

The Use of Virtual Reality Simulator in Skill Training for Electric Arc Welding Processes

A Utilização de Simulador de Realidade Virtual no Treinamento de Habilidades nos Processos de Soldagem ao Arco Elétrico
El Uso de Simulador de Realidad Virtual en el Entrenamiento de Habilidades en Procesos de Soldadura por Arco Eléctrico

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Abstract:

This study comprehensively examines how virtual reality (VR) simulators can enhance learning in arc welding processes compared to training on real welding equipment. By creating a safe and controlled virtual environment, this technology allows training to take place without the risks associated with real-world settings. Virtual reality enables students to practice welding immersively, avoiding exposure to hazardous materials and adding a vital layer of safety. Our analysis delves into the simulator's effects on training efficiency, particularly highlighting the positive impact of immediate feedback, which accelerates skill development and comprehension of techniques. Moreover, this approach promotes resource savings, including materials and energy. The results indicate educational and economic benefits, underscoring the growing importance of this technology in training specialized welding professionals.

Keywords: Virtual Reality; Training; Arc Welding; Simulator.

Resumo:

Este trabalho estuda de forma abrangente o impacto de duas estratégias de ensino no aprendizado de processos de soldagem ao arco elétrico, comparando o uso de simuladores de realidade virtual (VR) com o treinamento prático em equipamentos de soldagem reais. Ao criar um ambiente virtual seguro e controlado, essa tecnologia possibilita que o treinamento aconteça sem os riscos do ambiente real. A realidade virtual permite que os alunos pratiquem soldagem de forma imersiva, evitando a exposição a materiais perigosos, o que adiciona uma camada de segurança essencial. Nossa análise aprofunda-se nos efeitos do simulador sobre a eficiência do

treinamento, destacando especialmente o impacto positivo do feedback imediato, que acelera o desenvolvimento de habilidades e a compreensão das técnicas envolvidas. Além disso, essa abordagem promove a economia de recursos como materiais e energia. Os resultados indicam não só ganhos educativos, mas também econômicos, evidenciando a crescente importância dessa tecnologia na capacitação de profissionais especializados em soldagem.

Palavras-chave: Realidade Virtual; Treinamento; Soldagem a arco; Simulador.

Resumen:

Este trabajo estudia de forma exhaustiva cómo los simuladores de realidad virtual (VR) pueden optimizar el aprendizaje en los procesos de soldadura al arco eléctrico, en comparación con el entrenamiento en equipos de soldadura reales. Al crear un entorno virtual seguro y controlado, esta tecnología permite que el entrenamiento se realice sin los riesgos del entorno real. La realidad virtual permite a los estudiantes practicar soldadura de forma inmersiva, evitando la exposición a materiales peligrosos, lo que añade una capa esencial de seguridad. Nuestro análisis se profundiza en los efectos del simulador sobre la eficiencia del entrenamiento, destacando especialmente el impacto positivo de la retroalimentación inmediata, que acelera el desarrollo de habilidades y la comprensión de las técnicas involucradas. Además, este enfoque fomenta el ahorro de recursos, como materiales y energía. Los resultados indican no solo beneficios educativos, sino también económicos, evidenciando la creciente importancia de esta tecnología en la capacitación de profesionales especializados en soldadura.

Palabras clave: Realidad Virtual; Entrenamiento; Soldadura por Arco; Simulador.

1. INTRODUCTION

Welding, one of the most widely used joining processes in the manufacture of metal structures and equipment in different segments, is widely recognized for its ability to permanently join components, ensuring the structural integrity of the final piece (Lassiter et al., 2023).

Mastering the skills of electric arc welding processes is essential to ensure compliance with minimum requirements and the integrity of a welded joint. Students, especially beginners in practical activities such as welding, often experience frustration due to the initial learning curve (Prasetya et al., 2023).

According to Okimoto et al. (2015), training in manual or semi-automatic welding requires in-depth technical skills and familiarity with specific equipment and consumables, essential for performing tasks in complex geometries or hard-to-reach locations where automation is impractical.

Rodríguez and González (2019) emphasize that, despite its widespread application, welding poses significant challenges that require continuous development and innovation. Welding is a critical component in several engineering disciplines, including industrial, mechanical, aeronautical, and naval engineering. It is essential for the design, implementation, and quality control of welded structures.

Welding is potentially dangerous, especially when there is no complete understanding of the health and safety risks and can negatively impact trainees' physical integrity if procedures and personal protective equipment are not used (Zulkifli et al., 2022).

