Applied ergonomics for operator compartment design in an EJC 88 XLP loader

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Synopsis

In engineering design of operator's compartments, in underground mining equipment, ergonomics principles are often neglected or not given the full recognition they deserve. This paper defines ergonomics, applies it to machinery in an underground mining environment and describes the ergonomics analysis undertaken during the design phase of an EJC extra-low-profile mining loader. Encompassing the design of the operator's compartment of this new loader, this paper illustrates the importance of ergonomics principles within the collective design process, ensuring that it is fully integrated into the design approach. An ultimate aim of this study is to ensure that all future designs follow this route to guarantee not only the outcome of a highly efficient, cost-effective and productive machine but that it is also takes the human factor into account, not only in maintenance but also in operation. Maximizing comfort will have the ultimate outcome of actually increasing productivity.

Introduction

The mining industry in South Africa has undergone significant changes since the 1980s with increased mechanization and development of new technologies. Despite changes, many jobs continue to be labour intensive, physically demanding and repetitive, and human-centred design principles are often neglected in the design and development of new equipment and technologies.

This research details an ergonomic study on the operator's compartment of an EJC extra-low-profile loader (LHD—load-haul-dump machine), where human-centred design principles are taken into consideration in the design and development of this new product. It is because of the development and evolution of mechanized, low-seam mining in the South African platinum mining industry that the need for this loader, and thus this ergonomics study, arose.

The market needs for extra-low-profile equipment arose at the turn of the century with the platinum industry's drive towards mechanization. The detailed market study for the XLP (extra-low-profile) loader design started at the end of 2001, with the concept designs being put forward in mid 2002 and the actual prototype machines being designed, constructed and delivered by early 2003. The prototype machines were tested, analysed and perfected until it was deemed a product in early 2004.

This LHD had to meet the design criteria determined by the environment in which it had to function. With the general consensus, at the time of design and development, being that the machine had to operate in a stope with a width of 1.1 m, it was determined that the machine would be 880 mm high, meaning that the allowable space for the operator's compartment was basically the size of a 'coffin'. One can conceive that the disregard of ergonomics principles in the design of this cabin could lead to severe operator discomfort and dissatisfaction, or serious bodily injury from continued operation, due to the fact that this operator would have to operate this machine lying in a supine position.

Ergonomics

Definition

The aim of defining ergonomics is to create a better perception of the term 'ergonomics', and develop a suitable understanding of how and why it should be applied to the design of equipment, products and systems. It also highlights the benefits that applying ergonomics principles may have for both the organization and the individual workers.

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The term ‘ergonomics’ was formally established in 1949 by KFH Murrel from the two Greek words *ergon*, meaning ‘work or effort’, and *nomos*, meaning ‘law or rule’. Literally translated, ergonomics means ‘the laws of work’ (Bridger, 1995; Galer, 1987; MacLeod, 1995; Murrel, 1965).

The applied science of ergonomics was formally established in the late 1940s. As a science, ergonomics studies human capabilities, limitations and other characteristics for the purpose of developing human-system interface technology. As a practice, ergonomics applies human-system interfaces to the design, standardization, and control of systems. Ergonomics promotes human reliability and improved health and safety. It ensures that equipment, tasks and the physical work environment are designed to take account of the capabilities and limitations of people.

With the promulgation of the Mine Health and Safety Act REF (Act 29 of 1996) the concept of ‘ergonomics’ was legislated into occupational health and safety. For the first time in South Africa specific reference was made to ergonomics in legislation, that is, the application of ‘ergonomic principles’. However, the responsibility was limited to the manufacturers and suppliers of mining equipment (Section 21(1)(c)).

The objectives of ergonomics

The International Ergonomics Association defines ergonomics as ‘the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance’. The main objectives of ergonomics are therefore to decrease the risk of injury and illness, to improve worker performance, to decrease worker discomfort and to improve the quality of work life.

The aims or objectives of ergonomics are summarized in Figure 1.

The ultimate goal of ergonomics is to improve and maintain the welfare of the individual worker, while at the same time improving and maintaining the welfare of the organization.

