 AP > 30	Sum Recorded tags	n_{TUb}		
May-12	941	433	2.17		
	Sum Locations AP 12/15 AP > 30	Sum Recorded tags	n_{TUa}	I_{ITU} (%)	Remarks
Nov-12	328	154	2.13	-1.99	Software update
Dec-12	973	378	2.57	18.45	Test
Jan-13	1740	613	2.84	30.61	Commissioning and test
Feb-13	1799	597	3.01	38.66	AP12: antenna does not send
Mar-13	2019	601	3.36	54.58	AP12: antenna does not send
Apr-13	2267	591	3.84	76.51	AP: 70 added
May-13	1962	552	3.55	63.55	
Jun-13	2924	684	4.27	96.71	
Jul-13	2657	718	3.70	70.28	
Aug-13	3576	696	5.14	136.42	
Sep-13	3272	701	4.67	114.78	
Oct-13	2522	690	3.66	68.19	AP: 35 added
Nov-13	3244	702	4.62	112.64	
Dec-13	2782	606	4.59	111.24	Optimization shaft entry
Jan-14	2718	765	3.55	63.49	State 30.01.2014

Table III

Expenditure for IPC underground and on surface (Kuschel and Misz, 2013)

	Number of IPC underground	Number of IPC on surface	Expenses IPC underground	Expenses IPC on surface	Expenses IPC before ICT-Inst.	Expenses IPC after ICT-Inst.
2010	4	0	39.781 €	5.849 €	159.124 €	159.124 €
2011	3	1	43.987 €	5.908 €	159.124 €	137.869 €
2012	2	2	43.987 €	5.944 €	159.124 €	99.862 €
2013	0	4	43.987 €	5.944 €	159.124 €	23.776 €

IPCs come to 5944 Euro each, which is about 15% of the price of an IPC underground. Consequently, a cost saving indicator, SIPC, was introduced, which indicates a saving of 85%. That does not take into account the reduced effort for installation, maintenance, and the improved reliability.

KPIs applied by Hulleras del Norte S.A. (HUNOSA), Spain

HUNOSA expects that the new ICT system will have an influence on the performance of extraction functions, including secondary/auxiliary ventilation and haulage of coal by belt conveyors. The main reasons for production or haulage disturbances are breakdowns resulting from mechanical or control systems failures. The new ICT system should improve extraction, conveying, and lead to better use of time during production shifts. The new network infrastructure for communication and information is shown in Figure 4.

HUNOSA stated that KPIs should be related to the average time required to rectify a breakdown affecting the extraction process or the horizontal conveying, *i.e.* mean time to repair (MTTR). The introduction of the new ICT system will deliver a level of information at the control room which is more accurate in time and more detailed than previously. It is expected that this will facilitate remote diagnostics, which in combination with better communication will reduce the MTTR.

KPI: 'D_{MTTR}' Decrease of *MTTR* (Mean Time to Repair), caused by breakdowns, either mechanical or due to a failure of the control systems

$$D_{MTTR} = \left(1 - \frac{MTTR_a}{MTTR_b}\right).100\% \qquad [3]$$

D_{MTTR} Decrease of *MTTR* after implementation of the new ICT [%]
$MTTR_a$ *MTTR* after implementation of new ICT [h]
$MTTR_b$ *MTTR* before implementation of new ICT [h]

MTTR represents the average time required to repair a failed device. The data sampling refers always to one month.

$$MTTR = \frac{\text{Total corrective maintenance time}}{\text{Total number of maintenance actions}} \qquad [4]$$

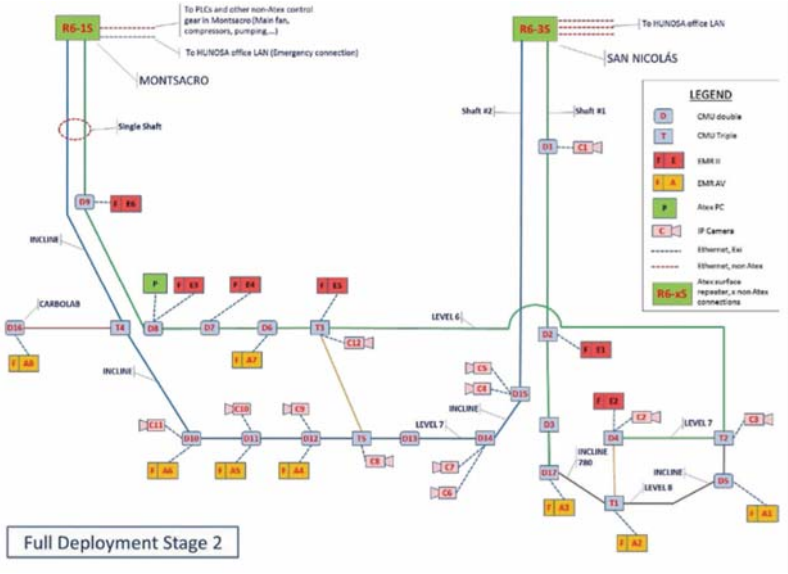

Figure 4—Network infrastructure at the Hunosa Mines, Shaft Montsacro and San Nicolas (Garcia José, González Ruisánchez, and Rodri-guez, 2013)

Preliminary findings

- $MTTR_b$ ranges between 3 and 7 hours (when expert staff necessary must go on the next shift to resolve a problem), with an average of 5 hours
- $MTTR_a$ ranges between 2 and 5 hours (when expert staff help to resolve a problem during the shift with the help of ICT technologies), with an average of 3.5 hours
- D_{MTTR} ranges between 33% and 28%, with an average of 30%.

The objective is the maximization of D_{MTTR}, as this indicates a decrease of the mean time required to repair a failed device. The calculated value of the KPI shows the positive impact of the ICT for a failure-reduced operation.

KPIs applied by Premogovnik Velenje d.d. (PRV), Slovenia

At the current stage of implementing the new ICT infrastructure at the Velenje mine, a LAN/WLAN infrastructure has been installed in one longwall area. The specific objective is to facilitate wireless communication between workforce and staff at all important places at the longwall, at the head- and tailgate, and in the surrounding workings. Some details of this network are shown in Figure 5. Improved personal communication methods are expected to improve transport performance (in terms of increased efficiency or reduce labour consumption) and reduce downtimes as a result of faster response time.

The following described KPI is aimed at measuring the decrease in time required to reach a person.

KPI: 'D_{RT}' Average decrease of time to reach a person, %:

$$D_{RT} = \frac{t_{RTb} - t_{RTa}}{t_{RTb}}.100\% \qquad [5]$$

D^{RT} Average decrease of time to reach a person [%]

t_{RTb} Mean time to reach a person before implementation of new ICT [min]

t_{RTa} Mean time to reach a person after implementation of new ICT [min.

- Explanation:
  - Mean values should be determined by two test series, one for the day shift and one for the afternoon shift
  - The central control room should make about 10 attempts to contact a fitter or an electrician
  - The time from the first request until reaching the person is to be captured. Both tests should cover a period of 5 days minimum.

Preliminary findings

Figure 6 shows the measured response times for two different coal faces:

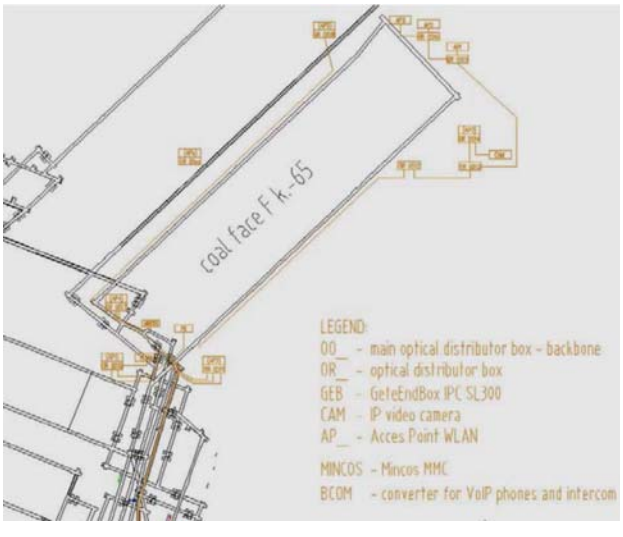

Figure 5—Network infrastructure at the face Fk.-65, Velenje Mine (Krenker and Skarja, 2013)

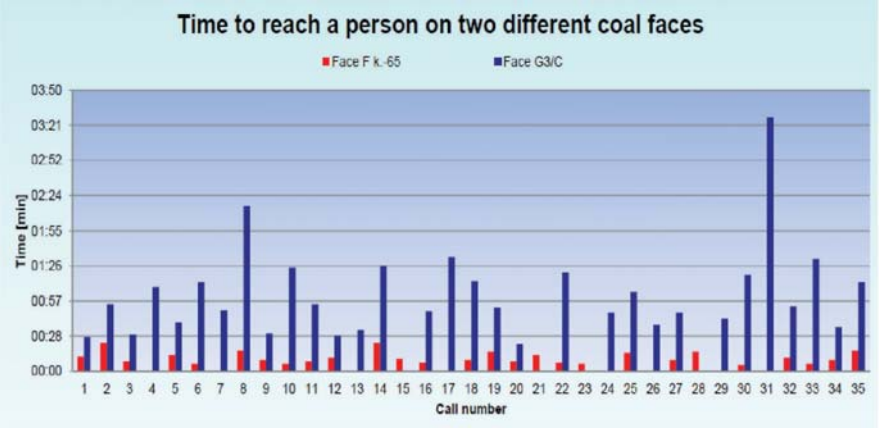

Figure 6—Time to reach a person at two different coal faces, Velenje Mine (Krenker and Skarja, 2013)

- Coal face 'G3/C' without ICT—Face length was 177 m, total length 675 m, average seam thickness 5.14 m, average efficiency (productivity) was 145 t per man and shift
- Coal face 'Fk.-65' with ICT, Face width was 154 m, length 480 m, average thickness 6.20 m, average efficiency (productivity) was 112 t per man and shift

The objective is the maximization of DRT, as this indicates the reduced time required to reach a craftsman in the longwall area. With regard to the successful attempts, the calculated value of DTR is 82%, which is a welcome improvement

Another KPI is aimed at measuring the ratio of successful call attempts. This should indicate the range of the WLAN network in the face area and the reliability of the installed devices.

KPI: 'R_{SC}' Average ratio of successful call attempts to a person equipped with VoIP phone or smartphone when within the range of the wireless communication network

$$R_{SC} = \frac{n_{SC}}{n_{TC}} \times 100\% \qquad [6]$$

R_{SC} Average ratio of successful call attempts [%]
n_{SC} Number of successful call attempts
n_{TC} Total number of call attempts.

Voice communication within the range of wireless network should in principle allow immediate contact to a person equipped with a VoIP phone or smartphone. In real conditions, some gaps may occur and a connection may not be established at some moments. This factor is incomparable with the state-of-the-art before and after implementation, but describes the reliability of the system and also reflects coverage failures of the wireless network. Measuring this factor could also help to determine areas where the system efficiency is low and requires, for instance, a denser node net.

Preliminary findings

The objective is the maximization of R_{FC}. The collected data indicates a R_{FC} of 77%, which shows the positive impact of the ICT on the time required to reach a person but also indicates that there is room for improvement.

Summary and outlook

In the demonstration project OPTI-MINE, funded by the European Union's RFCS programme, five underground coal mines have applied the latest information and communication technologies (ICTs) to improve efficiency, mine safety, occupational health, and environmental impacts of their operations. The improvements set by these technologies have been assessed with key performance indicators. Some of the KPIs cover transport performance, the increase of the level of information, the decrease of mean time to repair, the average decrease of time to call a person, and cost savings. The preliminary results give clear evidence that the new enhanced ICT will positively impact mine productivity and mine safety.

The research leading to these results was supported by the European Unions's Research Fund for Coal and Steel (RFCS) research programme under grant agreement No. RFCP-CT-2011-00001. (Malesza, A. and Szarafinski, M. and Strozik, G.)

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Geomechanics challenges of contemporary deep mining: a suggested model for increasing future mining safety and productivity

by F.T. Suorineni*, B. Hebblewhite*, and S. Saydam*

Synopsis

This paper pays tribute to the pioneers in geomechanics, and addresses some of the most pressing issues of our time related to deep mining, and how to mitigate these issues. Solutions developed by our predecessors seem to have reached their limits as mines continue to go deeper. The International Society for Rock Mechanics (ISRM) guidelines for rock mass characterization for excavation design also require re-thinking to reflect current knowledge and experience. Thus, a whole new approach is urgently required to increase mine safety and productivity. The paper will draw on the challenges and experiences in medicine and science that have been overcome through genuine collaboration, advances in technology, and impressive funding, which can be adopted to provide solutions to contemporary geomechanics challenges for increased safety and productivity as mines continue to go deeper.

Keywords

pioneers in geomechanics, pressing issues, new thinking, collaboration.

Introduction

Rock mechanics, and therefore geomechanics, is a relatively young subject compared to soil mechanics in geotechnical engineering. Suorineni (2013a) discussed in detail the difference between geomechanics and geotechnical engineering. Most failure criteria and test procedures in rock mechanics are adopted from soil mechanics and the mechanics of solids such as steel. The Mohr-Coulomb failure criterion (Mohr, 1900) is one such example and remains popular in rock mechanics today. Approaches to rock testing (such as triaxial testing) are adopted from soil mechanics. However, there is a fundamental difference between soil, concrete, steel, and rock, and in particular between soil and rock. Craig (1982) defines soil as any uncemented or weakly cemented accumulation of mineral particles formed by the weathering of rocks, the void space between the particles containing particles and/or air. On the other hand, in geology, a rock is a naturally occurring solid aggregate of one or more minerals or mineraloids (http://en.wikipedia.org/wiki/Rock (geology)). The key words in these definitions are 'uncemented' and 'aggregate' for soil and rock respectively. These keywords explain why a failure criterion for soils such as the Mohr-Coulomb failure criterion (Equation [1]) will work for soils, but is not applicable to rock.

$$\tau = c + \sigma_n \tan\phi \qquad [1]$$

where τ is the shear strength, c is cohesion, and ϕ is angle of internal friction.

As noted by others (*e.g.* Hajiabdolmajid *et al.*, 2000) Equation [1] implies that the shear strength of soil is determined by simultaneous mobilization of its cohesive resistance and frictional resistance. This is correct for 'uncemented' materials such as soil, but incorrect for an 'aggregate' of particles or minerals as in rocks. In the latter case the bond (cohesion) between the minerals need to be broken to generate frictional resistance and therefore the cohesive and frictional strength components cannot be simultaneously mobilized. Hence, some adoptions of experience in soil mechanics into rock mechanics can be misleading.

While soil and steel can be assumed to satisfy the criteria of continuity, homogeneity, isotropicity, linearity, and elasticity (CHILE), applying these assumptions to the rock leads to difficulty. Müller (1966) was first to recognize that the rock mass is a discontinuum, and has continuously emphasized the importance of geology in rock mechanics or geomechanics throughout his distinguished life and career. In 1988, Muller wrote:

'*Geology is the indispensable base of all the applied geosciences. Therefore, never Rock Mechanics without Engineering Geology; … But should I become confronted with the alternative: Rock Mechanics without Engineering Geology or Engineering Geology*

* *UNSW Australia School of Ming Engineering, Australia.*

without Rock Mechanics, I would choose the latter being the lesser evil. I am saying so as an Engineer, as a Rock Mechanics too.' Müller (1988).

On the passing of Dr J.A. Franklin in June 2012, Professor M.B. Dusseault sent out the following message:

'… John profoundly understood the intersection between geosciences and rock engineering, an attitude that pervaded his career.'

Franklin (1993) wrote: 'Empirical methods often prove "closer" to the "truth" than the apparently more precise predictions of theoretical analysis, … based on real data empirical methods provide a standard against which theoretical predictions are measured and can be judged.'

Similarly, Mathews *et al.* (1981), in developing the stability graph, stated that empirical methods based on back-analysis are powerful predictive tools, particularly if combined with numerical modelling and analysis techniques. Note that this statement regards theoretical predictions as supporting tools rather than stand-alone tools.

The importance of geology in rock mechanics, geomechanics, or geotechnical engineering cannot be overemphasized. This fact is underlain by the complexity of the rock mass as opposed to soil, concrete, or steel. The complexity of the rock mass cannot be fully accounted for in our constitutive models that underlie numerical models. While these numerical models can be tricked into giving us the answers we want, the rock mass is so idiosyncratic that it will behave in the manner it wants. Müller (1988) noted that the dominating geological conditions at site do not care what kind of theoretical ideas we may have and what our economic situation may be. He continued to state that the rock mass will act in the way that is predetermined by geological conditions on the one hand, as well as by the manner in which we treat it during excavation and support.

Pells (2008) posed the ultimate question: 'what happened to the mechanics in rock mechanics and the geology in engineering geology?' Pells's question separated rock mechanics and engineering geology and treated them independently. As shown above, rock mechanics cannot be treated from the purely mechanistic viewpoint without due consideration to the underlying geological complexities of the rock mass. As rightly pointed out by Peck (see Müller, (1988) 'where has all our judgement gone?' According to Peck, a good rock mechanics engineer should have good intuition to guide his decisions – a characteristic that the majority of the young generation of engineers today lacks, as a consequence of deficient knowledge in geology and field experience. Peck's concern is re-echoed by Karl Terzaghi: 'The geotechnical engineer should apply theory and experimentation but temper them by putting them into the context of the uncertainty of nature. Judgement enters through engineering geology.'

At the 44th United States Rock Mechanics Symposium, which was also the 4th United States-Canada Rock Mechanics Symposium, a pre-conference workshop was organized with invited panellists including Don Banks, William Pariseau, Maurice Dusseault, John Curran, Richard Goodman, and Charles Dowding, with Priscilla Nelson as moderator, to present their perspectives on the important achievements of rock mechanics and engineering in the past 50 years, and to identify what we did not achieve. The most common issue and problem identified was the deficiency in the training of rock mechanics engineers today. That deficiency is the absence of sufficient geology in the curricula of civil and mining engineering programmes.

It cannot be overemphasized that the great pioneers of rock mechanics, geomechanics, and engineering geology (including Karl Terzaghi, Ralph Peck, Leopold Muller, Evert Hoek, John Franklin, Denis Laubscher, Nick Barton, Z.T. Bieniawski, and Rimas Pakalnis) recognized the importance of geology, observed and learnt from the idiosyncratic rock behaviour, and guided by their intuition managed to discipline it. Empirical methods are the outcome of patient observations, intuition, and a keen interest in geology.

This paper pays tribute to these great men, but recognizes that although their contributions worked well to solve the problems of their time, they have now reached their limits and new thinking is urgently required. The paper draws on lessons from medicine and science to suggest that for significant breakthroughs in rock mechanics or geomechanics, genuine multidisciplinary approach supported by generous funding and rigorous overview is required. The next sections address these requirements in detail.

Empirical methods – state-of-the-art

The following empirical methods are discussed in view of their popularity and widespread use in geomechanics:

(i) The Rock Mass Rating (RMR) system (Bieniawski, 1973)
(ii) The Laubscher rules in block cave mining (Laubscher, 1994)
(iii) The open stope stability graph (Mathews *et al.*, 1981; Clark and Pakalnis, 1997)
(iv) The hard-rock pillar design graph (Lunder and Pakalnis, 1997)
(v) The Tunnelling Quality Index (Q) system (Barton *et al.*, 1974)
(vi) The Hoek and Brown failure criterion (Hoek and Brown, 1980).

These methods all depend on proper characterization of the rock mass. Critical factors in these methods depend on the purpose. Such purposes include support selection, caveability prediction, determination of rock mass properties for design, and evaluation of the stability of open stopes. In each specific case there are insufficient guidelines from the International Society for Rock Mechanics (ISRM) Suggested Methods for Rock Characterization, Testing and Monitoring (Brown 1981). Obvious difficulties are encountered in the caveability of rock masses. The ISRM suggestion that induced fractures be ignored in geotechnical mapping for rock mass characterization is suspect when the purpose of such a mapping is for support selection.

The Rock Mass Rating (RMR) system

RMR (Bieniawski 1973) became the most widely accepted and used rock mass classification system following its development in 1973. Its popularity stemmed from the fact that it could be used for excavation design in rock with significant capacity to predict excavation stand-up time. RMR was also adopted by Hoek and Brown (Hoek and Brown, 1980) for the determination of the Hoek and Brown failure criterion parameters. RMR was replaced by the Geological

Strength Index (GSI) in 1995 (Hoek *et al.*, 1995) for that role because it became ineffective in performing that function for values of RMR less than about 25.

Various critiques of RMR have been published, out of which evolved the Modified or Mining Rock Mass Rating (MRMR) system (Laubscher and Taylor, 1976). Milne *et al.* (1998) outline a chronological development of the method between 1973 and 1989. Within this period the RMR factors have been modified as more experience in its application was gained.

Suorineni (2013b) critically re-examined the original RMR database for its validity, robustness, and application independent of the geological environments or rock types and depth. The validity of the method with regard to its stand-up time prediction was also examined. Figure 1 summarizes the composition of the RMR database in terms of rock origin as published in Bieniawski (1989). The figure shows that the RMR (1989) database consists of 63% sedimentary rocks, 17% metamorphic, and 20% igneous rocks. Of the 63% sedimentary rocks, about 45% are shale (Figure 2). Figure 3 is a plot of depth against frequency of data points. The figure shows that about 90% of the data came from depths less than 500 m below surface.

From Figures 1 to 3 it is obvious that the RMR database comprises mainly soft rocks, dominated by shales, from depths less than 500 m below surface. The significance of this revelation for the composition of the RMR database is discussed under the Laubscher block caving rules (Laubscher, 1994, 2001) later in this paper. The implication of the database as it relates to stand-up time (Figure 4) of excavations is discussed here.

Sedimentary rocks, and in particular, shales, are susceptible to the vagaries of the environment on exposure, depending on their composition. Domination of the RMR database by sedimentary rocks gives logic to the stand-up time concept. While this may also be true for some igneous rock such as olivine-rich rocks, it is difficult to argue the concept of stand-up time for excavations in these rocks. As pointed out by Müller (1988), while timing is important in rock engineering or geomechanics it can hardly be computed or even assessed without deep geological knowledge and intuition. This is further buttressed by the fact that 'one cannot wait until the rock itself announces its stand-up time by roof falls and slabbing of the side walls' (Müller, 1988). One must make decisions before the stand-up time is reached. Isaacson (2007) states that Albert Einstein's intelligence and breakthroughs hinged on his ability to mix intuition with a feel for the patterns to be found in experimental data. He adds 'The scientist has to worm these general principles out of nature by discerning, when looking at complexes of empirical facts, certain general features.'

