2025 European Conference on Computing in Construction
CIB W78 Conference on IT in Construction
Porto, Portugal
July 14-17, 2025

VR-ENABLED TRAINING PROGRAM FOR MINING CONSTRUCTION OPERATORS

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Abstract

Mining construction in Chile faces significant productivity challenges, largely due to inefficiencies in equipment operation. Therefore, improving operators training is essential. This paper proposes the use of virtual reality (VR) technology as an innovative training tool for mining construction operators. This approach aims to enhance operator proficiency and ultimately improve productivity in underground mining projects. The proposed VR-enabled training program is implemented in two case studies covering two underground mining construction equipment. The results obtained demonstrated that the proposed program yield positive impacts on operator's productivity, indicating that VR could be a useful tool for boosting job performance.

Introduction

Virtual reality (VR) is defined as a simulation that creates immersive virtual environments, enabling users to experience and gain unique insights into real-world elements, projects, and activities (Whyte, 2007). By offering a high degree of representational fidelity, VR allows users to manipulate, interact with, and explore 3D environments in real-time. This interaction generates improved visualization of tasks, increased employee engagement, and practical skill building achieving enhanced performances at work (Hosny et al., 2025).In terms of workers' safety, workers' behavior is a critical factor influencing their risk exposure, as unsafe actions are the leading cause of injuries in the construction industry (Li et al., 2015). One of the primary influences on such behavior is the worker's capacity to recognize and evaluate risks—a competency developed through both training and practical experience (Sacks et al., 2013). As such, continuous investment in training strategies is essential to ensure employees develop the skills necessary to perform tasks accurately and safely. In terms of training, VR offers an effective solution that significantly reduces costs and safety risks associated with traditional training methods (Barkokebas et al., 2019; Dias Barkokebas and Li, 2023; Seidel and Chatelier, 1997). VR can provide situational training on real-world scenarios while posing negligible risk (Joshi et al., 2021; Pavlou et al., 2021). According to Mala et al. (2024), VR allows users to experience tasks in a realistic setting thus fostering immersive learning. Moreover, VR allows users to practice tasks in a safety and cost-effective environment. The ability of VR to replicate job-specific contexts with high realism not only supports repetitive practice but also fosters the development of muscle memory and spatial awareness in a way that traditional training methods often fail to achieve (Abotaleb et al., 2025; Blumstein et al., 2020). Given these capabilities, VR-based training solutions are well positioned to provide interactive learning experiences that address both technical competencies and behavioral safety—key elements for reducing injury risks among mining construction operators.

VR is increasingly being adopted across various disciplines, particularly in education and training, where its immersive capabilities offer significant pedagogical advantages. In the construction sector, Barkokebas et al. (2019) developed a VR training system using head-mounted displays (HMDs) to instruct workers in the repair and maintenance of construction machinery, demonstrating its potential to support hands-on technical skill development. Similarly, Eiris et al. (2020) employed 360-degree panoramic imagery to create a proof-of-concept virtual training platform, focusing on improving users' risk perception, hazard identification, and sense of presence within simulated construction environments. Building on the pedagogical applications of immersive technologies, Yang and Miang Goh (2022) designed a mixed-reality simulation grounded in an authentic learning framework and compared its effectiveness to conventional recorded video lessons, finding notable improvements in engagement and learning outcomes. More recently, Shah and Din (2021) utilized the Oculus Quest HMD to explore VR applications specifically tailored for construction safety education, showcasing how instructors and learners alike can benefit from immersive, interactive learning experiences. These individual efforts align with broader research findings demonstrating the measurable benefits of VR-based training in construction. For instance, Man et al. (2024), after reviewing 12 studies, concluded that VR significantly improves outcomes in general safety training. Similarly, Adami et al. (2021) compared VR-based and traditional in-person training in construction robotics, finding that VR led to notable gains in workers' knowledge, operational skills, and safety behaviors, particularly during robotic teleoperation tasks. Supporting these findings, (Scorgie et al., 2024) conducted a systematic review of 52 studies published between 2013 and 2021, further confirming that VR-based safety training consistently outperforms traditional training methods in enhancing learning effectiveness and behavioral change in the construction industry. Despite the mentioned benefits of VR-based training, the mentioned studies also highlight the need for more scientific studies encompassing detailed results of the implementation of VR for training purpuses so a strong generalization of the results can be drawn. In addition, there is a lack of studies presenting results of retention tests to demonstrate the effectiveness of VR-based methods after long periods (e.g., more than 4 weeks) (Scorgie et al., 2024). Li et al. (2024) also conducted a review of existing studies on VR training and grouped some of the challenges associated with the implementation of VR-based training in the construction industry. They pointed out that the accessibility of VR training can be a challenge in terms of ensuring training to workers of different backgrounds, abilities, and ages.

