The Exploration of Modern Noise Control Measures for Mining Operations

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Abstract

Operations managers are confronted with both first-level noise control (noise engineering) and second-level (hearing conservation) measures. The exploration of the full spectrum noise control is highlighted by a case study of South Africa's largest gold mining group. While modern factories will use sound cameras and new types of electromagnetic noise will occur, mine workers are continuously more exposed to potentially dangerous noise levels than to similar levels of any other noxious agent. The paper shows how second-level measures are not further compromised with second best quality. It focuses on a best-practice hearing conservation case, designed and implemented (maintained) on a large scale for more than 25 000 mine workers. The paper contributes to the prevention of NIHL (noise-induced hearing loss) and provides management with an overview and practical principles for best-practice noise control.

Keywords
Noise pollution; noise-induced hearing loss; noise engineering; hearing conservation; mining case study

Background to the Problem

The science of sound, noise, acoustics and vibration is technical and complex. The control of the physical laws of sound is necessary for reasons of productivity, quality of life and health. The Massachusetts Institute of Technology (MIT), the University of South Hampton's Institute of Sound and Vibration Research (ISVR) and highly ranked journals such as the Sound and Vibration Journal, the Noise Control Engineering Journal and the Journal of the Acoustical Society of America are leading contributors to the challenge.

Millions of healthy life years are lost because of traffic noise pollution and noise became the second biggest health risk in Europe. With all the technologies available, mine workers are still more exposed to potentially dangerous noise levels than to similar levels of any other noxious agent. Occupational hygiene of humans is at risk due to the negative impact of noise on general health and productivity, affecting tasks requiring accuracy rather than speed. Noise also detrimentally affects demanding tasks, especially those requiring attention to multiple signal sources. Noise-induced hearing loss (NIHL) compensation statistics are so alarming as to be unbelievable. Noise and NIHL should therefore not merely be accepted as a common, inevitable fact of life. Nobody should continue to 'whisper to' the problem and first defences against noise should be first priority.

The problem is also underlined by desperate pharmaceutical companies seeking quick fixes by pursuing drug therapy in their search for developing an oral capsule for (NIHL). Many other industries such as the military are in dire straits in seeking a drug that will prevent hearing loss if taken just before noise exposure, or for treatment after exposure. Hearing damage is unfortunately detected too late in most cases and the conventional audiogram (measuring hearing status in terms of frequencies and sound levels) needs to be improved (see OAE technology in the case study).

If the noise epidemic in the world could kill it would have been declared as a pandemic by the World Health Organization (WHO). The state of affairs is exacerbated by the complacent culture of acceptance of the problem because noise is natural to the science of physics and the gradual harm and insidious nature of NIHL is deceiving.

Making a real difference to address the continuous exposure to excessively high levels of noise at work is such a complex and prevalent challenge that it needs drastic measures and corporate control. Noise has become a generic hazard common to all industries but to a greater extent to operations within mining.

Research Problem

Conventional methods will not (and many have not) suffice in the modern factory of the future. New types of noise and the Industrial Internet of Things (IIoT) led to electromagnetic noise replacing audible noise. In the context of the background to the problem (the challenge of noise pollution and NIHL), noise control excellence will remain to be a highly sought after goal. The complexity of first-level noise engineering makes second-level measures (hearing conservation) more cost-effective and easily opted for. This brings second-level noise control in terms of hearing conservation excellence to the fore. Mining in general (and the focus on gold mining in South Africa) is highly significant to the economy and mines in South Africa embarked on comprehensive best-practice hearing conservation programs (HCP). Research on custom-made hearing conservation is important in view of its uniqueness, paucity of literature and because it is not associated with mass operations systems. The need of OSH (occupational safety and health) managers to understand the operational demands of implementing large-scale personal hearing conservation must be addressed as a potential benchmark for second-level noise control.

Methods

To address the problem, an explorative design was used to identify the core dimensions of both first- and second-level noise control. Plowright (2011) supports integrated research methodologies and data may be collected by means of a less structured approach to obtain a large amount of in-depth detail. Cooper and Endacott (2007) refer to generic qualitative research that may entail experiential knowledge of researchers and practitioners. Qualitative research provides for researchers to engage, observe and expose themselves to a particular phenomenon. Single case studies are highly focused and allow for a deeper look into a phenomenon by means of a combination of measures. Most of the data is narrative in terms of unique characteristics and specific accounts of experience. A case study of large scale hearing conservation program of mine workers in South Africa (with a focus on gold mines) was studied. Literature was also explored and Saunders, Lewis and Thornhill (2012: 307) categorise the types of secondary data into categories such as documentary and multiple source publications. The exploratory approach did not commit to a singular paradigmatic research practice, nor did it attempt to generalise results through external validity.

Research Objectives

In general the paper contributes to the paucity of literature in terms of best practice hearing conservation and other noise control dimensions. The primary aim of the exploratory study is to address the research problem and provide a comprehensive overview in terms of the following:

- To contribute to the international challenge for effective first-level noise control (noise engineering) and second-level noise control (hearing conservation) to eliminate NIHL (noise-induced hearing loss).
- To provide managers with a practical case of the implementation of a complex and personal custom-made HCP for mine workers on a large-scale.