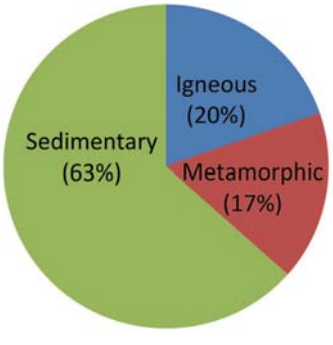

Figure 1—Composition of RMR database by rock type (Suorineni, 2013b)

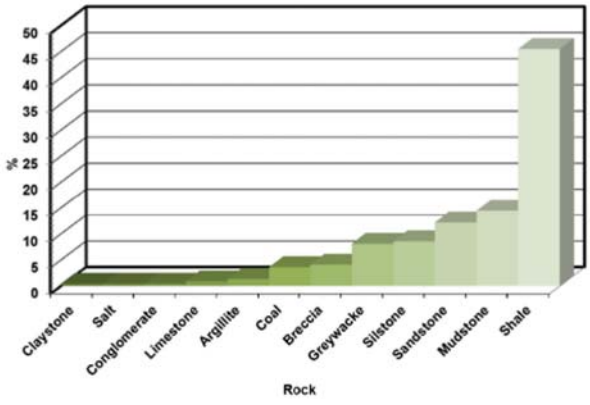

Figure 2—Distribution of RMR database according to sedimentary rock type (Suorineni, 2013b)

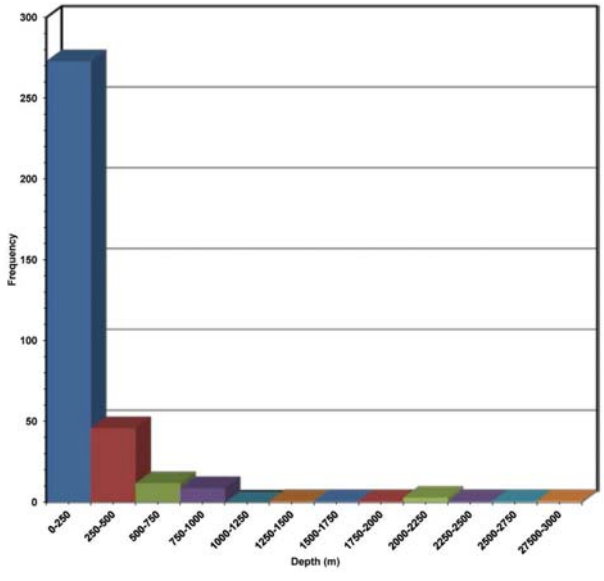

Figure 3—Distribution of RMR database with depth (Suorineni, 2013b)

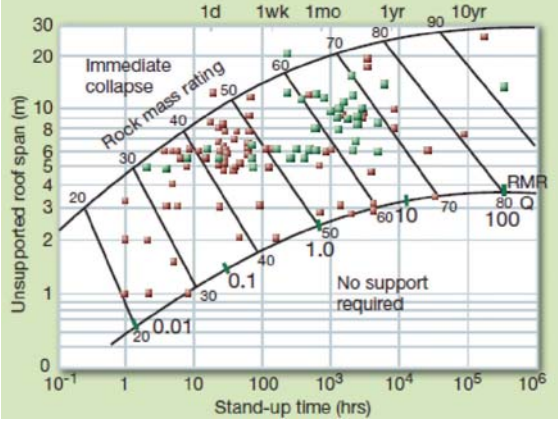

Figure 4—Stand-up time chart (Barton and Bieniawski, 2008)

Laubscher block caving rules

The Laubscher block caving rules are based on a modified RMR, the MRMR. Figure 5 is a chart for predicting the critical undercut size (hydraulic radius – HR) in a rock mass of given MRMR quality to induce natural caving under gravity. RMR, and for that matter MRMR, were developed between 1973 and 1976 respectively. The recent modification to the MRMR termed IRMR (Laubscher and Jakubec, 2000) is not significantly different (Dyke, 2008) from the MRMR. At time of development of RMR and MRMR most block caving mines were operating at depths less than 450 m (Figure 6). The rocks in the RMR database involved are mainly weak and dominated by shales, with most data coming from depths less than 500 m below surface. Block caving mines today are located at depths far in excess of 500 m and in metamorphic and/or igneous geological environments. Under these conditions, stronger rocks at depths will be subjected to higher confinements and the Laubscher caving rules become suspect. It is the opinion of the authors that while the Laubscher caving rules would have been effective at the time of their development, they have reached their limits in contemporary block caving practice and new thinking is required.

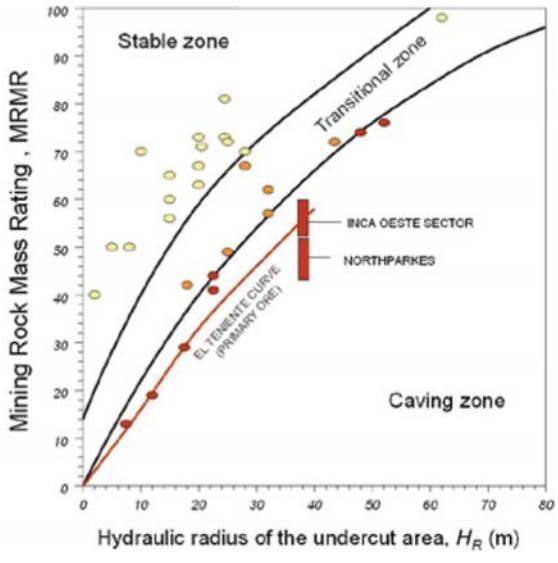

Figure 5—Laubscher caveability prediction chart (Flores and Karzulovic 2003)

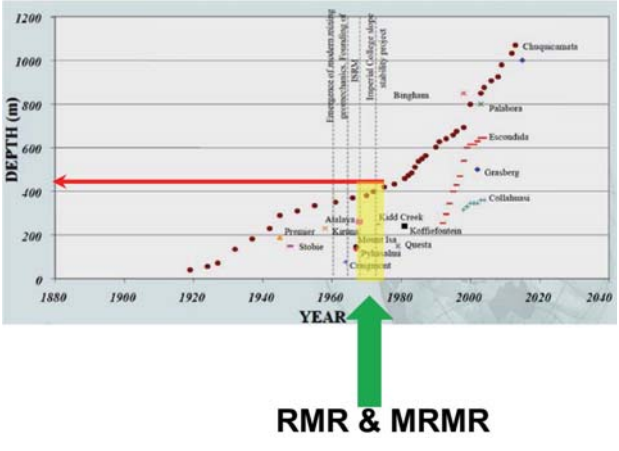

Figure 6—Evolution of mining depth with time and RMR and MRMR database (after Brown, 2004)

The stability graph

The stability graph was developed by Mathews *et al.* (1981) as a tool for guiding bulk mining methods. It is one of the most discussed empirical methods in geomechanics. Suorineni (2010, 2011, 2012) discusses in detail the modifications to the stability graph since its development in 1981. The paper concludes as follows:

(i) As an empirical method, the reliability of the stability graph method is largely dependent on the size, quality, and consistency of the database. Hence, there must be consistency in the determination of the stability graph factors and accepted stope stability state transition zones

(ii) The present tendency for authors to arbitrarily choose between the original and modified stability number factors results in incomparable data that cannot be combined

(iii) The different transition zones produced by different authors result in different interpretations of the stability state of stopes

(iv) There is need for factors that account for stope stand-up time, blast damage, and a gravity factor that is stress-factor dependent

(v) There is a need to develop procedures for determining stability of open stope surfaces that consist of backfill

(vi) The stability graph should be used with caution when applied to narrow vein orebodies because no version of the graphs accounts for orebody thickness in the definitions of the stability states.

In addition to these conclusions, some criticisms of the stability graph emanate from authors who do know the assumptions behind the development of the stability graph but do not know the limits of the database. Suorineni (2010, 2011, 2012) discusses in detail the assumptions behind the development of the stability graph. Obviously, if the underlying assumptions are understood, there need not be criticism about the stress factor not accounting for tension, or the stability graph not being applicable to narrow vein stopes and shallow-dipping stopes. Additionally, while open stope mining is limited to good quality rock masses, the method has been extended to poor quality rock masses, resulting in unacceptable dilutions for which the method has been blamed.

A positive contribution to the stability graph is its quantification by Lunder and Pakalnis (1997). The original and modified stability graphs are qualitative. A stope is stable, unstable, or caved. The miner is keen to know his dilution numbers and whether those numbers are acceptable or not. The equivalent linear overbreak slough (ELOS) stability graph introduced by Lunder and Pakalnis (1997) overcame this deficiency. However, it is still uncertain how orebody size is accommodated in the ELOS stability graph. This has implications for the application of the graph to wide and narrow vein situations.

The extended Mathews stability graph (Trueman and Mawdesley, 2003) also contributed positively to the stability graph by expanding the database from 175 case histories to over 400. However, unfortunately, the authors used the original stability graph factors based on 26 case histories instead of the calibrated factors from 175 case histories. More importantly, not all the case histories are from open stope mining and hard rock environments. Figure 7 shows the composition of the database by mining method.

The hard-rock empirical pillar design chart

Credit is given to Professor Rimas Pakalnis for his endeavours in promoting and developing empirical methods that are simple, practical, and easy to use by the mining/rock engineer.

The ELOS stability graph, the critical span graph, and pillar design charts are widely used in mining camps and by consultants around the world. Dr Pakalnis continues to serve the industry in more practical issues, remote from the academic quest. 'An academic career in which a person is forced to produce scientific writings in great amounts creates a danger of intellectual superficiality' (Einstein).

It is argued here that mechanistic approaches and the use of numerical modelling have become pervasive in today's geomechanics practice because they are governed by rules (equations) such that presumably they are used without thinking and beautiful computer graphics outputs are all that we need in reports and theses. There is an urgent need for more effort in field data collection to understand the behaviour of the rock mass so that we can effectively and efficiently use our fast machines and complex models to make more reliable predictions.

Admittedly, empiricism alone does not solve all geomechanics problems (neither will mechanistic approaches alone), but the latter must be treated with more caution in geomechanics when used by inexperienced engineers with little or no field exposure.

There are benefits to the use of technology and computers in geomechanics, but these must be guided by reason. Einstein stated that '… Instead of being a liberating force it (technology) has enslaved men to machines.' (Isaacson, 2007).

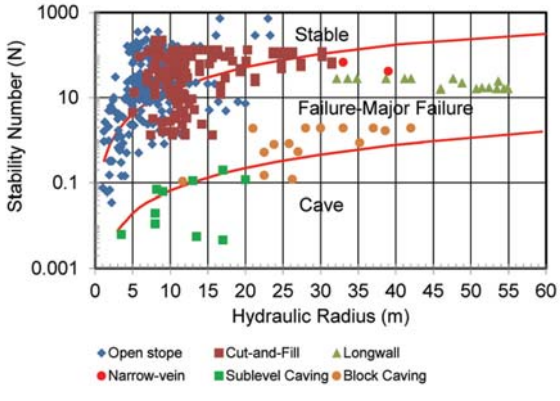

Figure 7—The extended stability graph database replotted with data grouped according to mining method

The Tunnelling Quality Index: Q-system

The Q-system (Barton *et al.*, 1974) is well detailed in several publications, and the discussion here is limited to what many never venture to look at – the footnotes and assumptions. These apparent oversights have resulted in unwarranted criticisms of the method. Here are some significant points from Barton *et al.*, (1974):

(i) Joint orientation relative to tunnel axis did not appear to be a significant factor because the database is from civil tunnels, which are often placed in the best orientation

(ii) Different personal, national, and continental engineering practices lead inevitably to variations in methods of support, even for the same quality of rock. In mining, regulations will dictate support levels and practice

(iii) Support recommendations in the Q-system are for permanent support

(iv) Support recommendations assume good blasting or excavation practice. For better drilling and blasting or poorer drilling and blasting (deviation from average) the support recommended by the Q-system may tend to be conservative or inadequate respectively. To account for poor blasting practice, adjust *Jn* and RQD accordingly

(v) The joint set with minimum *Jr*/*Ja* should always be used in computing Q.

The Q-system is a major contribution to rock mechanics/geomechanics and Barton *et al.* (1974) deserve commendation. Today, there is a general feeling that its applications have been too much extended beyond its database limits. QTBM is one such version of extended application. Palmström and Broch (2006) provide a critical review of the Q-applications and chronicle its various developments between 1974 and 2002. They advise that potential users of the Q-system, and for that matter any other empirical method, should carefully study the limitations of the system before taking it into use.

What seems to be an implicit problem is the definition of the term 'block size'. In the equation expressing the Q-system:

$$Q = \left(\frac{RQD}{J_n}\right)\left(\frac{J_r}{J_a}\right)\left(\frac{J_w}{SRF}\right) \qquad [2]$$

the following interpretations are assigned to the quotients on the right hand side:

$\frac{RQD}{J_n}$ = Block size

$\frac{J_r}{J_a}$ = Interblock shear strength

$\frac{J_w}{SRF}$ = Measure of active stresses

The block size and interblock shear strength definitions seem to imply that every rock mass is made up of discrete blocks defined by continuous joints. This interpretation implies that the three rock masses shown in Figure 8 will have the same Q value and therefore the same self-supporting capacities. Obviously, this is not the case, either intuitively or in our experience.

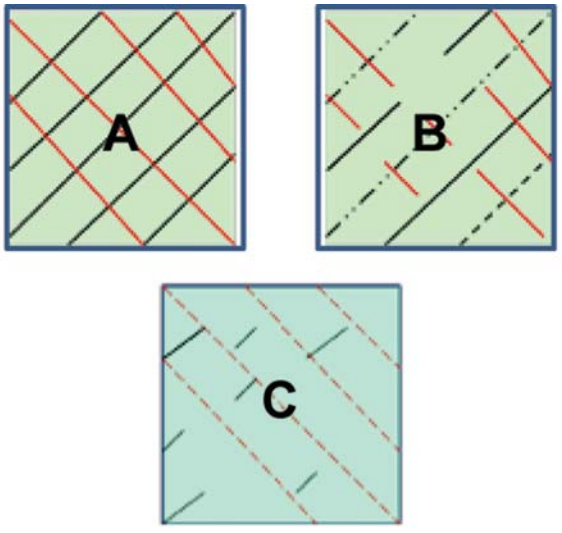

Figure 8—Schematic representation of the influence of rock mass self-support capacity based on joint persistence (Suorineni *et al.*, 2008)

Since most of the initial data came from civil engineering tunnels, it is not surprising that relative orientation was not considered a significant factor for inclusion in the Q-system, since most civil tunnels are aligned in the best orientation for stability. In mining, engineers have no such luxury of choosing the drift alignment in the most stable orientation, but often have to deal with the consequences and the effect of relative orientation of excavations with geologic structures that must be accounted for in stability analysis.

Another implicit problem with the Q-system is the difficulty in applying it to weak rock masses. In weak rock masses the Q-system parameters are difficult to determine and excessive deformation may be the mode of failure rather than structural or brittle failure. This weakness of the Q-system appears not to be obvious to many users of the method. Løset (1999) states:

'*The Q-system was primarily suited to hard jointed rocks … but for the classes of poorest rock quality the system has not provided detailed description of the support constructions. This means that for weak rock masses the dimensioning of the support must usually be verified by numerical modelling or some other means of calculation.*'

Løset (1999) identify six types of weak rock masses as follows:

(i) Heavily jointed strong rocks (Q<0.01)
(ii) Zones with altered or strong rock (squeezing or swelling may take place)
(iii) Weak rocks with joints (young sedimentary rocks (sandstone) or weakly metamorphic rocks such as shale, slate, or phyllites)
(iv) Weak rocks with excavation-induced fractures (e.g. young homogeneous sedimentary rocks (chalk, sandstone) or low-grade metamorphic rocks (shale, phyllites)
(v) Weak rocks without joints or induced excavation fractures (young homogeneous sedimentary rocks such as chalk, sandstone, and mudstone)
(vi) Weathered rocks.

The Hoek-Brown failure criterion

The Hoek and Brown failure criterion (Equation [3]) has dominated the rock mechanics/geomechanics world in terms of use and acceptability.

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a \qquad [3]$$

where σ_1 and σ_3 are the effective major and minor principal stresses at failure respectively, σ_c is the intact rock uniaxial compressive strength, and a, m_b, and s are constants that depend upon the characteristics of the rock mass.

Hoek and Marinos (2007) provide a summary of the various modifications to the Hoek and Brown failure criterion and Geological Strength Index (GSI) (Hoek *et al.* 1995) from 1980 to 2006. The most recent version of the Hoek and Brown failure criterion is given in Hoek *et al.* (2002). In this update, a new parameter referred to as the rock mass disturbance factor (D) is introduced to deal with blast damage and other disturbances. This factor allows for the determination of more appropriate Hoek-Brown parameters depending on the degree of disturbance inflicted on the rock mass by the excavation method.

The Hoek–Brown failure criterion is based on the assumption that a jointed rock mass is fundamentally weaker in shear than intact rock (Diederichs *et al.*, 2004). Although the Hoek-Brown failure criterion has been widely accepted, it is not free from criticism. Following these criticisms, various authors including (Martin, 1994; Pelli *et al.*, 1991; Diederichs *et al.*, 2004; Carter *et al.*, 2008) have offered some modifications to the criterion, claiming that it is not universally applicable to the full range of rock mass qualities as defined by the GSI.

In 1994 Hoek, in a letter to editor of International Society for Rock Mechanics (ISRM) News Journal, wrote:

'In writing Underground Excavations in Rock 15 years ago Professor E T Brown and I developed the Hoek-Brown failure criterion to fill a vacuum which we saw in the process of designing underground excavations. *Our approach was entirely empirical and we worked from very limited data of rather poor quality. Our empirical criterion and our estimates of the input parameters were offered as a temporary solution to an urgent problem.*

'*The fact that the criterion works, more by good fortune than because of its inherent scientific merits, is no excuse for the current lack of effort or even apparent desire to find a better way.*'

What is surprising is that a flawed 'temporary solution' has become a permanent solution. As further alluded to by the authors, instead of engineers of today going back to the fundamentals to develop a better failure criterion based on a good understanding of geology and 'physics', more time is spent criticizing the criterion – sometimes without suggesting solutions. Nor is any effort made to collect field data to back up any criticisms or suggested modifications.

More time is spent on computer modelling, with little fieldwork to validate such models. The input parameters to these models mostly cannot be justified, as the current generation of engineers does not understand the significant role of geology and the resulting uncertainties governing the input parameters and failure criteria. Hence it is not

surprising to come across research results like those shown in Figure 9. Ironically, after knowing how the tunnel Figure 9 failed, we are then able to capture the failure (as in Hadjiabdolmajid 2001; Carter *et al*., 2008) after manipulating the input parameters and failure criterion.

Thus in most cases we are able to correctly predict the behaviour of excavations in our numerical models only after the fact, by manipulating input parameters to match observations under the cover of so-called 'back-analysis' or 'model calibration'. While we will most often satisfy ourselves this way in our offices, the rock mass is so idiosyncratic that in our next project it will defy our prediction and behave again in its own way.

Challenges of our time

Our predecessors made efforts to solve the problems of their time. Today we are faced with challenges beyond the solutions of our predecessors. Those solutions have reached their limits. The challenges in our time include development of failure criteria suitable for rock, guidelines for optimized block cave mine design based on a deep understanding of caving mechanics, predicting rockbursts, and seeing through the *in situ* rockmass.

We need ways to see inside the block cave and to resolve issues like unexpected ground conditions. The prospect of rockburst prediction still remains remote and all we can do is monitor, mitigate, and identify potential high-risk areas. We are also faced with the issue of reducing *in situ* stress measurement errors to acceptable levels. Excavation face fatalities continue to occur.

Recent events in the mining industry, including the Northparkes airblast fatalities, Grasberg mine disaster, Beaconsfield fatalities, and fatalities in mines in the Sudbury Basin, have exposed the limits of our current knowledge. The reports from these investigations mostly concluded that the circumstances leading the incidents could not have been foreseen. Our inability to foresee such circumstances indicates the limitations of our current knowledge. We need technology to see behind total cover surface support systems such as shotcrete and thin spray-on liners (TSLs). Ultimately, we need technology to see behind the excavation face and to monitor the inside of block caves in real time. We need technology to predict and mitigate rockbursts. The phrase 'unexpected ground conditions' is an example of an excuse that stifles the urgent need for technology required to overcome our limitations.

There are other valuable applications of technology in the mining industry. This is captured by Peterson *et al.* (2001), who states: 'It is the knowledge management benefits of new IT technology that will provide the greatest benefit to the industry (Mining). Although mine operations are generating more data, such information is rarely well utilized.'

To bridge and expand our knowledge to cope with current challenges require new thinking. Lessons learnt from science and medicine indicate the path to developing solutions in geomechanics through core rather than peripheral research. These are discussed next.

Lessons from medicine

The field of medicine faces serious challenges at any one time. However, these challenges are often met with enduring efforts by the medical community to understand their origins and develop the appropriate technologies to offset their impact. Until recently these efforts have been generally individualistic with various experts working in 'protective silos'.

While the silo approach to research in medicine produced results, it often took several decades and generous funding to produce significant results and or breakthroughs. A good example is the race for a cancer cure. For several decades, the search has been carried out by individuals working in silos. Each individual has been an 'authority' in his own right. This approach has not resulted in any major or significant breakthroughs.

The difficulty in curing cancer lies in the fact that it is not just one disease. Cancer has potentially thousands of causes, and not all cancers are caused by just one agent. Hence, it is now recognized the challenge to unravel the cancer myth and find a cure, cannot be achieved through the 'silo' research approach.

The Stand Up to Cancer (SU_2C) organization (Park, 2013) has brought a paradigm shift to medical research by bringing science and medicine together, fostering genuine collabo-

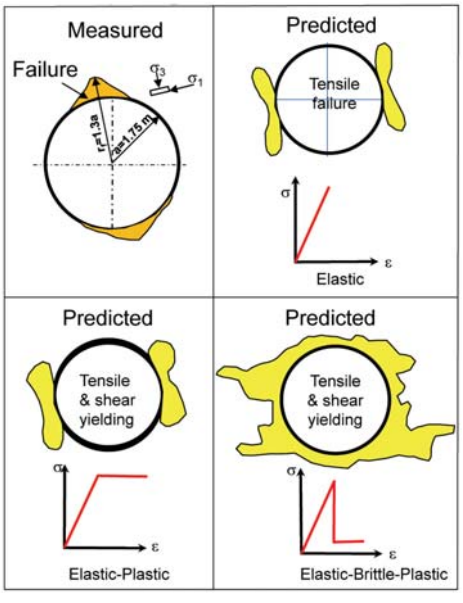

Figure 9—Tunnel failure – prediction *versus* reality (Read and Martin 1996)

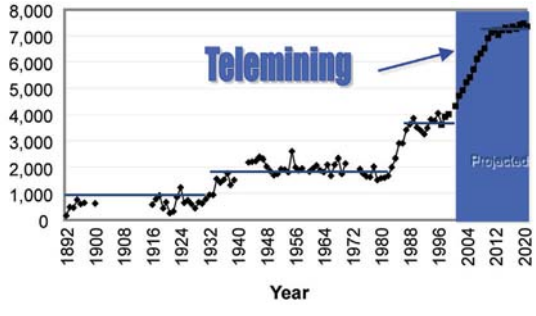

Figure 10—Step change increase in mine productivity from advances in technology G. Baiden (pers. comm.)

rative core research by breaking down individual expert research silos, and providing generous funding to collaborative core research groups.

With this strategy, individual experts working in defensive silos in secrecy on various aspects of cancer are brought together to form multidisciplinary collaborative core (not peripheral) research groups in which egoistic barriers are broken and former competitors are working together. This approach brings the best talents together and is seen to lead to significant medical breakthroughs in relatively short timeframes.

Park (2013) notes that multidisciplinary collaborative breakthroughs in medicine are enhanced and accelerated by development and use of relevant technology. Technological advances in medicine have come from bioengineering, nanotechnology, new drug compounds, data gathering, and cheaper and more powerful computers. Collaboration results in strength in numbers, and combined with technology, leads to dazzling scientific and research advances.

Lesson from science

Like the lessons in medicine, breakthrough in science in recent times is also a result of technology and genuine collaboration.