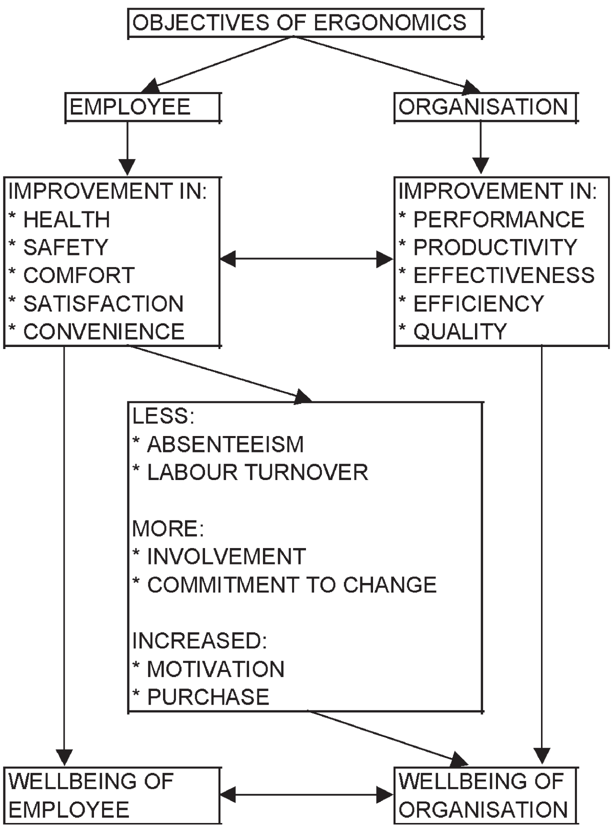

Figure 1—The objective of ergonomics (adapted from Wilson and Corlett (1990:6))

Anthropometric data

In order to be able to apply ergonomics principles when doing a design, and to achieve ergonomics objectives, it is necessary to have an anthropometric database from which to work.

At the time that the study was conducted there was no applicable anthropometric database available that specifically targeted the South African mining population, comprised mainly of the negroid population. A collection of readily available anthropometric data from ARMSCOR primarily, as well as the American and Chinese population, was therefore collected and used as an initial basis from which to formulate our own data, in order to ergonomically design the operator’s compartment of the loader. Specific anthropometric data of the negroid mining population was also gathered, using a sample population of miners currently working in the platinum mines of the Bushveld Complex, and compiled to obtain anthropometric data for the ninety-fifth percentile negroid miner.

The study for the design of the operator’s compartment

Previous designs

The second step in the theoretical part of the design of the operator’s compartment, once the ergonomics study was complete, involved the examination and assessment of existing underground mining equipment. It was necessary to analyse previous designs and to understand the issues and problems experienced in the field with the current operators’ compartments. This investigation allowed us to learn from previous mistakes, and take this design opportunity to provide for possible solutions to the identified issues by applying ergonomics principles.

In order to obtain applicable and beneficial information from this sort of study it was necessary to look at comparative equipment.

The machines’ operator compartment (Figure 2) was examined and assessed according to human-centered design principles. The objective of any ergonomic design is to position the operator’s seat, headrest and armrests to optimize comfort and health and safety, and also to ergonomically place all the operating controls and instrumentation to maximize operator performance, ultimately promoting human reliability. It can clearly be seen from Figure 2 that the design of this operator’s compartment was not based on fundamental ergonomic principles.