In light of the information provided, the present study focuses on proposing and implementing a VR-enabled training program tailored for mining construction operators with the objective of verifying the impacts of the proposed program on operators' productivity in a short and a long-term period. As such, this study contributes to the critical analysis of the feasibility of adopting VR technologies to training of construction personnel. Furthermore, the present study also aims to assess whether workers' age impacts on knowledge acquisition and retention in VR training programs; as such, it collaborates to address one of the challenges for the implementation of VR-based trainings as pointed out by Li et al. (2024) in their literature review study.

Method

This study is built upon the hypothesis that *the implementation of virtual reality in the training of operators for underground mining construction equipment will aid in increasing efficiency in projects*. To test this hypothesis and fill the identified research gap, the objective of this study is two-fold: (1) design a VR training program adaptable to the specific needs of operators of underground mining construction equipment; (2) verify the impacts of the proposed program on operators' productivity through two case studies encompassing two underground mining construction equipment. Moreover, this study evaluates whether the age of workers submitted to the VR training is relevant to the efficiency of this technology. The evaluation by age group is performed to identify if the efficiency of VR trainings is affected by generational gaps as pointed out by Li et al. (2024). To assess the impact of the proposed VR-based training program, a pre-test/post-test research experiment is conducted with mining construction worker; this approach was chosen for the present study since it has been recommended in the literature as a suitable method for measuring the effectiveness of deploying a given intervention (Williamson and Johanson, 2018). The development of this study is divided into four main processes: initial data acquisition, design training program, implement training program, and analyze results.

Initial Data Acquisition

To establish a baseline for evaluating the VR-enabled training program, data was collected from a specific mining project. Focus areas included mineral extraction using LHDs and blasting with Jumbo equipment. Key steps included data collection, project background review, KPI definition, stakeholder identification, and selection of improvement-focused KPIs.

Design Training Program

In Phase 2, the VR training program is designed addressing the challenges/opportunities observed in Phase 1 with the aim of improving productivity of operators. The primary objective of the developed training program is to provide operators with training on how to efficiently use their equipment in order to improve operator's productivity. The following steps are followed in this phase: identify the existing issues, select and analyze the primary issue, identify the primary reasons for the selected issue, verify the impacts of the selected issue on productivity, identify and select the operators that require training taking into consideration operators' age during the selection process, develop a document highlighting the potential improvements in terms of training related to the selected operators, and develop an improved training program using VR.

Implement Training Program

The VR training program was implemented across two case studies. Results were measured and compared against operators who did not receive VR training, to assess its effectiveness.

Analyze Results

Post-implementation, results were evaluated to determine the training's impact on operator performance and to identify opportunities for further improvement in both implementation and training design.

Case Study

Description

This study takes place in a Chilean mining construction company, focusing on two key pieces of equipment: the LHD and the Jumbo. LHDs handle material loading and transport in confined underground spaces, while Jumbos are used for drilling tasks essential for tunnel advancement and structural stability. Due to their significant operational and financial impact, both were chosen for the VR-enabled training program.

