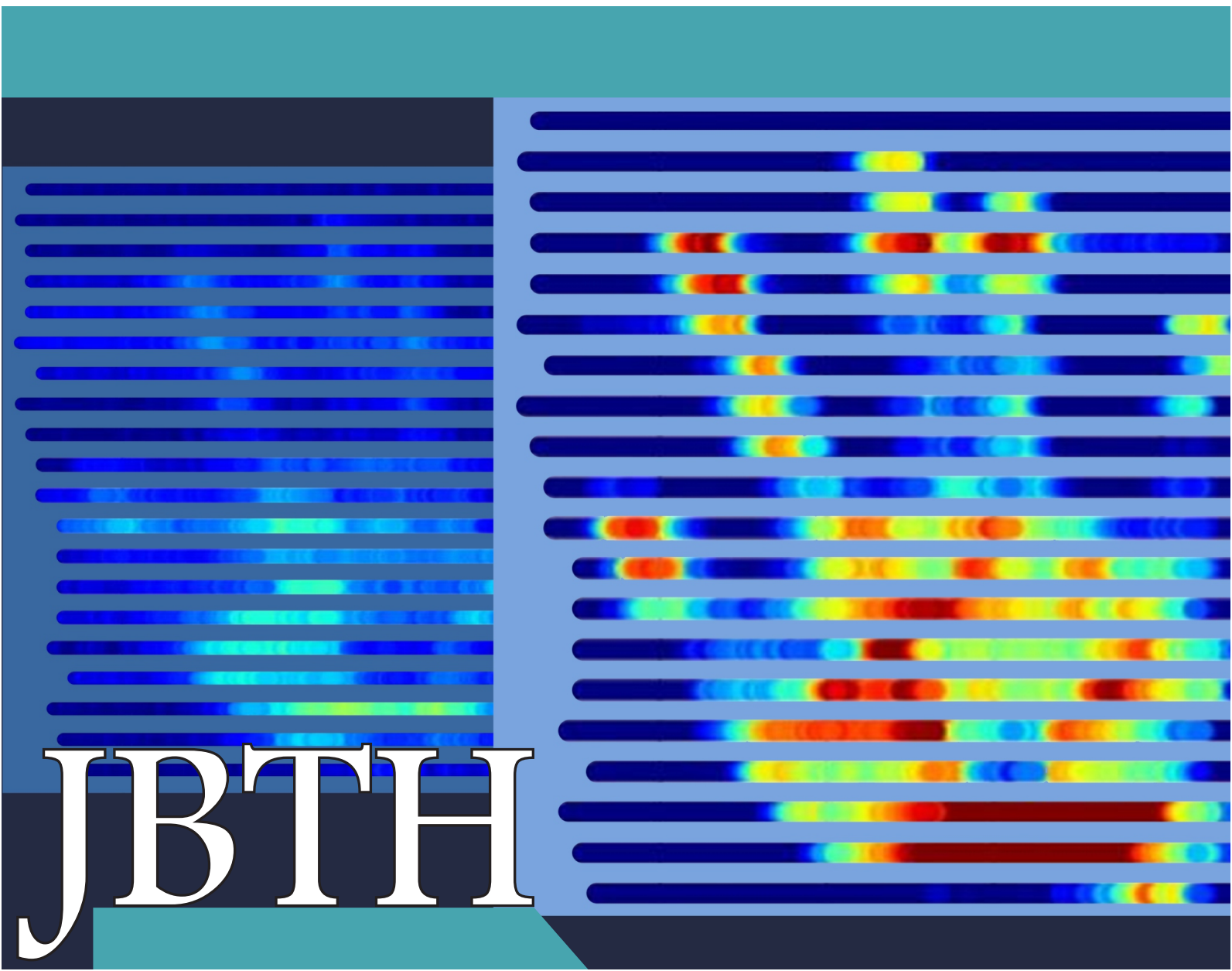




Journal of Bioengineering, Technologies and Health

An Official Publication of
SENAI CIMATEC



ISSN: 2764-5886 / e-ISSN 2764-622X

Volume 9 • Number 8 • August 2026



JOURNAL OF BIOENGINEERING TECHNOLOGIES AND HEALTH

An Official Publication of SENAI CIMATEC

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Alex Álisson Bandeira Santos

PUBLISHED BY SENAI CIMATEC

Sistema FIEB



August 2026
Printed in Brazil

JOURNAL OF BIOENGINEERING TECHNOLOGIES AND HEALTH

An Official Publication of SENAI CIMATEC

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DOI:10.34178



ISSN: 2764-5886 / e-ISSN 2764-622X

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COVER: Figure 9. Sensor modeling of a non-heated hand. Figure 10. Sensor modeling of a hand heated by friction. Temperature Sensing and Modeling Based on Optical Fiber Using the OFDR Technique by Leonardo Santos Magalhães et al. J Bioeng. Tech. Health 2026;9(8):828.

Evaluation of the Mechanical Behavior of ABS/HIPS Blends from WEEE by Single Screw Extrusion

Francis Oliveira de Menezes^{1*}, Rodrygo Silveira de Carvalho Viana¹, Zora Ionara Gama dos Santos¹

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Waste electrical and electronic equipment (WEEE) has seen its useful life significantly shortened due to rapid technological development and innovation, growing commercial demand for updated equipment, and increasingly broad applications. To avoid the accumulation of waste in waste facilities, new recycling methods for this material have been studied. In this regard, this study aimed to optimize the composition and processing method of thermoplastic blends (ABS/HIPS) using polymers from the mechanical recycling of WEEE. This blend was then used to produce filaments for 3D printers. It also aimed to evaluate the effect of six recycling cycles on the mechanical properties of these blends, always comparing them to commercial, virgin ABS. To this end, the materials, primarily derived from discarded air conditioning housings, were processed in a single-screw extruder, where the blends underwent six successive processing cycles. The test specimens were obtained through the injection molding process, sectioned at the end of each extrusion cycle, thus separating them into samples ranging from zero to five processes, and studied via uniaxial tensile testing and impact strength testing. The results show that regarding mechanical tensile performance, the consecutive reprocessing may have slightly influenced the blend's properties, although they remained acceptable consistency. This was also true for impact strength values, although they appear to have less influence on this property, i.e., better reprocessing tolerance. Overall, the results are promising and suggest the possibility of recycling the ABS/HIPS blend without significant changes resulting from the degradation process; the new application simply requires mechanical stresses within the limits that the recycled blend can meet. Furthermore, the blend did not exhibit inferior properties to the filament used in printing during printing and is considered suitable as a raw material.

Keywords: Single Screw. Blends. WEEE. HIPS. ABS.

Abbreviations: WEEE, Waste electrical and electronic equipment. ABS, Acrylonitrile Butadiene Styrene. HIPS, High Impact Polystyrene.

Rapid technological evolution and the growing demand for electronic devices have intensified the generation of waste electrical and electronic equipment (WEEE), which represents one of the fastest-growing waste streams worldwide. This waste is a complex source of materials, including metals, plastics, glass, and hazardous chemicals, requiring effective management strategies to minimize its environmental impact [1]. The lack of adequate infrastructure for the treatment and recycling of this waste in many countries contributes to landfill accumulation and environmental contamination [2].

In this context, polymer recycling has emerged as a sustainable solution, not only for reducing waste volume but also for recovering valuable materials for reuse. ABS (Acrylonitrile Butadiene Styrene) and HIPS (High Impact Polystyrene) plastics are widely used in electronic products due to their mechanical properties, impact resistance, and ease of processing [3-6]. However, the short life cycle of many electronic devices leads to premature disposal of these materials, highlighting the need for effective recycling processes [6].

Mechanical recycling is a viable technique for reusing plastics, converting waste into new products through grinding, extrusion, and molding processes.

This method is particularly advantageous because it does not require the use of harsh chemicals and can be implemented with low operating costs [5,6]. Studies indicate that the use of recycled ABS and HIPS blends can maintain physical and mechanical properties comparable to those of virgin materials,

Received on 20 May 2026; revised 28 July 2026.

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J Bioeng. Tech. Health 2026;9(8):785-790
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allowing their use in demanding applications, such as 3D printing [4,7].

Additive manufacturing, or 3D printing, represents a disruptive innovation in industrial production, offering versatility in the rapid and efficient manufacture of complex components [4]. The use of recycled filaments not only aligns 3D printing with sustainable practices but also presents an economic opportunity to reduce costs and dependence on virgin raw materials [7]. The integration of recycled materials into 3D printing can contribute to a more robust circular economy, encouraging the development of technologies that minimize waste and maximize resource efficiency [4].

The results are expected to demonstrate the technical and economic viability of mechanical recycling as a sustainable source of HIPS/ABS blends for additive manufacturing, since the proportion of polymers found in WEEE is predominantly HIPS and ABS, especially in air conditioners [8].

Materials and Methods

To produce the blends, both ABS and HIPS were sourced from different types and brands of damaged or obsolete air conditioner housings, donated by the Assets Division (DIPATRI) affiliated with

the Department of Material Resources (DRM/PROAD) at the Federal University of Sergipe. After collection, the material was disassembled, separated into polymeric parts, cleaned, and combined in a knife mill.

Blend Preparation by Extrusion

The blend was initially obtained using an AX Plastics single-screw extruder with a screw diameter of 16 mm and a L/D ratio of 26, located in the Polymer Rheology and Processing Laboratory of the Materials Engineering Department at the Federal University of Rio Grande do Norte. The machine's operating conditions for the various cycles are listed in Table 1.

Once the blend was finished, a sample (V0) was collected, and the remainder was reprocessed five times, with samples collected from each process, as shown in Table 2. It is worth noting that after each extrusion, the material was dried in a SOLAB oven (model SL 102/408) at 90°C for four hours.

Preparation of Test Specimens

The test specimens were manufactured in accordance with ASTM D-638 type I. The injection molding process was used on an Arbug All Rounder

Tabel 1. Extrusion Parameters of HIPS/ABS Blends.

Parameter		V0	V1	V2	V3	V4	V5
Rotational Speed (rpm)		100	100	100	100	100	100
	Zone 1	190	189	190	189	190	188
	Zone 2	210	210	209	210	210	210
	Zone 3	220	219	220	219	220	219
	Zone 4	200	221	221	219	221	220
Extruder Temperature (°C)	Zone 5	220	219	219	222	220	220
	Zone 4	225	226	226	224	226	225
	Zone 5	221	220	220	223	221	220
Melt Temperature (°C)							
Melt Pressure (bar)							
	Zone 5	50	54	52	52	53	53

Tabel 2. Sample coding.

Cycle	V0	V1	V2	V3	V4	V5
Number of Processing Cycles	1	2	3	4	5	6

270S 400-100 injection molding machine at the Rheology and Polymer Processing Laboratory (LabPol) of the Federal University of Rio Grande do Norte. The injection molding processing conditions are shown in Table 3.

Table 3. Injection parameters.

Parameter	Value
Temperature Profile	190/200/210/220/210° C
Mold Temperature	40 °C
Injection Speed	20 cm ³ /s
Holding Pressure	100 bar
Holding Time	4 s
Dosing Volume	32 cm ³

Mechanical Tests

Impact Tests

The impact test was conducted in accordance with ISO 180, using an Izod pendulum device. The notches were previously made using a notching machine. The cross-sectional width and thickness measurements of the specimens were obtained using a micrometer and used to obtain impact toughness results. That is, the energy required for complete rupture of the specimens was measured, resulting in a measurement of energy per area (J/mm²).

Tensile Tests

These tests were conducted in accordance with ASTM D256 to analyze the modulus of elasticity and tensile strength at break. The specimens were tested in the mechanical testing laboratory (DCEM) of the Federal University of Sergipe on

an INSTRON model 3367 universal mechanical testing machine, operating at a speed of 5 mm/min and a grip distance of 115 mm. The data were processed and graphed for subsequent analysis and comparison.