Results

The results of the exploratory study are presented in three parts namely (A) an overview of first-level noise control (for mining and other operations), (B) an overview of second-level noise control (for mining operations) and (C) the four-dimensional best practice HCP applied in the case study of the gold mine.

(A) Overview of First-Level Noise Control

The science of sound and noise

The Massachusetts Institute of Technology (MIT) was one of the first leaders in noise control education. The lack of homogeneity reflects the multidisciplinary nature of noise control engineering. In general it is an operations management responsibility but a physics and engineering science. Today most programs are housed in mechanical engineering departments, although many other academic departments are involved in noise control engineering education (Sheppard, Sullivan, Colby, Macatangay and Shulman, 2009). These scientists and the National Academy of Engineering (NAE) confirms the complex body of knowledge as industry specific such as underground mining noise, aircraft noise, airport noise, rail traffic noise, road traffic noise, community noise, wind turbine noise and research in disciplines such as computational acoustics, electro-acoustics, linear and non-linear acoustics, thermos-acoustics, building and room acoustics, noise barriers, noise mapping, vibration control, sound propagation, soundscapes and source identification (localisation) (NAE, 2004).

The University of Southampton is a world-class institution with the largest and most diverse engineering and environmental science grouping in the UK. Research at the Institute of Sound and Vibration Research (ISVR) has led to several innovations and a new understanding of a number of complex challenges in acoustics such as multiple-input multiple-output (MIMO) problems. ISVR is also known for its research in reducing aircraft noise with its active control of propeller aircraft interior noise. Similar technology from the ISVR is used to suppress noise in ships (https://www.southampton.ac.uk/engineering/research/centres/isvr.page).

The works by Reynolds (1981) and Bell (1982) were of the earliest scientists on noise control fundamentals and engineering principles. Mitchell and Else (1993) specialised on noise control for mining and the work of Hansen is acknowledged by the World Health Organisation (WHO). Bies and Hansen (1996) provided several contributions to noise control theory and their work is still applicable today. Hansen and Snyder (1996) introduced the concept of active control of sound and vibration and another useful work by Hansen and Goelzer (1996) cover the core concepts of engineering noise control concepts and principles.

Social ergonomics

Respect for human well-being makes ergonomics a social-technical science. The overwhelming focus on aesthetics of things at the cost of the well–being and quality of work–life (QWL) of people has led to this concept (social ergonomics) utilising a combination of engineering, design, and social science to assist companies to change how people interact with technology (MacLeod, 2008). In addition, Karwowski (2005) views ergonomics as a science for engineering, design, technology and management of human–compatibility systems. Self-management of ergonomics is powerful when individuals are educated to improve their own ergonomics in terms of their own work environment to work smarter, safer and healthier. The negative effects of noise (unwanted sound) must be viewed in this context. The focus is on empowerment, job enrichment, community ergonomics, new work paradigms, participatory design and virtual organisations. The social ergonomics philosophy promotes the best technology that fits people by challenging the status quo (www.socialergonomics.com).

Primary noise control dimensions

A holistic view of the entire noise control science has three primary dimensions: (1) the noise source, (2) the process of noise propagation (transmission) and (3) the effect (response) of noise to the receiver. First-level noise control applies to the source in terms of noise engineering to reduce and eliminate noise. Second-level noise control is to manage the release reality of noise before it harms the receiver. This refers to the interventions during the process of propagation by means of barriers, observers, mufflers and hearing protection. This implies all types of measures, technologies, metrics, standards, algorithms, formulas and methods to control noise pollution and its negative effects on safety, productivity and quality of life. Noise source systems (machines, processes, methods and equipment) making noise must be understood in terms of vibration, resonance frequencies, excitation frequencies, transmissibility, isolation efficiency and many others. The focus must first be on noise hazard control and noise propagation. If first-level controls cannot come into play, then protection against noise is imperative (see figure 1). To protect workers from 100dB noise implies several variables – one will need a calibrated noise protector to attenuate noise from 100dB to below 85dB, because higher attenuation will result in overprotection resulting in other risks**.** Then the fitment also implies another variable namely a seal test to make sure workers are not under protected. Figure 1 illustrates a view of first and second defenses against noise.