Welding plays a central role in contemporary industrial manufacturing and is identified as one of the most relevant technologies in the global manufacturing sector, as observed by Gao (2020). Considering this relevance, the focus on qualifying professionals and integrating innovative technologies is not only justified but essential. This direction seeks to optimize processes, promoting the efficient use of materials and energy while reducing environmental impacts, such as carbon emissions, which is a growing concern in current industrial practices.

Based on these statements, the search is justified not only for welding processes that meet emerging demands, but also for the training of professionals capable of fully exploiting available processes, aiming to meet increasingly demanding quality and productivity requirements. To respond to the growing demand for qualified professionals, the American Welding Society (AWS) (2024) reports that 330,000 new professionals will be needed by 2028, with an average of 82,500 job openings to be filled from 2024 onwards.

Chung, Tung and Lou (2020) highlight the advantages of VR simulators in terms of safety, cost efficiency and engagement compared to traditional methods, suggesting that further research could improve the understanding of these differences.

The study aims to evaluate the effectiveness of VR simulators for training and skill development in electric arc welding, focusing on performance, knowledge

retention, and users' perceptions of the learning experience compared to conventional methods.

2. THEORETICAL FRAMEWORK

Virtual Reality (VR) technology is used to design and simulate industrial processes, such as welding (Prasetya et al., 2023).

As stated by Rodríguez and González (2019), teaching strategies using VR and augmented reality (AR) resources are an economical alternative for conducting laboratory practices aimed at developing skills. Teaching welding skills has always been a challenge, not only because of the need for basic knowledge of each process, but also because skill development requires intensive, often exhaustive training, and exposes students and those close to them to health and safety risks.

Welding practice, known for its demand for precise technical skills, finds in VR simulators a tool for the safe and progressive development of competencies. These simulators create controlled environments where students can safely practice welding techniques, overcoming initial challenges and avoiding the costs of physical training. As observed by Prasetya et al. (2023), virtual reality offers a more economical and effective solution, promoting deep, repetition-based learning without wasting materials.

Scotti (2017) states that technological and automation solutions for welding can help address the shortage of skilled labor and make the production process more efficient, sustainable, and high-quality.

Welding practice poses risks that can directly affect trainees' health and safety. These dangers become even more significant when safety standards are not adequately followed, increasing the likelihood of accidents and harm to those involved. The students' lack of experience can increase the risk of accidents, highlighting the importance of a controlled training environment (Zulkifli et al., 2022). Faced with these challenges, VR simulators stand out as a solution to improve training. This technology provides an immersive learning environment where students can develop welding skills in a safe, controlled setting (Chung et al., 2020).

In this scenario, the use of virtual reality simulators becomes even more relevant, as it not only improves access to training but also provides economic and environmental benefits, such as resource savings and reduced emissions.

3. METHOD

To understand the effectiveness of VR simulators compared to training with real equipment, an experimental study was structured involving students from the Mechanical Technology course, focusing on Welding Processes, at Fatec Itaquera. The sample included 10 students with no prior welding experience, randomly divided into two groups of 5 participants, a decision made to ensure comparability between the groups and minimize potential biases.

One group's training was conducted exclusively using the VRTEX 360 VR simulator, while the second group used real welding equipment. Both groups followed a 180-minute schedule focused on developing fundamental welding techniques, ensuring uniformity in practice conditions. At the end of the training, all participants performed a weld on real equipment, allowing for a direct evaluation of the teaching methods.

The variables analyzed were weld joint quality, productivity, process time, and cost per piece. To assess weld quality, we performed only visual and dimensional inspections of the welded parts after training (one piece from each student in both groups) using the actual welding equipment. The discontinuity criteria analyzed were: slag, overlap, spatter, insufficient deposition, misalignment, lack of fusion, undercut, excessive reinforcement, and porosity, all of which are essential to ensure weld integrity.

Productivity was measured by the number of joints completed in 180 minutes, with emphasis on the efficiency and consistency of each method. Process time encompassed the timing of the joint preparation and welding stages, offering a detailed view of the pace and speed of each approach.

Finally, the cost per piece was calculated based on processing, inspection, raw materials, welding wire, shielding gas, and electricity costs.

This research investigates whether training with virtual reality simulators for GMAW welding offers a safer, more economical, and more efficient alternative to the traditional method, especially for developing practical skills. The analysis seeks to identify the competitive advantages that simulators offer, providing a solid basis for their adoption in professional training programs.