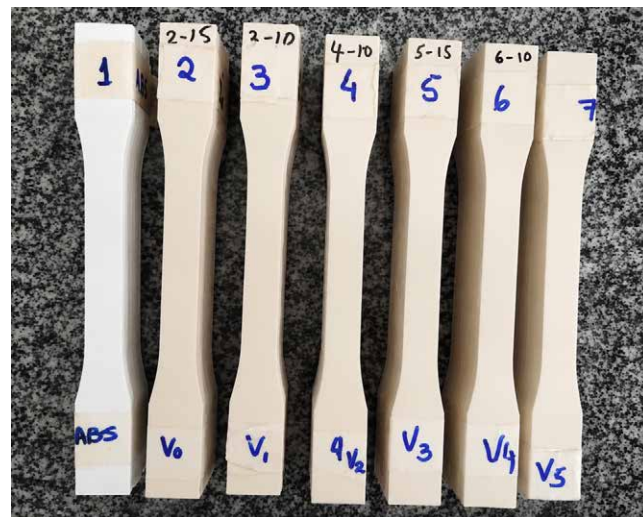
Results and Discussion

Appearance of Samples

As Figure 1 shows a photograph of all the test specimens obtained after each extrusion cycle. By observing the images, it is possible to identify a change in visual appearance, especially in color. There is a loss of appearance, from a glossy white (in virgin ABS), to a light beige tone.

This change is believed to be due to the presence of various contaminants, which cannot be completely separated. These include metallic components and even other polymers in small quantities. Another determining factor in the decline in optical properties is the degradation of the blend, since, after several extrusion cycles, the

Figure 1. Photograph of test specimens produced from pure ABS and reprocessed WEEE casings (V0 to V5).



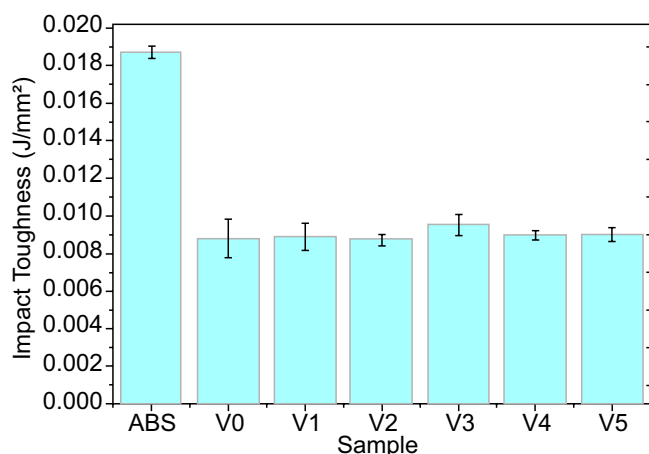
ABS, Acrylonitrile Butadiene Styrene. WEEE, Waste electrical and electronic equipment. V0, sample with 1 reprocessing. V1, sample with 2 reprocessing. V2, sample with 3 reprocessing. V3, sample with 4 reprocessing. V4, sample with 5 reprocessing. V5, sample with 6 reprocessing.

rupture of some of the constituent polymer chains is inevitable.

Impact Assay

The Figure 2 shows a comparison of the average impact strength values and their respective standard deviations for virgin ABS and ABS/HIPS blends after successive extrusion cycles. Observing this figure, two findings are clear: A priori, the recycled ABS/HIPS blends presented mechanical performance approximately half that of pure ABS, implying that the blends are mechanically more fragile than the virgin filament material. On the other hand, this property remains consistent throughout the blends reprocessing cycles.

Figure 2. Average impact toughness (J/mm^2), with standard deviation obtained by the Izod impact test, ISO 180 standard.



Therefore, this greater fragility of the recycled blends was expected, given that all samples had a useful life, such as air conditioning equipment, before disposal. That is, at the time of product conception, the product initially underwent an injection process, its lifespan was established and was ultimately discarded. Furthermore, after disposal, it underwent at least two more heating cycles. In the case of V0, it underwent another extrusion cycle to prepare the blend and another injection cycle to prepare the test specimens, with the others undergoing a subsequent, progressively

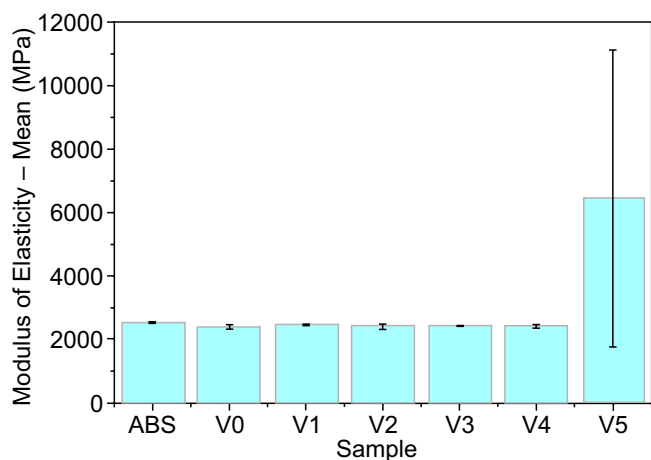
increasing stage. Thus, the poor performance compared to virgin ABS can be associated with the degradation of the polybutadiene segments that occurs during the material's reprocessing, since, during the reprocessing of polymers grafted with tough rubbers, degradation occurs preferentially in the rubber phase, with chain scission and cross-linking. This is consistent with recent studies in the literature [9,10]. The constancy of this property after multiple reprocessing supports the ideals of sustainable additive manufacturing, since products generated through 3D printing can be recycled multiple times without significantly reducing the property in question. It's important to note that manufactured products must fit within the range of applications for which the determined impact resistance value is acceptable. It's important to emphasize that when we say, "recycle multiple times," there's still a limit. Six reprocessing were performed in this project, and therefore, this is the known limit. Further claims are not possible until further testing is conducted within this line of research.

Tensile Assay

The Figure 3 shows a comparison of the elastic modulus values obtained from the tensile test for virgin ABS and the ABS/HIPS blends after the various reprocessing processes. The reprocessed samples presented similar elastic modulus values, indicating that the various recycling cycles did not significantly alter this property. However, sample V5 presented a different value with a standard deviation outside the proposed statistical range, thus requiring this test to be repeated for this sample. Regarding the commercial ABS sample, which exhibits a slightly higher average elastic modulus than the reprocessed samples, based on the standard deviation, it is plausible to assume that the stiffness of only sample V5 is not within the range of that of pure ABS, requiring a repeat test for this sample. Thus, the modulus variation for all samples was small, and therefore, the reprocessed ABS/HIPS blend presents a stiffness similar to that of the

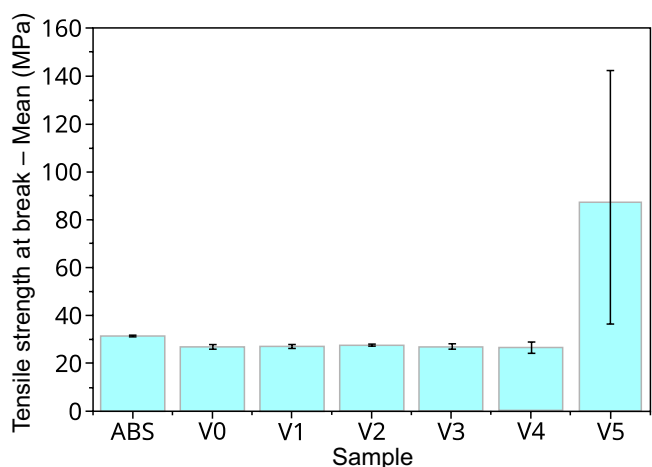
filament material. Figure 3. A Average modulus of elasticity (MPa), with standard deviation, of virgin ABS and HIPS/ABS blends under successive reprocessing.

Figure 3. A Average modulus of elasticity (MPa), with standard deviation, of virgin ABS and HIPS/ABS blends under successive reprocessing.



The Figure 4 shows the average tensile stress values at break obtained from the tensile test of virgin commercial ABS samples and recycled ABS/HIPS blends. The commercial ABS sample exhibits a slightly higher average value for this property than the other samples, corroborating the elastic modulus data.

Figure 4. Mean tensile strength (MPa), with standard deviation, of virgin ABS and HIPS/ABS blends after successive reprocessing.



Furthermore, in order to meet the main objective of this study, which was to primarily evaluate the effect of consecutive reprocessing on the mechanical properties of ABS/HIPS blends from WEEE, we observed that the mechanical properties of the blends did not vary significantly when the extrusion rate was increased. However, for V5, the experiment needed to be repeated due to the large standard deviation; that is, there were no statistically significant changes in the evaluated properties. This maintenance of properties guarantees the usability of these blends, even after six processing cycles, in the manufacture of 3D printing filaments.

Conclusion

Regarding the preparation of ABS/HIPS blends from WEEE, using a single-screw extruder, simulating recycling cycles through successive extrusions, the aim was to demonstrate the feasibility of using these blends in the production of 3D printing filaments. The study concluded that, after several extrusion cycles, a change in the visual appearance of the test specimens was observed, especially in color, going from a glossy white to a light beige tone.

Regarding impact strength, the recycled ABS/HIPS blends presented an average value, equivalent to approximately half the performance of virgin commercial ABS. On the other hand, a consistency in this property is evident throughout the blends' reprocessing.

The modulus of elasticity values was similar, indicating that the various recycling cycles did not cause significant changes in this property, and this behavior was similar in terms of tensile strength.

Thus, the mechanical properties remained virtually constant throughout the reprocessing cycles. The decline in properties, compared to virgin ABS, was also not significant.

In summary, the results were very promising and the idea of using the HIPS/ABS blend from WEEE in the production of 3D printing filaments proves viable in terms of mechanical requirements. However, it would be beneficial to continue

the project, through thermal and rheological characterization of the material, to confirm the quality of the final product.

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Influence of Titanium Dioxide Photocatalytic Residue Incorporation on Fresh State Properties of Cement-Based Materials

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Nowadays, due to high levels of emission of polluting gases such as carbon dioxide (CO₂), it is very common in the construction industry to search for sustainable alternatives that contribute to the reduction of environmental impacts. Therefore, the incorporation of photocatalytic residues, such as titanium dioxide (TiO₂), has shown to be a valuable ally in this approach, since it is known for its photocatalytic properties, which contribute to the degradation of atmospheric pollutants and to the improvement of concrete durability. This study aims to analyze the behavior of the insertion of different contents of photocatalytic residue in cement pastes and evaluation of its impact on fresh state properties, especially investigating an optimal dosage that balances workability and environmental sustainability. This work represents only a first step, though an essential one, toward more comprehensive studies that consider the photocatalytic properties of TiO₂ and its potential to contribute to environmentally responsible solutions in civil construction. In this regard, different contents of titanium dioxide were incorporated in cementitious matrices (10%, 15%, and 20%) with a constant water-to-cement ratio of 0.5 to analyze the influence of the residue on fresh state properties of cement-based materials. The experimental methodology involved the preparation of cement paste samples using Portland Cement V-ARI RS, with standardized mixing procedures, aiming to ensure homogeneous TiO₂ dispersion and optimize the results of the experiments. In addition, the proposal also aims to understand the performance and evolution of the paste strength over time, as well as to evaluate the effects of TiO₂ incorporation focusing on paste workability. The analyses were conducted through mini-slump and setting time tests. The study reinforces the potential of TiO₂ potential as a sustainable additive, especially when properly dosed and incorporated.

Keywords: Titanium Dioxide. Photocatalytic Properties. Cement Paste. Fresh-State Properties.

Abbreviations: CO₂, Carbon dioxide. TiO₂, Titanium dioxide.

The current problematic of environmental impacts caused by human activities is historical. Since the Industrial Revolution, with the advancement of industrial and technological practices, there has been an aggravation of problems related to the environment, whether due to the generation of solid waste or the emission of polluting gases [1].

Furthermore, in addition to the emission of carbon dioxide resulting from human activities, the release of other atmospheric pollutants, such as nitrogen oxides (NO_x), is also emphasized, being

considered hundreds of times more harmful than CO₂, for example. In this context, the heterogeneous photocatalytic activity of titanium dioxide is capable of acting in the degradation of these pollutants and other organic compounds, causing a decrease in the concentration of these gases in the environment. In this sense, the ability to "break down" organic molecules adsorbed on its surface gives this residue the property of self-cleaning [2].

Thus, there is an urgent need for combinations in cement-based-materials that can contribute to sustainability. A good example of this is the incorporation of titanium dioxide residues in cement pastes, mainly because of their effective catalytic properties in photocatalytic degradation processes. Its application, through heterogeneous photocatalysis, in which TiO₂ acts as a solid semiconductor, either in powder or film form, proves efficient in the decomposition of organic

Received on 15 April 2026; revised 25 July 2026.

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J Bioeng. Tech. Health 2026;9(8):791-796
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compounds. Moreover, studies indicate that photocatalysis is not especially effective in breaking down large amounts of dirt or organic matter, such as on already deteriorated surfaces. However, it is capable of preventing the accumulation of these substances when applied to new coatings, promoting the decomposition of organic particles or polluting gases upon contact with the surface [3-4].