The recent discovery of the Higgs boson, the so-called 'God particle' which had eluded physicists for nearly five decades since its existence was proposed, was a result of genuine multidisciplinary collaboration and availability of the relevant technology backed by generous funding. The A Toroidal Large Hadron Collider (LHC) Apparatus (ATLAS) Collaborations (2012) reports that in this project nearly 2000 physicists from US institutions (89 universities and seven Department of Energy laboratories) participated in the ATLAS and Compact Muon Solenoid (CMS) experiments, making up about 23 per cent of the ATLAS collaboration and 33 percent of CMS at the time of the Higgs discovery. The LHC apparatus cost US$10 billion.

The LHC is the enabling technology in the project that was built by the Centre Européen de Recherche Nucléaire (CERN) particle physics laboratory on the Swiss-French border. This was a multinational genuine collaborative research project.

The prediction of the existence of Higgs boson as part of the Standard Model (SM) in 1964 and its eventual discovery (proof) through experiments was a demonstration of the strength of genuine multidisciplinary collaboration backed by persistence and generous funding. The SM explains the prevailing theory that describes the basic constituents of matter and the fundamental forces by which they interact (Veltman, 1986) and is the most successful explanation of the universe to date.

Model for progress in geomechanics

If physics were geomechanics, the Higgs boson would never have been predicted, much less discovered. It is also frustrating that, unlike in medicine, silo rather than genuine collaborative research persists in geomechanics. Research silos exist and thrive in geomechanics and academia for the following reasons:

(i) Who owns the credit for what is achieved?
(ii) Who owns the intellectual property?
(iii) Who is the lead author of the paper?
(iv) How many papers can I publish?
(v) How much of the money can I get?
(vi) I should be better than all others

The collaboration of the best brains, independent of initial individual differences, leading to major breakthroughs in geomechanics is still decades away. Müller (1988) notes that no doubt much goodwill and intimate collaboration is required to translate into reality the synthesis of rock mechanics and engineering geology. Terzaghi had a similar ambition, that of a synthesis between soil mechanics and engineering geology. To the contrary, Müller notes:

'*Unfortunately collaboration is rare between human beings and is still more rare between specialists. I consider the lack of real and through going collaboration one of our daily problems. Many failures, waste of many and even disastrous events and loss of life I have experienced by this reason.*'

Müller's statement, made in 1988, still hold true in geomechanics and among rock engineers, engineering geologists, and geologists. It is sad to note that there is no two-way communication between ground control engineers and geologists in our mining camps. Such constant communication could alleviate most of the fatalities on record.

The inconvenient truth is that rock is the most complicated material to deal with compared to soil, concrete, or steel. To control or manage this complicated material we have to understand it. Neither the geologists, rock engineers, nor engineering geologists have sufficient knowledge individually to understand rock behaviour. Understanding rock behaviour requires genuine multidisciplinary collaboration between the best brains in geoscience and engineering, independent of personal differences, coupled with development or adoption of the appropriate technology and generous funding.

The challenges facing geomechanics practice today can be solved through the following model adopted from the experiences in science and medicine:

'*Bring the best and most talented possible brains from multidisciplines in earth science and engineering together independent of personal differences, fund them generously, oversee their progress rigorously in a tight schedule, and they will unravel the challenges in geomechanics.*'

The multidisciplinary collaboration should include the identification, adoption, and development of appropriate technologies for seeing through the rock mass in a manner similar to the way in which medical CT scanners can see through the human body to diagnose ailments. We need a 'transparent rock mass'.

Rockbursts are the 'cancer' in geomechanics. The phenomenon of rockbursts has been studied for over a century, and yet the causes remain poorly understood and the prospect of being able to predict them remains remote. Salamon, in 1983, stated 'A disconcerting feature of rockbursts is that they defy conventional explanation.'

This statement remains true today. We could solve rockbursts and prevent associated fatalities in our underground mines through genuine multidisciplinary collaboration and generous funding. We need to stand -up to rockbursts (SU_2R), just as the medical scientists are standing up to cancer (SU_2C).

We can remove workers from the work face by developing and adopting appropriate technologies. Technology exists for doing this. If the National Aeronautics and Space Administration (NASA) can send robots to explore Mars, there is no excuse for the mining industry's inability to remove workers from the excavation face and mine remotely. Unmanned robots such as the 'Rover' could drill, charge, blast, muck, and support. Steve Perry and Larry Knight would be alive today.

Current proposed technologies for mining seem to focus on peripheral issues rather than core issues, which if tackled successfully would bring about enormous benefits in terms of safety and productivity. Evidence exists (Figure 9) that step changes in technology result in equivalent increases in mining productivity.

A suitable failure criterion for rocks remains elusive, while the determination of rock mass properties remains a challenge. Our inability to overcome the myth of 'unexpected ground conditions' remains. The ability to see behind total cover surface support systems (such as shotcrete and TSLs remains daunting. Errors in *in situ* stress measurements continue to be unacceptable, and are continuously becoming worse as we mine at deeper levels. Hoek (1994) states:

'*Techniques for measuring in situ stress while greatly improved from what they were still give an amount of scatter which would be unacceptable in almost any other branch of engineering.*'

The solutions to these problems require a multidisciplinary genuine collaborative research in geoscience and engineering, coupled with the development and adoption of appropriate technologies.

Conclusions and recommendations

Our predecessors developed solutions to the problems of their time that we continue to use, albeit with mixed results. As our mines continue to go deeper, so do the solutions of our predecessors continue to become less adequate in terms of their predictive abilities.

Increasing computing power is not accompanied by a similar ability to collect and determine appropriate rock properties for our powerful and complex numerical modelling codes. Indeed, field work and laboratory investigations are now being replaced with computer simulations and laboratories are shutting down. We need to reverse course, as computer simulations need realistic inputs to be valid.

To control and manage structures in rock, we need to understand rock. Geology is the pathway to understanding rock. Geology should be emphasized in mining and civil engineering programmes.

Experience in science and medicine shows that the problems in geomechanics can be overcome through genuine interdisciplinary collaboration, generous funding, and development of appropriate technologies. The future of safe and productive mining lies in the development/adoption of relevant technologies that can assist our understanding of rock behaviour and remove man from the excavation face.

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Efficient use of energy in the ventilation and cooling of mines

by J.J.L. Du Plessis*, W.M. Marx†, and C. Nell‡

Synopsis

Escalating energy and electricity costs have become one of the largest drivers of expenditure in mining operations. Over the last eight years, energy costs have tripled when expressed as a percentage of total expenses in South African mines. In an effort to manage and reduce electricity costs, energy management strategies can be developed, inefficient operating units replaced, and the operation of energy-consuming components of ventilation systems optimized.

Power consumption on mines is controlled mainly by three strategies, namely *load clipping*, by which energy use is reduced for certain parts of the day; *load shifting*, by which energy use is shifted to other parts of the day; and *energy efficiency*, by which energy use is reduced permanently.

In this paper several projects that were implemented using the first two strategies of load clipping and load shifting are investigated. The actual and potential savings that can be achieved by implementing such energy-saving interventions are presented.

To reduce the operating costs of ventilating and cooling underground mines permanently, system optimization studies must be completed. Methods that can be used to reduce energy usage by optimizing cooling and ventilation systems are described, and network simulation models that accurately reflect the current and planned ventilation conditions are discussed.

These models are then used to examine various options for improving the overall ventilation and cooling strategy. Different optimization scenarios can be simulated, and this assists the design engineer in obtaining the most energy-efficient system that will satisfy design workplace conditions. The final outcome is a reduction in operating costs, which can result in better operating margins and an extension of the life of mine.

Keywords

energy, electricity costs, efficiency, ventilation, cooling, optimization, simulation, energy management, energy strategy, load clipping, load shifting.

Introduction and background

South African electrical power costs have traditionally been low by international standards. However, recent tariff increases and future projections of power costs have resulted in a significant rise in operating costs. Power tariff structures vary throughout the day, differ on Saturdays and Sundays, and change between winter and summer. The difference between the lowest and highest tariffs is as much as a 1 000% (Eskom, 2013). Although difficult to quantify, the cost of non-delivery of power will have an even greater effect on mine costs, productivity, and safety. Eskom (the South African electricity public utility) has attempted to alleviate the scarcity of electricity in South Africa by contacting and asking large users of electricity, including the mines, to reduce consumption, which could have an adverse impact on mine production.

Internationally, increasing electricity costs are among the largest drivers of expenditure in the mining industry and the reduction of energy use, and thus power costs, can assist in offsetting lower commodity prices and reducing margins.

Many of the larger corporations and mining houses have identified energy and the management thereof as a production and cost driver. One such study (Du Plessis and Van Heeswijk, 2012) showed that energy now constitutes over 20% of the mines' cost base. From this study, an integrated energy and carbon management strategy was developed to facilitate a holistic approach to managing energy and carbon emissions. It covered generation sources and the main fuel- and electricity-consuming assets, and considered mining methods and how they affect energy intensity. The strategy arrived at considered six key elements, namely:

- *Understand:* measuring, monitoring, and managing energy consumption and carbon emissions
- *Plan:* factoring energy and carbon emissions into operational and life-of-mine plans
- *Operate:* operating core assets more efficiently to achieve lower energy intensity

* *Department of Mining Engineering, University of Pretoria.*

† *BBE Consulting.*

‡ *BBEnergy.*

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- *Replace:* replacing carbon-intensive sources of energy with renewable energy
- *Invest:* spending now to reduce energy costs in the future
- *Enable:* addressing underlying factors that will enable the company to reach its energy and carbon goals.

All of these elements must be considered in the life-cycle design. Furthermore, it is important that mine ventilation and cooling systems operate as efficiently as possible to reduce capital requirements and operating costs, without compromising a safe and healthy working environment.

There are several stages during the design, implementation, and operation of mine ventilation and cooling systems where energy efficiency can and should be optimized. The initial stage is planning and optimization of primary variables for the proposed system. Next, individual system components are optimally designed, followed by the efficient integration of these components. Finally, energy efficiency is further improved during operation through cyclical control of systems and ultimately by supplying ventilation and cooling on demand. Any reduction of electrical power cost must be evaluated in relation to the effect on production and the overall mine operating cost per ton mined.

System optimization

Although it is important to ensure that single ventilation and cooling components (fans, pumps, compressors, *etc.*) are appropriately designed and energy-efficient equipment is procured, reducing the operating costs significantly requires overall system optimization. A typical ventilation system in a deep South African mine consists of downcast and upcast shafts, intake and return airways, and a main exhaust fan installed at the top of the upcast shaft. A typical cooling system includes a refrigeration plant producing cold water and heat exchangers cooling the mine's intake air by direct or indirect contact with the cold water. This strategy applies to current ventilation and refrigeration systems in operating mines, as well as to the designs of future operations.

System energy efficiency is achieved by operating mines at optimum airflow quantities and cooling capacity, and by cyclical and on-demand operation. For instance, large amounts of power are consumed by refrigeration equipment in the South African gold and platinum mining industries, with total installed refrigeration capacity of the order of 1 400 MWR. This relates to about 350 MWE of electrical motor ratings for refrigerant compressor drives, with motor sizes generally ranging from 0.5 to 2.5 MWE. In addition, the direct auxiliaries (cooling towers, condenser pumps, *etc.*) will have a total electrical rating of approximately 150 MWE, with motor sizes ranging from small to about 0.3 MWE. Thus, in the South African gold and platinum mining sectors, the total electrical nameplate rating for refrigeration equipment is about 500 MWE.

The engineering and operation of these systems has evolved over some decades to the current state of the art and significant achievements in energy efficiency have resulted (Gunderson *et al.*, 2005). The integration of energy-efficient systems (pumping, ventilation, refrigeration, *etc.*) and ventilation-on-demand (VOD) is still not commonly implemented, and there is room for further improvement in future (Acuña *et al.*, 2014).

Energy saving methods and strategies

Power consumption on mines is controlled mainly by three strategies, namely *load clipping*, by which energy use is reduced for certain parts of the day; *load shifting*, by which energy use is shifted to other parts of the day; and *energy efficiency*, by which energy use is reduced permanently.

The typical South African mining cycle in hard rock mining consists of two eight-hour shifts per day, one mainly for drilling and charge-up and one for removing the broken rock from the production zone. The third eight-hour period is dedicated to blasting and the clearing of the blasting fumes and dust, which is normally done in the afternoon. Production zones are thus occupied for a maximum of 16 hours per day. Although personnel are underground during the blasting shift, they will be in intake airways around the shaft. The conventional approach to mine ventilation and cooling is to ventilate and cool the entire mine all of the time. This approach fails to exploit the cyclical nature of mining, diurnal variations in ambient temperature, and variations in the cost of electrical power, and does not allow load clipping or shifting tactics to be implemented.

This cyclical schedule is ideal for implementing the operation of an energy-efficient ventilation and cooling system, as there are periods of the day when there are no personnel in the production zones. Fan power and refrigeration can be reduced during these times in a structured way. The following main methods and strategies have been implemented.

Main fans

Major work has been done on the energy optimization of main fans in South African mines. In most of the deeper mines, load clipping projects are implemented where inlet guide vane (IGV) control is used to reduce the load during periods of peak power demand (Du Plessis and Marx, 2007, 2008). IGV control involves specially designed, adjustable vanes installed in the air stream entering the fan inlet. These static (angle-adjustable) vanes are used to generate a swirl of air in the direction of the impeller rotation. As the swirl is increased by changing the IGV angle setting, the performance capability of the fan gradually reduces pressure/volume and power curves. The fan's characteristic effect is that the operating point is moved down the system resistance curve, resulting in reduced power consumption (Figure 1).

Improving overall main fan efficiency generally involves entire impeller replacements or even entire fan replacements. This is required where main fans are operating far off their original design duty points, due to changes between the planned and actual mine resistance or wrong specification during design. This strategy is still fairly new in South Africa, but it has huge potential as the average efficiency of main fan stations is much lower than it should be. In addition, variable speed drives (VSDs) can be implemented on secondary ventilation fans and flow can be reduced during certain parts of the day and mining cycle.

Refrigeration

The first line of defence includes the optimization of the pre-cooling towers. These systems cool the warm return water (from underground) to a point close to the ambient surface

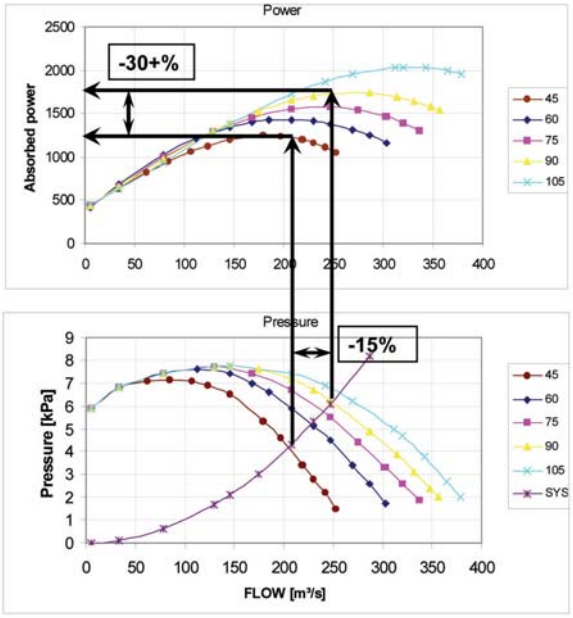

Figure 1—Fan curve showing operational points with IGV settings

temperature in direct contact cooling towers. This can account for a significant portion of the cooling required and is virtually free.

Conventional refrigeration machines are switched off during periods of peak demand, or thermal storage is used to store cooling for periods of high cooling demand (Roman *et al.*, 2013). In cooling systems, thermal storage that uses ice banks or water storage dams must be considered (Els, 2014). Ice banks produce ice on the outside of submerged heat exchanger coils during periods of low power cost and lower diurnal temperatures, and melt this ice during periods of high power cost and peak demand. Mine ice thermal storage also allows for power consumption profiling aimed at shifting the electrical load out of peak demand periods. Ice is produced during standard and off-peak power periods, and is subsequently melted by diverting water flow to the ice coils (Figure 2) to provide cooling during peak demand periods, thus reducing the load on all the water chillers.

Water mass is also effective for thermal storage because water has the highest specific heat of all common materials. In water mass thermal storage, the thermal capacity is dependent on the water mass and the temperature difference between the stored cold water and the returning warm water. In general, thermal storage will not be economical if this temperature difference is less than 5°C. However, in these mine applications this temperature difference is approximately 10°C. The fundamental feature of this storage is that it separates the cold and warm water volumes. One such system implemented at a South African gold mine was described by Du Plessis *et al.* (2005). This system uses ammonia refrigeration machines that cool water to 1°C. It consists of a warm water dam (18°C), a medium temperature dam (8°C), and a cold water dam (1°C).

Thermal stratification is the most common method of separating cold and warm water due to its simplicity, reliability, and low cost. In thermally stratified storage, the warmer, less dense returning water floats on top of the stored chilled water. The water from the storage is supplied and withdrawn at low velocity so that the buoyancy forces dominate any other effects. Water is most dense at 4°C and it cannot be stratified below this temperature. This approach has been used on a number of mines (Wilson *et al.*, 2005) (see below), but it generally requires tanks/dams with a minimum height-to-diameter ratio of 1.0 (Khalifa *et al.*, 2011).

Another method uses multiple compartments and labyrinth tanks. Pumping is scheduled so that one compartment is always partially empty for receiving return water, and water at different temperatures is thus stored in separate compartments. Labyrinth tank systems apply cold water and warm water at either end of a complex path through the dam and will generally have both horizontal and vertical traverses. The design commonly takes the form of successive partitions, with high and low ports.

By understanding the demand for underground cooling conditions in specific areas, control systems can be implemented on these units (Le Roux *et al.*, 2014). Any over-supply is inefficient and the goal is to control the cooling units to follow the demand. Besides fixing leaks in water piping, there are various ways in which energy savings can be obtained on the chilled water usage underground, such as:

- Controlling underground bulk air coolers
- Controlling underground cooling cars
- Installing isolation valves on the service water supply.

Saving potential

To provide a convincing argument for the viability of ventilation and cooling system optimization, it is necessary to look at the costs of providing ventilation, refrigeration, and cooling. Although these vary significantly from mine to mine, on a deep hot mine the costs can be as much as 15% of capital (US$200 million) and 25% of energy costs (*e.g.* 20 MW peak, 12 x 106 kWh/month for a large South African gold mine) (Gold Fields International internal data). The world-wide cost of power ranges from US$0.02 to US$0.10 per kilowatt-hour, with instantaneous peak rates being over US$0.20 per kilowatt-hour. Every 1% saving on the ventilation and refrigeration energy costs amounts to US$80 000 per annum (at US$0.05 per kilowatt-hour).

Figure 2—Ice storage dam

A case study example (Du Plessis and Marx, 2009) describes the development and implementation of a fan absorbed power control system using IGVs at a total of 23 fan stations (52 fans) between three mining business units (BUs). A target of 5.6 MW saving out of a 22.8 MW base load was set for BU 1, 7.5 MW saving out of a 30.0 MW base load for BU 2, and 7.4 MW out of a 25.5 MW base load for BU 3.

Fan absorbed power was measured at half-hour intervals and then analysed for the evening peak period (18:00 to 20:00) to determine whether the targets had been met. Performance should ideally be above 90% of target.

Figure 3 shows a graph of the actual load clipping achieved at BU 1.

The targeted and achieved power savings for BU 1, 2, and 3 were as shown in Table I.

The success of implementing IGV control to reduce airflow and save electricity is evident from the data presented in Table I, which shows that the targeted savings were achieved and exceeded.

Simulation for optimization studies

Ventilation and cooling system energy optimization generally includes the development of simulation network models that accurately reflect the current mining scenario and ventilation conditions. The calibration and verification of the predictions with measured environmental conditions are important to ensure a high level of confidence. These models are used to examine various options for improving the overall ventilation and cooling strategy, as well as for determining the effect of possible future changes. A number of scenarios, including different ventilation (fan/airway) and cooling (refrigeration/pumping) configurations, are typically examined to obtain the most energy-efficient system that satisfies the design and safe workplace conditions.

Network simulation software is specifically designed and developed to assist underground ventilation control engineers and practitioners in planning, designing, and operating mine ventilation systems. Interactive network simulation programs allow the simultaneous modelling of airflow, air thermo-dynamic behaviour, as well as gas and dust emissions in an underground mine. These programs cater for a wide range of mining methods and allow the rapid construction of simulation networks, thereby enabling online 'what-if' studies to be done to determine system requirements for optimal design and operation.

A typical integrated optimization system will consist of a properly calibrated mine model, as mentioned above, and an optimizer. The optimizer will generate different possible operational scenarios and pass these to the modelling package. The modelling package will model the mine and determine whether minimum ventilation and cooling standards are met. If this is the case, the specific combination of parameters is considered for control. This iterative process continues and the best combination of cost/operational conditions will be chosen for control purposes. By combining this process with time-differentiated set-points, an effective cooling and VOD system is implemented.

Typically, what-if studies are used to determine the optimal airflow quantity and cooling duty, and to reduce air leakage to a minimum. The system is then further optimized by determining the optimal positioning of ventilation and cooling infrastructure. Figure 4 is an example of a typical simulation network mine model.

In a case study (Hoffman *et al.*, 2012; Du Plessis *et al.*, 2012) conducted at a deep-level gold mine, a number of scenarios were simulated. After all the potential ventilation scenarios had been reviewed, the recommended optimized ventilation option was with the surface fans operating at

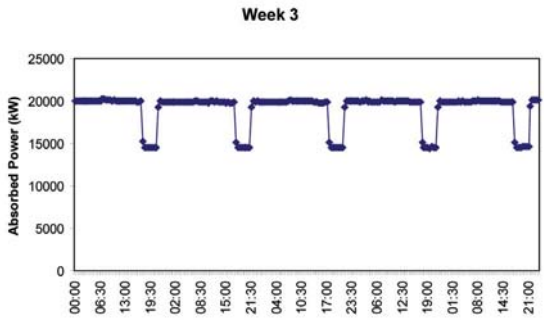

Figure 3—Measurement of absorbed power at BU 1

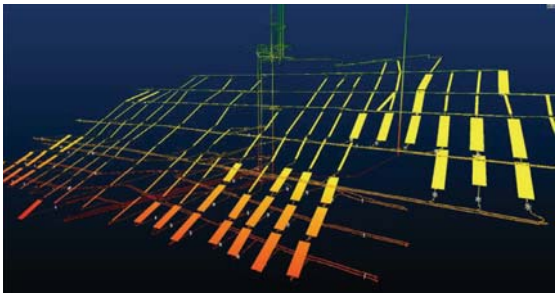

Figure 4—Simulation network model

Table I

Targeted and achieved power savings

Mine	Target			Achieved		
	Baseline (MW)	Savings (MW)	% of Baseline	Baseline (MW)	Savings (MW)	% of baseline
BU 1	22.8	5.6	24.6	20.2	5.4	26.7
BU 2	30.0	7.5	25.0	19.3	5.3	27.5
BU 3	25.5	7.4	29.0	24.5	7.1	29.0

20%, closed IGVs, and the stopping of some booster fans. Combined with this, the installation of underground refrigeration machines with energy-recovery turbines was recommended due to the shorter implementation time, lowest implementation cost, and least complexity.

The result of this study proved that, with careful planning, changes to current ventilation and refrigeration systems in deep-level mines can result in major electricity operating cost savings. At this particular mine, energy savings of 10 400 MWh per annum were achieved, resulting in an energy cost saving of US$2 million per annum, by changing the IGV setting of the main surface fans. It would be possible for the mine to save an additional 3 300 MWh and effect a further energy cost saving of US$0.5 million per annum by stopping an underground booster fan. The main penalty attached to these changes is that the underground airflow would be reduced by nominally 7%.