To ensure a thorough and accurate analysis of the data, the t-test was initially applied to provide a quantitative assessment and verify the significance of the performance differences between the two training methods. Subsequently, the Pareto Diagram was used to qualitatively evaluate discontinuities, providing a detailed view of the leading causes and their frequencies (Rodríguez and González, 2019; Prasetya et al., 2023).

3.1 Data Dictionary

The data dictionary (Table 1) is an essential tool for organizing and documenting information about the variables involved in a study or data analysis, serving as a clear and structured reference, facilitating the understanding of each variable used in the research, including its purpose, type, unit of measurement, and any other relevant information.

The purpose of this tool in this work was to detail the variables collected in this study (Table 2) and to compare the use of VR simulators with that of real welding equipment.

Table 1 – Data Dictionary

Variable	Description
Student	Student identification (categorical variable)
Age	Student's age (in years)
Group	Training group (virtual reality simulator or real equipment)
Discontinuities	Number of discontinuities in the welds performed (quantitative variable)
Training Time	Total training time (in minutes)
Gaskets Produced	Number of welded joints produced during training.
Total Cost	Total cost of training (in reais)

Source: Author's own work

Table 2 – Breakdown of variables by group

Variable	Virtual Reality Simulator Group	Real Equipment Group
Student	A1, A2, A3, A4, A5	A6, A7, A8, A9, A10
Age	20, 38, 52, 46, 19	20, 27, 42, 31, 38
Discontinuities	Lack of fusion, Porosity, Slag, Overlap, Undercut, Insufficient deposition, Spatter, Over-reinforcement, Misalignment	Lack of fusion, Porosity, Slag, Overlap, Undercut, Insufficient deposition, Spatter, Over-reinforcement, Misalignment
Training Time	36, 36, 36, 36, 36	36, 36, 36, 36, 36
Gaskets Produced	20, 20, 20, 20, 20	4, 4, 4, 4, 4
Total cost per joint	2.40, 2.40, 2.40, 2.40, 2.40	22.94, 22.94, 22.94, 22.94, 22.94

Source: Author's own work

Each variable analyzed is described in a way that makes its meaning and function in the analysis clear to everyone involved in the project. This level of detail allows researchers and analysts to understand precisely how the data were structured, facilitating both the interpretation of the results and the replication of the study in other circumstances or with new samples.

3.2. Exploratory Data Analysis and Visualization

To perform the data analysis (Table 3), we used both Microsoft Excel and Minitab. Excel was essential for constructing graphs such as the Pareto chart, which helped us identify the main discontinuities. Minitab was used to conduct more complex statistical analyses, such as the t-test, enabling us to compare the training methods rigorously.

Table 3 – Exploratory Data Analysis

Metric	t-test (p-value)	Difference between Real and VR
Discontinuities	0.291	-
Gaskets Produced	-	500%
Processing Time	-	500%
Costs	-	956%

Source: Author's own work

3.3. Student's t-test

To compare the means of the primary metrics between the groups that trained with the VR simulator and those that used the real equipment, we applied a t-test in Minitab software. This statistical test is ideal for evaluating whether the

observed differences in the means of the two groups are significant or attributable to chance, helping us scientifically validate whether the productivity, efficiency, and cost advantages offered by the VR simulator are truly superior.

Using this tool, we rigorously validated the differences in productivity, efficiency, and cost savings between the simulator and the traditional method, providing a solid basis for our conclusions. This test is particularly suitable when comparing two independent samples, as it allows us to verify whether the difference between the means is genuinely significant. It is worth remembering that it is based on two assumptions: the data must follow a normal distribution, and the variances between the groups must be similar.

In this study, we compared the performance of two welding training methods, one using a VR simulator and the other with real equipment. We analyzed four essential metrics: discontinuities, number of joints produced, process time, and costs. However, the t-test was applied only to examine the discontinuities observed in the welds. Data were collected from two groups, each with five students, after 180 minutes of training. The results found for each metric are detailed below. The discontinuities evaluated in the welds produced were: slag inclusion, overlap, spatter, insufficient deposition, misalignment, lack of fusion, undercut, over-reinforcement, and porosity.