Figure 2—Example of a low-profile machine

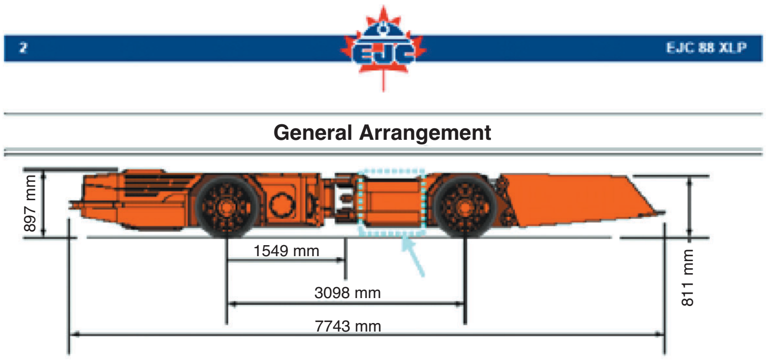

Figure 3—Side view of the EJC 88 XLP

Main problems identified during the above study included: positioning of joysticks and levers in relation to 'reach' and well as armrest support; position and operating angle of foot pedals in relation to 'reach' and with respect to a fixed point of reference, and positioning of the knobs and instrumentation in relation to 'reach' and visibility. In summation, the workspace envelopes were not adequately examined during the design phase.

Scope

The development and design of the EJC 88XLP loader was a complete paradigm shift from the normal type of low-profile loader. It involved not only a completely new type of technology, but was also far lower than any loader EJC has ever made. The move to extra-low-profile, mechanized, trackless, mining machinery has not yet been successfully implemented by the mining world.

It is because of the orebody being much narrower and because of the need to maintain low dilution levels, as well as because of labour issues, safety and a need for increased output and revenue, that low seam mining came about. And it is from the evolution to mechanized, low-seam mining that the need for the EJC 88 XLP developed.

The machine on the drawing board (and as can be seen in Figures 3 and 4) was only 0.88 m in height, which meant that the operator's compartment was going to be longer than it was high (approx. 2 m x 0.5 m). There were, therefore, a lot more constraints and limitations that had to be taken into account when designing this operator's compartment. These include mining, health and safety, environmental and size constraints (cabin envelope).

In Figures 3 and 4 a dashed, blue line outlines the operator's compartment. From these figures it can be seen that this is certainly not the norm as far as operator compartments of mining machinery go because the operator lies in a supine position, perpendicular to the direction of motion, turning his head to the left when driving forwards and to the right when driving in reverse.

Objective

The objective was to ergonomically design and place the operator's seat, headrest and armrests, and also to ergonomically place all the operating controls and instrumentation according to human-centered design principles. The ergonomics with regards to the entrance and exit of the machine had to also be carefully considered, because the operator only had a small doorway area as can be seen in Figure 5. The study had to be undertaken, within the capabilities, cost constraints and manufacturing capacity of the product company designing and assembling the machine. The ultimate objective was to design the cabin to maximize operator performance, while ensuring operator comfort, health and safety and promoting human reliability.

Application of ergonomics principles in the design of the operator's compartment

A useful concept in understanding the occupational application of ergonomics is that of an 'ergosystem' (Galer,1987). An ergosystem consists of three interacting components, namely human, machine or technology, and environment (Figure 8).

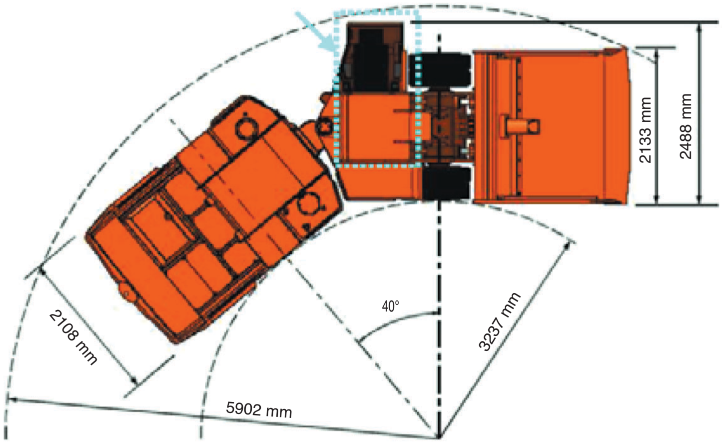

Figure 4—Top view of the EJC 88 XLP

Figure 5—EJC 88 XLP in operation

Figure 6—Operator's compartment of an EJC 88 XLP in operation

The most general approach to ergonomics is to consider a person interacting with technology. The interaction occurs by means of displays whereby the machine or technology provides information to the user and controls and the user passes information to the machine (Figure 7). There is therefore a complete information flow loop with a proper functioning of all the parts. In order to ensure successful, safe and effective use, there should be no delays in the information flow (Galer, 1987).