Furthermore, according to studies, the incorporation of photocatalytic residues can help increase concrete strength. However, when used at high contents, mechanical strength may be compromised due to the agglomeration of photocatalytic particles, leading to non-uniform distribution in the cementitious matrix [5-6].

Additionally, the method of incorporating photocatalytic residues into cement-based-materials can affect both mechanical strength and fresh-state properties, especially when improperly incorporated. Thus, the correct handling and incorporation of the residue are crucial to obtain good responses, concerning strength and workability, providing long term structural performance in residences or buildings [7].

Given the critical importance of proper incorporation methods and the need to understand their impact on material performance, this work will focus on studying analytical experiments to evaluate the incorporation process impacts on fresh state properties, aiming to prove how characterization methods can provide valuable knowledge about how photocatalytic residues interact with the cement matrix and how photocatalytic residues affect fresh concrete behavior.

The evaluation of properties in the fresh state is essential to consolidate the use of this cement paste, in order to guarantee that the cement-based material meets required performance standards in civil construction [7].

Thereby, the cement paste characterization will be done in the fresh state, by analyzing the behavior of the materials with or without the residue incorporated in both stages, evaluating the impacts that the incorporation of the residue may cause in

the pastes, specifically to understand its effect on their workability [8-9].

Hence, the work aims to evaluate the properties of the mixtures in the fresh state, analyzing consistency through mini-slump and setting time.

Materials and Methods

The experimental procedure was developed in the following stages: materials characterization, formulation of mixtures and analysis of concrete in its fresh state. For this, mixtures produced with Portland Cement V-ARI RS were

developed. An industrial residue from pigment production, rich in titanium dioxide, in powder form with irregular granulometry (Figure 1), was incorporated, used without grinding to simulate real industrial environmental conditions.

The materials used in the mixtures included: Portland Cement V-ARI RS, potable water and the photocatalytic residue. No chemical additives were added, aiming to analyze the isolated effect of the residue on the concrete behavior in the fresh state.

For each mixture, the components were weighed on precision scales, and the mixing procedure followed standard procedures. Initially, the cement was mixed with the residue, followed by gradual addition of water. The mixing was performed in a standardized mixer in order to guarantee the homogeneity of the material.

All tests were performed at ambient laboratory temperature, and each measurement was carried out precisely, following the standard procedures specified in the respective norms.

Residue contents of 10%, 15%, and 20% were incorporated into the pastes, maintaining a constant water-to-cement ratio of 0.5, to evaluate their influence on cement paste consistency.

The mix proportions were designated as CREF, C10, C15, and C20, respectively for 0%, 10%, 15%, and 20% of incorporated residue present in the mixture, as presented in Table 1. This nomenclature will be adopted in all subsequent figures and tables to refer to each cement paste proportion.

Figure 1. Photocatalytic titanium dioxide residue used in the mixtures.



Table 1. Mix proportions and nomenclature used in the study.

Nomenclature	Mix Proportions
CREF	Reference paste (without titanium dioxide residue)
C10	Paste with 10% incorporated titanium dioxide residue
C15	Paste with 15% incorporated titanium dioxide residue
C20	Paste with 20% incorporated titanium dioxide residue

Thus, setting time tests were conducted on both residue-incorporated and non-incorporated pastes to evaluate the impact of residue incorporation on the hardening of the pastes.

Moreover, mini-slump tests were performed to analyze the influence of the residue on the fluidity and workability of the mixtures [12].

Setting Time Test

The setting time test was executed for the reference cement (without the residue) CP V ARI RS, according to NBR 16607:2018, using the normal consistency that was previously determined by testing, according to the norm NBR 16606:2018. This test was also performed for cement pastes with

different incorporated residue contents, following NBR 16607:2018 as well, aiming to analyze the impact of residue incorporation on the pastes [10-11].

Mini-Slump Test

The mini-slump test was made, in accordance with NBR 16889:2020, using a mini cone. The tests were applied to both the reference cement paste and the pastes with different incorporated titanium dioxide contents, aiming to evaluate the residue's influence on the fluidity and workability of the pastes [12].

Mini-slump spread diameters were obtained and compared between the reference paste and the pastes with different incorporated titanium dioxide residue contents. The spread diameter measurements were analyzed using ImageJ software.

Results and Discussions

Setting Time Test

The setting time test was performed on the pastes in their fresh state. The Figure 2 presents the results of the test for the reference paste and for the pastes with different contents of incorporated residue.

Regarding the setting time, a considerable reduction in setting time was observed in the mixtures with addition of titanium dioxide residue, mainly at higher contents. As shown in Figure 2 and Figure 3, which demonstrated that increasing residue content decreased the setting time in the mixtures, both considering the time from initial to final setting stages and from initial water contact with cement and residue to final setting stage, with the most significant reductions observed in pastes containing 10% and 15% incorporated residue content.

Mini-Slump Test

The mini-slump test was performed in the fresh state, following the NBR 16889:2020 standard, for

a cone of reduced volume. Figures 4 to 7 present the results of the mini-slump test for the reference paste and for the pastes with different residue contents [12].

Throughout the figures, as the incorporation of residue in the pastes increases, it makes the paste mixtures drier, thus they lose consistency. This way, it can be seen that titanium dioxide directly affects the workability of the mixtures, as its content in them increases. This can be verified with the decrease in the spread diameter of the pastes, as the photocatalytic residue content is increased. The spread diameter values obtained were approximately

Figure 2. Total setting time from initial water contact with cement and residue to final setting stage.

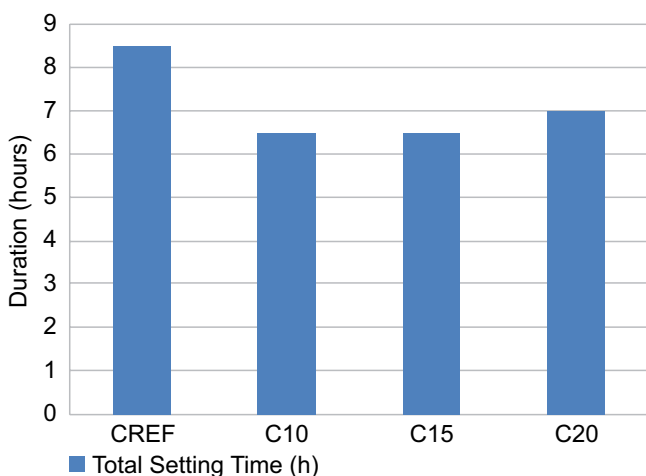
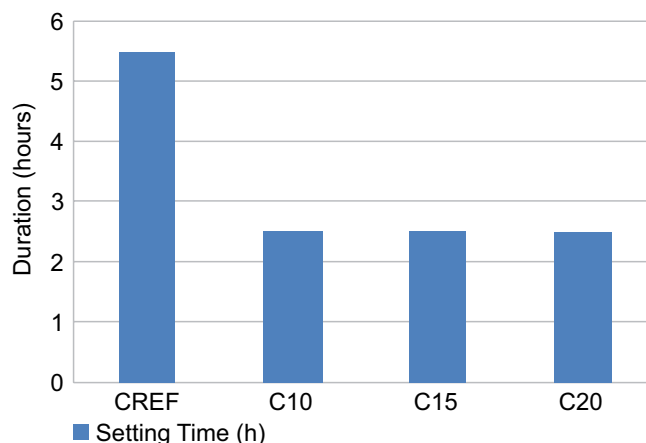


Figure 3. Duration of the setting time of the cement paste, determined between the initial and final setting stages.



56 mm for the reference paste, 53 mm for the paste with 10% incorporated residue, 49 mm for the paste with 15% incorporated residue, and 47 mm for the paste with 20% incorporated residue.

We emphasize that, even during the preparation of the samples for the test, the alteration in the consistency of each paste was already perceptible, becoming more evident as the content of titanium dioxide residue in the mixture was elevated.

Figure 4. Mini-slump for reference paste (without residue).

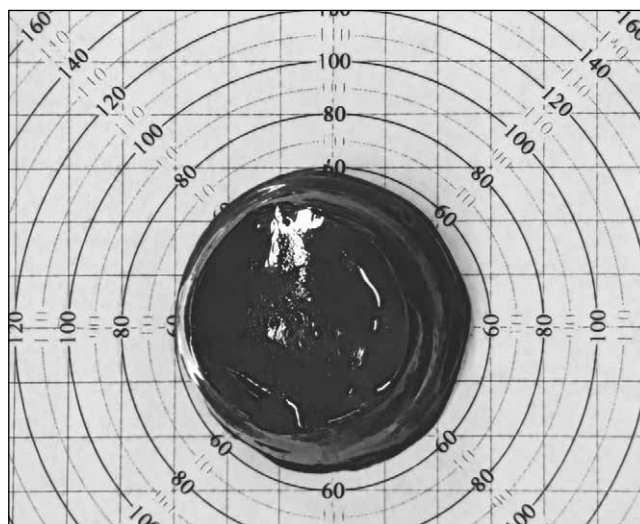


Figure 5. Mini-slump for paste with 10% incorporated residue.

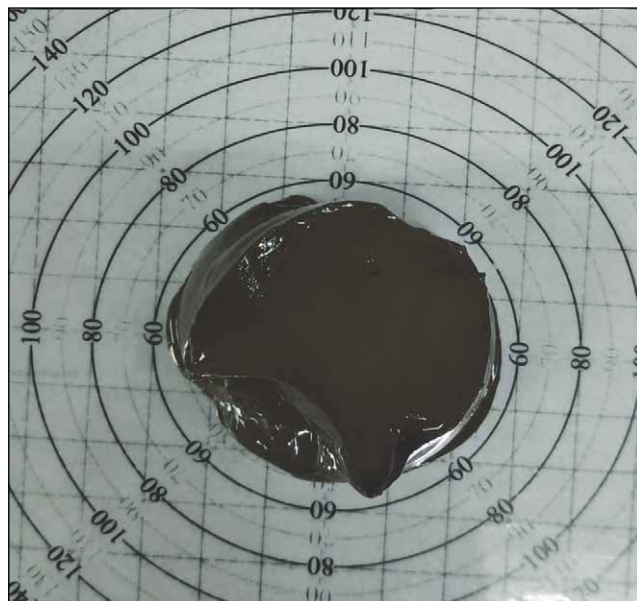


Figure 6. Mini-slump for paste with 15% incorporated residue.

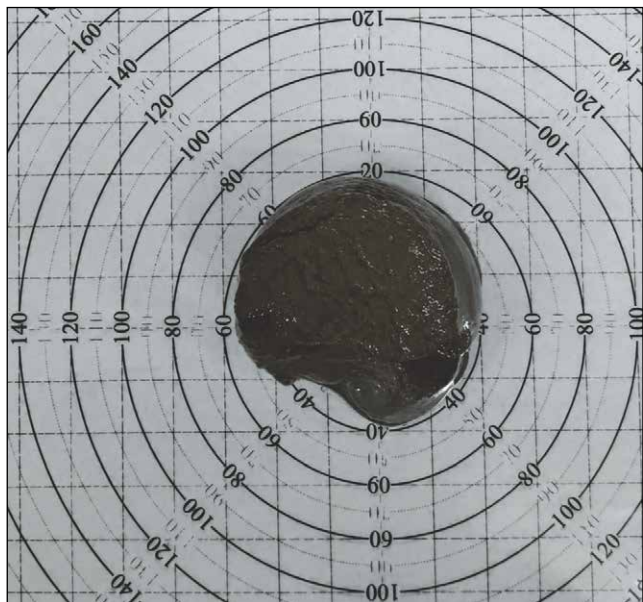
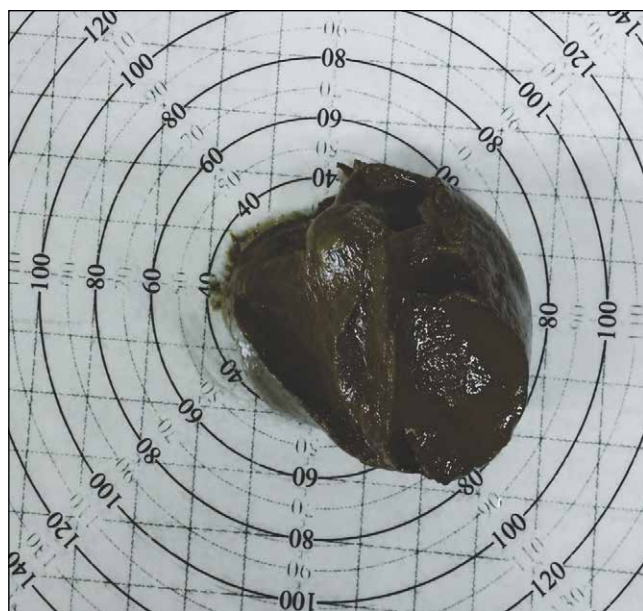


Figure 7. Mini-slump for paste with 20% incorporated residue.