Results of the t-test (discontinuities):

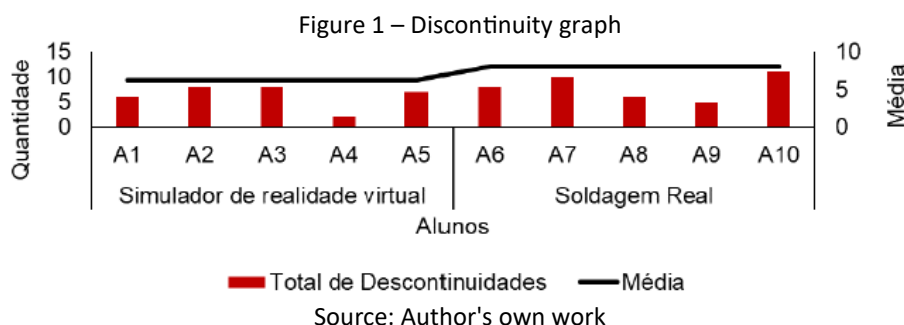
- t-statistic: -1.129
- p-value: 0.291

The hypothesis test was performed for the metric "Discontinuities" (defects in welds):

- Null Hypothesis (H0): There is no significant difference between the average number of discontinuities in the two training methods.
- Alternative Hypothesis (H1): There is a significant difference between the average number of discontinuities in the two methods.

Since the p-value (0.291) is greater than the significance level of 0.05, we do not reject the null hypothesis. We conclude that there is insufficient evidence to assert a significant difference in discontinuities between the two training methods.

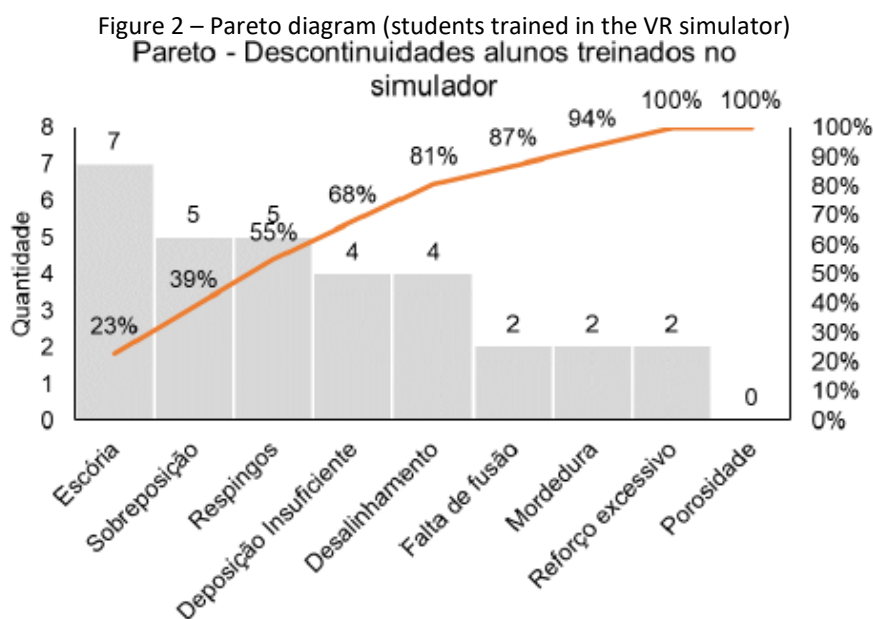
The graph below (Figure 1) shows the evolution of discontinuities identified during weld-quality analysis for both training methods.



Although this tool shows no significant difference in the average number of discontinuities between the two training methods, it is crucial to conduct a more detailed, qualitative analysis to better understand the specific defect types that occur more frequently in each technique. Therefore, a subsequent analysis will also be conducted using a Pareto Diagram to assess the discontinuities qualitatively.

3.4. Pareto Diagram

To qualitatively analyze weld discontinuities, we used Microsoft Excel to create a Pareto diagram, which helped us identify the most frequent and critical defect types. This visual tool is handy for highlighting which problems most affect weld quality, guided by the principle that approximately 80% of issues originate from only 20% of the causes. Using the Pareto diagram, we identified and prioritized areas requiring greater attention and intervention, facilitating the implementation of targeted, efficient improvements in welding training. This is fundamental to ensure that both the simulator method and the traditional method can maintain high standards of weld quality.