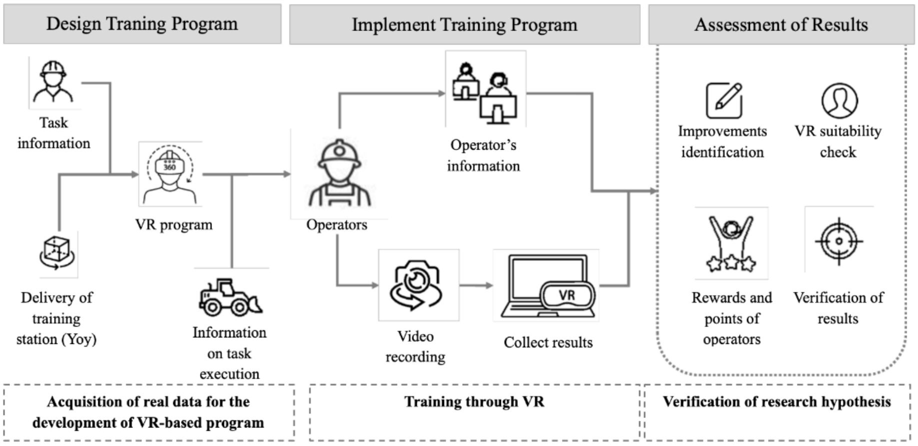

Figure 1: Main processes followed to design, implement, and analyze the VR-based training program

Participants

The workforce includes 573 individuals, with 35 specialized LHD and Jumbo operators (6.1%). These operators are critical to operations and were selected for the VR training due to their essential roles in loading, transport, and drilling. All participants had no previous experience with VR technology.

VR-enable training program

In order to verify which tasks can be adapted and integrated to the VR-enabled training program, iniatially, the training program is designed as if the operator would receive the training in the construction site. The implementation of VR training consists of three phases, as shown in Figure 1:

- Design the VR-enabled training program: This phase involves two key aspects: (1) the collection of information about the actual tasks as they are performed in the construction field by the operators; and (2) the provision of VR simulation provided by a third-party company.
- Implementation of VR-enabled training program: This phase focuses on guiding users through the use of the proposed VR-enabled training program. It consists of two primary components: the use of the training tool itself; and the collection of information and results from the users so the impact of the proposed training program can be assessed, as per Figure 2.
- Assessement of the implementation: This phase involves analyzing the results from the implementation process. It includes assessing the measured results from the training, verifying the suitability of the proposed VR training program, and identifying areas for improvement.

To ensure effective training and evaluation, operators will undergo the following assessments (Figure 2):

- Obstacle Avoidance ("*sorteo de obstaculos n° #*): Maneuvering without hitting cones.
- Arm Movement ("*movimientos de brazos n° #*): Precision and control in targeting holograms.
- Mine Driving ("*conducción mina n° #*"): Compliance with safety rules, proper distance, and minimal damage.
- Blind Spots ("*detección de puntos ciegos*"): Recognition of visibility limitations around equipment.
- Pre-Operational Check ("*chequeo operacional*"): Ensuring equipment readiness before use.
- Ignition Procedure ("*procedimiento de encendio*"): System checks before engine start.
- Drilling (Jumbo) ("*perforación n° #*"): Accuracy in drilling angles, arm positioning, and damage control.
- Material Transport (LHD) ("*translado de materiales n° #*): Efficiency in material handling and avoidance of operational errors.

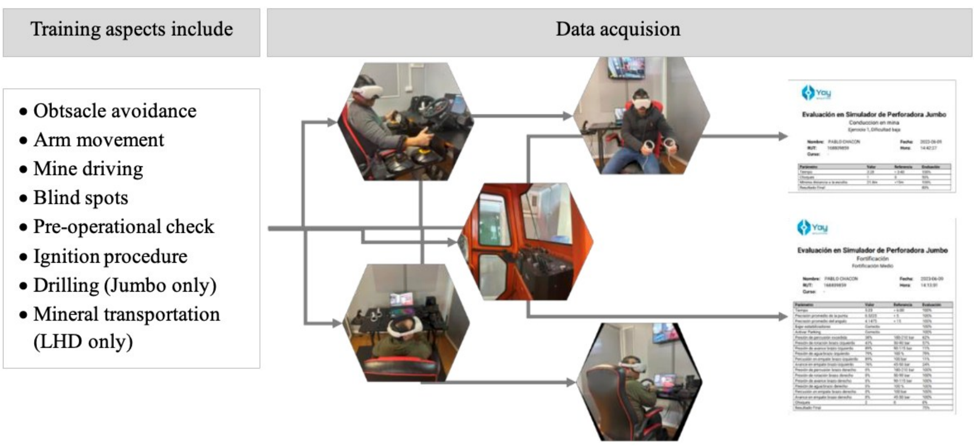

Figure 2: Implementation of VR-based training program.