Therefore, the utilization of the residue may require adjustments in the mix proportion in order to assist the workability. Thus, the use of additives may be required to maintain adequate consistency when incorporating higher residue contents in the mixtures.

Conclusion

The results obtained in this study show that incorporating titanium dioxide (TiO_2) into cement-based materials affects pastes behavior in their fresh-state. In this context, mini-slump tests indicated a significant reduction in fluidity as the TiO_2 content increased, revealing a negative impact on workability. On the other hand, setting time tests showed a considerable decrease in this parameter, possibly due to increased water demand and interference of the residue in the hydration process.

Therefore, it can be concluded that the incorporation of TiO_2 residue affects the consistency and hydration product formation in cement pastes, as observed through the results of setting time and mini-slump tests.

However, further studies are still needed to better understand the interaction between titanium dioxide residue and the cement matrix in cement-based materials.

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Production of Mixed Cement–Lime Mortars Incorporating Beige Bahia Marble Waste (BBMW) Filler and Construction and Demolition Waste (CDW)

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The civil construction sector consumes large volumes of non-renewable raw materials, especially in the production of hydraulic binders such as Portland cement and lime. The cement industry is one of the contributors to the worsening of the greenhouse effect due to the decarbonation of limestone and the use of fossil fuels, releasing large amounts of CO₂ into the atmosphere. At the same time, other stages of construction also cause changes in the landscape and generate significant amounts of waste in several segments, such as the extraction and processing of ornamental stones, which produce considerable waste ranging from block remnants to fine particulate material known as slurry. An alternative to mitigate these impacts is the partial replacement of binders with alternative materials in the formulation of mortars, which are widely used in different construction stages. Thus, this research aimed to evaluate the performance of mixed cement–lime mortars in which lime was partially replaced with Bahia Beige Marble Waste (BBMW) and Construction and Demolition Waste (CDW) at proportions of 10% and 20%, analyzing the physical–mechanical behavior of the mixtures. The materials used (cement, lime, BBMW, CDW, and sand) were characterized, and the water/binder ratio (w/b) was defined for the reference mixed mortar (1.00:0.5:6.90 — cement:lime:sand), using air-entraining and water-retaining additives, based on a flow of 260±5 mm. Subsequently, the w/b ratios were determined for each of the mixtures with lime replaced by 10% and 20% of BBMW or CDW. The results were compared with the reference mortar and showed a reduction in the water/binder ratio with the increase of waste content, in addition to greater cohesion of the mixtures. In the fresh state, mortars presented a reduction in bulk density with the use of both wastes. For water retention, there was a decrease with BBMW and an increase in this property in mixtures with CDW compared to the reference mortar. In the hardened state, the mortars showed improved flexural tensile strength and axial compressive strength. Therefore, based on the physical–mechanical results, both wastes, BBMW and CDW, demonstrated a predominantly physical effect of pore filling, favoring nucleation and improving physical–mechanical properties.

Keywords: Binders. Mortar. Filler. Waste.

Abbreviations: BBMW, Bahia Beige marble waste. RCD, construction and demolition waste.

The construction sector is responsible for the intensive use of raw materials from non-renewable sources and is a major generator of waste, contributing to significant environmental impacts. The production of hydraulic binders, such as Portland cement and lime, stands out in terms of CO₂ emissions and contribution to the worsening of the greenhouse effect, since the production process involves the decarbonation of limestone and the consumption of non-renewable energy [1].

In this context, the partial replacement of hydraulic binders with industrial wastes has become increasingly frequent and promising in order to make the construction sector more sustainable. Materials such as ornamental stone industry waste and construction and demolition waste (CDW) have been investigated for their beneficial properties to the cementitious matrix. Brazil holds a prominent position in the ornamental stone export sector.

According to the Brazilian Center of Ornamental Stone Exporters (2024) [2], the state of Bahia ranks fourth in exports. Bahia Beige Marble, whose main production is concentrated in the Ouro-lândia region (BA), is characterized by its beige coloration, fine grain, brecciated appearance, with small quartz veins and particles.

Its mineralogical composition consists of approximately 98% carbonate and only 2%

Received on 17 April 2026; revised 24 July 2026.

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quartz [3]. All production stages of Bahia Beige Marble pieces generate waste. The extraction of blocks for slab production results in a significant amount of coarse waste, originating from the breakage of pieces during cutting [4].

Another residue with significant environmental impact is Construction and Demolition Waste (CDW), popularly known as rubble. CDW is generated from construction, renovations, repairs, and demolitions in civil works [5]. Its composition generally includes concrete, bricks, gypsum, wood, glass, metals, plastics, and excavated soil, allowing for reuse within the construction industry itself [6]. According to the Brazilian Association of Waste and Environment (ABREMA) [7], the country generated around 45 thousand tons of CDW in 2022. As noted by Leite (2001) [8], issues related to waste management, the shortage of disposal areas, and urban cleaning are factors that must be considered when analyzing the environmental impact of CDW. Both BMW and CDW present potential for use as fillers in cementitious mixtures.

According to Neville (2016) [9], a filler is a finely ground and chemically inert material that, through its physical effects, enhances the properties of cementitious mixtures. The incorporation of fillers improves workability and matrix density, reducing porosity and increasing durability [10]. Hydrated lime, commonly used in mixed mortars, contributes to properties such as plasticity, water retention, and durability [11].

Therefore, in addition to reducing the demand for non-renewable raw materials, this practice supports the reuse of waste in cementitious matrices and contributes to mitigating environmental impacts. In this context, the aim of this study is to evaluate the production of mixed cement–lime mortars with partial replacement of lime by BMW and CDW.

Experimental Procedure

The experimental program consisted of producing five mixes of cement–lime mortars with partial replacement of lime by Bahia Beige Marble Waste (BMW) and Construction and Demolition

Waste (CDW) at replacement levels of 10% and 20%, in order to evaluate the physical–mechanical behavior of the mixtures.

First, both wastes were subjected to crushing in a knife mill and subsequently sieved to obtain a particle size smaller than 150 μm . It is important to note that the CDW used consisted only of gray-colored material, predominantly mortar and concrete. The research was divided into three stages: 1) Characterization of the materials used; 2) Production of the mortars; 3) Characterization of the mortars in the fresh and hardened states.

Material Characterization

The characterization of the materials used — CP II-F 32 cement, CH-I lime, BMW, CDW, and sand — was carried out through the determination of their specific gravity, which were 2.98 g/cm³, 2.27 g/cm³, 2.68 g/cm³, and 2.60 g/cm³, respectively. Additionally, the packing density was evaluated according to the method proposed by Larrard (1999a). Table 1 presents the results.

Production Mortar

In the mortar production stage, the materials used included cement, hydrated lime, BMW and CDW, fine sand, 0.30 by mass of air-entraining additive, and 0.08 by mass of water-retaining additive. The water/binder ratios were determined based on a flow of 260 ± 5 mm, according to ABNT NBR 13276:2005, and the packing density, as presented in Table 1.

Mortar Characterization

The mixed cement–lime mortars with partial replacement of lime by BMW and CDW were characterized in the fresh state through tests for bulk density, entrained air content, and water retention, with the results shown in Figures 1 and 2. In the hardened state, the mortars were evaluated by flexural tensile strength and axial compressive strength tests.

Table 1. Mixes with BMW, by mass, and the resulting packing density and workability of the mortars.

	REF	T10 BMW	T20 BMW	T10 CDW	T20 CDW
Cement	1.00	1.00	1.00	1.00	1.00
Lime	0.50	0.45	0.40	0.45	0.40
RMBB	-	0.05	0.10	-	-
CDW	-	-	-	0.05	0.10
Fine sand	6.90	6.90	6.90	6.90	6.90
Water/binder	1.08	1.10	1.04	1.11	1.06
Compactness	0.557	0.553	0.507	0.563	0.560
Consistency $\pm$ Sd (mm)	258 $\pm$ 1.70	264 $\pm$ 1.25	262 $\pm$ 1.25	263 $\pm$ 1.25	265 $\pm$ 1.25

SD – standard deviations.

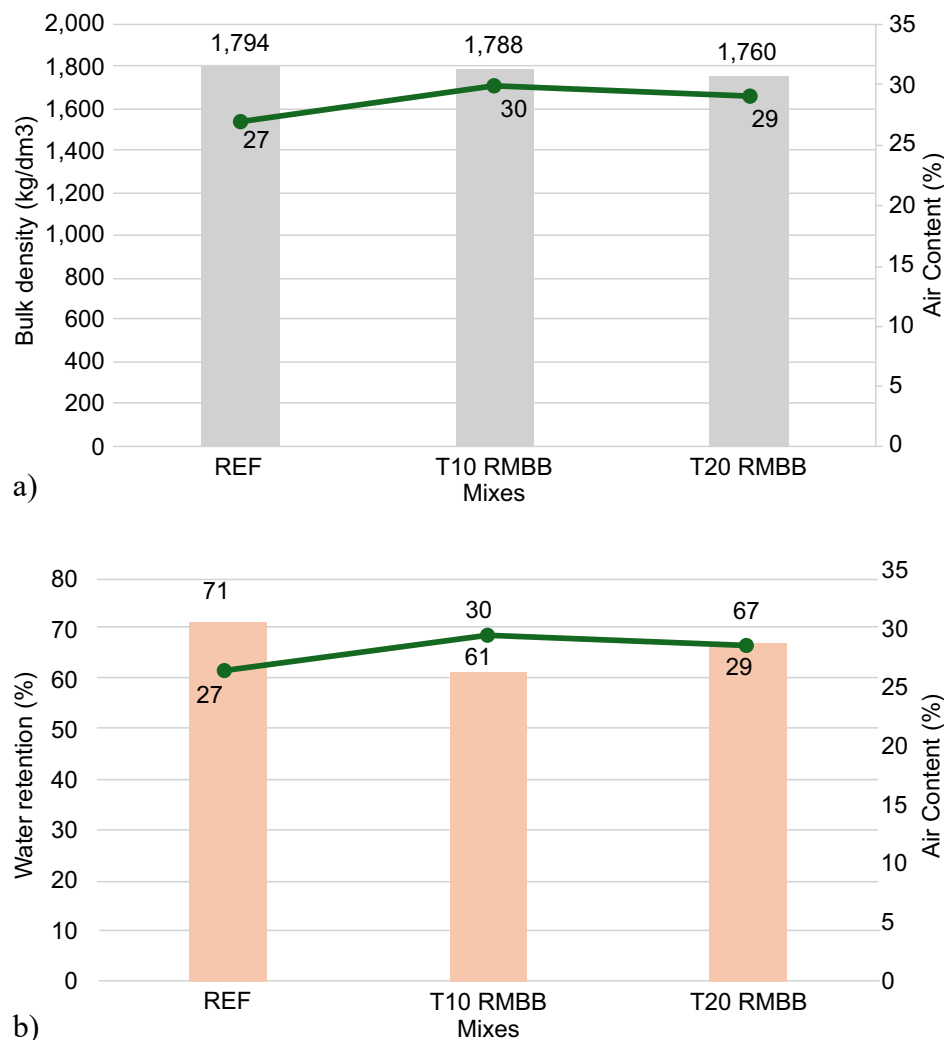
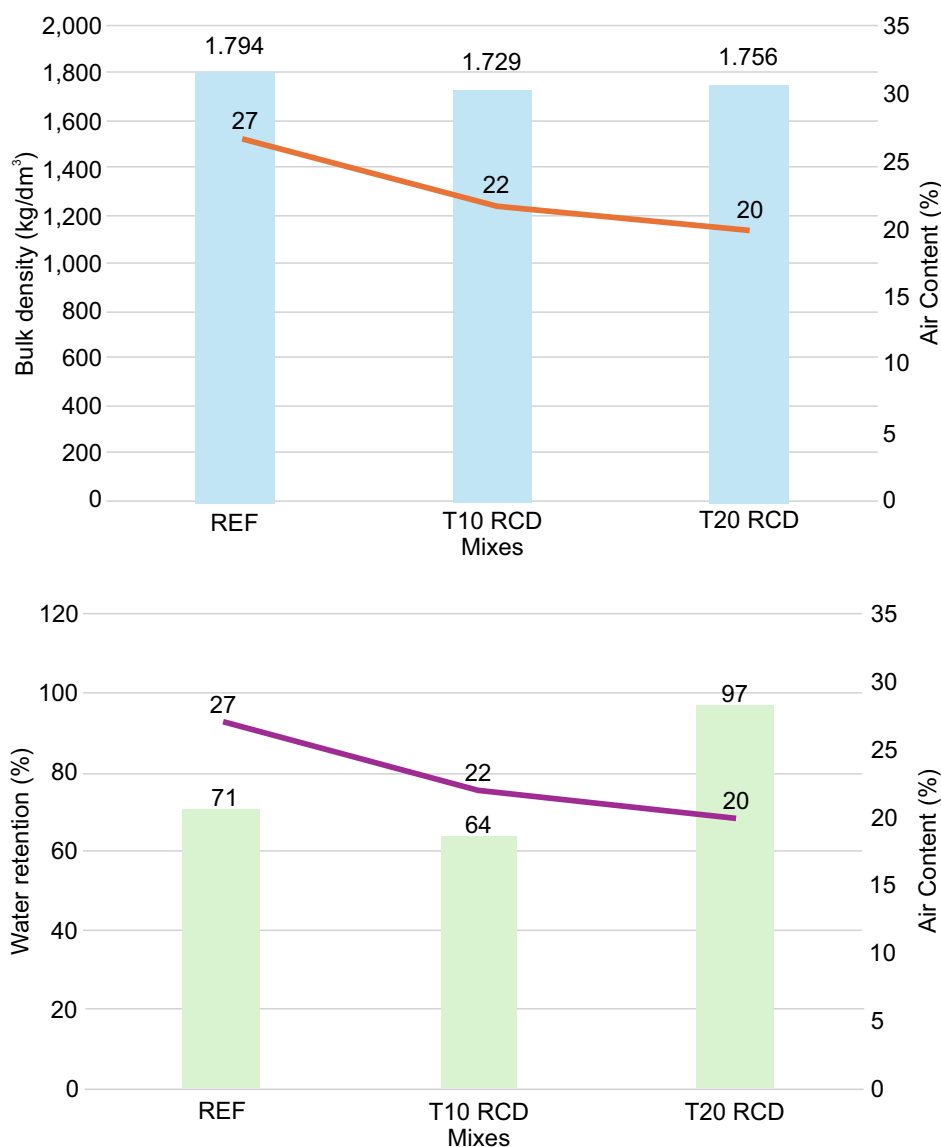
Figure 1. Results of fresh-state properties: a) Variation of bulk density and air content; b) Variation of water retention and air content.