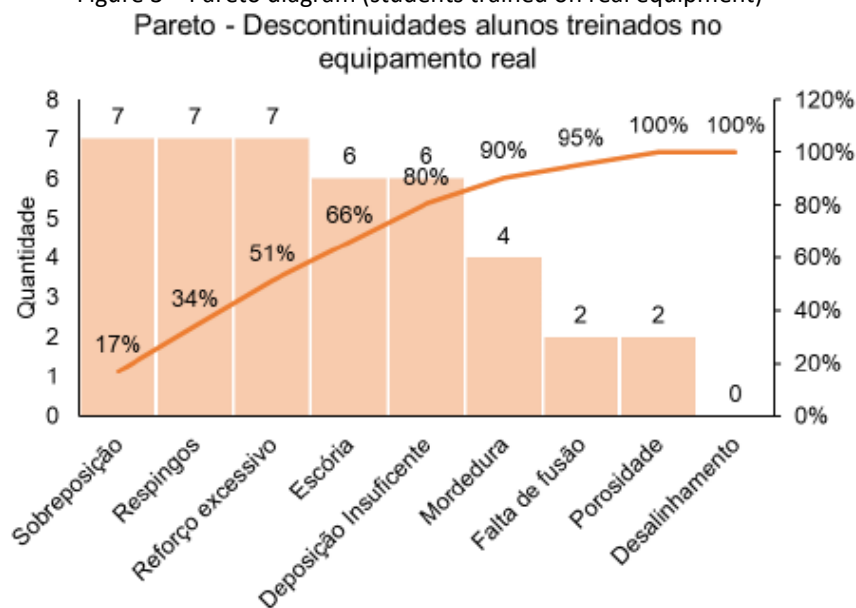
Source: Author's own work

In identifying the most common causes of discontinuities, the Pareto chart proved effective for visualizing the fundamental factors contributing to the defects. In the data analysis, as illustrated in Figures 2 and 3, we observed that, in the virtual reality simulator, discontinuities such as vitreous slag, overlap, spatter, insufficient deposition, and misalignment accounted for 81% of the problems identified. These results guide our focus towards more targeted training, adjusting the variables that affect these five main issues.

In results from activities involving students trained with real equipment (Figure 3), overlapping, spatter, and over-reinforcement defects were most frequent. Combined with slag and insufficient deposition, these defects account for 80% of the discontinuities found, underscoring the need for training focused on these

specific areas.

Figure 3 – Pareto diagram (students trained on real equipment)



Source: Author's own work

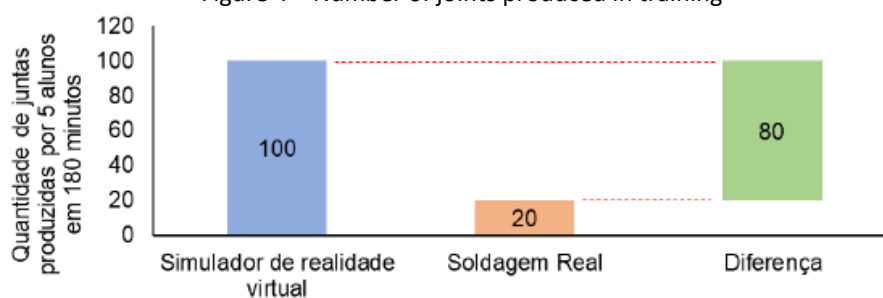
4. COMPARATIVE ANALYSIS

4.1 Gaskets Produced

In comparison, each group of students completed the training within the 180-minute timeframe set as the metric.

Figure 4 below shows the quantity of gaskets produced in the specified period.

Figure 4 – Number of joints produced in training



Source: Author's own work

4.2. Discontinuities

Table 4 presents a summary of the discontinuities found in the parts produced during the training, the analysis based on the Pareto Chart, and the relevant actions for an improvement action plan.

- Slag is the most frequent discontinuity in the simulator, while overlap and splashes are common in both methods, but predominate in real training.
- Excessive reinforcement is a significant problem in training with real

equipment, suggesting possible over-reinforcement of the deposited material.

- Misalignment is not a significant problem in real-world training, but it does appear in the simulator, suggesting the need to improve alignment techniques in the virtual environment.

Focusing on 80% of the main problems, the most relevant actions are those indicated in the table above for both groups.

Hence, we can see that the group that used the virtual reality simulator produced significantly more joints than the group that used the real welding equipment, indicating better time use and learning.