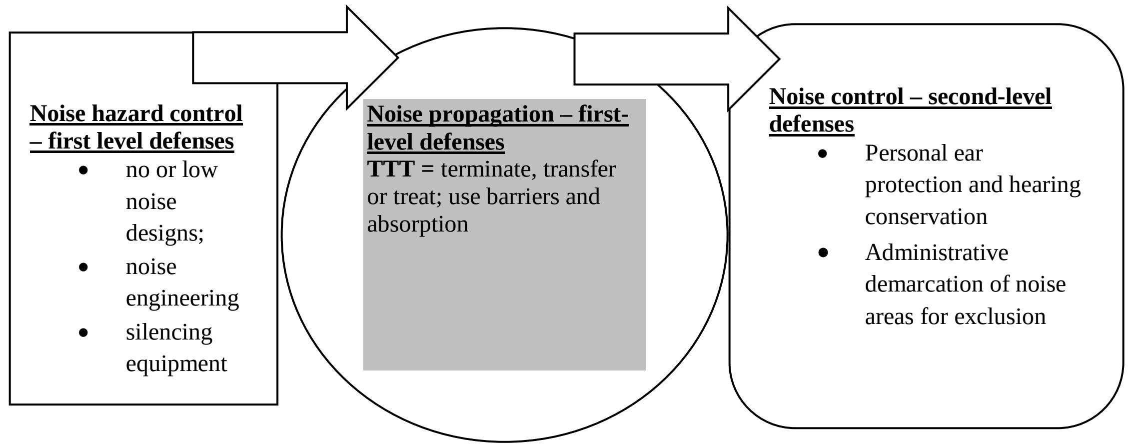

Figure 1. First and second defenses against noise

The sources of noise

TQM (total quality management) teaches quality starts at the source and the exploration of first-level noise control commences with the understanding of its complexity. The challenge is huge and the only generic solution is strict process design principles and a culture of noise minimisation. The complexity of noise engineering is clear when each possible noise source (production methods, system processes and machines) and multiple noise sources is identified and specifically controlled. Mining has its own challenges but technology used at airports (and other industries) can also be utilised. Airplane noise is a common problem and may need a total different approach such as nanofibers with special characteristics such as high porosity, flexibility, and extremely low weight that is ideal for acoustical damping performance.

Examples of noise sources are production machinery and processes composed of various noise sources such as fans, stators, gears, vibrating panels, turbulent fluid flow, electrical machines, process impacts, internal combustion engines and many more. The physics of noise generation depends on the combination of operations system designs and equipment (process technologies). This is a combination of methods and processes such as riveting, blasting (quarries and mines), crushing, shake-out (foundries), drilling, pneumatic equipment (e.g. jack hammers), tumbling barrels, plasma jets, punch presses, sandblasting, boiler making, metal cutting (punching, pressing and shearing), grinding, beverage filling, printing and systems such as compressing, hand-guided machines, in-plant repetitive conveying systems and transport systems (trains, trolleys and vehicles). Each noise source needs a different control approach.

Any noise problem (usually defined as a pollutant because of exceeding the legal limit in decibels) may be described in terms of a source, the transmission path and a receiver (in this context, the mine worker). Noise control is about managing (control and improve) or altering any one, a combination or all of these elements. To focus on the source of noise is the science of eliminating or decreasing noise. The source of noise is where the vibratory mechanical energy originates. This results from physical laws in terms of friction, impacts or turbulent airflow. The physical phenomena gives origin to noise such as mechanical shock between solids, unbalanced rotating equipment, friction between metal parts, vibration of large plates, irregular fluid flow and so forth.

The design of noise

Industries with manufacturing factories are responsible for several operations systems and transformation process causing noise. The economic need for production easily oversees the safety risks such as noise pollution. Today we need green production and society is more aware of NIHL than ever before. In theory noise must be eliminated from the start (design stage) and should be addressed (improved) with good system designs. Some markets also demands “green products” forcing noise control compliance. Many noise systems could have been designed with much less or without noise if design was not dominated by production. Design of the noise-producing mechanism is the most important process to eliminate noise or to produce a quieter process. Quality at the source implies the best controls are those implemented in the original design. When noise control is considered in the initial design of a new machine, the outcome is a better machine overall.

The entrepreneurial universities of Holland are well-known and Hofste-Kuipers (2016) from the University of Twente (UT) indicated how UT became number one in the valorisation ranking of Dutch universities. Rick Scholte (Mechanical engineering, Eindhoven University of Technology) devoted years to analyzing the sound of products, culminating with the creation of the "sound camera" because issues with noise and sound are often overlooked in the whole design process. The sound camera is compared to finding energy leaks in houses. It pinpoints where the source of the noise is located and how it behaves over time. In one company they tested a real problem scenario where they used the camera, analyzed images and identified four to five different sources causing the noise. They managed to get the noise level down more than 80 percent in two to three days and it became one of the quietest systems on the market. Such technologies are highly sought after for the new industrial revolution.

General conventional principles of reducing noise

Conventional principles remain very effective when applied. The following principles from Hansen and Goelzer (1996) can have a huge positive impact:

- Maintenance: replacement or adjustment of worn or loose parts, balancing of unbalanced equipment, lubrication of moving parts and use of proper cutting tools.
- Substitution of less noisy materials such as flexible polyamide plastics and substitution of processes. Substitution of equipment such as stepped dies rather than single-operation dies, rotating shears rather than square shears and hydraulic rather than mechanical presses. Substitution of parts of equipment such as modification of gear teeth by replacing spur gears with helical gears (generally resulting in 10 dB noise reduction).
- Change of work methods: moulding holes in concrete rather than cutting after production of concrete component. Select slowest machine speed appropriate for a job and minimise width of tools.

Control of noise propagation

Noise (when not eliminated at the source), can still be controlled during its propagation. The following principles are still useful to control noise during its propagation from the source to the receiver (Hansen and Goelzer, 1996):

- The use of barriers (single walls), partial or full enclosures of the equipment. Reactive or dissipative mufflers are also useful. The use of lined ducts or lined plenum chambers for air handling systems.
- Reverberation control by the addition of sound absorbing material to reverberant spaces to reduce reflected noise fields.
- Active noise control, which involves suppression, reflection or absorption of the noise radiated by an existing sound source by use of one or more secondary or control sources.