Figure 2. Results of fresh-state properties: a) Variation of bulk density and air content; b) Variation of water retention and air content.

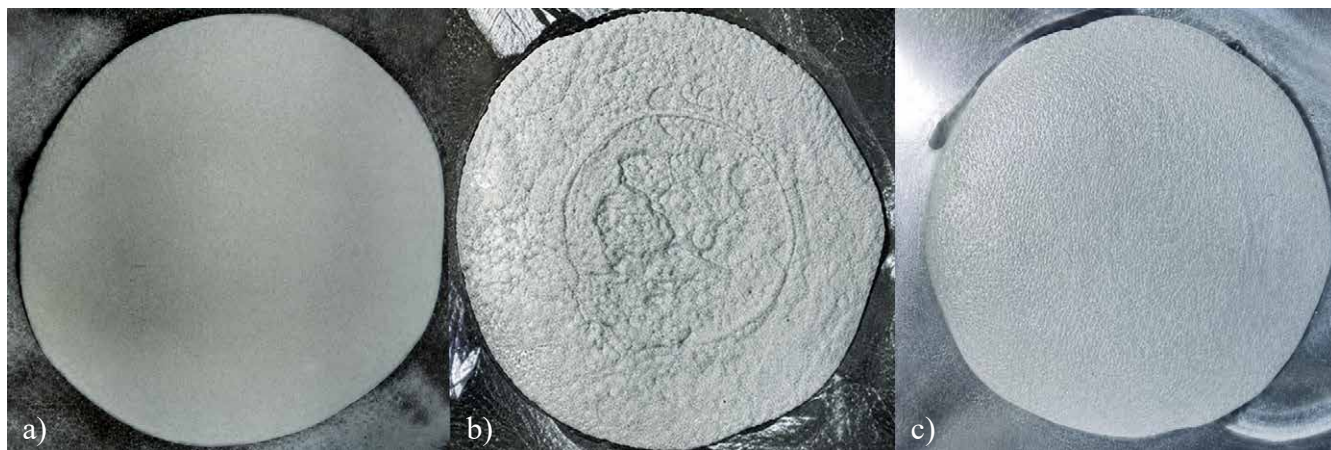


Results and Discussion

Regarding the qualitative evaluation of the mixed cement–lime mortars with partial replacement of lime by BBMW, when comparing the REF, T10 BBMW, and T20 BBMW mixes, it was observed that the T10 BBMW mix presented a flow value close to the upper limit (265 mm). This behavior is attributed to the filling of intergranular voids previously occupied by water [12], resulting in good plasticity, although with higher bleeding due to the increase in the water/binder ratio, as indicated

in Table 1. On the other hand, the T20 BBMW mix showed lower fluidity, with reduced plasticity. Nevertheless, all mixes exhibited good cohesion, a matte appearance, and satisfactory workability, as shown in Figure 3.

As observed in Figure 1.a, there was a slight reduction in bulk density with the increase in lime replacement by BBMW. According to Ruhnke (2024) [10], this phenomenon may be related to the saturation points of particle packing, in which the filler acts as an internal lubricant, or to higher water retention, as also

Figure 3. Mortar flow. a) REF; b) T10 BMW; c) T20 BMW.

evidenced in Figure 1.b. Regarding the increase in entrained air content, the author associates this behavior with the same saturation effect, since particle accumulation can form agglomerates capable of trapping air pockets.

According to Figure 2.b, a decrease in water retention is observed in mixes with lime replacement by BMW compared to the REF mix. This is due to lime having a finer particle size than BMW, resulting in a greater specific surface area, which favors water retention through adsorption on the particle surfaces.

For the mixed mortars with lime replaced by CDW, qualitative analyses showed that the mixture behavior is similar to the T10 BMW and T20 BMW mixes. When compared to the

REF mix, T10 CDW and T20 CDW, the T10 CDW mix exhibited higher fluidity, similar to T10 BMW, which can be explained by the filling of intergranular voids, resulting in higher workability; the increase in water/binder ratio causes greater bleeding in the CDW mixes. The T20 CDW mix showed lower fluidity, similar to T20 BMW. According to Fortnatto (2019) [13], this occurs because the particle shape of CDW is less rounded compared to the binder. Finally, both CDW mixes exhibited good workability, cohesion, and a matte appearance, as shown in Figure 4.

As observed in Figure 2.a, there was a reduction in bulk density in the T10 CDW and T20 CDW mixes compared to REF. This behavior can be explained by the fact that the specific gravity of CDW is higher

Figure 4. Mortar flow. a) REF; b) T10 CDW; c) T20 CDW.

than that of lime, meaning less material is needed to occupy the same space previously filled by lime. The packing density of the mixes increased with higher levels of lime replacement (10% and 20%), which also explains the reduction in entrained air content in T10 CDW and T20 CDW mixes, evidencing the effect of particle packing in the cementitious matrix, reducing voids and air bubbles.

When comparing the T10 CDW mix with REF, a decrease in water retention is observed, as lime has a larger specific surface area, thus retaining more water than CDW. Ferreira (2017) [14] incorporated CDW fines (<0.15 mm) into mortars and observed high water absorption due to the porosity and very fine particles of the material — exceeding the effect of surface area, which increases the water retention capacity of the mortar, an effect observed in the T20 CDW mix.

Analyzing the mortars in the hardened state (Table 2), all mixes containing BMW and CDW showed improved flexural tensile strength, averaging 27% for mixes with BMW and 20% for CDW, compared to the REF mortar.

According to Gonçalves (2000) apud Apolinário (2014) [15], the filler effect is responsible for the strength gain due to its physical role in accelerating cement hydration at early ages. The same behavior was observed for axial compressive strength, with all mixes containing the wastes achieving higher results. According to Moraes (2001) apud Apolinário (2014) [15], the effect of BMW and CDW in mortars is predominantly physical, related to pore filling.

The high fineness of the fillers promotes cement hydration by acting as nucleation sites, stimulating the precipitation of hydrated products and accelerating early-age strength gain, resulting in a denser and more homogeneous paste due to better pore distribution.

Conclusion

The study evaluated mixed cement–lime mortars with partial replacement of lime by BMW and CDW, aiming to explore sustainable alternatives in civil construction and the management of waste generated by marble extraction and construction and demolition activities.

Based on the results obtained, the T20 BMW and T20 CDW mixes exhibited lower water/binder ratios — a factor that, according to the literature, increases strength — while maintaining workability. Furthermore, although the T20 BMW mix showed a decrease in bulk density, the air content was also reduced compared to T10 BMW, indicating better particle packing. In addition, water retention was not as significantly affected as in the 10% replacement mix. Regarding CDW replacement, the improved compaction of the mixture and the reduction in entrained air in the T20 CDW mix demonstrate the more effective filler action of the material.

The mixes containing these wastes showed improvements in both flexural tensile strength and axial compressive strength, once again evidencing the effect of pore filling and particle packing in the

Table 2. Average results, standard deviations, and coefficients of variation of the mechanical properties of mortars with BMW and CDW replacement at 7 days.

Mixing Sequence	Flexural Tensile Strength ft ± SD(CV%)	Axial Compressive Strength fc ± SD(CV%)
REF	1.60 ± 0.08(5.25)	3.67 ± 0.27(7.39)
T10 BMW	1.90 ± 0.09(7.00)	4.31 ± 0.11(2.65)
T20 BMW	2.15 ± 0.05(2.40)	4.49 ± 0.14(3.06)
T10 CDW	1.95 ± 0.28(14.46)	3.77 ± 0.66(17.58)
T20 CDW	1.72 ± 0.04(2.38)	3.73 ± 0.20(5.26)

cementitious matrix through the partial replacement of lime by BBMW and CDW.

In light of these findings, the partial replacement of lime by BBMW and CDW in coating mortars is feasible, provided a prior analysis of the materials is conducted to ensure adequate physical–mechanical performance. Moreover, incorporating waste into construction contributes to sustainability, offers better final disposal for various types of waste, and reduces environmental pollution from production to final deposition of the materials.

Acknowledgement

We thank UEFS and SENAI Cimatec for the opportunity, infrastructure, and support provided during the experimental project. We are grateful to ASSOBEGE (Association of Bahia Beige Marble Entrepreneurs) for the partnership and donation of Bahia Beige Marble waste, and to the Institute of Chemistry at UFBA for their collaboration in conducting the tests. We also acknowledge CNPq for the financial support of the project (TO Process: 407786/2022-8).

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Development of a 3D Environment for Digital Twins in an Advanced Manufacturing Didactic Plant

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The monitoring, analysis, and optimization of industrial processes are crucial for improving productivity and efficiency in industrial environments. A significant challenge is the need for effective platforms that allow for scenario simulation, training, and predictive maintenance in real-time. Addressing it, this work proposes the development of a 3D environment for the creation of Digital Twins in an Advanced Manufacturing Didactic Plant. The objective is to provide a platform for scenario simulation, training, and predictive maintenance, contributing to the optimization of productivity and efficiency in industrial environments, while specifically, it develops a digital model that accurately represents the physical environment of the didactic plan, facilitate the simulation of real-world scenarios for process optimization and operator training and ensure seamless integration with the plant's existing Programmable Logic Controllers (PLCs) for real-time data acquisition and control.

Keywords: Digital Twins. 3D Environment. Advanced Manufacturing Didactic Plant. Industry 4.0.

Industry 4.0 has driven the integration of advanced technologies, such as digital twins (DTs), to optimize processes and increase efficiency in manufacturing. DTs emerge as a transformative tool, offering a dynamic and interactive virtual representation of physical assets. This representation allows for real-time monitoring, predictive analysis, and optimization of operations, as highlighted by [1]. The ability to simulate scenarios and predict behaviors makes DTs indispensable for strategic and tactical decision-making, resulting in significant savings for organizations. The development of immersive 3D environments is a useful component for the effectiveness of Digital Twins, as it facilitates interaction and data visualization in a more intuitive context.