The interaction between human and machine always takes place in a certain workspace, which is located in a specific physical and psychological environment (Figure 8). The characteristics of the workspace and the environment will affect the task performance of the human. The workspace, in relation to this study, is described in terms of the size and layout of the seat and its accessories, controls and display of the operator's cabin. Factors such as size and layout will have an effect on the body position, body posture and reach distance of the expected user population, and consequently on comfort and efficiency. Entrance and exit from the workspace (i.e. the cabin) will also have an affect on the health and safety of the operator.

The environment can be described in terms such as temperature, lighting, noise and vibration. It can also be described in psychological terms such as teamwork, management structure, shift conditions and psychosocial factors, which are beyond the scope of the current research.

When one approaches the design of the operator's compartment from an ergonomic point of view, all the above-mentioned criteria have to be considered. It can be concluded that one must initiate an ergonomic study right at the beginning of a project, to design a new product, and continue it right through the feasibility study, functional analysis, design phase and development of the machine, as well as after the machine is in production. Ergonomics is an ongoing process and can constantly be applied to improve the working conditions for the operator.

The detail design of the operator's compartment

Design process

The design of the operator's compartment started with an extensive ergonomics literature study, as discussed above. A number of constraints also had to be taken into account during the design of this extra-low-profile loader. These constraints included operational, design and mining constraints. An anthropometric database was also created in order to aid in the researcher's ergonomic design.

This section deals with the design of the operator's compartment. At this point the design of the machine, as a whole, was in its preliminary stages. The researcher had to firstly verify the envelope size and access points, which was done by means of using a miniature scale mock-up. Once this was done, the machine parameters could be finalized, after which a complete dimensional organization of the cab interior was done, by means of using a full-scale mock-up. The dimensional organization of the cab interior includes access, seating, operator's posture, layout of the controls and displays, and visual fields.

A miniature size, to scale (6:1), mock-up was made of the EJC 88 XLP's operator compartment based on the preliminary design dimensions. A to-scale wooden man model, of the 95th percentile negroid male, was also used to aid in the validation experiment (refer to Figure 9).

The mock-up seen in Figure 9 was made in order to determine whether the proposed size of the cabin was adequate for operator access. It was also used to confirm that the operator could lie comfortably and operate the machine successfully. It was made as a means to confirm the proposed size and placement of the entrance/exit and emergency exit. The model man was moved into and out of the cabin by hand, as a means of simulating the operator's actual body motion.

From this investigation it could be concluded that the operator's compartment is not only more than adequate in size, but that the size and placement of the entrance/exit and

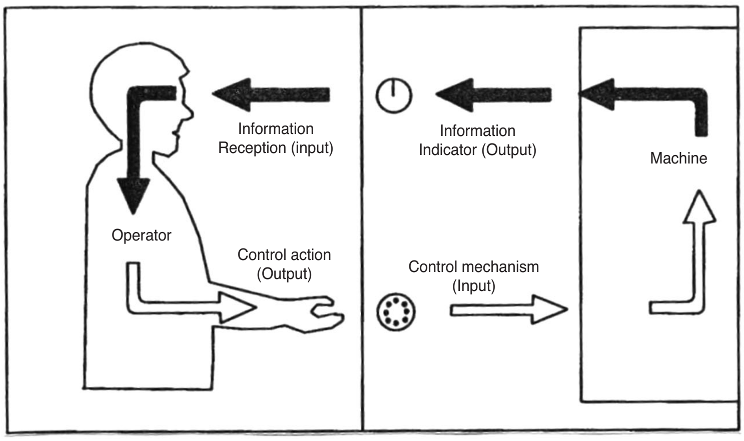

Figure 7—Communication between human and machine viewed as an information flow loop (after Galer, 1987:18)