Acoustic barriers

Another traditional method is placing barriers between a noise source and a receiver as a means of reducing the direct sound observed by the receiver. In rooms, barriers suitably treated with sound-absorbing material may also slightly attenuate reverberant sound field levels by increasing the overall room absorption (Bies and Hansen, 1996). Examples are glass partition walls, wooden acoustic panels, polyester acoustic panels, mass loaded vinyl, sound barriers, sound absorbers and acoustic diffusers for indoor and outdoor soundproof treatment.

Sound absorption and reflection

Another control mechanism is sound absorption. This is when sound is absorbed by transformation of acoustic energy into ultimately thermal energy (heat). Absorption always happens when a sound wave encounters an obstacle, but in this case it is directed to sound absorbing material that is fibrous, lightweight and possesses a cellular structure of intercommunicating spaces. Sound can also reflect within boundaries and increase or "accumulates" because of the addition of the reflected sound to the original sound. Sounds may even continue after the original source in terms of "reverberation". A reverberant field is one which is characterised by sound which has been reflected from one or more surfaces in a particular room or enclosure (Hansen and Goelzer, 1996).

Nanocomposite fiber technology

Researchers at Wichita State University demonstrated electrospun nanocomposite fibres to be the ideal solution for aircraft. The university have discovered that high-surface nanoscale electrospun materials display enhanced absorption coefficients at the nanoscale. Electrospun nanocomposite fibers are lightweight, dimensionally stable, porous, flexible, and can absorb high, medium, and low frequencies. The two-microphone transfer-function method was used to determine the acoustical properties of the electrospun fibers at different frequencies. Nanofibers have special characteristics such as large specific surface area, high porosity, flexibility, and extremely low weight obtaining preferable acoustical damping performance (https://www.asme.org/engineering-topics/ articles/aerospace-defense/reducing-airplane-noise-with-nanofibers).

The future of noise control innovation

The modern future of industrial innovation (the next industrial revolution) will need new perspectives on noise to approach the field with "new ergonomics glasses". The constantly increasing technology and understanding of pressure wave physics and the possibilities for noise mitigation could be endless. More comprehensive and innovative source noise control could involve the re-design of conventional compressor packages, making the engines quieter, or possibly to eliminate some of the noise sources altogether. The global awareness levels are much higher and a new generation of acousticians will bring new ideas and technology to industry.

Factories will remain to be noisy places while the Industrial Internet of Things (IIoT) leads to more electronics in factories and electromagnetic noise replace audible noise. As the need for process efficiency increased, factories will be filled with sensors for process monitoring, to reduce costs and pre-emptively predict failures. Each sensor produces a magnitude of data (so called "big data") which travels through wires and across the airwaves, creating electromagnetic noise. With the addition of hundreds (or even thousands) of sensors, along with computer and other communication networks, there are more devices than ever. Although modern electronics is a long way from the heavy equipment originally found in factories, modern devices may run on low voltages (even a few millivolts) of noise, but a signal line can wreak havoc with high-speed data feeds (https://www.eeworldonline.com/modern-factories-electromagnetic-noise-is-replacing-audible-noise/).

A growing resource of experience in acoustics generate both source and path noise control for almost any emitter of sound. A significant challenge remains in the education of all parties involved on the impacts of noise, the choice of correct solutions and the implementation thereof. To control noise actively is the ironic process of reducing existing noise by the introduction of additional noise by means of one or more secondary noise source. The added noise may achieve the required noise reduction by way of a combination of a few different physical mechanisms. A growing resource of modern acousticians may still leave us with noise to be treated with second-level measures discussed next.

(B) Overview of Second-Level Noise Control

If noise cannot be reduced or eliminated through first-level noise engineering, second-level noise control should be excellent and not compromised to second best. This will simply result in another ineffective noise control program. Several mines in South Africa realised this and embarked on best-practice hearing conservation programs.

Mining in South Africa remain an arduous task and much of a 'pick and shovel proposition'. The highest noise exposure (from 100 dBs and above) from plant and equipment are associated with chain conveyors, fans, loaders, long-wall shearers, and pneumatic percussion tools. Scientists wrestled with the challenge ever since such as Mitchell and Else (1993) who focused on noise control for mining. They confirmed the complexity of the challenge in need of multifunctional teams to address the multifaceted challenges of noise pollution. NIHL is still not under control and miners remain to have a difficult job description that should be respected with safe work conditions.

The multiple ineffective hearing conservation programs indicate that the system can only be as effective as its weakest link. All mine workers have protection programs, mostly without the intended results. The following are a few of many case examples (McBride, 2004:292). A study of 2484 South African gold miners defined social impairment as an average loss of >25 dB for the audiometric frequencies 0.5, 1 and 2 kHz. At age 58, 21.6% fell into this group. Another case of an analysis of a large sample of audiograms also showed that 90% of coal miners and 49% of metal and non-metal miners had a hearing impairment at age 50.