Significant energy savings are attainable by improving refrigeration positional efficiency and reducing the volume of cooling water that is pumped from the bottom of the mine to the surface. Mackay *et al.* (2014) investigated the use of hard ice and concluded that hard ice as a refrigeration and cooling means has become more attractive at lesser depths.

Not only will this also allow greater flexibility, but the additional refrigeration and cooling water required for future mining will be produced by an underground plant, eliminating the need to pump 50 ℓ/s over 2 000 m back to the surface, and utilizing the existing two energy-recovery turbine stations. The total operational savings for this system will be approximately US$2.5 million per annum. The cost of the required modification will be US$8.5 million, with a capital payback period of just more than three years.

Conclusion

The rising costs of ventilating and cooling mines safely and efficiently dictate that operators have to implement optimized energy management and control strategies in mines. Ventilation-on-demand and cooling-on-demand strategies have the potential to reduce both the capital and operating costs of mine ventilation and cooling systems, and the mechanisms required are technically feasible.

From several case studies presented in this paper it is clear that a large financial benefit is possible through optimizing ventilation and cooling within a mine.

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Accessing Africa's Mineral Wealth:

Mining Transport Infrastructure and Logistics

24–25 March 2015

Emperors Palace Hotel Casino Convention Resort, Johannesburg

BACKGROUND

Sub-Saharan Africa is endowed with vast mineral wealth, yet many of the region's deposits have remained undeveloped. A key constraint is the lack of suitable transportation infrastructure from remote locations to the coast.

The scale of infrastructure investment required to support mine developments is often beyond the funding and institutional ability of any one mining company or government. Governments are also under pressure to leverage these investments for broader social benefit. Properly designed and structured shared-use infrastructure, by opening up rail, road, river, port, and other transport facilities to multiple projects and industries, can improve mining project economics while also promoting sustained national development.

Who then should design, finance, construct, own, operate, regulate, maintain, access, and fund mining transport infrastructure? Designing, building, and operating a system-wide shared-use transport corridor which effectively and optimally addresses the needs and expectations of all stakeholders, users, and beneficiaries while respecting environmental and social concerns is challenging and often stretches local capabilities and experience.

The solution will entail collaboration and partnerships between multiple stakeholders, including mining competitors, governments, multilateral organisations, transport planners and operators, engineers and constructors, and the financial and legal communities. It will require workable frameworks and processes which build on lessons learnt in more developed jurisdictions while considering the unique challenges of the SSA environment.

OBJECTIVES

The conference will provide a forum for key stakeholders to share perspectives on the opportunity, its challenges, and possible solutions.

WHO SHOULD ATTEND

Key decision makers/influencers in the stakeholder groups are invited to attend, including:

- Mine project developers and sponsors, mining companies
- Government officials, ministers of economy and transport
- Project and engineering consultants in mining and infrastructure
- Infrastructure construction companies
- Transport planners—rail, road, river, port
- Transport operators
- Financial institutions, investment fund managers
- Multilateral and regional organisations and development banks
- Financial and legal advisors
- Economists, academics, and researchers

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Conference Announcement

Mining off-Earth minerals: a long-term play?

by G.A. Craig*, S. Saydam*, and A.G. Dempster†

Synopsis

The Moon, asteroids, and planets of the solar system represent the most distant caches of wealth that humanity has ever considered recovering. Yet, in addition to the potentially recoverable values represented there, harvesting off-Earth resources has a second, almost incalculable sustainable benefit in that they can be retrieved with absolutely no damage to Earth.

Previous research mostly assessed the potential of asteroids and the Moon for mining purposes from a theoretical and scientific point of view. These studies investigated drawbacks that could be experienced in this type of operation, but no detailed economic evaluation that is meaningful for mining project management has been conducted and the parameters that are most likely to make an operation feasible are unknown. This paper provides a preliminary economic and sensitivity analysis of a possible off-Earth mining business extracting minerals from an existing asteroid.

Keywords

off-Earth mining, space mining, *in situ* resource utilization, future mining.

Background

As history has repeatedly shown, where there are valuable minerals to be mined, adventurous humans will arrive in droves – even if it means battling extreme conditions and excessive risks. The motivation for off-Earth mining is clear: an abundance of valuable resources that can feed our technologically-driven society, the necessity of discovering new places that our society can colonise, and the development of new technologies and processes to enable these missions, which will generate spin-off technologies that can be used in fully-automated terrestrial mining endeavours.

By widening the scope of mining engineering to incorporate off-Earth opportunities, the mining industry can be sustained from an economic standpoint. In a similar way, the increased costs of mining and diminishing natural resources available close to the surface of the Earth may soon support the idea that off-Earth resources are more profitable.

Limited research has been conducted in this area. O'Leary (1988) initiated one of the first off-Earth mining studies and identified that the surfaces of the Earth's Moon, Mars's two moons, and an asteroid named 1982 DB have the potential for developing missions for space mining. However, he focused on a manned mission, which entails high operational and safety risks. Duke *et al.* (1997) designed three operational scenarios to extract water ice at the lunar poles, using microwave energy for heating the ice, thermal processing and steam pipe transportation, and using a dragline with thermal processing. Their designs were conceptual and did not consider the economic feasibility of the operations.

Sonter (1997) investigated the design process for feasibility studies of off-Earth mining operations and developed a net present value (NPV) analysis including variables based on orbital mechanics, rocket fuel requirements, mining and processing methods, product mass returned, and duration of the return trip. A new analysis concept was also utilized by Sonter (1997; 2001), the 'mass payback ratio', which illustrates the need to expend mass in the form of propellants, rocket bodies, and mining consumables in order to return product mass to the market. Moreover, Sonter (2001) applied a scenario where resources obtained from asteroids are brought into low Earth orbit (LEO) and sold as construction material for LEO infrastructure. These materials include water to make propellant, nickel and iron for

* *School of Mining Engineering, The University of New South Wales, Australia.*

† *The Australian Centre for Space Engineering Research, The University of New South Wales, Australia.*

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construction, and semiconductors to make solar cells. Sonter's studies (1997; 2001) were the first that considered the economic viability of such missions.

Ross (2001) published a report on the important factors in determining the feasibility of an asteroid mine. This report considers the extraction of several commodities from asteroid orebodies, including water and volatiles, precious metals, rare earth metals, refractory material, and iron and nickel. Ross's study, like Sonter's, used NPV analysis as the primary tool. Ross also outlines the market demand, which is subject to continual iteration due to its size and nature. Notably, geological characteristics were not mentioned and the actual analysis stage was not undertaken. This limits the credibility of the study, in that it suggests principles without testing. However, Blair *et al.* (2002) from the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) investigated the feasibility of off-Earth mining for water extraction. A simple NPV analysis was found to be insufficient to make an investment decision, due to the high capital and research investment required for a start-up operation, creating unpredictable risks and uncertainties in the business model.

Erickson (2006) studied asteroid mining with a particular focus on optimal return on investment (ROI) from near-Earth asteroids (NEAs), and stressed the cost efficiency and risks of a possible operation. He further recommended that the mining equipment to be used at such an operation should be flexible, adaptable, and re-usable to handle a variety of NEA conditions. He particularly pointed out that robotics with artificial intelligence is essential to stage such a mission.

Zacharias *et al.* (2011) compared feasibility studies of potential mining projects on asteroids, the Moon, and Mars based on each of their dynamic locations. They conducted an NPV analysis of possible 10-year mining operations for an arbitrary mineral and found that the Moon returned the most favourable NPV compared to Mars and two selected asteroids. Based on their assumptions, both the Moon and Mars provided positive NPVs, but the asteroids had negative NPVs. However, a possible asteroid-mining operation would be expected have a much longer lifespan than a typical Earth-based operation, so the economic analysis could be quite different considering all the variables and risks associated with the operation.

Pelech (2013) studied an economic evaluation of mining comets and the Moon for an off-Earth water market. He developed four water-mining scenarios to supply a H_2/LOx propellant market in LEO and established a ratio, named 'propellant payback ratio', inspired from Sonter's studies (1997; 2001), which indicates the economic return on the forgone opportunity to launch the propellant directly from the Earth. He used the opportunity cost concept considering infrastructure and equipment launched from Earth. In this study, for every kilogram of mining equipment and infrastructure launched into LEO, the opportunity to launch a kilogram of propellant has been forgone.

Gertsch and Gertsch (2003) applied terrestrial surface mine design and planning techniques to the production of lunar regolith for extracting gases for life-support for 100 people at a lunar base. They discussed various hypothetical scenarios with basic assumptions for mining regolith from five large cold trap craters near south lunar pole. Muff *et al.* (2004) conducted a study at NASA that includes a prototype design of a bucket wheel excavator to be used on the surface of the Moon and Mars to extract surface regolith. Both studies focused on using similar excavation techniques and equipment to those that are used in terrestrial mining operations.

Schmitt *et al.* (2008) summarized the vision for space exploration, determining that the first stage would incorporate the development of mining initiatives on the Moon to extract life-sustaining elements such as H, He, C, N, and O. These elements are all available in various concentrations in the lunar regolith or surface rock. They proposed that a base would be needed on the Moon to provide an extensive refuelling and life-support system.

Yoshikawa *et al.* (2007) and Raymond *et al.* (2012) studied asteroid characteristics providing valuable information. Subsequent spacecraft missions reduced the geological uncertainty surrounding this analysis.

Karr *et al.* (2012) from NASA studied the potential of using ionic liquids (ILs) to dissolve metal-bearing regolith in order to exploit the water and metal present within it. Acidic IL was used to dissolve small samples of a nickel/iron meteorite (named Campo del Cielo) and the metals were recovered by electrowinning. When the voltage was slowly raised from an initially low level, it was possible to recover the different metals separately at the anode. The water was removed using a micro-distillation apparatus. This represents the first extraction of oxygen, in the form of water, from an extraterrestrial source, as well as a possible method of processing metals in space. The authors also mentioned that this dissolution technique in prospector drilling could be used for the analysis of regolith.

Balla *et al.* (2012) discussed the use of direct laser fabrication technology to mine off-Earth minerals. The feasibility of this method was evaluated through a series of experiments using lunar regolith simulant. The experiments were able to demonstrate that this method is able to produce bulk amounts of mineral products through the melting and re-solidification of regolith. The laser absorption of materials is directly proportional to electrical resistivity, therefore the lunar regolith melted completely with a laser power as low as 50 W. However, they noted that more work will be needed before the process can be regarded as feasible on a large scale.

Buet *et al.* (2013) developed a robotic mining system for rapid Earth orbit capture of asteroid resources. They aimed to capture and bring asteroid regolith to the Earth's surface. Prado (2013) evaluated terrestrial mining systems such as strip mining, but the problem in using this system off-Earth in an extremely low-gravity situation is that the dust and rock would be expelled into space above the surface, obscuring and inhibiting the mining operation.

Bernold (2013) developed a method and machine to 'vacuum up' regolith material as a form of material collection. This machine has been tested with the lunar simulant developed by the research team (Creagh, 2013). To overcome the lack of atmosphere, two concentric tubes were used. A gas is forced through the outermost tube and regolith dust is removed inside the inner tube, suspended within the gas.

Lucas and Hagan (2014) conducted a study to analyse and compare the feasibility of conventional pick cutting

systems and pneumatic excavation systems in an off-Earth environment. The samples tested were the Australian Lunar Regolith Simulant-1 (ALRS-1), designed by Bernold (2013). While more research and development is required on the prototype pneumatic excavation system to determine the rate of excavation and other factors that would assist with assessing the mining efficiency of this system, it was determined that both machines were capable of excavating lunar regolith at any relative density. It was also concluded that although neither system was feasible for lunar excavation with current technology, the pneumatic excavation system was superior under the lunar conditions analysed.

Owing to the rapid development of the private commercial space industry, continual iteration is required to keep the results of these investigations relevant. There has not been a concentrated effort to reduce costs through investigation of alternative capital expenditure models. None of the previous investigations have taken the geological characteristics of each deposit into account. Almost all mine design and planning activity on the Earth is heavily influenced by geology and the knowledge gained from previous experience. A lack of sufficient geological information is one of the most detrimental uncertainties in making investment decisions.

The previous studies indicate that bodies in NEOs are the most likely to be economically viable, while the more distant comets are unlikely to support a positive cash flow. These results appear to be heavily dependent on the accessibility of each deposit by a spacecraft. Crucially, they also do not quantify the geological characteristics or extractability of each deposit as a cost factor in the analysis.

There are some USA-based companies intending to mine asteroids for volatiles and metals (Belfiore, 2013) due to the perceived accessibility. However, the Moon, and importantly (in terms of suitability of human colonization) Mars, must be given a fair trial and compared with asteroid resources in order to determine the most economically viable strategic business plans.

A case study for asteroid mining

Current knowledge of asteroids is derived from meteorite samples, long-range electromagnetic spectrum observations, and spacecraft observations and sampling. The asteroids are categorized by the spectral signatures from long-range observations (Price, 2004). The spectral signatures are divided into the categories given in Table I and referenced with respect to different composition characteristics found in meteorites. It should be noted that there are many more subclasses within each of these groups.

Launching a payload from the Earth's surface into space is generally considered one of the higher costs in space development (Ross, 2001); hence by starting a mining industry in space early in the space development phase, unnecessary costs can be avoided. To develop such an industry, a certain level of pre-existing space industry is required so as to provide fuelling services and/or energy sources for the mining operations, as well as a market for the raw materials so that payload values are not undermined by the costs of re-entry to Earth to access the terrestrial mineral market.

Astronauts walking on the Moon found that the regolith is very fine grained and possesses an electrostatic charge. This charge causes the dust to stick to equipment and astronaut suits. It is expected that the surface of many asteroids would be similar (Slezak, 2013).

Sonter (2013) described a typical target asteroid body and estimated that this target may contain approximately 10% Ni-Fe, 10% magnetite, 10% water, and 50 ppm platinum group elements. He further mentioned that in 2020, the value contained in this type of material could be over US$1 million per ton in space, but only US$4 000 per ton if the platinum was brought to the Earth's market.

In this case study, an M-type asteroid was chosen as the target for the mining operation. A high percentage of nickel and iron, which can be used for construction materials in orbit, was assumed. A number of M-type asteroids were identified but the one chosen has higher radar reflectivity compared to other asteroids (Ostro *et al.*, 1991), hence its mineral composition is widely accepted in the scientific community. 1986 DA is an NEA that is assumed to be 0.5 astronomical units (AU) away from the Earth and has a delta-V (a standard measure of the energy needed to complete space manoeuvres) value of 7.195 km.s^{-1} (Benner, 2013). This means that it is only slightly less accessible than the Moon – a round trip between the Earth and 1986 DA could take approximately one year.

It is already known that 1986 DA's orbit around the Sun passes within Mars' orbit, therefore at some points it is relatively close to the Earth, approaching as close as 0.2 AU (Yeomans *et al.*, 1987), but only for a very short time. The minimum distance between the asteroid and the Sun (the perihelion) is 1.17 AU, while the maximum distance is 4.46 AU. Since the distance between the Earth and the Sun is 1 AU, it is assumed that the distance between the Earth and asteroid is between 0.17 AU and 3.46 AU. For the purposes of this study, 1986 DA is assumed to be about 0.5 AU from the Earth, or the same distance as Mars from the Earth. In this respect, the time to travel to the asteroid would be comparable to the time taken to reach Mars. Figure 1 indicates a simplified possible orbital path of 1986 DA and the Earth. This diagram was constructed based on the abovementioned information and was used to make the assumption of the distance between the Earth and the asteroid.

1986 DA has the composition of naturally occurring stainless steel, or 88% Fe, 10% Ni, and 0.5% Co (Ross, 2001; Ingebretsen, 2001) making it a perfect resource to mine. This

Table I

Asteroid and meteorite cross-reference (Kowal, 1988)

Asteroid reflectance type	Meteorite sample type	Description
M-Group	Metallic 95%	Iron, nickel, other metals
S-Group	Stony irons Stones	Contains silicates with native metal inclusions Mainly olivine, enstatite, silicates.
C-Group	Chondrites	Olivine, contains hydrated minerals, carbon, silicates

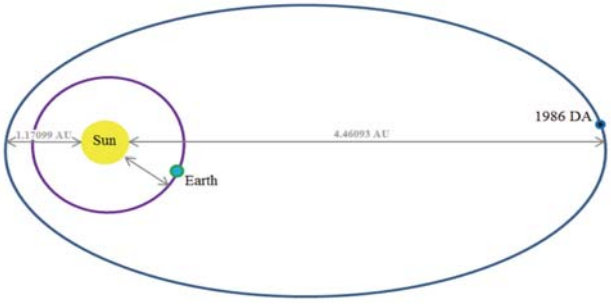

Figure 1—Diagram showing approximate orbit of 1986 DA compared to Earth

composition is assumed to be uniform throughout the asteroid, and hence the entire asteroid is considered as an orebody and therefore the reserve is equal to the resource. The mean density of the asteroid is assumed to be 5 g.cm^{-3} (Ostro *et al.*, 1991) and this equates to a total reserve of 20 Gt of raw stainless steel. If the minerals were to be processed and sold separately, it would be necessary to provide reserve estimates for each mineral. For 1986 DA, therefore, reserves of 17.6 Gt of iron, 2 Gt of nickel, and 100 Mt of cobalt were assumed. The remaining 300 Mt could be made up of a combination of gold and platinum, which together constitute 1% of the asteroid's reserve.

Possible mining methods

Since this study focuses on the economic analysis of such an operation, it was important to consider possible mining methods in order to make relevant assumptions. Therefore, two mining methods were investigated for extracting the metal from the asteroid: an open cut method and an underground method.

The open cut method is similar to terrestrial opencast methods, apart from any necessary surface securing systems. The near-zero gravity would mean that all equipment needs to be anchored to the surface of the asteroid. Mined material also needs to be prevented from leaving the mining area. This could be achieved through the addition of a canopy or 'mining cover', which is described by Prado (2013). A typical canopy system can be seen in Figure 2.

The mining system drills or breaks the ore and the broken material is released into the space above the surface. This displaced ore is drawn up and out of the system for storage. The velocity of rock that has been forced into motion by drilling or breakage is unknown, but some consideration would have to be given to high-speed projectiles when designing a mining cover. A typical diagram of this technique can be seen in Figure 3.

The underground mining method involves drilling large holes from one side of the asteroid through the centre to the other side using some form of tunnel boring machine (TBM), in a similar way to auger mining in terrestrial operations, as shown in Figure 4. This will allow an adequate production rate for the 1986 DA operation. The machinery is held in place by pressure against the walls of the drill-holes, thus eliminating the problem of very low gravity. Ore could be directed up the existing hole with ease due to the low gravity and collected at the top.

The most suitable mining method is to develop a strip mining system that incorporates anchorage to hold the equipment to the surface, as well as a mining cover to contain disturbed metal for storage.

It has been assumed that the entire asteroid will be mined eventually; however, the envisaged operation will exploit only one-tenth of the possible resource. In this respect, the final pit layout must not impede further mining operations. Another factor that should contribute to the design of the final pit layout is the effect that extraction could have on 1986 DA's orbit around the Sun. Removing an isolated section of the asteroid could change the rotation of 1986 DA and propel it into an altered and potentially dangerous orbit.

It is most appropriate to perform mining operations in such a way that the final pit layout consists of strips that encircle the asteroid to maintain its trajectory and minimise change in rotational kinetic energy.

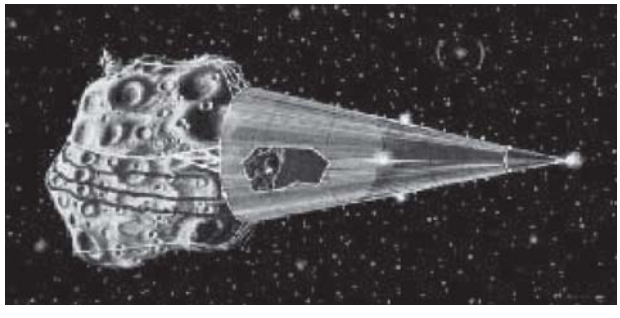

Figure 2—Canopy around an asteroid (after Prado, 2013)

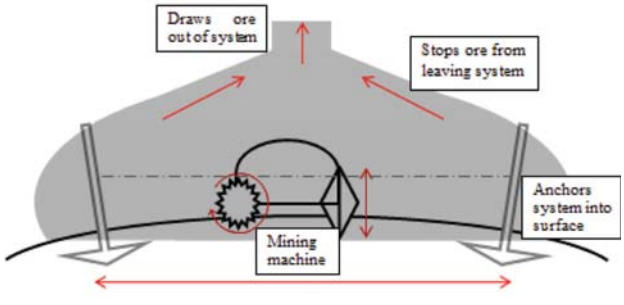

Figure 3—Open cut mining method

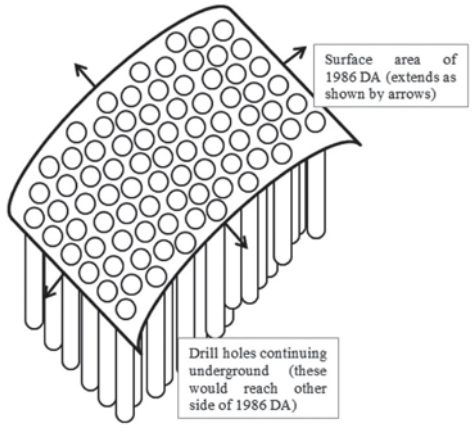

Figure 4—Diagram showing proposed underground mining method

All infrastructures would need to be adequately lightweight to minimize transport costs. Apart from this consideration and the additional stability measures required in a minimal gravity situation, infrastructure would generally be similar to equivalent terrestrial operations.

The smelting apparatus could be a stand-alone unit that uses the Sun's radiant energy. The smelter would be mobile, using low-powered thrusters to move around the asteroid, so as to always be on the side facing the Sun. This movement would depend on the current task of the smelter. Metal could then be fashioned into blocks ready for transport or moulded directly into shapes for building material. Because of the low gravity, soft metal could possibly be shaped in a similar way to glass-making, by pulling and shaping the metal as it solidifies (Roesler, 2013).

An economic evaluation of the 1986 DA operation, based on a typical NPV analysis, was performed to determine the financial and technical feasibility of an off-Earth mining project.

The design assumes that mining would be fully automated and that the relevant robotic technologies are available. Investigating the feasibility of a robotic operation is relatively simple; there are no provisions made for sustaining life. There would need to be a crew on Earth or in a spacecraft or station in orbit to monitor the operation to maximize productivity and utilization of the equipment fleet. In other words, full automation is not assumed.

Equipment selection and infrastructure

The main equipment components are machines for rock breakage and drilling, handling broken ore, and support. The latter include fuel replenishing machines, robotic service machinery (mobile or fixed), mobile anchorage systems, and mining cover to collect perturbed ore.

There would also need to be other on-site components that are separate from the task of mining, but are included in the equipment costs, such as the smelting apparatus and storage system (if payload is transported only when 1986 DA is a short distance from Earth).

On-site infrastructure includes components that are either fixed or mobile but are not directly involved in the mining operation. The other infrastructure components are the storage systems for both mined 'run-of-mine' ore and for the smelted metal. These have to be lightweight holding containers that are kept in position near the asteroid through the use of very low-power thrusters.

Economic analysis

The main part of the economic analysis involved a year-by-year cash flow analysis, and therefore a detailed financial and technical model was developed. The model included transport costs, mining/smelting equipment, mining costs, saleable material, and operating margin.