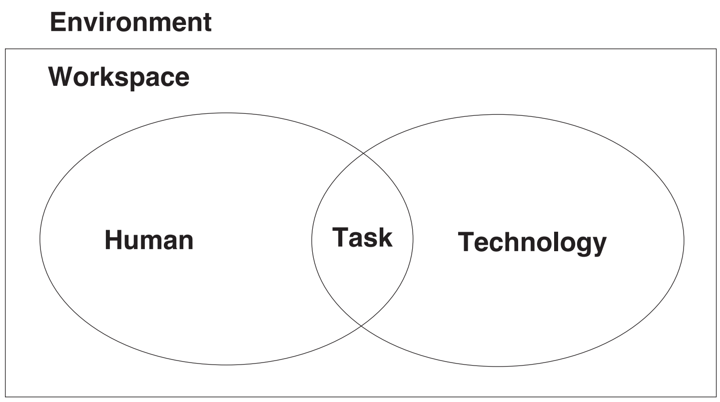

Figure 8—Human-technology-workspace-environment model (Guild, Ehrlich, Johnston, Ross, 2001)

emergency exit are also acceptable. The operator's visibility for forward and backward vehicle motion was also seen as being adequate.

The preliminary design was therefore approved and the final envelope design was then completed. The final design measurements were used in setting up the operator compartment design parameters.

Once the envelope as well as the entrance/exit sizes and placement were verified, a full-size, to-scale, mock-up was made. It included a seat base and backrest, a headrest, armrests and joysticks. The mock-up was made as a means of aiding in the design and placement of these items as well as the instrument panel, helmet and battery pack and basic cabin accessories such as handles (Figure 10).

In defining the design parameters of the cabin (i.e. placement of the seat components, joysticks and other trimmings), the researcher had to take into consideration ease of maintenance, assembly and operation. All the measurements, used in the design and placement of everything in the cabin, were obtained during the literature study. The values obtained during this stage were theoretical, ideal values. During the final design phase these values were altered and adjusted where necessary to accommodate for actual practice deviations, as well as to make the design more feasible and thus render it practicable.

If the operator were allowed to remove his belt, with the battery pack and rescue pack, and his helmet, entrance and exit, as well as normal operation of the machine, would be made a lot easier. The operator would also experience higher levels of comfort when seated if he were able to remove his PPE. The researcher obtained DME concession to remove his battery pack and helmet as long as they remain within arm's reach, but the rescue pack has to be body worn at all times. The ergonomic design of the seat and headrest was fundamentally based on the fact that the researcher received this DME concession.

Final design

➤ *Seat*—the seat design included the seat base, seat back, headrest and armrests. The researcher had to design the seat to provide adequate body support and absorb as much vibration as possible so as to protect the operator from transmitted vibrations because of the height constraints in the cabin eliminating the option of fitting suspension. Unlike a normal seat the backrest has to provide upper arm support because of the operator being in the supine position and having to operate the machine using joysticks. In the positioning of the backrest, the joystick-backrest and armrestbackrest interfaces also had to be considered. The armrests were designed primarily to support the operator's forearms while controlling the joysticks. In positioning the armrests the backrest-armrest and joystick-armrest interfaces also had to be carefully considered. The seatback and base were designed to be height adjustable to allow for different operators to

Figure 9—Miniature mock-up

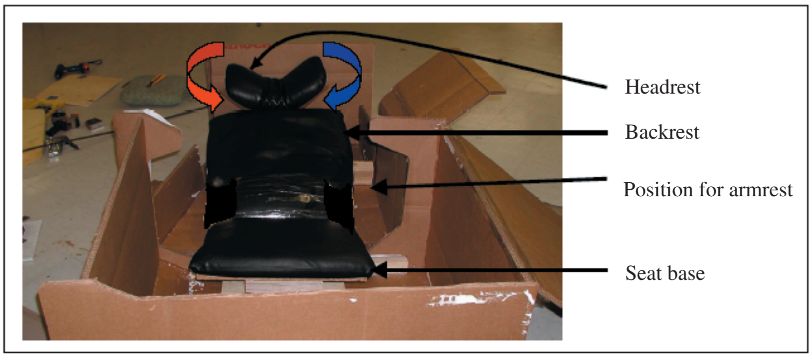

Figure10—Full-scale mock-up

alter their seat positions to maximize visibility, comfort and ultimately productivity. It will also be most practical if the headrest, and its mechanism, is fixed to the backrest, thus moving in relation to the axis of the seat back at all times.