Table 4 – Comparison of Discontinuities (80% of Problems)

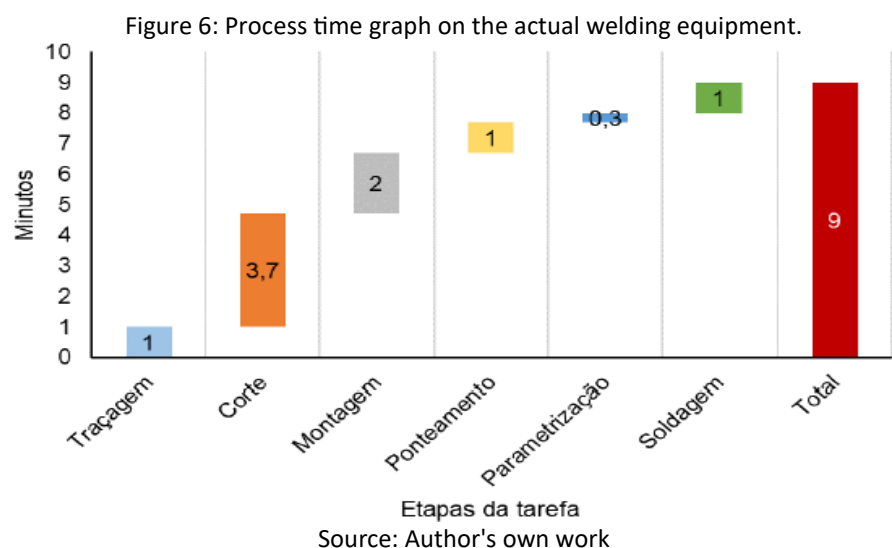
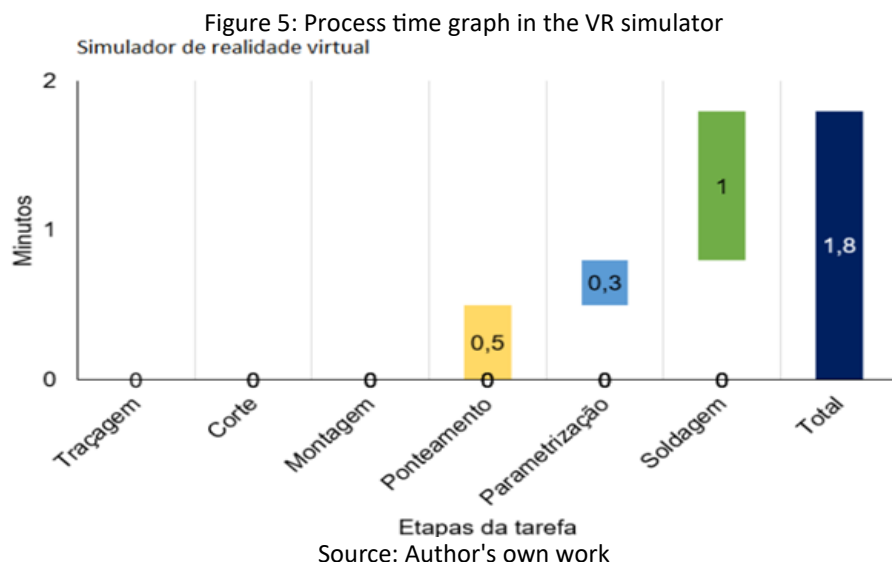
Discontinuity	Virtual Reality Simulator	Actual Equipment	Relevant Action
Slag	7 (23%)	6 (66% cumulative)	Develop specific training on slag removal, including welding techniques and the correct use of tools and accessories.
Overlap	5 (39% cumulative)	7 (17%)	Introduce focused training techniques to achieve uniform deposition and avoid overlapping. Use simulators to practice in a safe and controlled environment before applying the method to real equipment.
Splashes	5 (55% cumulative)	7 (34% cumulative)	Develop practical exercises that teach techniques for reducing spatter, including adjustments to welding parameters, torch tilt, and nozzle cleaning.
Insufficient Deposition	4 (68% cumulative)	6 (80% accumulated)	Focus on training to ensure the proper amount of welding material, adjusting welding speeds and wire feed/welding current.
Misalignment	4 (81% cumulative)	0 (0%)	Develop exercises to reinforce proper alignment of parts. Use the simulator for training this skill; on the actual equipment, draw lines to facilitate alignment control during welding.