For capital cost analysis, it was considered unnecessary to specify the number of spacecraft required to transport payloads of metal from 1986 DA to Earth orbit. Instead, the cost per ton of payload was used. A spacecraft configuration rule of thumb (Turner, 2010) is that the payload weight averages about one-third of a spacecraft's dry weight. Owing to the long transit time, it is assumed that each spacecraft will make one return trip per year. Because of this, the total weight of the spacecraft is comparable to the annual production of the operation. At 20 Mt per year, the total weight of the payload-bearing spacecraft would be 66.6 Mt.

Capital costs of all spacecraft were based on the Russian-based Angara A3 space vehicle, currently in development by Khrunichev State Research and Production Space Centre (Khrunichev State Research and Production Space Centre, 2013). The mass of this vehicle will be 14.6 t and the total development cost is US$70 million. In this respect, the cost per ton of spacecraft needed is about US$19.4 million.

Capital costs are made up of both the transport equipment and the mining equipment, which includes the costs of the smelting, anchorage, and extraction equipment. The transport capital was benchmarked at US$19 million per ton of machinery. Due to the limited level of knowledge about mining equipment costs, the assumed value for this element was also assumed to be US$19 million per ton. The total capital expenditure for the 1986 DA operation would be $1.31 × 10^{15}.

Operating costs include the fuel costs for operation of all equipment (mining equipment and transportation equipment) as well as consumables for the mining operation. The amount of fuel needed for the transportation between Earth orbit and 1986 DA was calculated by using the Tsiolkovsky rocket equation (Equation [1]) (Braeunig, 2012):

$$M(fuel) = M(vehicle) * \left[e^{deltaV/Isp} - 1 \right] \qquad [1]$$

This formula uses the 66.6 Mt for vehicles calculated previously, but this value is varied on each leg of the journey depending on whether the spacecraft would be empty, carrying payloads, or transporting mining equipment. The delta-V is the change in velocity necessary to reach 1986 DA and is known to be 7.195 km/s (Benner, 2013). Cost of fuel was assumed to be US$10 000 per ton, a relatively high cost due to the remote location of the operation. Consumables were assumed to be US$5 000 per ton of ore mined. The total operating costs associated with the 1986 DA mining operation equal just less than US$140 ×$10^{12}$ in present value. This value assumes that a low-cost technology option would be available in the orbit. Fuel costs comprise a major part of the total project costs, and will most likely be the parameter that has the greatest effect on the feasibility of the 1986 DA mining operation. Table II summarizes the assumptions for economic analysis.

Assuming that all of the mined material is sold, 20 Mt of stainless steel will be sold per annum, at a price of $8 million per ton. This provides a yearly income of just above US$160 × 10^{12}, starting in the second year and continuing until the 101st year, when the final shipment arrives at the market. The total revenue for steel sales throughout the life of the mine (LOM) would be just over $1.45 × 10^{15} in present value, before costs.

The NPV of the 1986 DA operation for a 100 year LOM is calculated as just over US$658 billion. For the scale and the length of life of the operation, this NPV cannot be considered feasible, even with an extremely high profit, since this operation has a payback period of 80 years (Figure 5). The profit made over the LOM is minimal compared to the initial

Table II

Assumptions for the economic analysis

Parameter	Value	Discussion/source
Composition of 1986 DA	88% Fe; 10% Ni; 0.5% Co	Ross, 2001
Distance from Earth	0.5 AU	Same as Mars, asteroid orbits between and outside Earth/Mars
Equipment capital	US$19.4 million per ton	Russian - Angara A3 space vehicle
Equipment mass	3 x payload	Spacecraft design 101 (Turner, 2010)
Fuel cost	US$10 000 ton	
Transport fuel amount	Varies on each trip	Tsiolkovsky rocket equation – (Braeunig, 2012)
Mining fuel amount	25 Mt	
Consumable cost	US$5k/t of ore	US$ per ton of ore mined
Transport time	One year for a round trip	This allows product to reach market in the year after it was mined
Value of metal	US$8 million per ton	Cost of buying and launching metal
Debt	100% Equity; 0% debt	

capital investment. This evaluation has assumed 100% equity finance; however, the results indicate that the large capital investment (Table II) will be only marginally repaid. The project would therefore not be attractive because of the relatively small profit expected over 100 years in relation to the large capital investment.

A sensitivity analysis was undertaken to indicate the effects of different variables on the project NPV. This is an important aspect of any financial evaluation, and even more so for an off-Earth operation because of the relative uncertainty of the NPV. The results of the sensitivity analysis can be seen in Figure 6, which indicates that a number of parameters strongly impact the NPV of the operation. This analysis indicates the most important areas where further research and technology advances are required in order to make asteroid mining and other forms of off-Earth mining operations viable.

The metal price was based on the cost of purchasing and launching material from Earth to the asteroid's orbit (NEA). As the NPV is very sensitive to this parameter, it is recommended that further analysis is done on the expected value of materials in space. This value would change constantly, as it does on Earth, and hence establishing a correct estimate for metal price would involve cross-disciplinary work beyond the scope of this project. This parameter cannot be changed by altering the project scope – the metal price is the cost of sourcing the material on the Earth and launching it into space. The value would increase as Earth's reserves of iron ore are diminished, but would decrease as space launches become more economical. Whatever the case, the results indicate that this parameter strongly affects the NPV of the 1986 DA mining operation.

The NPV is equally sensitive to the percentage of mined metal that the operation manages to sell. It is assumed that 20 Mt will be mined per annum; the market needs to be large enough to absorb this amount for the project to succeed at current figures. Mining in excess of the demand would be detrimental to the operation. This parameter would only negatively impact the NPV, as it is not possible to sell more product than the operation produces.

Another very critical parameter identified is the transport capital. Due to the long travel time between 1986 DA and Earth, it is assumed that enough payload shuttles to transport a year's worth of material are available. Costs for transport could be reduced by building faster shuttles, so as to reduce the total number needed, or by using lightweight materials to transport run-of-mine more efficiently.

The NPV of the operation is relatively insensitive to the the fuel cost and the amount of fuel needed for transportation, although it is still influenced by these parameters. As for metal, it is hard to assume a value for fuel in space, but fuel costs could be reduced by establishing an in-space fuel industry. More fuel-efficient equipment and vehicles would also reduce the amount of fuel needed for the project. Further research should be undertaken in this direction.

To further analyse the monetary value of the parameters that have the greatest effect on the NPV, a number of alternative case studies were developed from the base case. The first alternative assumes that the same mining rate, but

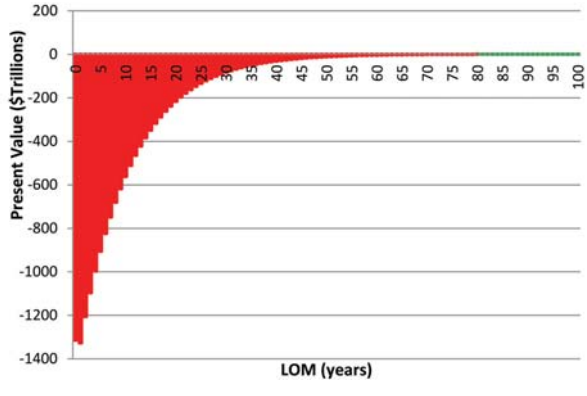

Figure 5—Discounted cash flow over the life of mine for the 1986 DA operation

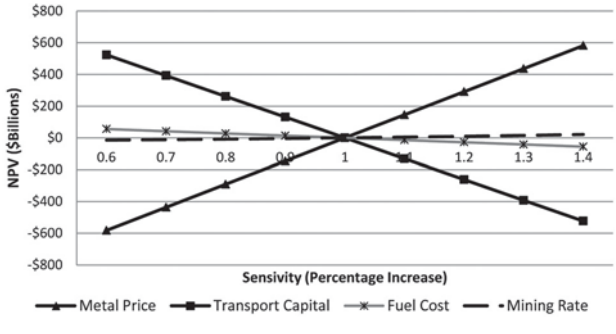

Figure 6—Sensitivity analysis for 1986 DA mining operation

only 80% of the ore transported back to Earth orbit is sold each year. This situation would have dramatic financial consequences for the 1986 DA operation. The operation would not make a profit, as shown in Figure 7.

The second alternative case study assumes that there is an equivalent asteroid that is half as distant from the Earth as 1986 DA. This would halve the transport capital as two trips could be made per year, utilizing the payload-bearing shuttles more productively. The payback period of this alternative is 8.5 years and the NPV for this scenario is just over US$630 × 10^{12}, which is much higher than for the base case (Figure 8). As can be seen, the capital investment is also great deal lower than that of the base case. This allows for a quicker payback and higher profit margin. This alternative is therefore much more feasible as a mining operation than the base case operation.

The final alternative study assumes that the market consumers for the stainless steel product are either mobile or located relatively close to the mine site, so that no transportation of the refined material is necessary. The only need for shuttles would be for yearly consumables and the initial transportation of mining equipment. Because of this smaller ongoing payload, it is important to spread the weight of the mining equipment transported to site across a number of years. The first three years will thus involve the transport of increasing amounts of mining equipment to 1986 DA, with production rates ramping up to the base case amount. In the first year, half of the mining equipment will be taken to 1986 DA, along with necessary fuel and consumables; in the second year other necessary equipment would be brought, with the remainder in the third year. This alternative yields a much higher return than the base case situation. The payback period would be 5.5 years and the NPV for this scenario would be almost US$916 × 10^{12} (Figure 9). As can be seen, this scenario is a much more attractive investment than the base case, due to the short payback period and the much higher NPV.

The risk of this project is that there would need to be a sufficient market close to 1986 DA, or that customers would have to collect the product from site themselves. This has the potential to decrease the value of the product from the current assumption of US$8 million per ton. As can be seen from the sensitivity analysis (Figure 6) and in Figure 5, the sales percentage is a very sensitive parameter and if this scenario cannot sustain a market of 20 Mt/a, the NPV of the project will suffer dramatically.

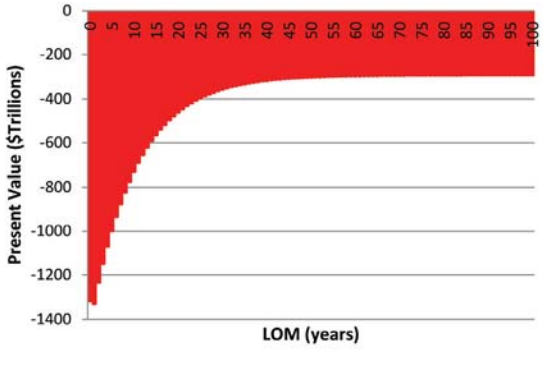

Figure 7—Discounted cash flow over the life of mine with 80% of production sold

Conclusions

The time is approaching when an industrial market will be developed in orbit around the Earth. Owing to the Earth's finite resources and the high costs of launching materials from the Earth's surface, this market may need an off-Earth minerals industry to supply it with essential raw materials, most importantly water. Before the industrial demand reaches an unmanageable level, relevant research needs to be conducted such that off-Earth mining is an attractive investment for mining companies.

The increased resources could push the terrestrial minerals market into a surplus, damaging mining companies' terrestrial operations and depressing mineral prices. There is, however, a huge opportunity for mining companies to utilize off-Earth deposits to support space exploration and development. The mining industry has valuable experience in developing and applying technologies for discovering, extracting, and processing natural resources. This experience will allow the space industry to create a permanent and self-sustaining presence in space. The space industry, conversely, can benefit the mining industry through the advancement of technologies that will allow mineral extraction in not only off-Earth situations, but also in hostile terrestrial environments such as deep oceans. A strategic partnership between mining, space, and research organizations and industries will be needed to achieve such a goal.

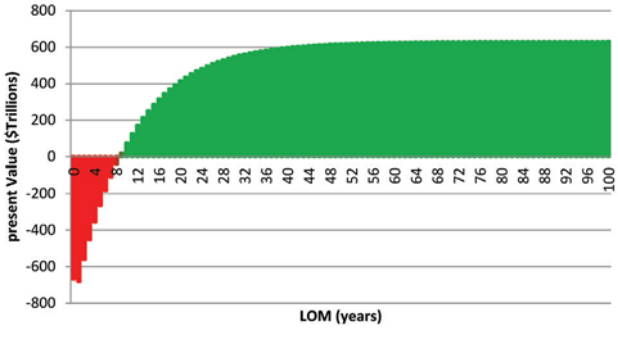

Figure 8—Discounted cash flow over the life of mine for an asteroid half the distance of 1986 DA from Earth

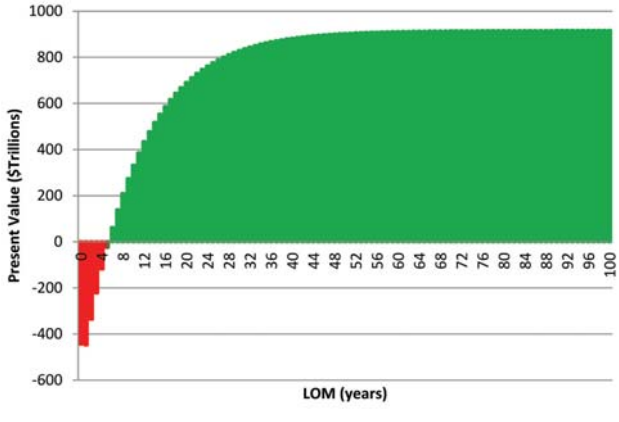

Figure 9—Discounted cash flow over the life of mine with the market near 1986 DA

The asteroid chosen to assess the feasibility of off-Earth mining in this study is a large metallic NEA approximately 0.5 AU (half the distance between Earth and the Sun) from Earth. The asteroid has a uniform composition that is essentially naturally-occurring stainless steel. This material could be used as a construction material for future satellites and spacecraft.

A theoretical assessment of 1986 DA as a suitable mining location was conducted and, using certain assumptions, of an economic model developed to determine the financial value of a mining operation on the asteroid.

1986 DA has a total reserve of 20×10^9 t of raw stainless steel which could be mined using an open cut strip-mining method or an underground drilling method. The operation would produce 20 Mt of stainless steel per year over a mine life of more than 100 years. This steel will be smelted and transported by shuttle to an Earth orbit and marketed for off-Earth construction.

The results of the financial and technical model indicate that the project would have a very high NPV of just over US$$658 \times 10^9$. However, due to the relatively large initial cost of US$$1.3 \times 10^{15}$, the project cannot be considered a worthwhile operation.

A number of alternative case studies were investigated, with the highest NPV attributed to a scenario in which the mined ore would be utilized near the mining operation and would not need to be transported to an Earth orbit. It was concluded that at current prices and with current technology, even with a number of assumptions such as a pre-existing fuel industry, the risk is too great for an asteroid mining operation to succeed. The alternative case studies may be economically viable, but in reality the likely market for the products of a space mining operation will be developed in orbit around the Earth, as in the original case.

The NPV of the 1986 DA operation was found to be most sensitive to the metal price, capital cost of transport, cost of fuel, and the amount of fuel required. It is recommended that these parameters be further assessed.

It is recommended that similar analyses should be performed for other known M-type NEAs. A comparison of different case studies would illustrate the benefits of targeting nearby asteroids compared with asteroids with a relatively low delta-V or those with a valuable orebody, as is the case with 1986 DA.

It is obvious that there is a severe lack of knowledge about specific NEAs (in terms of their compositions and surface properties). It is hence recommended that before any mining company commits to a full-scale operation, physical exploration be undertaken. This involves flybys and sample returns from the asteroids. Although the full-scale extraction of off-Earth minerals is not currently feasible, it is recommended that further research by the mining industry be undertaken, as space mining will eventually be inevitable as the pace of space exploration and development activity increases.

Acknowledgements

The authors would like to acknowledge Dr Gordon Roesler for his support and guidance during the research.

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MINING BUSINESS OPTIMISATION CONFERENCE 2015

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Conference Announcement

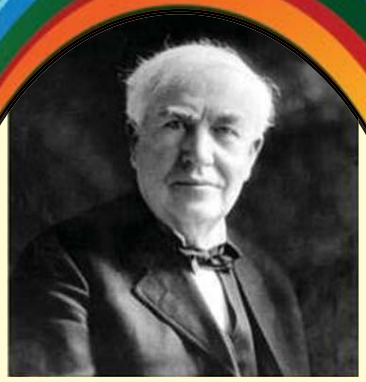
BACKGROUND

Any mine planning activity should explicitly be an optimisation exercise. Optimisation meaning; 'Pick the best option in the time available'. Mining companies aim to increase productivity, reduce unit costs and maximise return on capital. Programmes for business improvement abound. This conference is an opportunity to leverage collective knowledge and help focus and prioritise those initiatives that matter.

This conference is not for those who want tomorrow to look like yesterday. It is for those who want to improve the future by disrupting the present.

OBJECTIVES

- Share understanding and experience of ongoing efforts to improve the bottom line
- Establish a working framework and reference model for optimisation in the mining industry
- Focus on the initiatives that actually improve value
- Identify key value drivers across the mining value chain
- Understand the nature of interconnected activities and the impact of variability in the value chain performance
- Appreciate inherent trade offs in the context of generating extra value.



If I asked them what they wanted, they would have told me: 'We need bigger candles.'

Thomas Edison

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- Head of Operations
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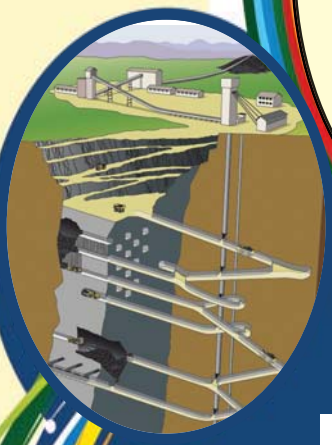

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The presence of shear stresses in pillars and the effect on factor of safety in a room-and-pillar layout

by J.A. Maritz*

Synopsis

Since the dawn of mining, pillars have been used as primary support to ensure stable workings. Early designs were based on trial and error, after which more scientific means developed over time. A vast amount of progress has been made, especially in soft-rock room-and-pillar design methodologies, from which hard-rock design theories developed with minor changes to constant parameter values. The commonly used Hedley and Grant method for hard rock and Salamon and Munro methodology for soft rock draw on the tributary area associated with the pillar, the width-to-height ratio of the pillar, and a back-analysed strength reduction factor. In these methods, only the vertical stress, or stress normal to the pillar influences the load applied to the pillar. This investigation considers the possible influence of shear stresses on pillars in a room-and-pillar layout in single reef planes and multi-reef environments, based on elastic numerical modelling methods. The possible shear stress poses a safety and financial risk to the design process, whereby an undersized pillar would lead to unstable working conditions, whereas oversized pillars could lead to an under-utilized ore resource.

Keywords

numerical modelling, shear stress, factor of safety.

Introduction

In recent times, mining of multi-reef horizons in hard-rock mines has attracted more attention. As these multi-reef environments are not yet fully understood and complex pillar stress regimes exists in these cases, design methodologies are adopted from other methods that have been successful in the past (*e.g.* Hedley and Grant application in single-reef hard-rock situations, adapted from Salamon and Munro for coal pillar designs).

It is known that a rock sample under uniaxial loading conditions will fail in one of the possible two modes; either indirect tension, when the ends have a low friction angle, or shear, when the ends (or the complete sample) are confined (Jaeger, Cook, and Zimmerman, 2007). A schematic of these two modes of failure is shown in Figure 1.

Furthermore, the uniaxial compressive strength differs greatly as the loading direction relative to the schistosity is changed (Salcedo, 1983). Hence, if the loading of the pillar is not perpendicular, as is assumed by the tributary area theory, and the direction of loading is not normal to the horizontal state of schistosity in the pillar, the pillar strength will be less than initially anticipated (Figure 2).

The purpose of this paper is to determine if the mining environment – including the dip of the mining horizon, the depth of extraction, and instances where multi-reefing is practiced – materially affects the loading of pillars, and the resulting influence of a possible shear stress component on the assumed factor of safety.

All modelling in this paper was done using the TEXAN numerical modelling code (Napier and Malan, 2007).

Complex pillar-loading environment

Room-and-pillar layouts for hard-rock mines are commonly designed based on the methodology of creating an environment in which the ratio between the pillar strength and pillar load, commonly known as the factor of safety (FoS), is satisfactory (Equation [1]).

$$FOS = \frac{Pillar\ strength}{Pillar\ load} \qquad [1]$$

'Stable' coal designs are considered to have safety factors of 1.6 and above. Jager and Ryder (1999) commented that the same should apply to hard rock.

Following the successes of the Salamon and Munro (1967) pillar strength formulation, the same approach was sought in the hard-rock environment. The Hedley and Grant (1972) strength methodology followed a few years later, fitting limited information from field studies. Equation [2] shows the formula used in determining the strength of a square pillar.

* *Department of Mining Engineering, University of Pretoria, Pretoria, South Africa.*

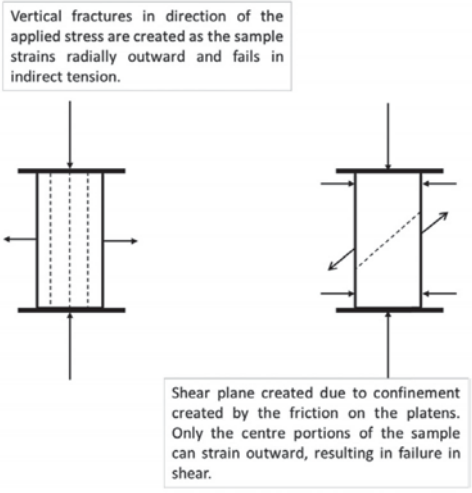

Figure 1—Failure modes (after Jaeger, Cook, and Zimmerman, 2007)

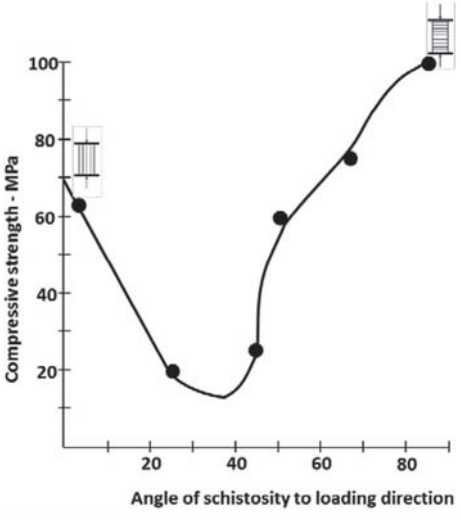

Figure 2—Effect of loading direction on the strength of graphitic phyllite (after Salcedo, 1983)

$$Strength_{(uranium\ ore)} = K\frac{w^{0.5}}{h^{0.75}} \qquad [2]$$

where K represents the pillar strength constant (downgraded uniaxial compressive value), w the width of the pillar, and h the height at which the mining is taking place. In the South African hard-rock mining industry, the values of K can range from 35 MPa for initial design calculations to around 60 MPa after back-analysis on actual pillar performance. The ranges are based on one-third of the UCS values of the typical rock mass in the hard-rock industry, which range from 100 to 180 MPa.

The lower limit for K is generally assumed as a first estimate when designing a room-and-pillar mine. After some mining has been done, leaving pillars based on the initial design parameters, and an increased confidence in the input parameters has been gained, the K value of that specific mining application could be back-analysed by means of elastic modelling to obtain a K value reflecting the conditions observed.

The loading of the pillar could also be calculated based on the tributary area theory (TAT), which assumes that the weight of the overburden directly above the pillar plus that halfway to the next pillar is being carried by the pillar. In application, the conservative TAT ignores the fact that the presence of abutments in a mining area results in a different distribution of stresses, and assumes that the mining area has a regular geometry extending over an infinite area.