Papers [2] on 'on-the-fly' 3D environments for open-source immersive DT applications, and [3] on the practical implementation of an Augmented Reality-based DT, demonstrate the relevance and potential of these technologies.

The integration of DTs has created immersive experiences that bridge the gap between the

physical and digital worlds, allowing users to visualize and manipulate robotic systems remotely more effectively [4]. This is further supported by the work of [5] who proposes an immersive digital twin applied to a Manufacturing Execution System for monitoring and controlling industry 4.0 processes, integrating various technologies including augmented (AR) and virtual (VR) realities. [6] also emphasizes the importance of incorporating other Industry 4.0 technologies, such as system integration, connectivity with industrial protocols, and cloud services, alongside AR/VR for developing digital twins in industrial environments.

The foundational aspects of Digital Twins, including their communication protocols and architectural considerations, are crucial for effective implementation in industrial settings, as explored by [7] in their study of Digital Twin and its communication protocol in factory automation cells.

A comprehensive understanding of DT technology, its applications, capabilities, and challenges within the built environment, as reviewed by [8], provides a broader context for their transformative potential, highlighting their role in enhancing operational efficiency and predictive maintenance while also addressing integration and data consistency challenges.

This project aims to develop a 3D environment for Digital Twins in an Advanced Manufacturing

Received on 26 April 2026; revised 28 July 2026.

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Didactic Plant. The focus will be on creating a digital model that not only represents the physical environment but also facilitates the simulation of real-world scenarios, operator training, and process optimization, adding the possibility to be smoothly integrated within the Plant's infrastructure (Figure 1), for its system includes robotic arms for material handling, followed by various stations for inspection, drilling, and cleaning, these components are interconnected and controlled by a network of PLCs, with a Supervisory Control and Data Acquisition (SCADA) system providing a central interface for monitoring and controlling the entire plant, gathering real-time data from sensors and machines. The steps of 3D data capture, modeling, and information integration are addressed (Figure 2), with the goal of overcoming the inherent complexity challenges in existing industrial environments.

The research will contribute to the advancement of knowledge in the application of DTs in educational and industrial contexts, preparing future professionals for the challenges of advanced manufacturing.

Materials and Methods

The method adopted for the development of the Digital Twin environment in the Advanced Manufacturing Didactic Plant followed a qualitative approach, grounded in best practices and tools identified through extensive literature analysis, case studies, and expert consultations. This approach was crucial for gaining an in-depth understanding of the complexities involved in creating a functional and immersive 3D environment for a Digital Twin. The initial research phase focused on identifying and evaluating various software solutions available in the market, considering not only their technical capabilities but also practical factors such as development time, team learning curve, and financial implications associated with software licenses. Collaboration with plant personnel was a crucial element in this and the next phase, providing valuable insights into operational requirements and the specificities of the existing infrastructure, especially regarding connectivity with the plant's PLCs. The software selection criteria were multifaceted, aiming to find

Figure 1. Plant's structure diagram.

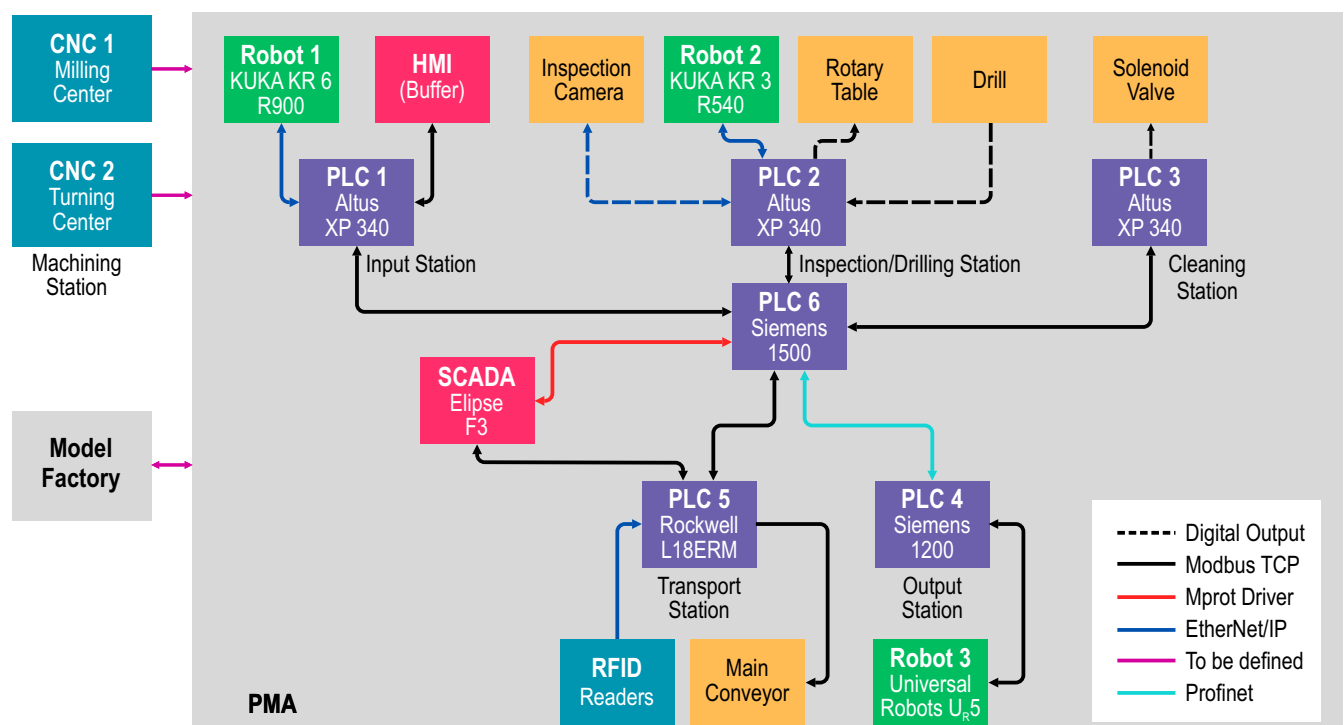
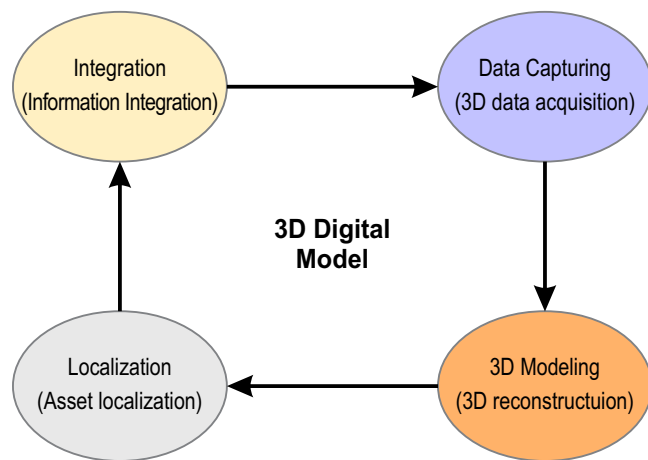


Figure 2. Proposed workflow to create a digital model for existing industrial environments.



a solution that offered an optimal balance between functionality, usability, and cost-effectiveness.

Platforms with robust 3D modeling, emulation, and simulation capabilities were evaluated, as well as the ability to integrate with industrial control systems. Interoperability was a key factor, given the need for fluid communication between the virtual 3D environment and the physical PLCs. The scalability of the solution was considered, ensuring that the environment could be expanded and adapted for future needs of the didactic plant.

The initial research phase, which spanned the first few months of the project, was intensive and comprehensive, involving literature analysis, case studies, and consultation with experts. This period was fundamental for building a solid knowledge base on Digital Twins and the nuances of 3D modeling and emulation, allowing the team to make informed decisions about the tools and approaches to be used.

Following the initial research, the subsequent phase focused on the meticulous development of the operational environment within the selected software. This process involved creating precise 3D models of the plant's equipment and infrastructure, configuring simulation parameters, and implementing control logics. Concurrently, significant efforts are made to establish seamless connectivity with the PLCs. To overcome the inherent difficulties of integrating diverse communication protocols (e.g., Siemens S7, Allen-Bradley Ethernet/IP, Modbus TCP), a

multi-strategy approach was employed. A dedicated industrial communication OPC UA server has been included to act as a standardized middleware, translating proprietary PLC protocols into a common language for the digital twin software, developing custom driver scripts where necessary for legacy systems and implementing robust error-handling and data buffering routines to ensure stability during network latency or interruption. This step is necessary for real-time data acquisition and for accurate monitoring and analysis of plant performance. The successful integration of PLC data with the 3D environment allows the digital twin to reflect the plant's current state with high fidelity, enabling early detection of anomalies, process optimization, and applications, such as predictive maintenance.

The validation of the digital twin's accuracy and performance was conducted against a stringent set of criteria throughout the development cycle. This validation strategy included a verification that every virtual asset correctly mimicked the behavior of its physical counterpart (e.g., motor start/stop, sensor state changes) through scripted test scenarios.

A comparison of time-synchronized data logs from the physical PLCs with the data received and visualized in the digital twin enabled to quantify latency and ensure data accuracy, that exceeded a threshold of 99.5%² subjecting the system to high-frequency data exchange and simulated network failures to evaluate the robustness of the OPC UA. It was also stressed communication and the effectiveness of the error-handling routines, having plant operators and control engineers interact with the digital twin to provide qualitative feedback on the realism and usability of the environment for its intended didactic and operational purposes. The complexity of this integration lies in the diversity of communication protocols and the need to ensure data synchronization between the physical and virtual systems.

Results and Discussion

The development of the environment within these chosen platforms is currently ongoing, with

an example being presented to visitors interested in the process (e.g. Figure 3).

A critical step was the selection of software tools. After evaluation, Rockwell Automation's Emulate 3D was chosen for simulation and emulation [9], while SolidWorks was selected for high-fidelity 3D modeling [10]. This bifurcated approach aligns with common industry practice but presents a notable integration challenge. Unlike unified platforms, which offer native CAD and control simulation integration, our chosen stack requires a robust data bridge between the separate modeling and simulation environments. While this approach offers flexibility in using best-in-class tools, it introduces potential complexity in maintaining model synchronization. The success of this architecture hinges on the stability of the communication layer, which became the next significant challenge.

The initial communication architecture proposed a dual-protocol strategy using Ethernet/IP and OPC UA to facilitate comprehensive data collection from the plant's programmable logic controllers (PLCs). However, practical integration issues with the legacy PLCs prevented a stable Ethernet/IP connection. Consequently, the architecture was adapted to utilize OPC UA as the sole protocol

for the main PLC, centralizing all data acquisition (Figure 4). This shift provide more reliable and secure data aggregation than attempting to manage multiple, complex protocol translations, even if it temporarily limits the scope of connected devices.

Within Emulate 3D, data acquisition is managed through a dedicated communication browser that establishes a one-to-one mapping between virtual "tags" in the simulation and their physical counterparts in the PLC (Figure 5). This method ensures real-time data reflection with minimal latency. While highly effective for emulation, this tight coupling can be a limitation for broader DT applications. Unlike a more abstracted data layer, such as a historical database or a cloud-based IoT hub, this direct tag-based system is less suited for long-term trend analysis and machine learning applications. For the current phase focused on control logic validation and operator training, however, its performance and simplicity are optimal.

The ongoing development of this 3D DT is poised to deliver significant benefits in training, optimization, and safety. The move towards an immersive 3D interface, as opposed to the 2D schematics common in traditional SCADA systems, offers an intuitive method for personnel to understand complex processes. Furthermore, the ability to

Figure 3. Current plant 3D environment.



simulate and analyze manufacturing processes without disrupting physical operations provides a vital sandbox for validation and optimization. By integrating real-time sensor data via OPC UA, the model transitions from a static simulation to a live DT, enabling predictive maintenance and rapid troubleshooting. The future success of the project will depend on effectively scaling the data architecture beyond emulation to support plant-wide data analytics while managing the inherent complexity of the multi-software environment.

Conclusion

This project embarked on the endeavor of developing a 3D environment for Digital Twins within an Advanced Manufacturing Didactic Plant. The methodology adopted emphasized a thorough research phase to understand the nuances of Digital Twins and 3D modeling/emulation, followed by the practical development of the environment and efforts to integrate with the plant's PLCs. The selection of Rockwell Emulate 3D for simulation and emulation, and Solidworks for 3D modeling, represents a strategic choice aimed at leveraging industry-standard tools for this complex undertaking, exceeding its original objectives and assignments.