Because of the placement of the operator's compartment, in relation to the direction of travel, the seat and therefore headrest have specific design criteria. The headrest has to support the head far more with the operator in the supine position than in a normal sitting-up position. It has to provide complete static and dynamic head and neck support, as well as allow for movement of the head between the forward and the reverse driving positions. The headrest has to be adjustable, along the z-axis, rotationally around the x- and y-axis and in relation to the backrest (y-axis), to maximize comfort for different operators. In order to achieve this desired headrest movement, a specific headrest mechanism was designed. To satisfy all the above stated design criteria, a curved headrest on a height adjustable, swivel mechanism is the best solution.

This entire seat mechanism was designed for easy maintenance and maximum durability. The construction of the final seat was outsourced, therefore the final material selection was dependent on what the supplier had available. The accuracy of the final manufactured seat was also reliant on the level of tools and skills available.

➤ *Controls*—the controls section initially comprised the joysticks, pedals, emergency stop, fire suppression system, instrument panel, battery pack, helmet storage and the trimmings, but after field and visibility testing a camera system comprising a screen and two cameras were added. The positioning of all the controls was determined using functional anthropometric data, obtained during the literature study, and verified through practical application.

➤ *Joysticks*—The specific joystick selection was beyond the scope of this research. The joystick boxes, as well as their positioning and mechanism for movement, however, had to be ergonomically designed and integrated by the researcher. The box housing needed to be watertight to avoid any damage to the electronics of the joystick as well as being as small as possible because of space constraints. The working interface between the operator (i.e. seat) and joysticks had to be considered when positioning the joysticks.

➤ *Pedals*—the choice and placement of the pedals did not form part of the original scope of research, but were positioned after the machine was built. The design was originally going to incorporate full dual-axis joystick control but was changed at a later stage to include foot pedals with the aim of increasing ease of operation for the operator by eliminating a number of functions from the joysticks.

➤ *Emergency stop*—it is imperative to include the emergency stop as a control in the design of an operator's compartment. This hand-activated, push-button is undoubtedly the most important item in the operator's compartment and therefore had to be placed such that almost instantaneous activation can take place, both during operation and maintenance. The researcher determined that the emergency stop be placed on the right side of the operator to allow for quick and easy right-hand activation from both within and outside (next to) the operator's compartment. In addition, another emergency stop was placed at the rear on the opposite side of the machine. By having two emergency stops, we are ensuring the safety of the operator, technicians and bystanders by allowing emergency stop activation to take place from both sides of the machine.

➤ *Fire suppression*—the fire suppression system was also only added to the cabin on arrival of the prototype in South Africa. Because of the size of the actuator and the limited available space, it was determined that the best position for the actuator, to allow for almost instantaneous activation, is on the left of the operator between the backrest and the cabin sidewall.

➤ *Instrument panel*—this control selection for the instrument panel was set, so the researcher had to work with the designated controls. The instrument panel and control box placement, either together or separately, had to be carefully thought through. A decision-matrix method of evaluation was therefore used to determine the best place for the panel and box to be placed. The following selection criteria were considered: available space in the cabin, instrument panel envelope, operator visibility, headrest-instrument panel interface, operator obstruction, and ease of maintenance

After looking at the above factors and using a 'decision-matrix' approach, it was concluded that on the left of the operator, on the back-side of the mud guard, was the best position for the instrument panel. Once this optimum position was determined, the electronics technicians designed the layout of the controls on the panel and positioned the electrical components. The researcher did, however, stipulate that the visual display also be fixed at a specified angle to the plane of the face of the instrument panel, based on the anthropometric visibility data. The instrument panel was designed to allow for easy access for maintenance, as well as to maximize visibility for the operator.