Case Study #1: VR-enabled training program for LHD operators

As per described in the Method section of this paper, conducting a preliminary analysis of the operators' performance before the implementation of the proposed training program is essential to verify the impact of the mentioned VR-enabled training program. Figure 3 presents a sample of the performance of the eight LHD operators prior to undergoing the proposed VR training program.

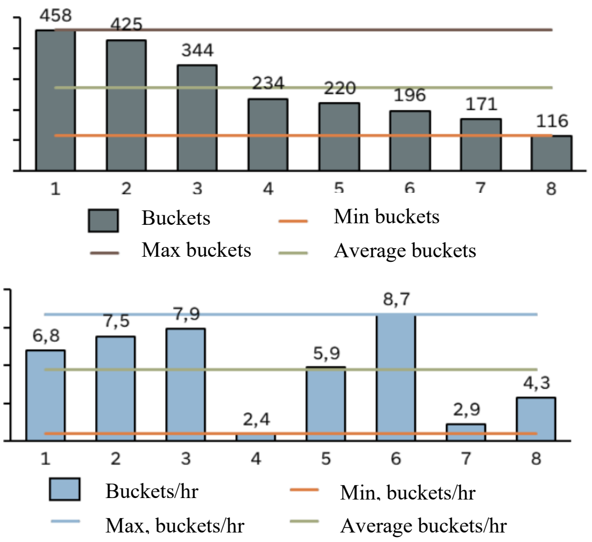

Figure 3: Baseline of the performance of LHD's operators.

As shown in Figure 3, two KPIs are analyzed: the number of buckets moved per operator and the number of buckets moved per hour. In the first KPI, the range of results shows a minimum of 116 buckets and a maximum of 458 buckets moved per operator over a month. The average number of buckets moved per operator per month is 270. In terms of number of buckets moved per house, the performance ranges from a minimum of 2.4 buckets per hour to a maximum of 8.7 buckets per hour, with an average of 5.8 buckets per hour. This quantitative information provides a general overview of the operators' productivity and helps identify opportunities for performance improvement through VR training.

For the assessment of the proposed VR-enabled training program, the Operator #3 was selected to have his/hers performance thoroughly analyzed. This analysis aids in the visualization of specific changes, whether positive or negative, resulting from the implementation of the proposed VR training. Figure 4 shows the results of Operator #3 in LHD equipment operation after a 90-minute VR training session, which covered the evaluation of 17 parameters as detailed in the figure. Overall, the operator achieved an approval rating of 86%. Notably, the material transport and mine driving processes stood out with lower approval scores compared to other parameters. In addition, areas for improvement were also identified for future evaluations. Additionally, Figure 4 presents the preliminary results obtained in the field by Operator #3, showing a remarkable 27.8% increase in productivity compared to the month prior to the VR training.

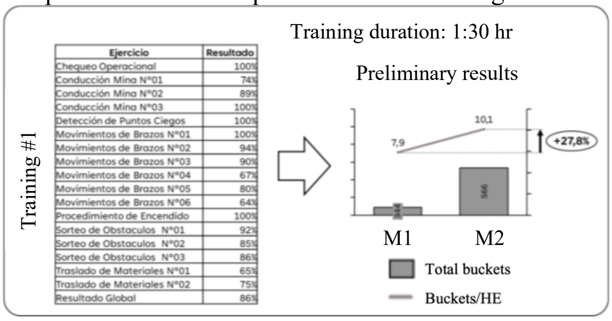

Figure 4: Results of operator #3 during and after the first training session.

The second training session in the proposed VR-enabled training program for Operator #3 evaluated 16 parameters, with an average evaluation score of 89% as shown in Figure 5. This represents a 3.4% improvement over the previous evaluation. Comparing the higher-weighted parameters, there is a clear increase in scores, indicating notable progress in these areas.