The hearing protection compromise

Most ear protection equipment used internationally is not personal therefore not comfortable. Lutz, Reed, Turner, Littau, Lee and Hu (2015: 287-293) evaluated the effectiveness of noise control measures of 22 miners over 56 rotating shifts performing deep shaft-sinking tasks and revealed how the problem remains despite advances in noise control technologies. One dimension measured was five types of earplugs with no significant difference among the types of earplug used. The researchers also admitted that the improper and inconsistent use of HPDs (hearing protection devices) compounded the study that could be different if custom-made HPDs were used.

By addressing the weakest link in a system, quality HPDs seems to be the catalyst of effective hearing conservation. The quality product must also have a quality fit. Donoghue, Frisch, Dixon-Ernst, Chesson and Cullen (2016: 208, 213) confirm that recent advances in technology have enabled quantitative fit testing of hearing protection for each individual. Their hearing conservation initiatives in the primary aluminium industry had positive results, but they posit that the most important initiatives were improved education, improved ownership of HPDs, and quantitative fit checking of HPD attenuation.

A one size fits all approach to hearing conservation is exactly the opposite of what the case (discussed next) are about. To overcome the typical compromise of ineffective and mediocre hearing conservation depends on a personal custom approach demanding a very unique implementation strategy. The case are very much about the implementation and the results of the program predicts to be significant and positive purely based on the buy-in of both the client (wearers and managers) and the supplier to embark on a professional service with such a large scope.

(C) The Hcp Case Study

The following case of the largest gold mine in South Africa briefly describes the primary dimensions and measures for a best-practice hearing conservation program. Several other mining operations (such as Platinum mines) also embarked on the best product (custom-made HPDs such as Variphone) and soon realised the importance of service quality in terms of the entire custom-made hearing conservation program. More mining groups are now in the process to outsource the entire hearing conservation service. The service provider is a central part of the success and inherently part of the case under study.

Pienaar (2017) from the service provider provided all the information of the cases (and written consent to be published). Impala platinum (Rustenburg) was one of the first large mine groups that embarked on large-scale (19 000) personal HPDs in terms of custom-made hearing protectors. Several other platinum mine groups such as Lonmin and Anglo Platinum also followed the trend managing their own HCPs. The personal custom-made concept was also introduced in several coal mines, steel manufacturers and gold mines.

The focus on the gold mines (the study of nine underground mines is part of the largest gold producers in Africa) provided the opportunity to obtain a rich understanding of the phenomenon by repeating the measures used (repeating observations, repeating visits, and obtaining the same information from multiple sources) to ensure reliability and to increase the breadth and depth of insight and understanding. The methods used to obtain the data are the observation and reporting documents of what is inherently part of the hearing conservation program. They are part of their full-time job descriptions of all the stakeholders involved in the hearing conservation program (eg. personal coaching, personal fitments, personal feedback, medical checks, record keeping and basic interviews).

The HCP service quality provider

The South African service provider of the HCP under study, is now an international service provider of both custom-made HPDs and custom-made hearing conservation. Several dimensions of service quality are inherently part of their strategic performance objectives. In-field research by audiologists revealed the need for an HPD that is not one-size-fits-all and they researched the weaknesses of conventional products. With the aid of the South African Council for Scientific and Industrial Research (CSIR) they studied several benchmarks of high-quality products from Europe. This led to the conceptualisation, designing and patent of a unique custom-made HPD for the local African market.

The most important part of their operation is their nimble ability to implement a solution on an efficient and cost-effective way. Without the ability to be in the field to service the mines with their unique needs, the quality features of the HPD would only remain theoretical. This is why the case focuses on practical implementation – it is especially unique and challenging to implement a custom-made product and a custom-made service (the HCP) on such a large-scale. This mass-customisation operation makes this case unique and of the first in the world in terms of technology, size and scope.

In terms of its manufacturing operation its project processes (for customised products and services) has a high variety of mine shafts (and mining operations outside the particular gold mine group) with different needs and conditions. In terms of the projects (or batch processes) itself the variety is low, but the volume of the units can vary from very low to very high. The supplier continues with the next phase of its operation in their laboratories where batch processes are used to transform the silicon impressions (of the worker's ears) to acrylic calibrated end products (custom-made HPDs).

In terms of the service operation they deploy professional operators, audiometrists (and audiologists) and agents to coordinate the personal and custom hearing conservation service. In terms of the professional service the variety is low because it focuses only on the core elements of the conservation program. So the variety of the services per se are low although the units (mine workers) serviced can be between low to very high.

The supplier therefore does not keep inventory (end products) and its lean system is typically associated with predictability (stable demand), low variety, low profit margins and eliminating waste by doing everything just-in-time. Modern firms must also be agile to react nimbly and dynamic in terms of short life cycles, high variety, high profit margins and less predictability. From these cases it seems that both these supply chains can co-exist. Although there are contradictions, leanness and agility are distinct yet corresponding paradigms (Slack, et al., 2017). The core characteristics of the service provider's operations system are:

- Operations management: the operations system of the hearing conservation service provider is a good example of servitization in terms of both a quality product package and a service package. Their primary marketing is done through excellent service quality (such as reliability and responsiveness). Another characteristic is their innovative abilities and willingness to design and develop its own process technologies.
- The laboratory consists of a typical batch operation with a process layout to produce small quantities per day. The operation is labour intensive because of the custom-made process. Capacity can fairly easily be adapted to meet demand.
- Lean manufacturing is possible because resource-to-order is based on manufacturing by order and the elimination of all kinds of waste. Small batch sizes and doing things in real-time with short lead-times is based on the JIT (just-in-time) philosophy.