The TAT assumptions can be shown to be valid by simple numerical modelling, e.g. by simulating a 240 m × 240 m room-and-pillar area with parameters as presented in Table I.

For the mining environment defined in Table I, the calculated vertical virgin stress level would be 11.8 MPa.

Figure 3 illustrates the values of the modelled pillars compared to the calculated TAT load on each pillar. The pillars towards the edges of the model indicate lower levels of stress since they are influenced by 'abutments', as seen by the numerical modelling package. It also highlights the increase in pillar load from virgin stress levels prior to mining. Figure 3 indicates that where the assumptions of the TAT are met (towards the middle of the modelling area), the modelled pillar stress level approach the calculated APS (Average Pillar Stress) values. Hence, if normal loading is the only stress applied to the pillar, TAT can be assumed to be a valid methodology to follow.

If the mining environment changes and the conditions of loading change, so should the considerations and application of the standard formulae. As proven by Maritz *et. al.* (2012), in multi-reef scenarios, normal stress levels reduce while shear stresses increase on the pillars for horizontal environments.

Maritz *et al.* simulated a multi-reef, 16 m × 144 m stabilizing pillar (0° dip) where the pillar stresses on the two reef horizons (Reef A and Reef B) were compared, firstly with

Table I

Tributary area numerical model input parameters

Parameter	Value
Density	3000 kg/m³
Pillar dimensions	8 m x 8 m
Mining span (rooms)	8 m
Mining height	2 m
Mining depth	400 m

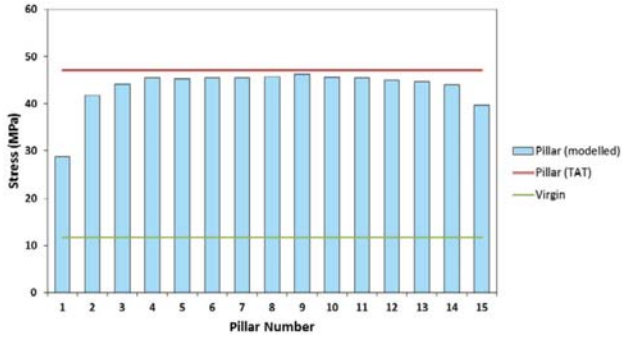

Figure 3—Pillar loading – numerical modelling results *vs* TAT calculated values

only Reef A being mined, and then comparing the pillar stresses when the second reef had been extracted. The middling between the reefs was set at 35 m (Figure 4), with the pillars on Reef A and Reef B being superimposed.

Figure 5 depicts the reduction in normal stresses on identical superimposed room-and-pillar layouts from a single-reef environment to a multi-reef scenario, whereas Figure 6 highlights the shear stresses on the Reef B pillar in the multi-reef scenario.

The significance of Figure 6 is that when Reef B is analysed in isolation (Reef A ignored), no shear stresses are present on the pillar. Shear stresses appear as soon as Reef A is considered.

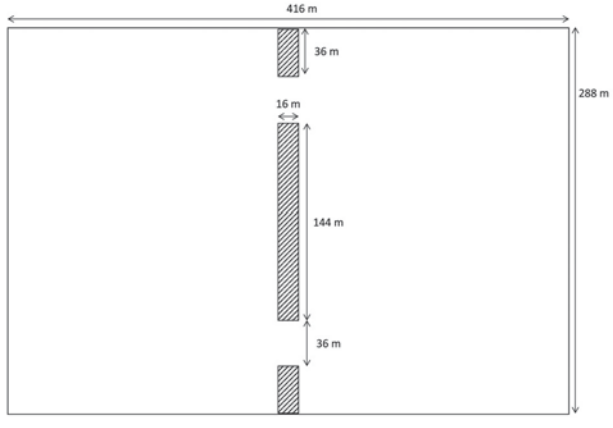

Figure 4—Simulated layout with regional pillars (after Maritz *et al.*, 2012)

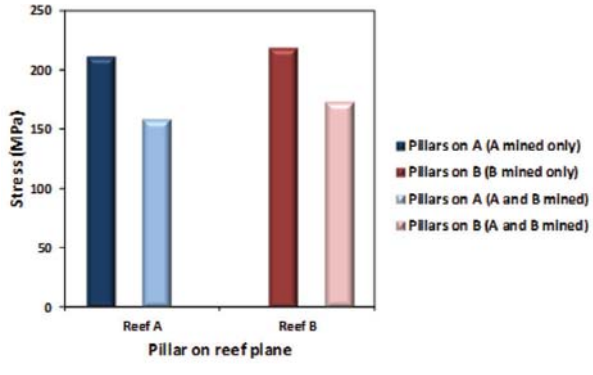

Figure 5—Normal stresses in single- and multi-reef scenarios (after Maritz *et al.*, 2012)

As the complex interaction of stresses in a multi-reef scenario is now apparent, this paper will investigate the changing ratios between normal and shear stresses on pillars as the reef dip angles changes and when multi-reef scenarios are introduced.

Simulating the effect of dip and mining depth

The effect of dip and mining depth on shear stress levels on a pillar will be investigated using the excess shear stress (ESS) – Equation [3]:

$$\mathrm{ESS} = \tau_{max} - \mu\sigma_n \qquad [3]$$

The simulated shear stress (τ_{max}) on a plane is resisted by a function of the friction angle (μ=tanϕ) and the normal 'clamping' stress (σ_n).

Positive ESS values suggest an unstable condition in the sense that shear failure could occur since the driving stress (τ_{max}) exceed that of the shear strength ($\mu\sigma_n$). A number of TEXAN simulations (Table II) were conducted on a standard 240 m × 240 m room-and-pillar layout (Figure 7) to ascertain the effect of dip and mining depth on the shear stress levels.

On a horizontal plane, as the depth increases the 'clamping' stress increases, hence reducing the ESS levels and resulting in a more stable shear environment. The plane assumed for the purpose of the ESS calculations was the contact between the pillar and the hangingwall. Figure 4 depicts the increasing level of stability on a horizontal plane at varying depths. ESS is simply a function of normal stress (increasing with depth) times the coefficient of friction, since the modelled shear stress component is zero. These ESS values are presented graphically in Figure 8.

Table II

List of models simulated with the associated parameters

Model number	Dip of reef plane (°)	Depth below surface (m)
Base (BC)	0	400
C1	0	600
C2	0	800
C3	30	400
C4	30	600
C5	30	800
C6	60	400
C7	60	600
C8	60	800

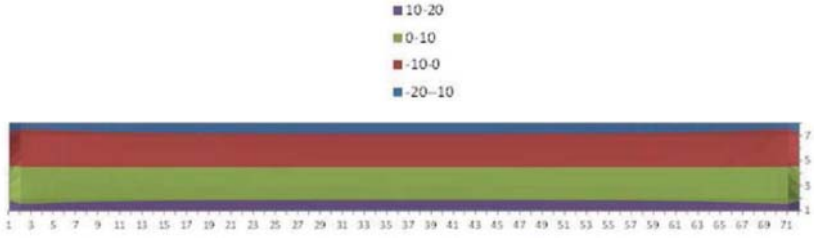

Figure 6—Contours of shear stress for the Reef B pillar when positioned exactly below the Reef A pillar (after Maritz *et al.*, 2012). The positive and negative values of the indicated shear stresses are only an indication of the direction

The expected change in ESS becomes more obvious in the cases where the dips change. When the dip increases, the driving shear stress increases, the normal stress reduces, and therefore indicates likely instability with ESS values approaching zero. Figure 9 depicts the change in the ESS values as the dip of the modelled horizon is increased.

The chances of observing ESS levels such as these in the South African context are considered to be very unlikely, since the hard-rock mining industry does not commonly employ room-and-pillar layouts on reefs with dip angles exceeding 15°.

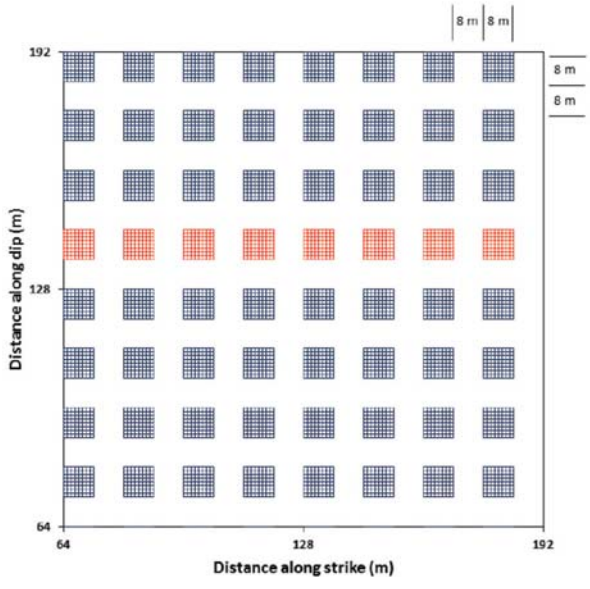

Figure 7—A portion of the pillar geometry simulated

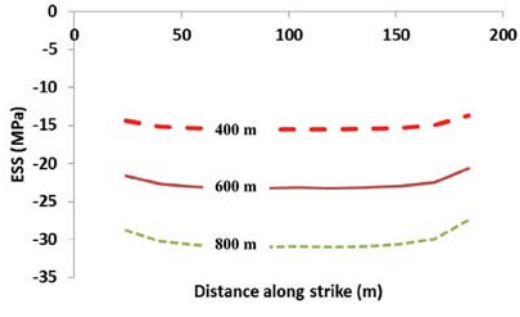

Figure 8—ESS values on the pillars for model with zero dip as a function of depth (friction angle of 20° on the plane)

Shear stress on stability pillars

Regional stability could be achieved by designing stability pillars, either on dip or along strike. These pillars are designed to control the energy release rate (ERR) associated with the mining span, reducing the incidence of seismic events and rockbursting at working stope faces (Jager *et al.*, 1999).

The shear stress values have been again scrutinized by means of a TEXAN set of numerical models comparing the dip configuration with the strike layout. A schematic of the two layouts is presented in Figure 10.

The model was set up with the parameters presented in Table III.

The resulting values are summarized below. From the analysis it was found that the APS on the strike orientation exceed that of the dip layout by 4% and the shear stress by 19%. The values obtained from the numerical modelling analysis are presented in Table IV.

The shear stresses in the dip direction are presented in Figure 11.

High shear stress peaks are observed on the pillar edges, reducing in magnitude as the core is approached. In Figure 11A the area of the red contour (lower stress levels) far exceeds that of strike pillar presented in Figure 11B. Being an elastic numerical model, the results indicate the reason for dip pillars being a better regional support, taking into account the K-ratio applicable to the environment and the ride direction.

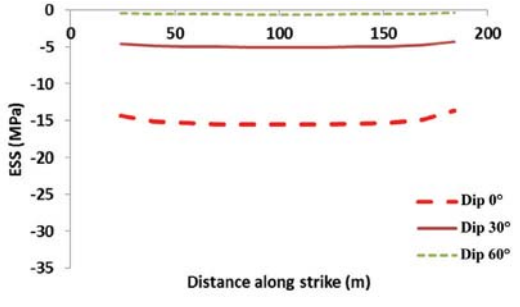

Figure 9—ESS values on a plane at constant 400 m depth as a function of dip with a friction angle of 20°

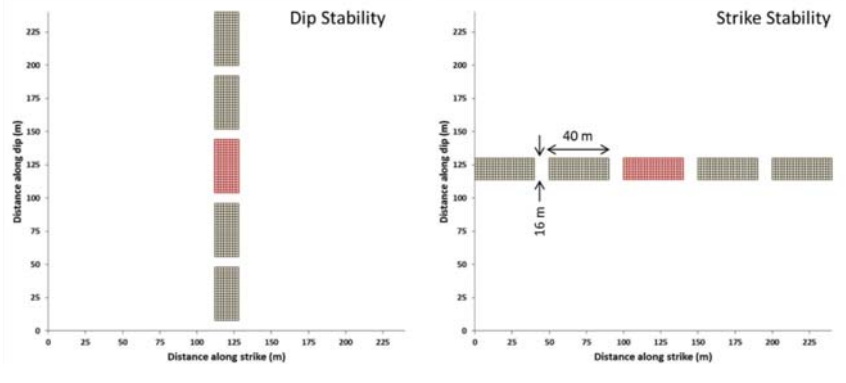

Figure 10—Schematic of modelled stability pillar layouts (red pillar indicating the pillar analysed)

Table III

Stability pillar – TEXAN input parameters

Parameter	Unit value	
Vertical stress gradient	0.03 MPa/m	
Depth below surface	1500 m	
Gravitational constant	g 9.81 m/s^2	
K-ratio	1.5	
Reef dip	30°	
Mined out / model size Strike (x dir) Dip (y dir)	 250 m 240 m	
Poisson's ratio	0.25	
Young's Modulus	65 GPa	
Pillar dimension	**Dip dimension**	**Strike dimension**
Dip stability	40 m	16 m
Strike stability	16 m	40 m
Holings	10 m	
Element size (modelling grid)	2 m x 2 m	

Table IV

Comparison of average stress levels – dip *vs* strike stability

Orientation		Single normal (MPa)	Shear (MPa)
Dip	Maximum	670	122
	Minimum	189	34
	Average	302	54
Strike	Maximum	724	145
	Minimum	191	39
	Average	313	64

The plot of the shear and normal stress in the ESS context (Figure 12) leads to similar conclusions with respect to the better layout in a dipping environment.

The ESS contours on the strike-orientated pillar indicate large areas where the ESS levels are approximately zero, indicating possible areas of instability (a positive ESS denotes instability). The dip pillar reflects a better tendency towards stability.

Factor of safety

As mentioned previously, the ratio between the pillar strength and pillar load should be designed to a value of 1.6. This entails that an optimal extraction should be pursued that shows economic value as well as providing the rock mass stability needed to ensure a safe working environment.

As discussed earlier in this paper, the loading could be calculated either by the TAT approach, considering the limitations and applications of the theory, or by means of numerical modelling. For the purpose of calculating the FoS in this section, the loading will be taken as that calculated during the numerical modelling process.

The foregoing analysis considers only the axial loading (normal stress), whereas Swart *et al.* (2000) suggested the strength-to-load ratio representing the FoS should be revised to include the shear stress levels of the pillar load stress matrix. A graphical representation is given in Figure 13.

In Figure 13, σ_n depicts the normal stress on the pillar. and P_S represents the uniaxial pillar strength. Swart *et al.* suggest that where the standard FoS equation is calculated by P_S/σ_n the real safety factor should be presented by OE/OF.

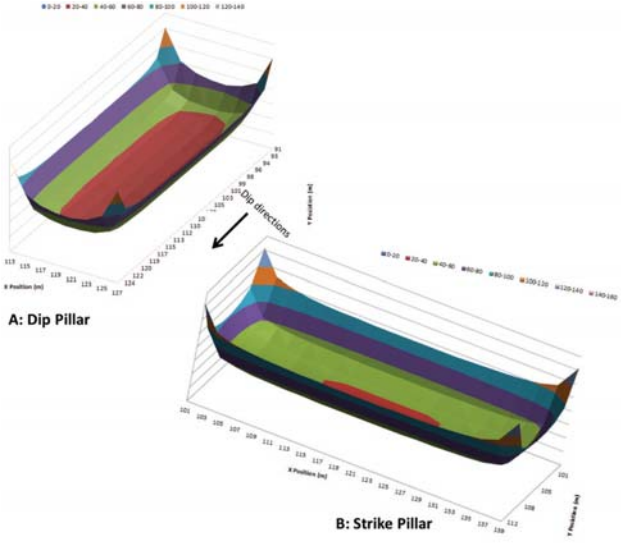

Figure 11—Simulated shear stresses on stability pillars

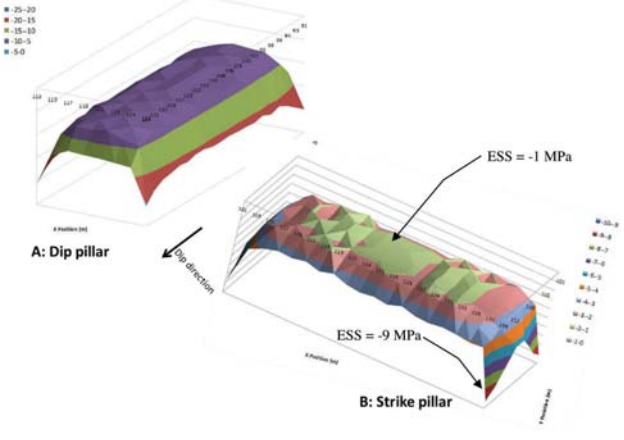

Figure 12—Comparatives ESS contours

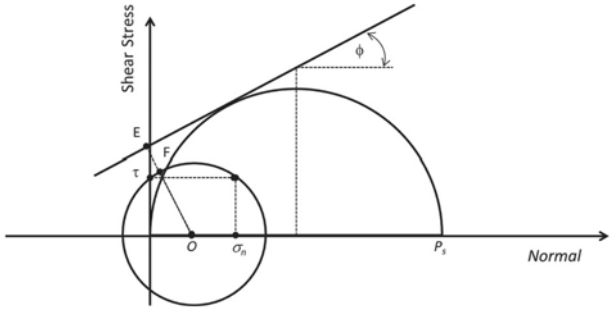

Figure 13—Mohr circles of stresses acting on a pillar (after Swart *et al.*, 2000)

The suggested FoS equation for inclusion of the shear component is:

$$FoS = \frac{c \cdot \cos(\phi) + \frac{1}{2} \cdot \sigma_n \cdot \sin(\phi)}{\sqrt{\frac{\sigma_n^2}{4} + \tau^2}} \quad [4]$$

with c being the cohesion and ϕ the friction angle. The stresses are given by σ_n for the normal and τ for the shear component.

Swart *et al.* also expressed the cohesion in terms of the downgraded strength of the rock mass (DRMS):

$$c = \frac{1}{2} \cdot \mathbf{DRMS} \cdot \frac{W_{eff}^{\alpha}}{H^{\beta}} \cdot \left(\frac{1-\sin(\phi)}{\cos(\phi)}\right) \quad [5]$$

A TEXAN model had been set up to illustrate the variance in FoS values when including and excluding various parameters. The model was adjusted to simulate a room-and-pillar layout at various dip angles (0° to 40°) so as to 'generate' a shear stress component on the pillars. The input parameters to the model can be read in Table V.

For illustrative purposes, the two versions of the FoS are calculated for each scenario – firstly, using the Hedley and Grant methodology for hard-rock strength calculation; and secondly, the Swart methodology, including the shear stress. Table VI summarizes the findings of this comparison.

Table VI shows that the FoS is reduced by around 37 per cent on average when the Swart formula is applied, suggesting a reduction in the extraction ratio to accommodate a safe environment. The Swart formula even suggests a reduction in the safety factor with no shear stress present, given the same strength constant in both formulae.

Conclusions

The complex loading environment in a room-and-pillar layout was investigated for both dipping and multiple reef scenarios. The existence of shear stress components as part of the pillar loading in a room-and-pillar layout has been identified by means of TEXAN numerical modelling code. From the elastic numerical modelling results, it can be concluded that the stress and loading regime of pillars is highly influenced by various factors, including the dip of the reef horizon, depth below surface, and multi-reef scenarios.

The orientation of larger scale pillar, such as regional stability pillars, seems to have some significance when the shear component is analysed. It appears that both the normal and the shear component for dip stability pillars are less than for the strike counterpart.

If consensus is achieved on which of the pillar strength formulae applies to the pillars in the extraction area, the influence of the shear stress, which reduces the safety factors, should be taken into account. It can thus be concluded that the tributary area theory and formula, which is believed to be conservative initially, might not be so conservative after all in cases where shear stresses are present.

Acknowledgements

This work forms part of the author's MEng studies at the University of Pretoria.

Table V

TEXAN numerical modelling input parameters

Parameters	Value
Friction angle	30°
Extraction ratio	75%
Pillar strength (K)	55 MPa
Pillar width	8 m
Mining height	1 m
K-ratio	1.5
Density	3000 kg/m3

Table VI

Factor of safety – Hedley and Grant *vs* Swart methods

Dip (°)	τ_{yz} (MPa)	τ_{zz} (MPa)	FoS (HG)	FoS (S)	Variance
0	-	45.68	3.41	2.20	35%
10	-3.98	46.39	3.35	2.15	36%
20	-7.27	48.29	3.22	2.02	37%
30	-9.89	51.41	3.03	1.88	38%
40	-11.22	55.11	2.82	1.77	37%

*Note: other simulation results omitted rendering the same results on the variance

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Interventions for ensuring sustainability of the minerals education programmes at the Polytechnic of Namibia

by D. Tesh*, H. Musiyarira*, G. Dzinomwa†, and H. Mischo‡

Synopsis

The mining industry worldwide is facing a tremendous shortage of minerals engineers in all fields of specialization. For instance, in Australia the skills shortage in the mining industry has been identified as one of the top risks facing the mining industry. In Namibia most minerals engineers employed are expatriates, with some being Namibians who studied abroad. The minerals engineering programmes at the Polytechnic of Namibia are still in their infancy. These programmes were designed to meet the mining industry skills needs. Being young has its advantages in that lessons can be learnt from older minerals education institutions that went through similar challenges. However, this does not imply just copying and implementing their approaches, since the context differs and, to ensure sustainability of the minerals education programmes, curricula have to be customized to the local context. This paper reviews the interventions made by the Polytechnic of Namibia in order to ensure the sustainability of its minerals education programmes. The methodology consisted of an extensive literature review, a *status quo* analysis of the mining and process engineering department, identifying the gaps between the current state and desired state, and mapping the goals and strategic actions required to progress to the desired state. The following factors were identified as major threats to the sustainability of minerals education at the Polytechnic of Namibia: the quality of students, low student enrolment rates, low pass rates in science and mathematics, shortage of academic staff, dwindling government funding, and limited involvement of the mining industry. The major outcomes of this research comprise the detailed strategic actions employed by the Polytechnic of Namibia to address the threats to sustainability of its minerals education programmes.

Keywords

mineral eduction, partnerships, Polytechnic of Namibia, sustainability.

Introduction

In the past decade, globalization and fluctuating mineral prices have had a significant impact on the minerals industry and the suppliers and manufacturers that service it. At the same time, the minerals tertiary education institutions in most countries have found themselves battling to be self-sustainable (Phillips, 1999; Galvin and McCarthy, 2001). The sustainability of minerals education is a worldwide problem and not merely limited to Namibia. For instance, in Australia the skills shortage in the mineral industry has been identified as one of the top risks facing the industry (Minerals Council of Australia, 1998; Ernest and Young, 2012). However, in Namibia, the skills shortage of mineral professionals is aggravated by the fact that the Namibian minerals education institutions are still in their infancy, with the first graduates having been produced only at the end of 2013. This means that the Namibian minerals industry recruits most of its skill needs from outside the country. Musiyarira et al. (2013) confirmed that the sustainability of the minerals education programmes in Namibia was a major issue in the country's effort to tackle the skills shortage. This study looks at the status of the minerals engineering programmes and reveals how the Polytechnic of Namibia has been tackling the threats to the sustainability of its minerals education. The overall objective of this study is to analyse the progress, challenges, and lessons learnt and seek ways of addressing the challenges.