Furthermore, Figure 5 shows the preliminary results obtained in the field by Operator #3, highlighting a significant 51.9% increase in productivity compared to the month prior to the VR training (baseline performance).

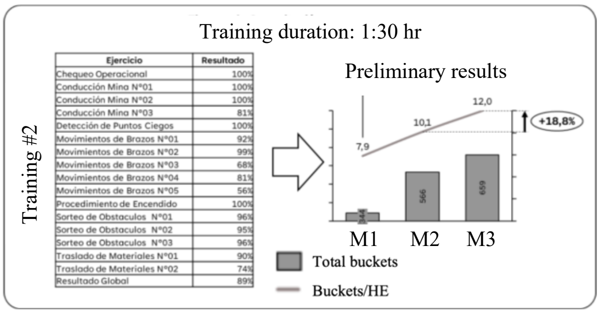

Figure 5: Results of operator #3 during and after the second training session.

Case Study #2: VR-enabled training program for Jumbo operators

Similarly to the Case Study #1, the performance of Jumbo's operators before the implementation of the proposed VR-enabled training system is obtained and analyzed to serve as the baseline performance for evaluation purposes. Figure 6 presents a sample of the performace of ten Jumbo operators prior to undergoing the proposed VR training program.

This preliminary analysis provides an overview of the skill level and knowledge of the operators prior to the introduction of the proposed VR-enabled training. Examining the individual results of the 10 operators allows for the identification of potential areas for improvement and the understanding of their strengths and weaknesses in operating the Jumbo drill.

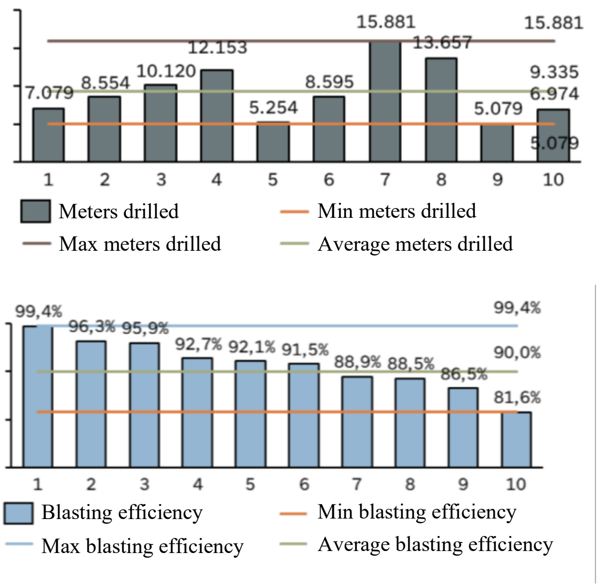

Figure 6: Baseline of the performance of Jumbo's operators.

As shown in Figure 6, two KPIs are presented for the Jumbo operators. These KPIs are the meters drilled per month and the achieved blasting efficiency. As observed, there is a greater variability in the amount of meters drilled per month in comparison with the number of achieved blasting efficiency. The minimum value for meters drilled per month was 5,079 meters, while the maximum reached 15,881 meters. The average amount of meters drilled per month was 9,335 meters. Considering the achieved blasting efficiency, Operator #1 stands out with an efficiency rate of nearly 100%, placing he/she at a significant advantage in this regard. However, he/she still need to improve performance in terms of meters drilled per month. In terms of the achieved blasting efficiency, the results vary from a minimum of 81.6% and a maximum of 99.4%, with an average of 90.0%. These results emphasize the importance of evaluating both KPIs to gain a comprehensive view of Jumbo operators' performance. The variability in the data indicates that there are opportunities for improvement in both performance and efficiency. This suggests the need for targeted training measures to achieve a higher level of performance in both KPIs. This analysis allows us to pinpoint specific areas requiring attention and work on developing skills and knowledge to improve the overall performance of Jumbo operators.