➤ *Accessory storage*—owing to the fact that the operator has DME concession to remove his helmet and battery pack, a storage place for both these items had to be determined. After investigating all the remaining space in the cabin, with the seat and controls in it, there is basically only one obvious solution as to where the battery pack and helmet should be stored. They should both be placed on the left of the operator's legs, in the central part of the cabin. A box frame will be welded onto the inside wall of the cab as a storage place for the battery pack. There will then also be a hook welded onto the wall, next to the box, to hang the helmet on. Both the helmet and battery remain within arm's reach. For maximum operator comfort, once the battery is removed from the belt, the rescue pack can be moved around to lie on the operator's stomach so as to minimize hindrance, between the rescue pack and seat, for the operator.

- *Entrance/exit*—in order to make the operator's normal entrance and exit as well as emergency exit of the machine, more comfortable and safe, a number of trimmings were to be added. Handles were to be added into the canopy along the edges bordering the entrance/exit areas to aid in both the entrance and exit of the machine. Another handle was added along the 'lid' of the centre of the cab to aid the operator when moving into his final position after having partially entered the machine. Due to time constraints, towards the end of the prototype design the canopy was made without any added trimmings. After field testing the prototype, in South Africa, handles were added along the edge of the canopy to assist with initial entrance and exit into the cabin, as well as along the 'lid' of the centre of the cabin to assist the operator with positioning himself correctly in the seat.
- *Camera system*—after having assessed the performance in the field and conducting a visibility study, it was determined that in order for the operator to be able to adequately perform his function, a camera system would have to be added to enhance visibility and enable the operator to load to his full capacity. The monitor was positioned in the centre of the cabin, between the forward and reverse head positions, to maximize visibility and minimize hindrance, with headrest-camera interface being the most important consideration. The camera eyes were placed in positions that proved to be the most obscured during operation—on the right side at the front and on the rear left of the machine, for maximum visibility.

Feedback

Feedback was given through to the OEM with the aim of re-applying ergonomics principles to the original design and bettering it to optimize operator comfort and satisfaction. The feedback was based primarily on conclusions drawn during the trial phase, through practical operations in the underground platinum mining environment, as well as from ergonomic and brake tests conducted and reported by independent organizations. An assessment of whole-body vibration and noise levels was also conducted.

An operators' survey was done, by means of a questionnaire and interviews for feedback purposes. The outcome was that the operator's compartment was comfortable and that there were no complaints of unusual pain from continued operation. This design was, however, a first of its kind, and was also made within considerable limitations, so there will always be room for development when feedback calls for it. Ergonomics is an ongoing process through the research, design, development and utilization phases of the product, so one can always improve in the efficiency of a design.

Conclusions and recommendations

The aim of this paper was to outline the ergonomics study conducted during the design of the operator's compartment of a new extra-low-profile loader, with the objective of creating a better understanding of the need and effect of the application of ergonomics principles on the design of new underground mining machinery.

It has become a challenge to give ergonomics higher consideration during the design of products. In the past, focus has always been on the performance, productivity, efficiency, effectiveness and quality of the machine itself while it was forgotten that improvement in health, safety, comfort, satisfaction and convenience of the operator leads to less absenteeism and labour turnover, more involvement and commitment and increased motivation and overall well-being, and thus profitability, of the organization.

Complaints, accidents, fatalities, occupational diseases, drops in both productivity and quality, increased running costs and a high downtime are just some of the consequences of the poor design of any product that does not take man and his role as a factor of reliability and safety into account.

Even though the operator of this machine had to be located lying down in a supine position, it is through the application of ergonomics principles, in the design of the cabin, that the operators now experience a higher lever of comfort and satisfaction and in turn generate higher production rates and profitability. With the mining conditions in these low-seam platinum mines being so demanding and strenuous, all one can do is hope to minimize these unaccommodating circumstances as much as is practically possible and practising ergonomics allows us to accomplish this.

Although ergonomics is an evolving science, proper application of its principles can achieve benefits that are significant and immediate.

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