Significant progress has been made in developing the 3D environment; however, integrating with the plant's PLCs remains a challenge due to hardware issues that complicate bridging virtual simulations and real-world industrial processes. Addressing these hardware impediments is essential to achieve full integration and unlock the Digital Twin's potential for real-time monitoring, analysis, and optimization within the didactic plant. Overcoming these challenges will enable a dynamic, interactive digital representation that supports advanced simulation, training, and predictive maintenance.

Acknowledgement

We would like to express my deepest gratitude to all those who did and are still supporting the project. We also extend our sincere appreciation to Senai Cimatec for providing the necessary resources, infrastructure, and a conducive environment for research and experimentation.

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Machine Learning for Predictive Maintenance of Industrial Machines

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This work presents a novel approach to constructing a predictive model using machine learning techniques for the early identification of machine faults for industrial maintenance purposes. The topic is justified by the importance of predictive maintenance in increasing operational efficiency, reducing costs, and improving the reliability of industrial equipment. The early identification of failures makes it possible to carry out preventive interventions, avoiding negative consequences and optimizing the use of industrial resources. Traditional maintenance techniques, such as corrective and preventive maintenance based on fixed intervals, cannot adequately predict unexpected events that could lead to equipment failure. The main objective is to develop and validate a predictive model capable of detecting patterns that indicate possible failures in industrial machinery before they occur. To this end, a hybrid algorithm combining fuzzy logic and machine learning will be applied compared to three traditional models widely used in the literature. The study includes a comparative analysis of the results obtained, evaluating the performance, accuracy, and effectiveness of each model. The advantages and limitations of the developed model will also be discussed, as well as suggestions for future research to improve predictive systems in the sector continuously. This article is divided into sections, starting with the introduction, with a general contextualization of the problem, the arguments, the justifications, the objective, and the structure of the work. The following section presents research into related work. Then the methodology used to develop the fault prediction, and identification models will be presented, followed by the experimental results, and finally the conclusions.

Keywords: Machine Learning. Predictive Modeling. Fault Identification. Decision Making.

Industrial maintenance is a critical activity for ensuring the efficiency, safety, and productivity of production processes in various economic sectors. Unexpected failures in machinery and equipment can result in unplanned downtime, compromising operational continuity, significantly increasing maintenance costs, and reducing equipment lifespan. In this context, the ability to identify these failures in advance becomes an important competitive advantage for companies. There are a variety of machine learning predictive models, and some hybrids, found in the literature. However, these traditional models need to be retrained when there is a significant change in the pattern of information.

Combined with the fact that in industries, due to cybersecurity concerns, there are significant restrictions on the connection between automation devices and external networks, real-time monitoring

becomes a significant challenge. Hybrid fuzzy models have been applied in industry in additive manufacturing and cybersecurity processes.

Early identification of failures enables preventive interventions, avoiding negative consequences and optimizing the use of industrial resources. Traditional maintenance techniques, such as corrective and preventive maintenance based on fixed intervals, are insufficient to adequately predict unexpected events that can lead to equipment failure. Therefore, the need for predictive maintenance arises, which uses advanced techniques to predict failures based on continuous analysis of the condition of machinery and equipment. Among the most effective techniques for this purpose are predictive models based on machine learning. These models can learn complex patterns from operational data collected in real time, thus enabling accurate prediction of the conditions that precede failure.

The model that integrates Three-Way Decision (3WD) theory in Pythagorean Fuzzy environments excels in modern scenarios that require flexibility and behavioral realism, applying the concept of cognitive computing to emulate human behavior for decision-making under uncertainty.

Received on 18 April 2026; revised 10 July 2026.

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The main objective of this paper is to develop a predictive model for machine maintenance failure identification that integrates 3WD theory within Pythagorean Fuzzy environments, leveraging cognitive computing principles to emulate human decision-making under uncertainty and thus deliver the flexibility and behavioral realism required by modern industrial scenarios. This paper is organized as follows: Section 2 presents the related work. Section 3 explains the design of the methodology for predicting and identifying failures. Section 4 presents experimental results. The conclusions section closes the paper.

Related Work

A systematized literature review was carried out to gather empirical evidence from studies related to this article. The search was conducted in March 2025 to identify relevant research addressing works using 3WD for industrial applications in academic portals such as Google Scholar, IEEE Xplore, and Research Gate. The keyword "Three-Way Decision-Making" was used without filters. Initially, 6,509 references were retrieved. After applying the inclusion criteria (titles related to the research scope) and exclusion criteria (duplicate works), 229 references were selected. In the eligibility phase, titles and abstracts of articles, dissertations, and book chapters were screened to identify those related to industrial applications. Nine related works were identified: three on material selection for additive manufacturing [1-3], one on aviation equipment [4], three on anomalies and threats in industrial networks [5-7], and one on air quality monitoring [8]. The concept of Zhang and colleagues [9] was incorporated into this article. The articles evaluated but not used presented sophisticated approaches to integrating 3WD fuzzy and advanced algorithms, but for specific applications, being adaptable to related problems of material selection and malware detection. The model chosen for further study presented a more transparent and precise structural and mathematical approach to problems with an uncertain context.

Three-Way Decision Models with Pythagorean Fuzzy Loss Functions

Using the theory of 3WD and previous studies, an improved decision-making model was developed to improve the accuracy of loss functions. Using real-value loss functions, the 3WD model in Pythagorean Fuzzy information systems aimed to classify regions of positive acceptance, negative acceptance, and hesitation as a differential in the third dimension. The advantages of 3WD fuzzy models over purely statistical approaches are the reduction of unnecessary calculations [10], the ability to deal with multiple decision-makers [10], a solid theoretical foundation [11], and cognitive advantages [12]. The main components of this model are the Pythagorean Fuzzy information system, the fundamental value loss functions, and the expected losses [9].

The structure of the information system is defined as:

$$S = (U, A, V_{PF}, f) \quad (1)$$

Where U is the set of objects, A is the set of attributes, V_{PF} represents the Pythagorean Fuzzy values used to describe the attributes, and f is the function that associates each object with a Pythagorean Fuzzy value. In Pythagorean Fuzzy numbers, each object $u \in U$ is assigned as:

$$W(u) = l(l_{W(u)}, v_{W(u)}) \quad (2)$$

Where $l_{W(u)}$ is the aggregate degree of pertinence and $v_{W(u)}$ is the aggregate degree of non-pertinence. The degree of hesitation is:

$$\pi_{W(u)} = \sqrt{1 - l^2 - v^2} \quad (3)$$

Materials and Methods

Based on a concept presented in an article identified during the systematized review, a model was developed using the 3WD approach [9]. This concept involves a decision-making process considering three possible outcomes, which are particularly useful in our context. A synthetic dataset simulating machine telemetry [13], available online, was used to test the proposed model. The

model was evaluated to check its viability in predicting anomalies based on signals from sensors connected to the machines using model efficiency indicators. It was then compared with traditional machine learning models using the same database. Finally, the results and discussions of the study were presented before the final considerations. The stages for the experiment were pre-processing for filtering, normalization, and selection of the variables derived from the database, modeling, training, validation, and comparison of the model, as shown in the diagram in Figure 1.

This model actively monitors the decisions made and, through feedback from the results, feeds back the parameters to redefine the losses, engaging the readers in their operation. Three traditional machine learning models were also trained, validated, and evaluated in comparison with the decision model. The code was implemented using the theoretical 3WD concepts with Pythagorean Fuzzy numbers:

- Pythagorean Fuzzy information system, with the equations (1), (2), and (3);
- Loss functions with Pythagorean Fuzzy values, with losses represented as pairs (l, v) ;

- Calculation of expected combination losses via Pythagorean Fuzzy operations;
- Integration of hesitation (π);
- Three decision strategies (s_1, s_2, s_3), for choosing between $\{a_P, a_B, a_N\}$.

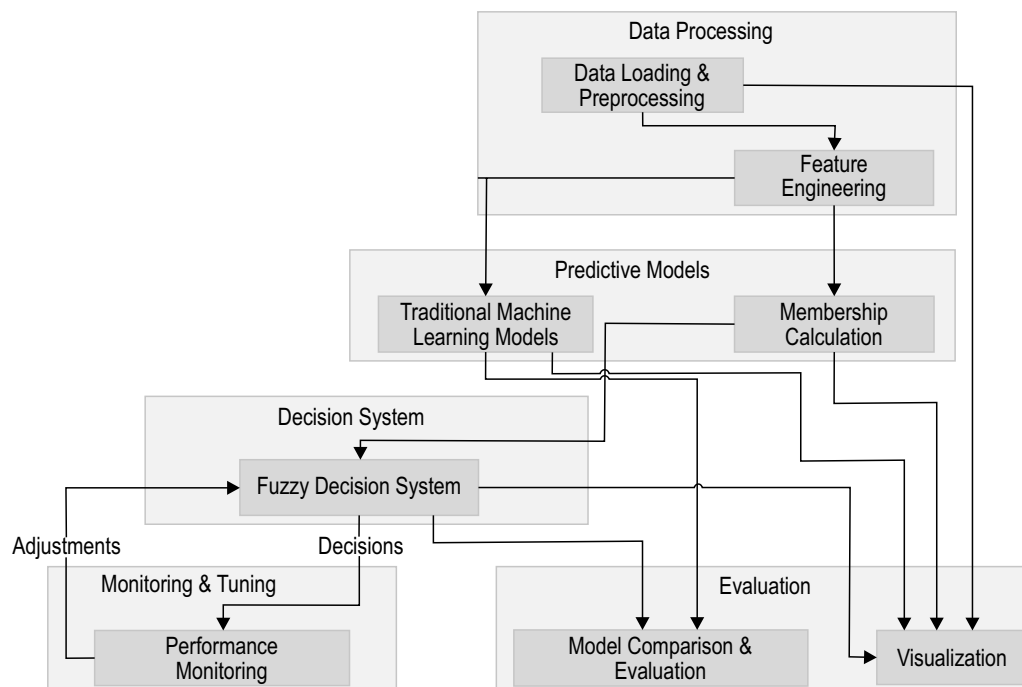
Predictive Model

Three algorithms based on the gradient boosting – recommended for continuous monitoring of imbalanced data in industrial fault prediction – were designed. The parameters of each machine learning model were adjusted to the features of the dataset, ensuring the minimization of false positives and negatives, reducing losses, optimizing performance, balancing speed and accuracy, and controlling stall and depth levels. The algorithms are XGBoost [14], LightGBM [15], and CatBoost [16]. Each algorithm has unique strengths that cater to different data types and needs.

Decision System

The fuzzy system algorithm was developed to combine the diverse perspectives of three experts,

Figure 1. The predictive model for identifying machine failures for maintenance using machine learning.



with inputs being the relevance values μ , ν , π , and and failure-risk scores produced by the XGBoost model. Actions were defined as a_P for preventive, a_B for basic acceptance, and a_N for no action.. Pythagorean Fuzzy numbers were used to calculate losses, which were then aggregated using weights assigned to the experts. The decision strategies were: s_1 , a conservative one that minimizes $\nu - \mu$; s_2 , a moderate one which minimizes π , which represents hesitation one, and s_3 , a dynamic one based on SHAP, which triggers a_N if $\pi > 0.7$.

Monitoring and Optimization

The Optuna framework, a set of libraries designed explicitly for machine learning, was used to determine the optimal parameters for the fuzzy model in effective fault detection. The Matthews Coefficient (MCC) was used as the optimization metric. The optimization process consisted of generating initial parameters, configuring the decision model, evaluating temporal data, calculating the MCC, updating, and returning to the model configuration stage for 50 iterations to select the best parameters for the result.