To conduct a thorough analysis of the implementation of the proposed VR-enabled training program, Operator #10 was selected as the subject of study to observe the impacts related to the mentioned VR training. The choice of Operator #10 was based on their relatively low blasting efficiency compared to the other operators. Figure 7 illustrates the results of Operator #10 during the training with the proposed VR training program on Jumbo operation. The first training session lasted 60 minutes and covered the evaluation of 6 parameters. Overall, the operator achieved a score of 70.7%. Furthermore, preliminary field results for Operator #10, as shown in Figure 7, highlight a significant 12.9% increase in productivity compared to the month prior to the implementation of the proposed VR training. The drilling process with the Jumbo equipment is of particular importance, as it is the key parameter used to assess operator productivity improvements. This evaluation allows visualizing the operator's performance and, based on these results, provide precise and relevant feedback. By focusing on the drilling process, training aspects tailored to this process can be incorporated to the VR-enabled training program to ultimately enhance the operator's performance. Therefore, this will aid in the verification of the hypothesis which the present study is built upon. Additionally, the focus on one process assists in the assessment of the impact of the implementation of the proposed VR-enabled training program.

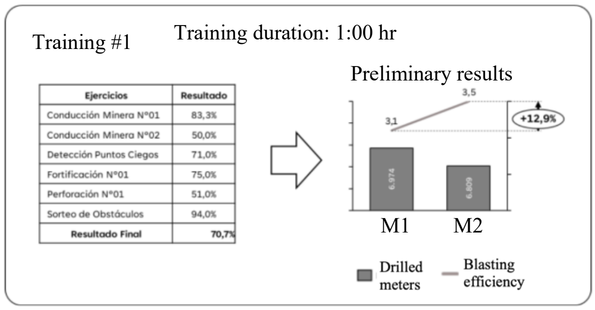

Figure 7: Results of operator #10 during and after the first training session.

The second VR training session for Operator #10 evaluated 6 key aspects, resulting in an average score of 56.3% as shown in Figure 8. This marked a 20.3% decrease from the previous evaluation. However, comparing the aspects with the highest importance reveals an improvement in their scores, demonstrating notable progress in those areas. Finally, preliminary field results for Operator #10, presented in Figure 8, show a notable 16.1% improvement in productivity compared to the month before the proposed VR training. This increase in blasting efficiency translates to an advancement of 3.6 meters per blast, reaching an efficiency of 94.7%, successfully achieving the desired target.

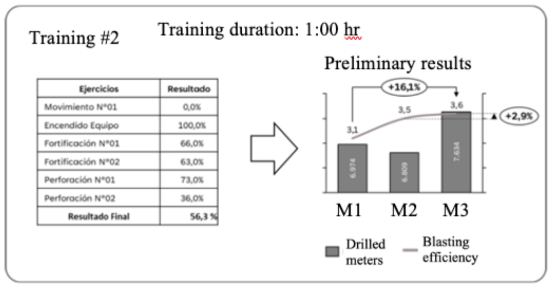

Figure 8: Results of operator #10 during and after the second training session.

Analysis of Results

LHD operators: performance analysis and assessment of proposed VR-enabled training system

LHD operator results were analyzed in two ways: (1) total monthly buckets extracted per operator, and (2) performance by age group to assess the impact of age on VR training outcomes. Extraction totals ranged from 879 to 4,419 buckets, with an average of 2,592, highlighting performance variability. Since differences in monthly workdays could skew results, data was standardized by calculating a daily bucket extraction rate per operator, which serves as the primary performance metric in this analysis.

Global Results for LHD Operators

In the analysis of the first three months, which correspond to the pre-training period, the average number of buckets extracted per operator per day was 31.6, as indicated in Figure 9. After the introduction of proposed VR-enabled training program, the daily average increased to 41.2 buckets per operator. This represents a notable 30.4% improvement in performance when comparing the pre- and post-training periods. This increase highlights the positive impact of the initial VR training on operator performance and suggests that the investment in training is yielding promising results.

After the VR-enabled training program was implemented, Figure 9 illustrates a consistent trend in maintaining productivity at around 40 buckets per operator per shift, with an average of 41.2 buckets during this period. However, between May and June, a slight decrease in the indicator of -5.5% was recorded. According to the study, this drop could be attributed to external factors impacting performance during that period. This is further supported by the standard deviation analysis, which shows a post-training value of 1.1, indicating a tendency to maintain the observed improvement.