Background

The Namibian economy is heavily dependent on the extraction and processing of minerals for export (Namibian Chamber of Mines, 2014). Mining accounts for approximately 11% of the GDP and for more than 50% of foreign exchange earnings (Namibia Statistics Agency, 2013). Namibia is a primary source of gem-quality diamonds and is ranked the fourth-largest producer of uranium in the world. It also produces large quantities of zinc, gold, acid-grade fluorspar, copper, lead,

* *Department of Mining and Process Engineering, Polytechnic of Namibia, Windhoek, Namibia..*

† *Paasol Resources (Pty) Ltd, Harare, Zimbabwe.*

‡ *Department of Mining Engineering, Technical University Bergakademie, Freiberg, Freiberg, Germany.*

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cement, salt, dimension stone, and other minerals (Namibian Chamber of Mines, 2014). The mining industry worldwide is facing a tremendous shortage of minerals engineers in all fields of specialization (Fraser Institute, 2013). In Namibia most mineral engineers employed are expatriates, with some being Namibians who studied abroad (Mischo, 2010). A study by the Namibian Chamber of Mines (2007) revealed that there were shortages of mining and metallurgical engineers in the mining sector. This situation is not unique to Namibia, and Musingwini *et al.* (2013) made similar observations for the South African mineral industry.

In response to the mining boom, the University of Namibia (UNAM) and Polytechnic of Namibia (PON) introduced minerals engineering degree programmes in 2008/2009 and are in the process of developing professional and further education programmes to meet future mining industry skills needs and build a workforce that incorporates sustainable development into the production environment. In order for minerals engineering education to be sustainable, it is important for Namibia to learn from experience and best practices all over the world. This paper considers the case of the Polytechnic of Namibia which is in the process of transforming into the Namibia University of Science and Technology.

The minerals engineering programmes at the Polytechnic of Namibia are still in their infancy, with the first intake having graduated in October 2013. These programmes were designed to meet the skills needs of the mining industry. The threats to minerals education are generic worldwide, but the solutions have to be context-specific. In a study of the sustainability of minerals education in Namibia, Musiyarira *et al.* (2013) identified seven interactive factors that may affect the sustainability of minerals education. These are: (1) the funding covering the essential needs of the institutions, (2) matching the number of graduates to the need of the mining and related industries, (3) the quality and quantity of students enrolling for the programmes, (4) alliances and partnerships with other educational institutions, (5) the quality and quantity of academic staff, (6) sound infrastructure, and (7) well-developed and dynamic curricula. It is important to realize that these factors are not unique to the Namibian mineral education system, but they are worldwide trends as noted by other researchers (Cawood, 2011; Galvin and McCarthy, 2001; Moudgil, 2006; Wagner, 1999). The only difference is that all institutions are affected differently and within the context of their development.

Methodology

An extensive literature review was conducted, as well as a *status quo* analysis of the Mining and Process Engineering Department at the Polytechnic of Namibia, identifying the gaps between current and desired states and mapping the goals and actions requires to progress to the desired state. Reports and documents from various stakeholders were analysed. Comparative studies with established institutions regionally and internationally were conducted in a bid to learn from the experience of others. Since two of the authors are Polytechnic of Namibia staff members and two are visiting academics at the same institution, the data was readily available.

Results and discussion

The following sections detail the strategic actions employed by the Department of Mining and Process Engineering (DMPE) at the Polytechnic of Namibia in tackling the threats to its sustainability. Figure 1 summarizes the elements used in strategies employed by the DMPE to tackle the threats to its sustainability. It can be seen that this is a holistic approach, involving different strategies, all of which are equally important.

Funding covering the essential needs of the institutions

Figure 2 shows the running costs of the department, which include operational, maintenance, and laboratory equipment (2010–2013). The value for 2014 is a projected figure. It can be observed from Figure 2 that the running cost has been increasing steadily each year. However, the authors note with concern that the funding is being threatened by a budget cut from the government.

The quality and quantity of student enrolments for the programmes

Enrolment into the programmes has gradually increased from 2009 to 2013, as shown in Figure 3. However, from 2013 to 2014 the enrolment decreased. This is mainly due to poor matric results, with most of the applicants not meeting the admission requirements. In order to address this challenge, the Polytechnic of Namibia has taken a proactive approach, which includes the establishment of a preparatory year (Pre-Engineering), with the aim of building up the students' skills in the core subjects, namely mathematics, physics, and

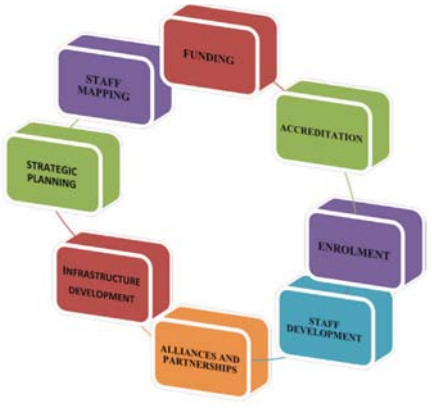

Figure 1—Minerals education strategies used by the DMPE

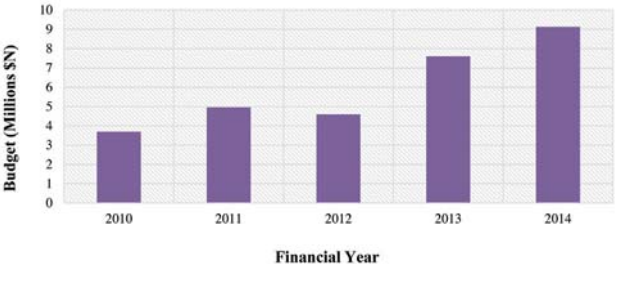

Figure 2—Operation and maintenance costs

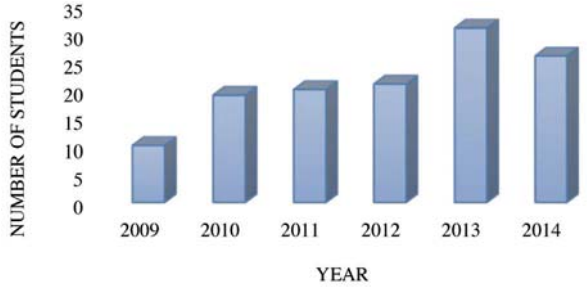

Figure 3—Student enrolment

chemistry. Another strategy employed is to organize schools outreach programmes with the aim of encouraging students to join the local minerals engineering programmes. These outreach trips are complemented by the annual career fairs that are held in March of every year. It was found that most of the best-performing school leavers prefer to study at South African universities, sometimes out of ignorance of what is available in their own country.

Staff development

Staffing levels in the Department of Mining and Process Engineering at the Polytechnic of Namibia have been growing steadily, as shown in Figure 4, but there are still 10 vacancies to be filled. The Department continues to rely on visiting academics in order to meet its teaching needs.

The authors noted that 95% of all the DMPE staff members who are not PhD holders are undertaking studies towards higher qualifications (are enrolled for MSc and PhD degrees); as shown in Figure 5. This will serve to increase the number of permanent academic staff in order to ensure that the programmes are sustainable.

Alliances and partnerships with educational institutions

Alliances with international and regional institutions play an important role in contributing to the sustainability of the DMPE. This has been the case for student and staff (visiting academics) exchange. It is expected that with time the reliance on visiting lecturers will decrease. Figure 6 shows the major partners of the DMPE.

Sound infrastructure

Investment for operations, maintenance, laboratory equipment, and salaries in the Department of Mining and Process Engineering has been increasing steadily, as shown in Figure 7. A five-storey, 200-million Namibian dollar building is being erected, and the DMPE will occupy 40% of the total space. Dedicated laboratories for mining and metallurgy will be set up and equipment is being acquired.

Sound strategic planning and development

The DMPE drafted its strategic plan in 2012. A strategic plan is important since it allows an organization to make fundamental decisions or choices by taking a long-range view of what it hopes to accomplish and how it will do so. This plan reasserts the department's vision, mission, and values and establishes eight strategic goals. The plan recognizes existing strengths – for example, providing a student-centred teaching and learning environment – and seeks to reinforce and develop these qualities. It blends both continuity and change, hence identifying niche areas on

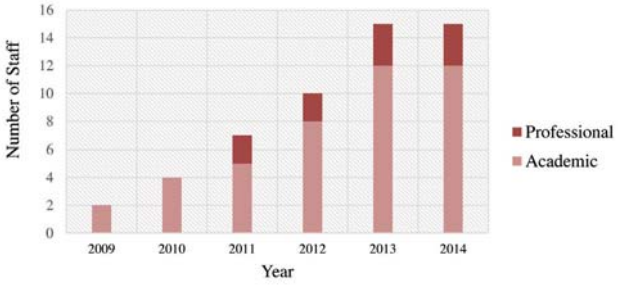

Figure 4—Academic staff profile of the DMPE

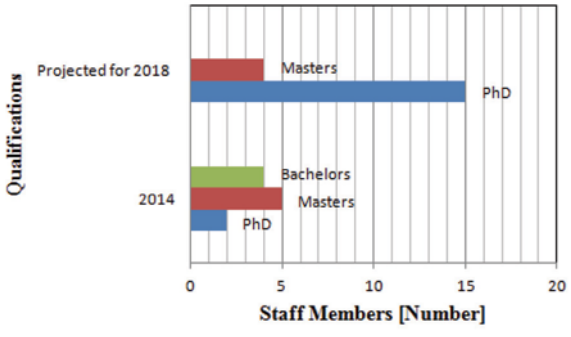

Figure 5—Staffing profile in the DMPE: current and projected

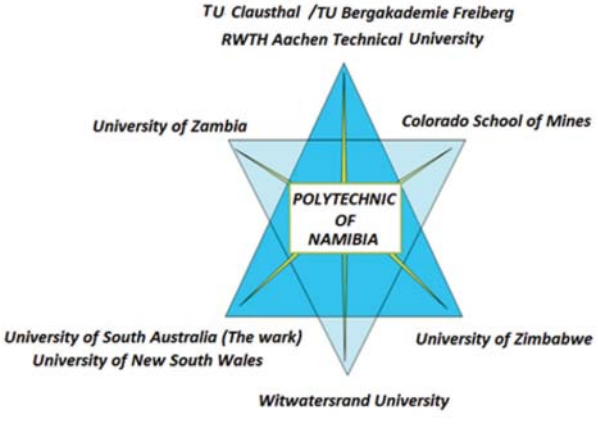

Figure 6—Alliances with external partners

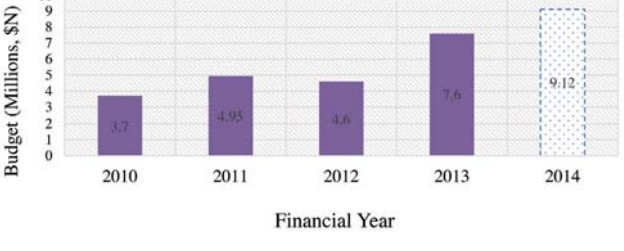

Figure 7—Budget for operational and maintenance

which the department needs to concentrate in order to realize its full potential. This plan articulates a course by which the Department of Mining and Process Engineering will build its reputation as a world-class department, dedicated to making a difference in the lives of its staff and students.

Linking staff to companies' needs

For any country to develop technologically and economically there must be a strong link between industry, government, and academic institutions. All courses and programmes offered by such institutions derive their relevance from the needs of the nations they serve, and hence should promote development of existing and future industries. The direction of the research of the DMPE was defined based on a thorough mapping of the Namibian mineral industry. This has the advantage of improving the synergy between the DMPE and the companies within the Namibian mineral industry.

Industrial advisory board

In March 2014, the DMPE set up an industrial advisory board with the primary role of providing strategic direction and advice to the Department. The Advisory Board is expected to have an oversight role in curriculum development as well as in ensuring a strong interaction between the department and the mineral industry. The principle behind the setting up of the board is to involve industry in the value chain for producing 'mineral-industry-ready' graduates. From a quality perspective, process ownership is critical in ensuring good output. This has major advantages for the mining companies since they get the opportunity to mould the quality of output/graduates instead of having to rework the graduates, which is termed '*end-of-pipe panelbeating*' and entails significant costs. The involvement of the minerals industry as advisors will also allow the timeous provision of feedback to the university for improvement.

International accreditation

Accreditation of engineering programmes is an important component of the sustainability of any teaching programme, as it ensures that the programme is aligned with internationally recognized bodies. It also serves as a quality standard and ensures that engineering graduates will be able to work in any country and not only in their own country. In southern Africa, the most prominent engineering body is the Engineering Council of South Africa (ECSA), which is aligned with the Washington Accord. In 2011 ECSA was requested by the Engineering Council of Namibia (ECN) and the Polytechnic of Namibia to assess the programmes for provisional accreditation of the degree programme in mining engineering. As everywhere else, there were teething problems that could not be overcome in the few years that the department had been in existence. The establishment of the industrial advisory board, the development of the strategic plan, staff development, acquisition of state-of-the-art laboratory equipment, and the expansion of the resource base for the department are some of the efforts to address the concerns raised by the ECSA delegation.

Conclusions

The minerals engineering programmes at the Polytechnic of Namibia are still in their infancy, with the first intake having graduated in October 2013. This study has looked at the status of the minerals engineering programmes and reveals how the Polytechnic of Namibia has been tackling the threats to their sustainability. The major outcomes of this study were the detailed strategic actions taken by the Polytechnic of Namibia to address the threats to the sustainability of its minerals education programmes. The engagement of local and international partners, coupled with the bridging year to ground students in mathematics and science, and staff development, among others, are regarded as being instrumental in ensuring the sustainability of the minerals education programmes at the Polytechnic of Namibia.

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Development of an atmospheric data-management system for underground coal mines

by Z. Agioutantis*, K. Luxbacher†, M. Karmis†, and S. Schafrik†

Synopsis

With increasing demand for real-time monitoring of mine parameters, the requirement for appropriate data management in many mining applications is also increasing. This includes atmospheric monitoring in underground coal and metal mines. Although a number of different (real-time) monitoring systems have been installed in underground mines, they all typically share the same systems or sub-systems, where each sub-system may include both custom hardware and / or software components. In addition, monitoring components installed in underground coal mines in the USA should also be intrinsically safe and approved by the US Mine Safety and Health Administration.

Real-time analysis adds complexity to the system since data validation and storage should be completed independently of filtering, data reduction operations, or visualization. Real-time processing may include statistical evaluation, trending, cross-correlation, and real-time alarm or warning generation.

This paper presents the concept and design of an integrated system under development for atmospheric monitoring in US coal mines.

Keywords

mine ventilation, real-time monitoring, data management.

Introduction

The monitoring of atmospheric conditions in underground coal mines is an important task that helps mine operators run the ventilation systems in a more efficient manner, therefore ensuring a safe environment for all mine personnel. The layout of the sensors in each mine depends on mine geometry, the design of the ventilation system, the availability of power and communication lines to each sensor location, and other factors. Currently, several real-time monitoring techniques are available that allow mine operators to monitor all ventilation parameters, such as air flow, air velocity, pressure drop, and gas concentration at various locations throughout a mine.

Although advances in electronics and data transmission systems have led to progress in this field in recent years, monitoring of atmospheric conditions still presents challenges due to the limitations in current technologies in terms of accuracy, response time, range, sensitivity, and ruggedness of equipment.

In the USA, atmospheric monitoring in underground coal mines is not only mandatory, but systems should be designed and implemented according to existing regulations, *i.e.*, Title 30 of the Code of Federal Regulations (CFR). More specifically, under current atmospheric monitoring system (AMS) regulations (CFR 30 §75.351), data archiving is not required. The regulation states that records must be kept regarding alert or alarm signals, AMS malfunctions, and seven-day tests of alert and alarm signals conducted. The records must note the person that recorded the information, and be kept in a secure book or electronic system that is not susceptible to alteration. These records must be kept for one year at a surface location at the mine and be available for inspection by miners and authorized representatives of the Secretary (CFR 30 §75.351). The required records are limited to alert or alarm signals, malfunctions, system tests, and calibration. Furthermore, in the case of coal mines, the equipment should be 'permissible' *i.e.* it should meet the specifications by the US Mine Safety and Health Administration (MSHA) for the construction and maintenance of such equipment, to assure that it will not cause a mine explosion or mine fire.

Depending on the size and type of the underground mine, atmospheric monitoring should gather data that covers several different parameters that characterize the atmospheric conditions underground, including (but not limited to) concentrations of various gases (CO, CO_2, CH_4, *etc.*), wet and dry temperature, humidity, barometric pressure, air flow, fan performance indicators, air velocity, and total air pressure loss.

* *University of Kentucky, USA.*

† *Virginia Center for Coal and Energy Research, Virginia Tech, USA.*

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Proper monitoring becomes even more important in the case of coal mines, where high methane concentrations present a hazard and/or high CO indicates development of a fire. In addition to everyday operations, atmospheric monitoring can be used to detect incidents such as explosions behind seals, a methane ignition at the face, a belt fire, *etc.* However, it should be noted that atmospheric monitoring sensors commonly used to detect the parameters of interest may be currently limited in response time and sensitivity.

Current monitoring technologies in US coal mines

A simplified layout of a typical system currently installed in US coal mines is shown in Figure 1. Any equipment installed in the mine area should be 'permissible'. Data transmission is currently accomplished mainly via fibre optic lines using commercial protocols such as ethernet over TCP/IP. Near-sensor communication is often via copper cable to a fibre junction box

The stations that provide power and coordinate data transmission to the surface are usually driven by programmable logic controllers (PLCs) that allow 'smart' communication between the surface computer(s) and the underground equipment. PLCs can usually report on the status of communications with a sensor, the status of a sensor, and keep track of multiple sensors per station. Power is usually transmitted to sensors via the same cable that gathers data. Data is usually converted from analog to digital at the sensor level and is transmitted as digital information to the surface.

At the surface location, dedicated computer units communicate with the PLCs at mine level and coordinate data flow to a database and a digital display system available to operators (Figure 2). These systems are typically called human-machine interfaces (HMIs) or supervisory control and data acquisition (SCADA) systems. Operators can interface with PLCs through these systems, *e.g.*, acknowledge alarms, start / stop equipment, *etc.*

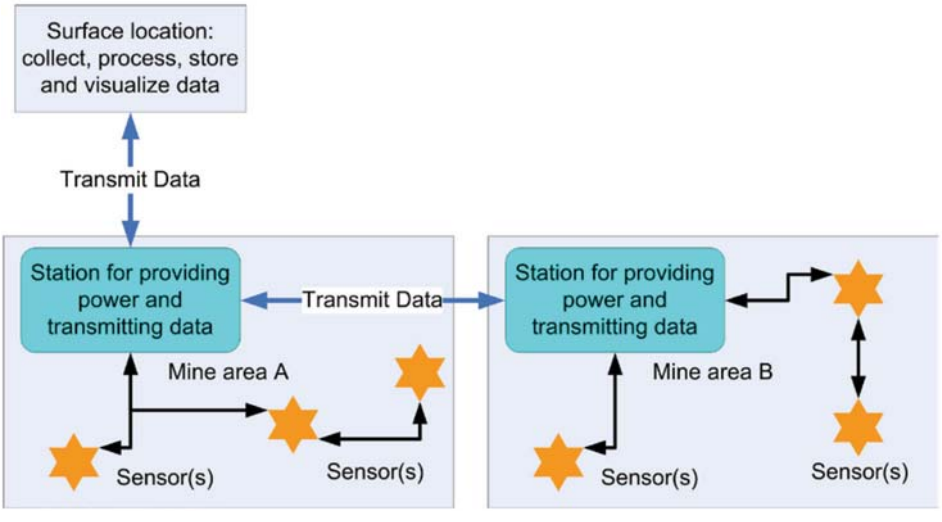

Figure 1—Simplified layout of sensor deployment in US coal mines

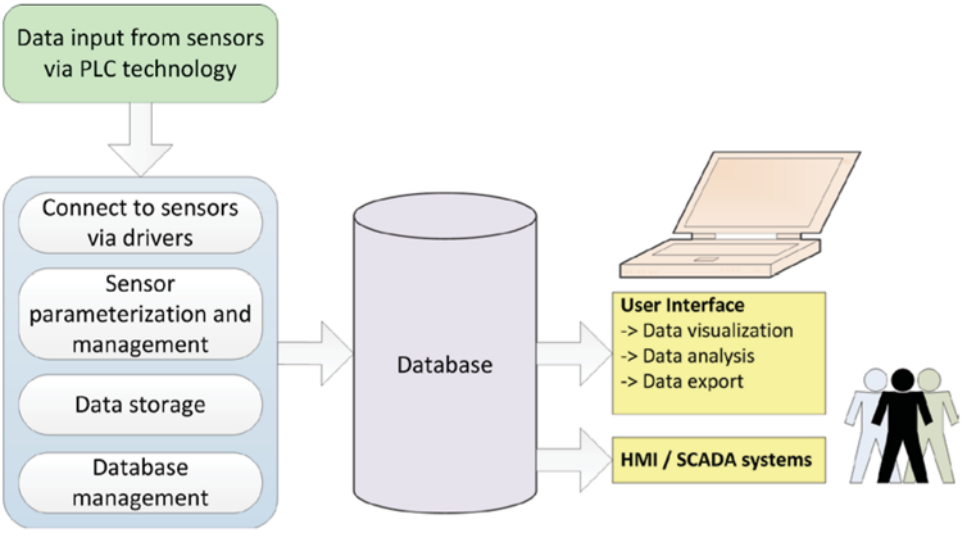

Figure 2—Data acquisition for atmospheric monitoring in coal mines

In terms of hardware, such systems typically include three basic component groups: (a) the sensors (and data loggers / converters) responsible for data acquisition, (b) the communication sub-system responsible for transmitting data to a central location, and (c) the processing and storage sub-system, comprising one or more computer units, responsible for data processing and temporary or permanent data storage. In addition, software operating off the processing and storage sub-system is responsible for coordinating data acquisition, validating collected data, visualization, data analysis, and report generation.

Such systems are usually built to comply with MSHA regulations as stated above, and lack advanced data analysis capabilities such as variable cross-correlation, correlation with variables external to the database, *etc*. Furthermore, a typical database system implemented on such systems is configured to store data on a moving 7-day or 14-day window, *i.e*. old data is erased every day.

In some system implementations, data for selected monitored parameters is exported to daily, weekly, or other files for archiving and storage. It is obvious that the data in such files cannot be easily managed and analysed unless it is stored in a common database.

Data management and analysis in mine ventilation is perhaps most heavily utilized in metal and nonmetal mines that have implemented ventilation on demand (VOD). Many of the same management and analysis challenges have been identified, such as the inherent complexity of mine ventilation systems, and development of robust data collection, storage, and management (*e.g*. Meyer, 2008; Tonnos and Allen, 2008). Additionally, these mines have demonstrated measureable improvements in safety and efficiency through application of such systems (*e.g*., Gunderson *et al.*, 2005; O'Connor, 2008; Karsten and Mackay, 2012) Although VOD is not applicable to underground coal mines in the USA, due to restrictions in the amount of airflow change allowed while people are underground (CFR 30 §75.324), the data management and analysis methods developed for application of VOD are certainly applicable.

Database design

A relational database application was developed that has built-in data capture and analysis capabilities. This application, called 'Atmospheric Monitoring Analysis and Database mAnagement' (or AMANDA), is specifically designed for AMS data. The capabilities of the system are discussed in this section.

Data management of an AMS should ensure that the integrity of historical data is maintained. Underground mines generate a large range of data, and this presents a challenge for the AMS database system, especially with systems that have many sensors reporting a large quantity of data. For instance, assume that each data record corresponding to a single measurement value from a given sensor may require a storage space of about 50 bytes (date-time stamp, tag number, project number, value, *etc*.). In typical applications, data may be gathered every few seconds. If one data value is sampled every ten seconds, there would be approximately 0.412 MB of data generated per sensor per day. For a mine with 20 sensors, approximately 8.2 MB of data is generated daily. One year of data with only 20 sensors corresponds to approximately 3.0 GB. Large mining operations and processing plants may incorporate several hundreds (even thousands) of sensors throughout the operation to control and monitor devices. If a large mining operation deploys 300 sensors and its processing plant utilizes 400 sensors, with a sampling frequency of 10 seconds, those sensors would generate approximately 288 MB daily and 105 GB each year. This estimate does not include other data that can illuminate trends further, *e.g.*, measures of loads on mechanized cutting and hauling equipment, physical locations of people and equipment via tracking technology, and maintenance, surveying, and production data.