The challenge of a dynamic master production schedule (MPS)

Service quality of the HCP is impossible without accurate scheduling of customers. A core function of any operations manager (and particularly in this case) relates to the MPS and the ability to adapt schedules. This is particularly important and challenging for a mass service provider of custom-made products. The 2015 figures for custom HPDs for the gold mines were: 16209 workers paraded (to be serviced) for impressions taken, 6971 realised, 2713 realised for fitments and 1615 for maintenance. From this it can be seen that the parading of workers can be challenging since some employees from certain shafts clock in at the wrong place or time. This poses a scheduling challenge between the operations managers of the mine and the service provider.

The following figures of the case merely indicate the scope of operational scheduling of parades per annum (in 2015). In the one province (the Free State) they had 1 851 paraded at mine (P), 811 at mine (T), 923 at mine (M), 491 at mine (B), 673 at mine (J) and 1 685 at the clinic. In another province (Gauteng) they paraded 1 784 at mine (K) and 1 280 at mine (D). The thousands of mine workers that were paraded for service and maintenance of the CHPDs are not part of these statistics. The number of custom-made HPDs that were fitted (seal tested and approved) in that year was 6 713 for these gold mines. Note that the custom-made HPD also has a life cycle regardless of its durable nature. This implies that some HPDs needs to be replaced for several reasons such as loss, damage, breakage, staff transfers, resignations and new appointments.

Best-practice hearing conservation program

The HCP of this case is based on the international four-dimensional HCP from Hearing Coach (www.hearingcoach.com). The model has been adopted (and adapted) in many mining operations in South Africa and other manufacturers worldwide. The program was awarded as 'Best Practice' by the European Agency for Safety and Health at Work (EU-OSHA). The four primary dimensions of this program are: (1) Corporate social responsibility (CSR) and top management (shareholders) support, (2) Coaching based on personal risk profiles for curative care and prevention, (3) Otoacoustic emissions (OAE) and the overall condition of the ear, and (4) Custom-made HPDs. Note: since coaching is central to all of these dimensions, the sequence of the four dimensions is applied on a flexible basis. The four core dimensions of the program applied to the gold mine in South Africa is discussed next.

1. Corporate social responsibility (CSR) and top management support

Leadership for OSH management excellence is the first dimension for top management buy-in, good corporate governance and resources. In this case top management is also visibly involved in the HCP due to the personal nature and large scope. The entire gold mine group approved and resourced the scope of the program (the statement of work) for 23 450 permanent mine workers (note – this paper report on data of 2015). The scope encompassed all primary hearing conservation components discussed next.

2. Coaching

Secondly the HCP is based on personal coaching in terms of the continuous communication principle employed to inform and address questions. This is done for the purposes of prevention and curative care. It focuses on how workers can protect the hair cells of their ears and when to wear hearing protection at work, outside the work environment in noisy stadiums (and concerts), and at home. The permanent and irreversible nature of NIHL is emphasised. Coaching is integrated in the entire HCP with a focus on both prevention and curative care.

Coaching involves a one-to-one approach bringing together all the elements of the HCP to elicit a positive behavioural change. Visual aids are used to explain the damage of outer hair cells, how it affects communication ability (speech understanding) and quality of life. This form of coaching is unique and effective and is combined with motivational group sessions, which has proven to consolidate the objectives of the company.

Since coaching is an integral part of the program, each mine worker will have several opportunities to engage with several stakeholders. This makes training ongoing because the entire process of the program is a learning process and an opportunity to ask questions, to minimise risks and adapt HPD fitment. The dimensions of coaching are therefore more than hearing conservation training because each person is coached (on–the-job training) during the program and not only when their hearing is tested and ears fitted. Each worker's risk profile must also be updated frequently in case some other more drastic interventions become necessary. The custom-made HPD fitment process is inter-active and entails the taking of impressions and the physical fitment process. Mine workers get another opportunity for queries and assistance during the servicing (maintenance) of the HPDs.

3. Otoacoustic emissions (OAE) technology and overall condition of the ear

This third dimension of the hearing conservation program is a significant technological improvement (not a substitution) of the conventional audiogram. Each individual is managed, coached and equipped according to a personal risk profile based on the ISO 1999 standard. This profile conveys all information of each employee such as a baseline picture based on audiometry, historical data and records of hearing tests and interventions undertaken.

OAE technology is a diagnostic tool providing an accurate picture of the cochlear status of the inner ear. This information is used for the prevention and detection of early warning signs of NIHL. The gold mine of this case commenced with the program in 2008 and all employees underwent OAE measurements to establish a baseline for each employee (similar to pure tone audiometry for obtaining a baseline). Each year, all employees are tested again and monitored for any hearing damage shifts or changes of the cochlear status.