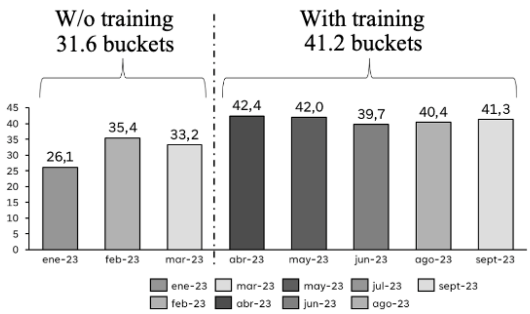

Figure 9: Global results of LHD operators.

Results Categorized by Age Group for LHD Operators

As part of the study, workers were segmented into seven age groups to perform more specific and detailed analyses. This segmentation was crucial to verify whether generational gaps can have an impact on the operators' performance during and after receiving training through VR technology. As shown in Figure 10, an improvement in performance was observed across six of the seven age groups compared to the pre-training period. This suggests that the proposed training affected each age group differently, with varying levels of impact. It is important to note that operators aged between 31 and 35 years demonstrated the highest increase in productivity, with a 98.4% improvement when comparing the pre-training and post-training averages.

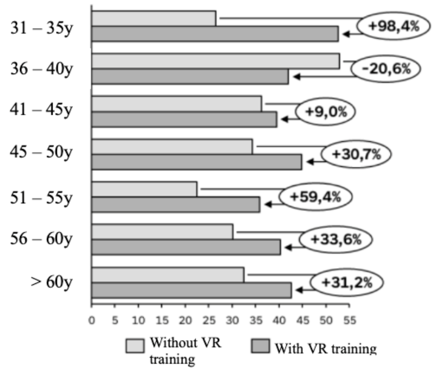

Figure 10: Results Categorized by Age Group of LHD Operators.

Jumbo Operators: performance analysis and assessment of proposed VR-enabled training system

As with LHD operators, Jumbo operator results were analyzed in two ways: (1) overall monthly performance and (2) performance by age group. Two KPIs were assessed monthly: meters drilled and blasting efficiency. These indicators provide a comprehensive view of productivity and execution quality, helping identify improvement areas and support informed decision-making to optimize operations.

Global Results for Jumbo Operators

A comparison between March (pre-VR training) and September shows a significant 8.7% increase in blasting efficiency, as shown in Figure 11. This improvement is particularly noteworthy as it raises the average blasting efficiency to 97.2%, which translates to a performance of 3.69 meters per shot—an increase of 0.30 meters per shot compared to the pre-training period. This improvement is substantial not only because of the potential gains in productivity but also due to the associated increase in revenue per shot. Additionally, when analyzing monthly performance post-training, we see that only a slight decrease occurred between May and June. However, this decrease is not large enough to be directly attributed to the VR training itself. A comparison between March (pre-training) and June (post-training) still shows a slight improvement, indicating that the VR training had a beneficial effect. When comparing pre-training months with post-training averages, results show an average efficiency of 89.2% versus 93.7%, respectively, representing a 5.0% increase in productivity. This corresponds to an improvement of 0.2 meters per shot, further reinforcing the positive impact of the proposed VR-enabled training program.

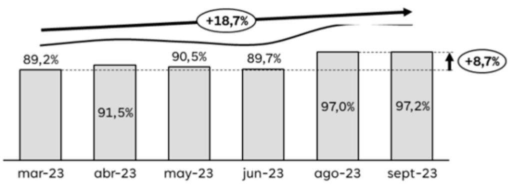

Figure 11: Blasting efficiency.

This increase in blasting efficiency positively influences the overall project progress. Higher efficiency means that time and resources are being used more effectively in achieving mining advances, ultimately leading to increased production and, consequently, higher revenue compared to the period without the proposed VR training. These results clearly demonstrate the benefits of VR training in the project, leading to improved blasting efficiency and, as a result, a positive impact on project advancement and profitability.

To account for difference in worked days, monthly performance was normalized to a daily performance indicator. Regarding the total meters drilled, Figure 12 reveals a consistent upward trend in the number of meters drilled globally. For the pre-VR training period, the average meters drilled per shift was 159.2 meters, whereas, after the proposed VR training, this number increased to 205.9 meters per shift. This represents a 29.3% increase in productivity, illustrating a significant improvement in the efficiency of Jumbo operators during drilling operations.