Source: Author's own work

4.3 Processing Time

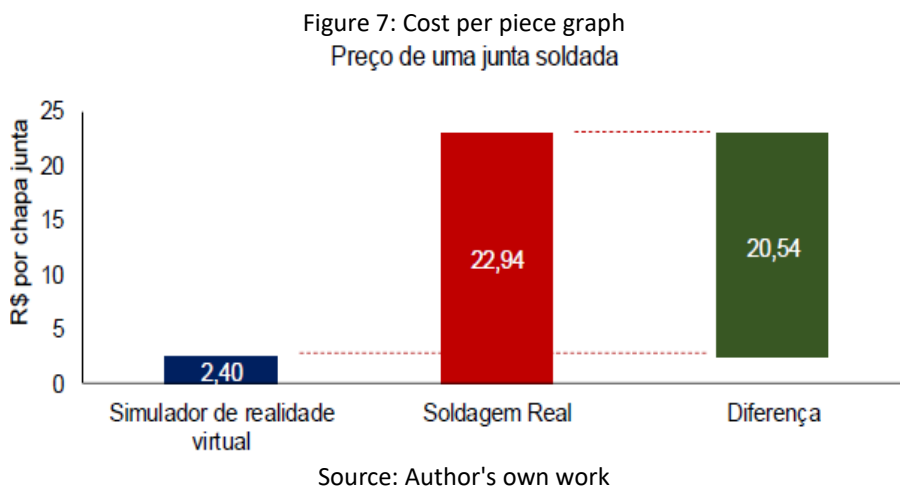
Regarding the process time, for this comparison, all stages for obtaining the joint were considered before the exercise was carried out, using the actual equipment to perform a cost comparison: layout, cutting, assembly, tack welding, parameterization, and welding.

The graph in Figure 5 shows a significant reduction in training time in the virtual reality simulator. The process time was significantly shorter for students who used the virtual reality simulator – 1.8 min/piece (Figure 5)- than for students who used the real welding equipment – 9.0 min/piece (Figure 6).



4.4 Costs

The costs refer to the total per piece produced per student during training, including materials used and other costs associated with the process.



The cost per piece was significantly lower for students who used the VR simulator (R\$ 2,40) than for those who used the real equipment (R\$ 22,94).

Below is a cost comparison between training using a VR simulator and real equipment.

The costs (Table 5) were analyzed considering several factors, including process costs, inspection time, raw materials, welding consumables (welding wire and shielding gas), and electricity.

The results presented in Table 5 indicate a significant difference in costs between the training methods. The cost per training session with the virtual reality simulator is substantially lower (R\$ 2,41) than with real equipment (R\$ 22,94). This difference is mainly attributed to the costs of the process and raw materials in real training.

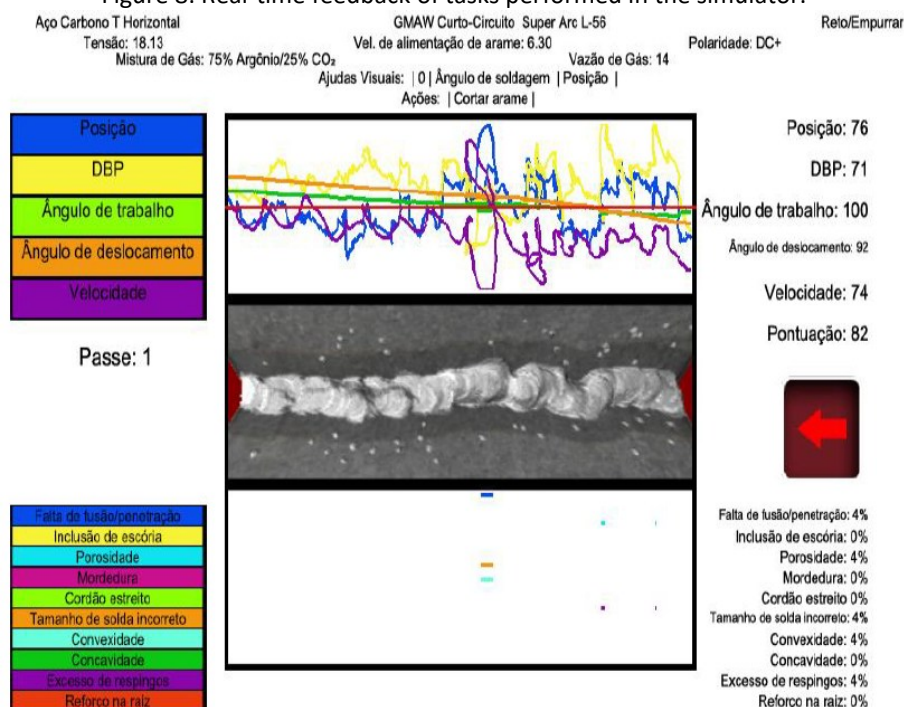
Regarding the cost of inspection time, we can consider another advantage of using virtual reality simulators: the feedback from the experiment is provided in real time (Figure 8), highlighting opportunities for improvement in welding techniques and the defects associated with each deviation.