Storage of this data presents a set of challenges; those with fairly simple solutions are not discussed in this paper. Management and utilization of the data is critical to the operation. Optimizing the placement of monitoring systems to acquire the most critical information, and transmitting the information to a centralized location with a sophisticated storage method has value only if the data can be understood and utilized by a decision-maker.

The AMANDA data management system has a number of subsystems, *e.g*. for data acquisition; data analysis, validation, and storage; visualization and reporting of the data; alarm generation; and tools for statistical evaluation and cross-correlation. Thus, the database was designed with the following characteristics:

- Deployable on a 64-bit system to allow for large files
- Built on a relational database model
- Implemented as a client / server system
- Allows multiple indexing of the data records to assure a quick response to queries.

In addition, the data management application allows:

- Data collection for multiple projects; a project is defined as a collection of sensor data as implemented in a single mine database
- A fully parametric definition of the sensor types that will be used in a project. Each parameter measured by a PLC-driven sensor is called a tag; multiple user-defined tags can be defined per project, and a unique sensor type can be assigned per tag
- Importing of data files exported by current AMS implementations (Figure 3)
- Importing of external data such as barometric pressure or temperature as recorded by weather stations available on the internet (Figure 3)
- Identification of missing data
- Setting of individual warning and alarm thresholds per tag.

Figure 3 presents a simplified diagram that shows data flow from the sensors to the currently available 'Mine Database'. AMANDA is external to this data flow and only reads data available by automatic export by the mine system. AMANDA thus cannot directly or indirectly interfere with the installed data acquisition system.

Data from a US coal mine was imported to the database (Griffin, 2013). In this coal mine, multiple methane and CO sensors have been installed, in addition to the usual sensors for fan, belt, and other operations. Data was available in DBF format on a daily basis. More specifically, for every day two files were generated by the existing system: a 'tag' file, which

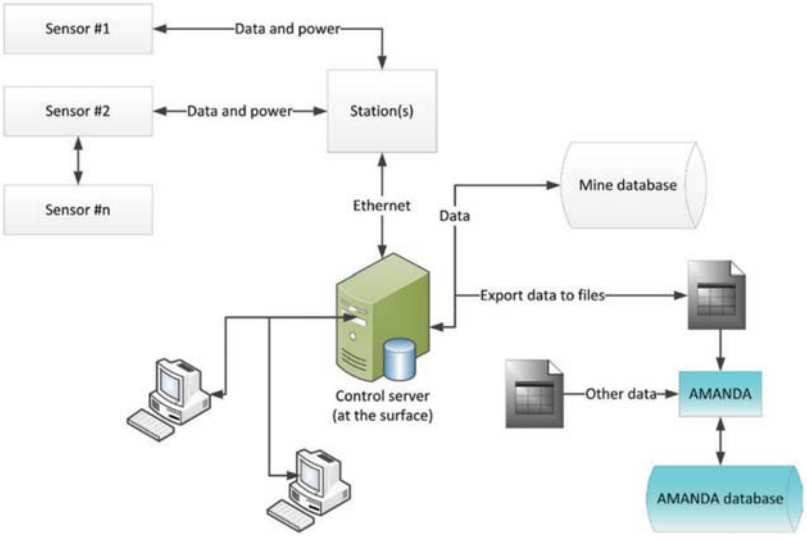

Figure 3—Data flow to the mine database and to the AMANDA database

listed the 'tags' or sensors that were monitored, and for which data was collected and saved; and the main data file (also in DBF format), which listed the data in columns. Each row represented measurements at a different timestamp. For each 'tag' two columns were provided, one with the value read from the sensor and one with the status of the sensor. A typical daily file included 8600 rows (sampling about every 10 seconds) and over 80 columns which correspond to 40 sensors. Prior to data import, a project was defined and the sensors were added to the project. When daily data was imported, each data value and its time stamp were assigned to the corresponding sensor and project.

There was no barometric pressure sensor installed at the mine at that time. Data from a nearby publicly available weather station was downloaded and imported into the database into a separate 'tag', which was assigned to the external sensor. During importing, data was not altered in any way. Erroneous values (*i.e.* negative or extreme values) were also imported. The user can isolate these values by flagging them, but the raw data is always available for inspection.

Once data has been imported into the relational database, it is easy to select specific data groups for plotting and analysis. The program can plot any of the recorded tags *versus* time. Data can also be displayed in a continuous mode by displaying a moving window of one or multiple days.

Figure 4 shows an example of ventilation fan motor amperes. The fan motor power consumption varies throughout daily operation, demonstrating that tracking fan performance can be just as important as monitoring underground gas levels. Fluctuations in the fan motor amperes can be due to the motor efficiency, outside temperature, air density, movement in mine openings, and a wide variety of other factors. Monitoring fan performance can also help the mine operator understand if changes in gas concentrations are related to fan performance. Fan performance is an example of a variable that can contribute to changes in gas concentration and must be analysed with other data to allow for the emergence of critical trends.

Figures 5a and 5b show examples of superimposed data collected by two methane sensors (right axis, methane concentration in per cent) at two different mine locations on return airways (green and blue curves) and the surface barometric pressure (left axis, inches Hg). It can be seen that sudden decreases in the barometric pressure coincide with an immediate increase in the methane percentage in these two locations. The horizontal axis corresponds to a time period of 7 days.

Although, the correlation of barometric pressure and methane concentration has been cited several times (Fauconnier, 1992; Lloyd and Cook 2004), with the new database management system this simple correlation by superposition was very easily accomplished.

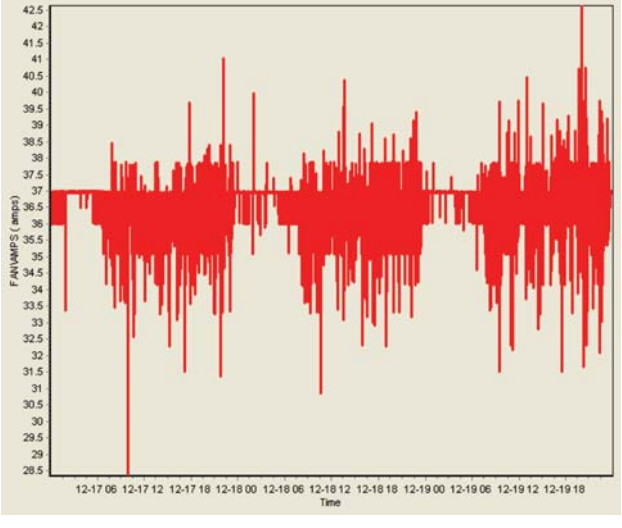

Figure 4—Monitoring of the electrical current on a fan motor over a three-day period

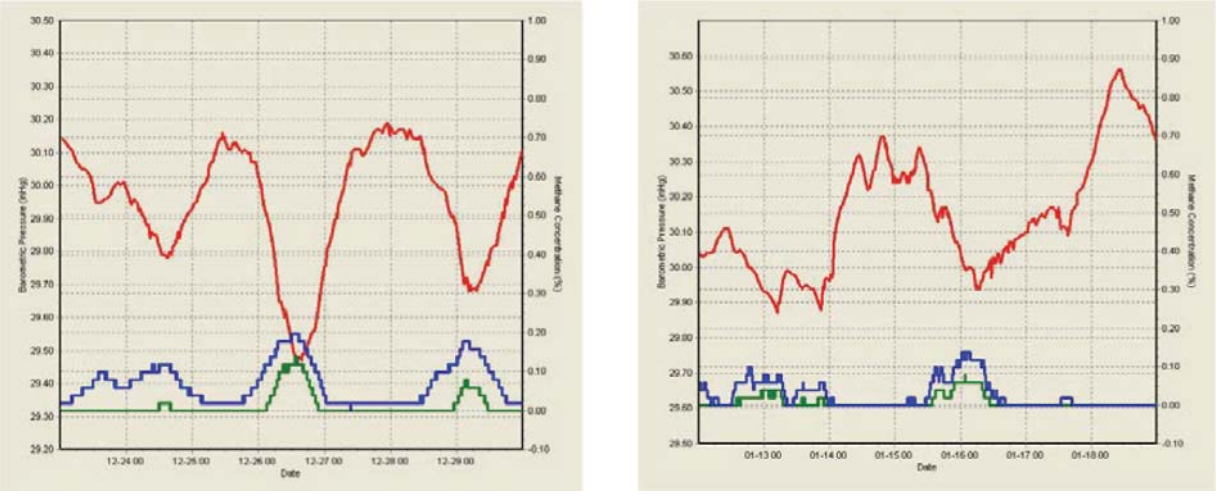

Figure 5—Superposition of barometric pressure and methane concentrations at two different locations for a time period of 7 days

Summary and conclusions

A new database management system was developed in order to facilitate the massive undertaking of maintaining, storing, reviewing, analysing, and interpreting large amounts of data generated daily by sensors installed in underground coal mines. The database is capable of handling multiple projects and multiple sensor sets per project. Data can also be imported from external sources.

In terms of application development, current work is focusing on identifying and analysing peaks (or spikes) in a given time-series. While it is easy to visually identify peaks in a short time window, there is a need to formalize peak detection to determine whether these peaks correspond to significant increases or decreases.

In terms of data analysis, the next step would be to correlate other collected parameters with each other, such as production and methane emissions, fan performance and barometric pressure or daily temperature variation, *etc*. This is a primary, but complex function; this data may be utilized to better characterize the behaviour of a mine environment, which is a complex engineered system. This includes determining and verifying causality (*e.g.* falling barometric pressure, malfunctioning fan, increased production) when a parameter trends in an alarming manner (*e.g.* rising methane concentrations), so that high-risk situations can be remediated.

The importance of the human interface will be also examined. The most advanced human-computer interfaces in mining have generally been directed toward the stationary operator, or a person who has oversight of all the sensors in a mine. While communication via these interfaces is essential, and has led to improved safety and efficiency, many mine personnel do not have access to data that can allow them to better assess situations and make more informed decisions. The challenge is to design technology that is portable, rugged, and safe for use in underground coal mines, and to design software that rapidly conveys emerging data trends to mine personnel. These trends should allow personnel to anticipate system failure (*e.g.*, ventilation, ground, equipment) or to verify safe conditions. An interface for the AMANDA software will be developed and assessed for ease of use, knowledge gains to the user, and speed of information uptake.

Implementation of advanced monitoring and analysis systems in mines is challenging due to the dynamic nature and unique attributes of any single mine, but the gains in health and safety as a result of more informed decision-making are well worth the investment in resources and technology.

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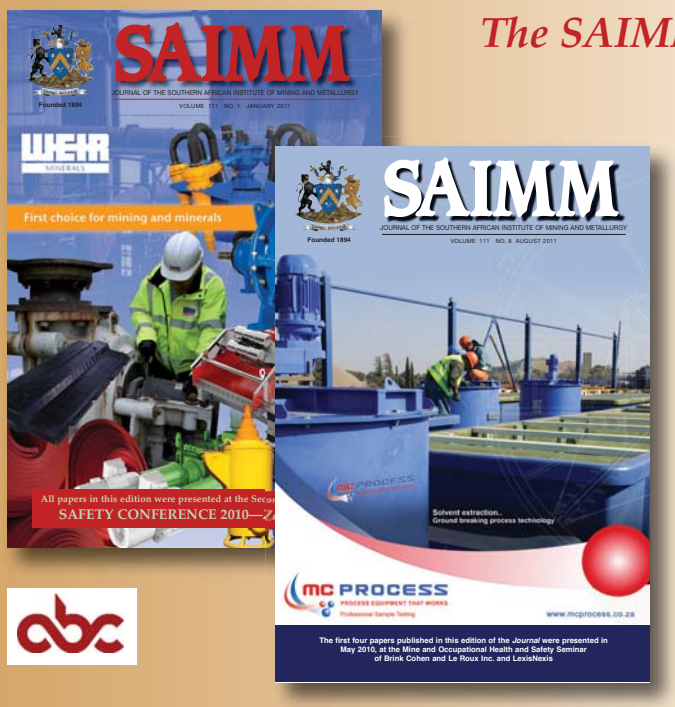

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Tel: +27 11 834-1273/7, Fax: +27 11 838-5923/833-8156
E-mail: camielah@saimm.co.za, Website: http://www.saimm.co.za

28–30 October 2015 — Nuclear Materials Development Network Conference (AMI)
Nelson Mandela Metropolitan University, North Campus Conference Centre, Port Elizabeth
Contact: Raymond van der Berg
Tel: +27 11 834-1273/7, Fax: +27 11 838-5923/833-8156
E-mail: raymond@saimm.co.za, Website: http://www.saimm.co.za

8–13 November 2015 — 23rd International Symposium on Mine Planning & Equipment Selection MPES 2015
Sandton Convention Centre, Johannesburg, South Africa
Contact: Raymond van der Berg
Tel: +27 11 834-1273/7, Fax: +27 11 838-5923/833-8156
E-mail: raymond@saimm.co.za, Website: http://www.saimm.co.za

Company Affiliates

The following organizations have been admitted to the Institute as Company Affiliates

AECOM SA (Pty) Ltd
AEL Mining Services Limited
Air Liquide (PTY) Ltd
AMEC Mining and Metals
AMIRA International Africa (Pty) Ltd
ANDRITZ Delkor(Pty) Ltd
Anglogold Ashanti Ltd
Anglo Operations Ltd
Anglo Platinum Management Services
Atlas Copco Holdings South Africa (Pty) Limited
Aurecon South Africa (Pty) Ltd
Aveng Moolmans (Pty) Ltd
Axis House (Pty) Ltd
Bafokeng Rasimone Platinum Mine
Barloworld Equipment -Mining
BASF Holdings SA (Pty) Ltd
Bateman Minerals and Metals (Pty) Ltd
BCL Limited
Becker Mining (Pty) Ltd
BedRock Mining Support (Pty) Ltd
Bell Equipment Company (Pty) Ltd
BHP Billiton Energy Coal SA Ltd
Blue Cube Systems (Pty) Ltd
Bluhm Burton Engineering (Pty) Ltd
Blyvooruitzicht Gold Mining Company Ltd
BSC Resources
CAE Mining (Pty) Limited
Caledonia Mining Corporation
CDM Group
CGG Services SA
Chamber of Mines
Concor Mining
Concor Technicrete
Council for Geoscience Library
CSIR-Natural Resources and the Environment
Department of Water Affairs and Forestry
Deutsche Securities (Pty) Ltd
Digby Wells and Associates
Downer EDI Mining
DRA Mineral Projects (Pty) Ltd
Duraset
Elbroc Mining Products (Pty) Ltd
Engineering and Project Company Ltd
eThekwini Municipality
Evraz Highveld Steel and Vanadium Corp Ltd
Exxaro Coal (Pty) Ltd
Exxaro Resources Limited
Fasken Martineau
FLSmidth Minerals (Pty) Ltd
Fluor Daniel SA (Pty) Ltd
Franki Africa (Pty) Ltd Johannesburg
Fraser Alexander Group
Glencore
Goba (Pty) Ltd
Hall Core Drilling (Pty) Ltd
Hatch (Pty) Ltd
Herrenknecht AG
HPE Hydro Power Equipment (Pty) Ltd
Impala Platinum Limited
IMS Engineering (Pty) Ltd
JENNMAR South Africa
Joy Global Inc. (Africa)
Leco Africa (Pty) Limited
Longyear South Africa (Pty) Ltd
Lonmin Plc
Ludowici Africa
Lull Storm Trading (PTY)Ltd T/A Wekaba Engineering
Magnetech (Pty) Ltd
Magotteaux(PTY) LTD
MBE Minerals SA Pty Ltd
MCC Contracts (Pty) Ltd
MDM Technical Africa (Pty) Ltd
Metalock Industrial Services Africa (Pty)Ltd
Metorex Limited
Metso Minerals (South Africa) (Pty) Ltd
Minerals Operations Executive (Pty) Ltd
MineRP Holding (Pty) Ltd
Mintek
Modular Mining Systems Africa (Pty) Ltd
Runge Pincock Minarco Limited
MSA Group (Pty) Ltd
Multotec (Pty) Ltd
Murray and Roberts Cementation
Nalco Africa (Pty) Ltd
Namakwa Sands (Pty) Ltd
New Concept Mining (Pty) Limited
Northam Platinum Ltd - Zondereinde
Osborn Engineered Products SA (Pty) Ltd
Outotec (RSA) (Proprietary) Limited
PANalytical (Pty) Ltd
Paterson and Cooke Consulting Engineers (Pty) Ltd
Polysius A Division Of Thyssenkrupp Industrial Solutions (Pty) Ltd
Precious Metals Refiners
Rand Refinery Limited
Redpath Mining (South Africa) (Pty) Ltd
Rosond (Pty) Ltd
Royal Bafokeng Platinum
Roymec Tecvhnologies (Pty) Ltd
RSV Misym Engineering Services (Pty) Ltd
Rustenburg Platinum Mines Limited
SAIEG
Salene Mining (Pty) Ltd
Sandvik Mining and Construction Delmas (Pty) Ltd
Sandvik Mining and Construction RSA(Pty) Ltd
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Sasol Mining(Pty) Ltd
Scanmin Africa (Pty) Ltd
Sebilo Resources (Pty) Ltd
SENET
Senmin International (Pty) Ltd
Shaft Sinkers (Pty) Limited
Sibanye Gold (Pty) Ltd
Smec SA
SMS Siemag South Africa (Pty) Ltd
SNC Lavalin (Pty) Ltd
Sound Mining Solutions (Pty) Ltd
SRK Consulting SA (Pty) Ltd
Time Mining and Processing (Pty) Ltd
Tomra Sorting Solutions Mining (Pty) Ltd
TWP Projects (Pty) Ltd
Ukwazi Mining Solutions (Pty) Ltd
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Forthcoming SAIMM events...

EXHIBITS/SPONSORSHIP

Companies wishing to sponsor and/or exhibit at any of these events should contact the conference co-ordinator as soon as possible

For the past 120 years, the Southern African Institute of Mining and Metallurgy, has promoted technical excellence in the minerals industry. We strive to continuously stay at the cutting edge of new developments in the mining and metallurgy industry. The SAIMM acts as the corporate voice for the mining and metallurgy industry in the South African economy. We actively encourage contact and networking between members and the strengthening of ties. The SAIMM offers a variety of conferences that are designed to bring you technical knowledge and information of interest for the good of the industry. Here is a glimpse of the events we have lined up for 2015. Visit our website for more information.

SAIMM DIARY

2015

- **CONFERENCE**
  Mining Business Optimisation Conference
  11–12 March 2015, Mintek, Randburg, Johannesburg, South Africa
- **CONFERENCE**
  Accessing Africa's Mineral Wealth
  24–25 March 2015, Emperors Palace Hotel Casino Convention Resort, Johannesburg, South Africa
- **CONFERENCE**
  5th Sulphur and Sulphuric Acid 2015 Conference
  7–10 April 2015, Southern Sun Elangeni Maharani, KwaZulu-Natal
- **CONFERENCE**
  Mining, Environment and Society Conference
  12–13 May 2015, Mintek, Randburg, South Africa
- **CONFERENCE**
  Risks in Mining 2015 Conference
  10–11 June 2015, Johannesburg, South Africa
- **CONFERENCE**
  Mine to Market Conference 2015
  24–25 June 2015, South Africa
- **CONFERENCE**
  The 8th Southern African Base Metals Conference
  6–8 July 2015, Zambezi Sun Hotel, Victoria Falls, Livingstone, Zambia
- **SCHOOL**
  School Production of Clean Steel
  13–14 July 2015, Emperors Palace, Johannesburg, South Africa
- **CONFERENCE**
  Virtual Reality (VR) and spatial information applications in the mining industry Conference
  15–17 July 2015, University of Pretoria, Pretoria, South Africa
- **CONFERENCE**
  MinProc 2015 Conference
  5–8 August 2015, Western Cape, South Africa
- **CONFERENCE**
  The Tenth International Heavy Minerals Conference
  11–14 August 2015, Sun City, South Africa
- **CONFERENCE**
  The Danie Krige Geostatistical Conference
  19–20 August 2015, Johannesburg, South Africa
- **CONFERENCE**
  WORLDGOLD Conference 2015
  28 September – 2 October 2015, Misty Hills, Gauteng, South Africa
- **SYMPOSIUM**
  International Symposium on slope stability in open pit mining and civil engineering
  12–14 October 2015, Cape Town Convention Centre, Cape Town
- **CONFERENCE**
  Young Professionals 2015 Conference
  20–21 October 2015, Mintek, Randburg, Johannesburg, South Africa
- **CONFERENCE**
  Nuclear Materials Development Network Conference (AMI)
  28–30 October 2015, Nelson Mandela Metropolitan University, North Campus Conference Centre, Port Elizabeth
- **SYMPOSIUM**
  23rd International Symposium on Mine Planning & Equipment Selection MPES 2015
  8–13 November 2015, Sandton Convention Centre, Johannesburg, South Africa

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For further information contact:
Conferencing, SAIMM
P O Box 61127, Marshalltown 2107
Tel: (011) 834-1273/7
Fax: (011) 833-8156 or (011) 838-5923
E-mail: raymond@saimm.co.za

Website: http://www.saimm.co.za

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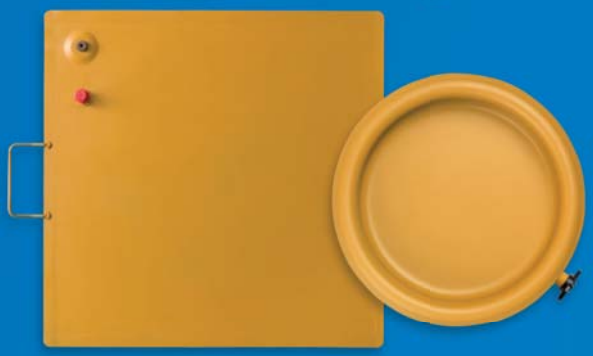
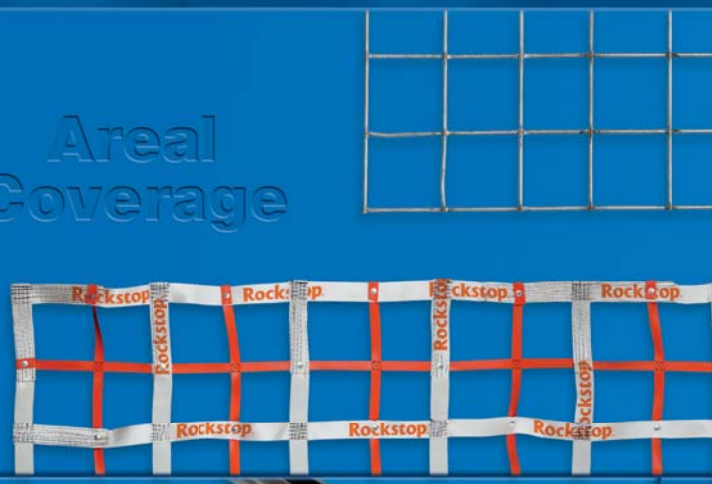


Areal Coverage



Roofbolts

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Applying Poka Yokes in the mining industry

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