The OAE measurements are done with a miniature microphone which is placed in the ear canal. A sound stimulus is sent through the ear canal, which makes the outer hair cells contract (if they do not react, they have been damaged or dormant). The purpose of this examination is to detect damage as early as possible and to identify any difficulty in understanding speech (speech discrimination for socialization). Damage to the outer hair cells (OHC) is shown as a percentage according to the OHC damage index. The higher this percentage, the more outer hair cells have been damaged and the more difficult it will be to follow a conversation. Any change in the condition of the cochlea can be detected as a change in OAE. This method is important since it detects a pattern not noticed in the standard audiogram (Pienaar, 2017). It is also used as a follow-up tool thanks to its high level of reproducibility, sensitivity and specificity. This is a major trump card in a preventive approach towards NIHL. A shift in the OAE is also an alarm signal regarding the effectiveness of the entire HCP.

The focus on the inner ear enables the audiologists to examine the entire condition of the ears. For this reason a preventive hearing examination is recommended during which the external ear, middle ear and inner ear are all examined, consecutively. The entire hearing evaluation therefore also includes an otoscopic evaluation and tympanometry (middle ear analysis to rule out any contraindication to testing). The otoscopic examination is done by means of a small light (otoscope) that is shone into the outer ear canal. The purpose is to check that the eardrum is intact (healthy) and that no wax build-up or foreign object is obstructing the passage to the middle ear. The third measurement is done with a tympanometer to examine the middle ear. The middle ear contains the eardrum, ossicles and the stapedius muscle. The proper functioning of these could be impaired by ear infections (a cold or allergies), perforation of the eardrum or calcification of the ossicles.

With reference to the gold mines, 25 868 persons were tested, and an average OHC damage index of 55% was found. A damage index of 20–49% indicates that the employee has slight damage to the outer hair cells and he/she might not notice the damage yet. A damage index of 50–84% indicates that the employee has great damage and consequently has communication loss. They do not hear moderately loud sounds and finds it difficult to understand speech if background noise is present. A damage index of 85–100% indicates that the employee has serious damage to the outer hair cells, indicating that soft and moderately loud sounds are not heard and understanding speech is difficult even in a quiet environment.

4. Hearing protectors

The fourth dimension of the program is high quality tailor-made hearing protectors. All the unique quality dimensions of the HPDs are with no avail without effective implementation (proper fitment). It implies a professional fitment service that is part of a personal approach to hearing protection and the catalyst of the entire HCP. A quality HPD is therefore not one-size-fits-all but truly personalised personal protective equipment (PPE).

The inner ear is seldom receptive to any inserted device. Even the most comfortable HPD must be maintained for wearability (ownership). Hard working conditions and dirt can influence the effectiveness of the HPD. It must be comfortable in many ways (temperature, ventilation, communication, localisation, signal detection, weight and user-friendliness). Other quality dimensions are attractiveness (e.g. colours, names and packaging), hypoallergenic properties (e.g. acrylic material) and durability (increased wearability, increase ownership and cost-effectiveness). The employee's number and date of manufacture of the HPD is embedded in the HPD. It is also recorded when it was checked for leak tightness.

A unique quality dimension of the HPD used at the mines is to calibrate the filter mechanism for specific noise areas to eliminate over-protection. This allows for communication ability such as alarm signals, important work-related sounds (for normal productivity), verbal instructions and general speech discrimination. The filter also allows for ventilation and localisation which are important features needed by mine workers. Communication ability can only be measured accurately by using audiometry tests for speech discrimination and speech detection tests. Apart from those tests communication ability remains very subjective. However, the results indicate that very few people are able to identify or realise that they have some degree of communication loss. This may be due to the brain's ability to compensate for each situation as well as other coping strategies such as lip reading, also depending on background or environmental noise. The positive aspect is that a small percentage of employees of the gold mines indicated that they have communication problems when in noise or when it is quiet.

At the end of 2015 the gold mines fitted a total of 23 450 employees with custom-made HPDs and the single most significant positive change was in terms of behaviour and ownership. The employees indicated that they are very satisfied with a hearing protector that is largely comfortable (in all dimensions). The behaviour change is an outcome from the integration of all the HCP embedded in the personal consultations and engagements with each employee. The program manager however does allow limited flexibility for other types of HPDs and the exceptions in 2015 were 746 for non-use, 3 530 disposable types and only four earmuffs.

Core observations of the case

The primary findings from the case (based on the 2015 data) of the South African gold mine are:

(A) International benchmark - the case of the largest gold mining groups in Africa and their buy-into the scope and complexity of this program is significant and a world-first.
(B) The outsourced service-providing company portrays the ability to be lean and agile in terms of several operations management performance objectives.
(C) Second-level noise control was demonstrated by means of a best-practice HCP. It distinguished itself in four unique dimensions with unique process technologies such as the OAE and sophisticated HPDs.
(D) The scope in terms of the cumulative facts and figures of the case are: individuals tested (25 560), questionnaires recorded (27 179), high risk (above 68% damage) (13 017), individuals referred for wax (909) and those referred to the doctor for pathology (873). Curative care is necessary to prevent further damage. Since NIHL is a disability it may be necessary to transfer workers out of noise areas to other jobs and financial compensation may come into play.
(E) Although the majority of the people are on the high OHC damage group (due to over exposure over the years), the HCP is regarded as a success in terms of the measures that are in place and the positive behaviour changes achieved. The basic questionnaire responses of 6 380 indicate that 315 employees were knowingly also exposed to private noise. The majority (6 324) were fully aware of noise risks and most (6265) knew where and when to use hearing protection.