Table 5 – Comparison of costs per piece

Cost of:	Simulator (R\$)	Actual Equipment (R\$)
Process	2,39	12,00
Inspection Time	0,00	5,33
Raw Material	0,00	4,67
Welding wire	0,00	0,62
Shielding Gas	0,00	0,21
Electrical Energy	0,01	0,11
Total Cost	2,40	22,94

Source: Author's own work

Figure 8: Real-time feedback of tasks performed in the simulator.



Source: VR Simulator

Regarding the costs of raw materials, welding wire, and shielding gases, these are not used in the virtual reality simulator, providing significant advantages in terms of safety, radiation exposure, and welding fumes for students, as well as contributing to environmental protection.

5. RESULTS AND DISCUSSION

The study confirms that VR simulators are a practical and safe alternative for welding training, offering substantial time and resource savings. The implementation of VR simulators as a tool to enhance superior learning outcomes can revolutionize the training of new professionals, with the potential to reduce costs and increase the efficiency of training programs, as shown in Table 6 below.

Table 6 – Comparison of positive and negative points

Positive Points	Virtual Reality Simulator	Actual Equipment	Negative Points	Virtual Reality Simulator	Actual Equipment
Reduced Cost	Lowest total cost (R\$ 2,41)	-	Less Realism	It may not perfectly replicate real-world conditions.	-
Enhanced Security	Safe environment, without physical risks.	-	Specific Discontinuities	High occurrence of slag.	-
Flexibility and Repetition	Unlimited repetition without material wear.	-	Technological Limitations	It doesn't capture all the nuances of the actual process.	-
Discontinuity Reduction	Reduced occurrence of over-reinforcement and misalignment.	-	High Cost	-	Highest total cost (R\$ 22,94)
Greater Realism and Transference	-	An experience close to real-life conditions.	Increased Occurrence of Discontinuities	-	Increased occurrence of overlapping and splashing.
Identifying Real Problems	-	Identifying specific problems in the field.	Security Risks	-	Physical risks such as burns and exposure to fumes.

Source: Author's own work

The results indicate that the VR simulator is an effective tool for welding training, resulting in substantial reductions in training costs and time compared to the traditional method. This financial gain is significant: a saving of almost 90% per piece, which, in addition to being economical, meets a practical demand highlighted by Scotti (2017), who noted that VR is a resource that saves materials and energy.

Furthermore, the processing time per piece was significantly reduced with VR, allowing students to make better use of their available practice time. The simulator eliminates several steps of conventional training, and the virtual environment offers complete safety. This is essential, especially in learning environments where frequent practice is fundamental for skill retention.

Although no statistically significant difference in the average number of discontinuities emerged between the methods (p -value = 0.291), each technique exhibited distinct error patterns. In the simulator tests, slag and misalignment stood out, indicating areas for improvement in the simulator's feedback, as noted by Okimoto (2015). With the real equipment, problems such as excessive reinforcement and overlapping occurred more frequently, suggesting that initial training on the simulator could help correct some of these errors before moving on to the real equipment.

Another strong point of the simulator is its instant feedback, which helps students identify and correct flaws in real time. Studies such as that of Prasetya et al. (2023) corroborate this advantage, highlighting that this type of rapid feedback helps students progress faster and better understand the details of the welding process. This makes learning more engaging and active, reducing the need for time-consuming inspections.

The findings reinforce that the VR simulator stands out as an economical and safe tool for accelerating and efficiently developing essential skills. In the context of the shortage of qualified welders (American Welding Society, 2023), VR technology offers an innovative and practical approach, improving both professional training and the quality of welding processes.

PRASETYA et al. (2023) state that VR simulators were developed for use as a teaching strategy rather than as a replacement for real training, with the primary objective of complementing and optimizing the teaching-learning process.

6. RESULTS AND DISCUSSION

The results of this study demonstrate that VR simulators are an advantageous and accessible option for electric arc welding training. This approach not only facilitates knowledge retention and the improvement of practical skills but also offers additional benefits in terms of safety, resource savings, and positive environmental impact. By examining the most common discontinuities, it is clear that there is still room to improve weld quality in a VR environment, thereby reinforcing the accuracy and effectiveness of learning.

Furthermore, to reduce material and supply costs, VR simulators provide real-time feedback, making them a promising training strategy with practical applications in educational and production contexts. This technology has the potential to mitigate the shortage of qualified professionals in the field of welding, forming teams better prepared for the practical challenges of the sector. We thence recommend adopting VR simulators to complement traditional training, optimize time and reduce costs, and ensure a more specialized workforce is trained more quickly.

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