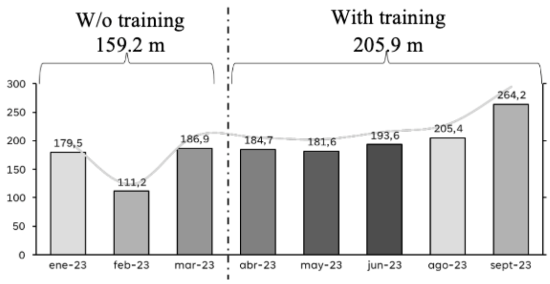

Figure 12: Total meters drilled per month.

Results Categorized by Age Group for Jumbo Operators

Six out of these seven groups showed an improvement in performance compared to previous periods, as illustrated in Figure 13. This suggests that the proposed VR-enabled training program had a positive impact across most age groups, enhancing their performance. One particularly notable result comes from operators in the 46-50 age group, who saw a 44.8% increase in productivity (still in Figure 13). This improvement is attributed to better posture management and more efficient use of equipment by these operators. These findings suggest that certain age groups benefited significantly from the VR training, leading to an increase in the number of meters drilled. While the results are generally encouraging, it is important to note that external disruptions, such as work stoppages, negatively impacted the execution of planned tasks and limited the ability to maintain a consistent upward trend in productivity.

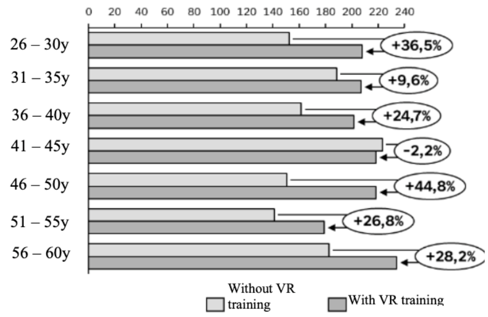

Figure 13: Results Categorized by Age Group of Jumbo Operators.

Conclusion

The adoption of new technological tools is critical for the improvement of processes in mining construction projects. Virtual reality (VR) has emerged as one of the key technological tools in the mining construction industry due to its flexibility in performing multiple analyses. Furthermore, VR allows for firsthand experience of how processes work and enables the visualization and testing of various scenarios. One of its most significant applications is in education and training. The adoption of VR for training mining operators is a decision that requires a comprehensive analysis. While this technology offers substantial advantages in terms of customization and training effectiveness, its implementation requires careful consideration of objectives, needs, and available resources within each organization. The ability to tailor content to the individual profile of each worker fosters deeper learning and better job performance. However, it is important to note that virtualization involves significant investments, and its return should be assessed against clear training goals. Designing a virtual reality training program tailored to the specific needs of underground mining construction equipment operators offers an innovative and efficient solution for improving training and safety in the industry. VR provides operators with an immersive and realistic experience, allowing them to practice and refine their skills in a controlled and safe environment. Moreover, such a program can be adapted to each operator's individual needs, delivering personalized and effective training. The implementation of this technology is expected to reduce accidents and errors, increase efficiency and productivity, and improve the quality of underground mining construction overall. In conclusion, using VR in the training of underground mining equipment operators is a promising strategy that could have a significant positive impact on the industry. After analyzing the results obtained from implementing the proposed VR-enabled training program in two case studies, it can be concluded that the program has a positive impact on productivity. Participants showed an increased ability to perform tasks efficiently and effectively, suggesting that VR can be a valuable tool for improving job performance. Moreover, it was identified in both case studies that the effectiveness of VR trainings is not affected by age groups. Therefore, the findings of this study are bi-fold: (1) it provides evidence that specific

VR trainings are effective in increasing worker's productivity, and (2) the effectiveness of VR trainings are not affected by age groups thus reducing claims that there is a generational gap that would impede the were introduction of novel technologies in worker's training. However, further research and development of VR training programs are necessary to fully benefit from its potential. Implementing the proposed VR training program in case studies with more operators is a direction of future research.

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