Conclusions

The paper described the problem of noise and addressed the research problem in terms of a review of first-level noise control (noise engineering and the modern future of noise) and second-level noise control (hearing conservation) to eliminate NIHL (noise-induced hearing loss). Most solutions to the noise challenge were explored in terms of the science of noise engineering, the design (sources) of noise, noise ergonomics, the three primary noise control dimensions, principles to reduce noise, control of noise propagation, the use of acoustic barriers, sound absorption (and reflection), reverberation , the future of innovative modern noise control and best-practice HCPs.

The focus of the paper was on second-level noise control in terms of a best-practice HCP for a South African gold mines describing how custom-made hearing conservation can be done on a large scale. It showed how important a competent HCP service provider is in terms of several operations management performance objectives and to manage complex MPSs. The four dimensions of the best-practice HCP indicated several unconventional measures needed for HCP effectiveness. The single most significant change at the gold mine was the overall buy-in in terms of the positive attitudes towards the HCP, ownership (wearability) of custom-made HPDs and hearing conservation awareness in general. The other success factor highlighted is the OAE technology providing an additional dimension for prevention. The majority of the workers are in the high risk groups for OAEs, but with normal hearing. This indicates the importance to sustain the HCP because the majority of employees have acquired OHC damage in the cochlear but still have normal hearing thresholds.

It is recommended that a personal approach to ergonomics, noise control and PPE be followed and that all the dimensions of noise control undergo continuous improvement. As long as the world economies demand mineral resources and while the laws of sound physics prevail, noise control excellence will be imperative. A culture against noise must overcome complacency and the insidious nature of NIHL. More drastic measures such as penalties or taxation are necessary to put the focus away from second defenses, while hearing conservation must be based on an international best-practice quality standard.

References

Bell, L.H., *Industrial Noise Control Fundamentals and Applications*. Marcel Dekker Inc., New York, 1982.

Bies, D.A., and Hansen, C.H., *Engineering noise control: theory and practice.* E&FN Spon., London, 1996.

Cooper, S., and Endacott, R., Generic qualitative research: A design for qualitative research in emergency care? *Emergency Medical Journal*, vol. 24, no 12, pp. 816-819, 2007.

Donoghue, A.M., Frisch, N., Dixon-Ernst, C., Chesson, B.J., and Cullen, M.R., Hearing conservation in the primary aluminium industry. *Occupational medicine,* vol. 66, no. 3, pp. 208-214, 2016.

Hansen, C.H., and Goelzer, B.I.F., *Engineering noise control*. Research Gate publication, Switzerland, 1996.

Hansen, C.H., and Snyder, S.D., *Active control of sound and vibration,* Chapman and Hall, London, 1996.

Hofste-Kuipers, M., *How UT became number one in the valorisation ranking of Dutch universities.* University Industry Interaction Conference, Amsterdam, Netherlands, 1-3 June, 2016.

Karwowski, W., Ergonomics and human factors: The paradigms for science, engineering, design, technology and management of human–compatibility systems, *Ergonomics*, vol. 48, pp. 436–463, 2005.

Lutz, E.A., Reed, R.J., Turner, D., Littau, S.R., Lee, V., and Hu, C., Effectiveness evaluation of existing noise controls in a deep shaft underground mine, *Journal of Occupational and Environmental Hygiene*, vol. 12, no.3, pp. 287-293, 2015.

McBride, D., Noise-induced hearing loss and conservation in mining, *Occupational Medicine*, vol. 54, pp. 290–296, 2004.

MacLeod, D., *Ten principles of ergonomics*, http://www.danmacleod.com/ ErgoForYou/ 10_principles_of_ergonomics.htm, 2008.

Mitchell, T., and Else, D., *Noise control in mining,* Ballarat University College, Victoria, Australia, 1993.

National Academy of Engineering (NAE), *The Engineer of 2020: Visions of Engineering in the New Century*, National Academies Press, Washington, DC, 2004.

Pienaar, T., Personal interview with the COO of Hearing Coach. Pretoria, 2017.

Plowright, P., *Using mixed methods – frameworks for an integrated methodology*, SAGE Publications Ltd, London, 2011.

Reynolds, D.D., *Engineering principles of acoustics (noise and vibration control)*, Allyn and Bacon, Boston, 1981.

Saunders, M., Lewis P., and Thornhill A., *Research methods for business students,* Pearson, London, 2012.

Sheppard, S.D., Sullivan, W, M., Colby, A., Macatangay, K., and Shulman, L.S., *Educating Engineers: Designing for the Future of the Field,* The Carnegie Foundation for the Advancement of Teaching., CA: Jossey-Bass, San Francisco, 2009.

Slack, N., Brandon-Jones, A., Johnston, R., Sing, H., and Phihlela, K., *Operations Management – global and Southern African perspectives,* 3rd ed. Pearson, Cape Town, 2017.

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