Experimental Results

This section presents experiments with detailed explanations and valuable insights. We used the

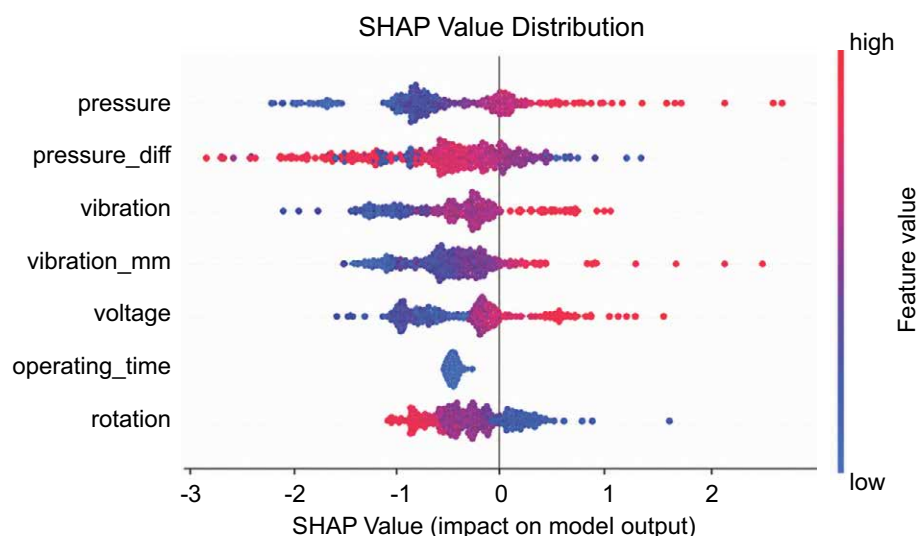
following execution environment: [System 1] Execution environment with 1 GPU. Comprises two Intel Xeons at 2.26 GHz and 24 GB DDR3 main memory. Each one is a quad-core processor with 12 MB of cache memory. It contains two NVIDIA Tesla C2050 GPUs, each with 14 Stream Multiprocessors (SM) and 32 Stream Processors (SP), totaling 448 cores.

In our experiments, we use a version of the proposed model, developed in Python using the Spyder IDE (Integrated Development Environment), which was designed with a robust feedback mechanism.

In the data evaluation phase, we found no null or infinite values, indicating a sound processing of the dataset, and we normalized the variables tension, rotation, pressure, vibration, age, and time_op. We identified 162 outliers, which may have come from real anomalies. Additionally, we found twelve outliers in binary_fault, confirming class imbalance.

In Figure 2, SHAP (SHapley Additive exPlanations) demonstrates the impact of each variable on the model output. The features are listed on the Y-axis on the left, in descending order of impact: *pressure*, *pressure_diff*, *tension*, *vibration*, *vibration_mm*, *time_op*, and *rotation*. The red features on the right side of the graph indicate that they help increase the prediction, while the blue features on the left side reduce it. The high-

Figure 2. SHAP value distribution.



pressure values increase the output of the model - a positive SHAP contribution - while low values reduce it. The other features also have an impact, the intensity of which can be verified by the value and its associated color.

The fuzzy contribution was assessed according to the following indicators:

- a. The pertinence impact of 99.17%, calculated as:

$$mu_{impact} = mu \cdot class_{weights}[a_p] \quad (4)$$

This indicator influences the decision to take preventive action (a_p). The higher it is, the greater the risk is detected and the higher the cost of preventive action;

- b. The risk analysis indicator, calculated as:

$$nu_{impact} = nu \cdot class_{weights}[a_B] \quad (5)$$

It denotes confidence in the absence of failure and its impact on backup decision-making (a_B). The higher the nu_{impact} , the lower the risk detected, and the less prioritized the action;

- c. The impact of hesitation of 0.83% - which represents the degree of uncertainty - calculated as:

$$pi_{impact} = \sqrt{1 - mu^2 - nu^2} \quad (6)$$

As a conclusion of the contribution assessment, decision-making prioritized preventive action due to the high mu_{impact} . In the context of Pythagorean Fuzzy logic, the three components mu , nu , and pi adhere to a specific constraint, ensuring a meticulous balance of impacts and comprehensively reflecting the nature of the three dimensions in the decision:

$$mu^2 + nu^2 + pi^2 = 1 \quad (7)$$

The comparison between the models is presented in Table 1.

XGBoost is an optimized algorithm for structured data and classification/regression problems. LightGBM is focused on computational efficiency and large volumes of data. CatBoost, however, excels in handling categorical data. The summary of the models evaluated is in Table 2.

Table 1. Comparison between models.

Models	F1-Score	AUC-ROC
XGBoost	0.0579	0.7923
LightGBM	0.0015	0.6814
CatBoost	0.1689	0.7396
Fuzzy	0.3414	0.8798

Fuzzy is the model developed based on logic, which deals with uncertainty and interpretable rules. With a high AUC-ROC, it performed well in ordering risks. However, its low F1-score indicated difficulties in correctly classifying borderline cases, which depend on the balance between precision and recall.

Figure 3 illustrates the predictions of each model in comparison with the actual faults of one machine. The purple diamonds represent the faults predicted by the fuzzy model. The numbers below the two occurrences indicate the elapsed hours between the prediction and the occurrence of the real fault, showcasing the models' predictive accuracy.

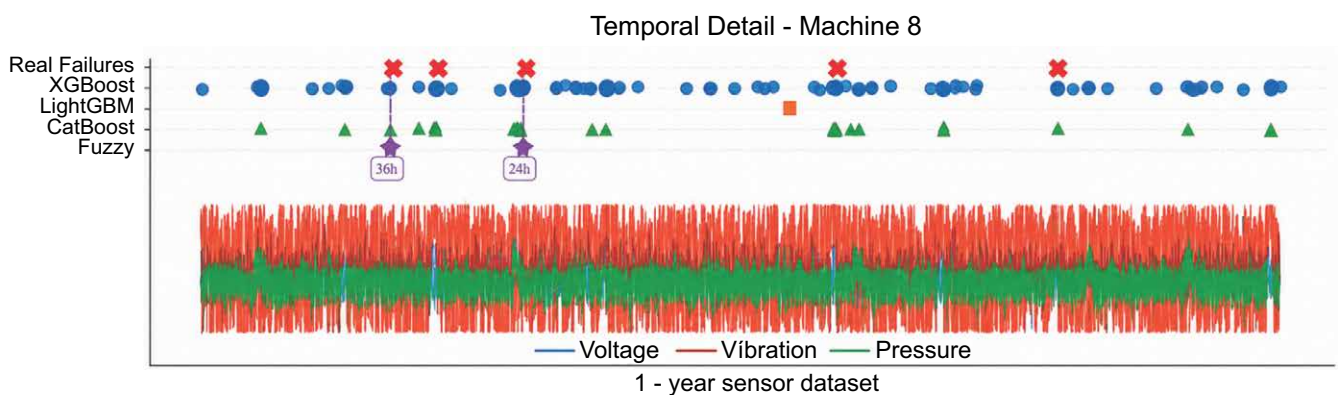
As practical results, the evaluation of the dataset containing sensor information from 100 machines over one year yielded 40% accuracy in predicting failures, indicating the conservative alerting behavior of the model. Of the alerts generated, 27.8% effectively predicted failures more than one hour in advance. The average time for early detection was 24.15 hours. The recall rate of 31.9% underscores the urgency of improving the model, as it reveals significant room for enhancement through refining the rules or incorporating new variables.

Conclusion

In conclusion, our proposed predictive model - anchored in three-way decision theory and implemented within a Pythagorean Fuzzy framework - achieved an AUC-ROC of 0.88, demonstrating superior risk-ranking capability by accurately prioritizing machines with the highest likelihood of failure. The model reliably detected subtle anomalies in pressure and vibration readings

Table 2. Summary of model results.

Models	Features	Limitations	Ideal Usage Scenario
Fuzzy	Best AUC	Low F1 in critical applications	Preventive maintenance
CatBoost	Best F1 between traditional	AUC lower than Fuzzy	When balanced precision/recall is critical
LightGBM	-	Poor overall performance	Not recommended for this problem
XGBoost	Medium-high AUC	F1 too low	When false negatives are tolerable

Figure 3. Actual failures *versus* predicted failures by models.

and complex non-linear sensor interactions, outperforming benchmark algorithms such as LightGBM and CatBoost. Its robustness to noisy or incomplete data further distinguishes it. At the same time, its inherently interpretable decision rules offer transparent failure-prediction criteria - an advantage that conventional models cannot match. Moreover, our real-time self-tuning mechanism effectively reduced false alarms following peak events, and the higher standard deviation of the model in terms of AUC-ROC across cross-validation folds attests to its resilience against overfitting. From an operational standpoint, the fuzzy approach also facilitated more nuanced cost-weighting strategies, contributing to maintenance expense reduction.

However, we acknowledge certain limitations: classification ambiguity arises for cases near decision-boundary thresholds - reflected in an F1 score of 0.34 - which may constrain applicability in safety-critical contexts. Additionally, inference throughput under continuous streaming remains

suboptimal, and the model depends on external preprocessing for feature engineering, manual weight calibration, and adaptation to shifting data distributions.

Overall, when the primary objective is to rank equipment by failure risk, our fuzzy decision-theoretic model provides a compelling balance of predictive performance, interpretability, and cost efficiency. Future work will focus on tests with other datasets with a larger volume of data, improving boundary discrimination using optimization algorithms or techniques such as fuzzy clustering, automating the adaptation of features and weights with automatic attribute selection algorithms or meta-learning, and improving real-time inference for large data streams with autoencoders.

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Mobile Robot Retrofit for the ROS2 Framework

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This article presents the retrofit of a TurtleBot2i mobile robotic platform to support the ROS2 framework. The motivation for this migration lies on the discontinuation of ROS1 and the growing need for educational and research platforms to align with current technologies. The retrofit process encompassed both hardware and software adaptations: the robot was upgraded with a new power system and additional sensors, including a Velodyne LiDAR and an Intel RealSense camera, while its software environment was updated to Ubuntu 22.04 and ROS2 Humble, with the robot model and drivers adapted to ensure full integration. The results confirm the platform's compatibility with the ROS2 ecosystem, enabling advanced perception and SLAM algorithms. These improvements enhance the applicability of the TurtleBot2i in educational and research contexts, ensuring its continued relevance in mobile robotics development.

Keywords:Robotics. ROS2. Retrofit. TurtleBot2i.

The TurtleBot2i is used in educational and research contexts due to its versatility, open architecture, and active developer community [1]. These factors have established the TurtleBot as an important tool in robotics education and scientific experimentation.

In this context, the platform is based on the Robot Operating System (ROS), an open-source framework that provides libraries and tools for the development of robotic applications, promoting interoperability, modularity, and reusability. ROS has been widely adopted in the robotics community for facilitating the integration of sensors, actuators, and algorithms into complex robotic systems.

However, given the continuous advancement of technology, modernizing legacy platforms becomes an alternative to maintain compatibility with current tools. Regular updates are essential to ensure compatibility with current technologies and standards. In this scenario, it is worth noting that the mobile platform version TurtleBot2i was officially archived in 2022 and no longer receives updates [2].

Despite its discontinuation, the TurtleBot2 remains a reference in academic research, as evidenced by several studies. The work of [3] implemented potential field control on the TurtleBot2 using ROS Melodic and Ubuntu 18.04. The study in [4] developed an indoor navigation system, also in ROS1. The research in [5] applied a visual simultaneous localization and mapping (SLAM) algorithm for autonomous navigation, integrating neural networks as real-time object detectors based on an RGB-D camera, also operating in ROS1 Melodic.

All of these studies share the characteristic of using a platform based on an outdated software ecosystem, built on ROS1 and older versions of the Ubuntu operating system. It is important to highlight that, according to [6], ROS1 has been discontinued and replaced by ROS2, with a recommendation for use in new developments.

ROS2 represents a significant evolution compared to ROS1 [7], incorporating substantial improvements in critical areas such as node-to-node communication, security, support for real-time systems, integration with multiple robots, and operation in distributed environments. While ROS1 was essential in standardizing robotic development, ROS2 provides a more robust, scalable foundation prepared for the contemporary challenges of robotics.

The migration of platforms from ROS1 to ROS2 involves the concept of technological retrofit,

Received on 12 April 2026; revised 11 July 2026.

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J Bioeng. Tech. Health 2026;9(8):817-823
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which is a strategy aimed at extending the lifespan of existing robotic systems by modernizing their software components [8] and, in some cases, also their hardware [9]. This approach allows for minimizing the disposal of still-functional hardware while enabling the incorporation of more recent technologies into already established platforms. This was exemplified in the study by Eon et al. (2020) [10], which describes the retrofit of a humanoid robot, maintaining its original physical structure but replacing the controller and performing electronic and mechanical upgrades.

The case study by Lyman and colleagues (2019) [9] demonstrates how obsolete robots from the 1980s were repurposed with new control systems and modern interfaces, allowing their use in practical robotics and automation courses. This approach not only reduces costs but also provides students with direct access to the internal components of the robots, promoting deeper learning aligned with industry demands. Similarly, Petrone and colleagues (2025) [11] presented the use of the UR10 manipulator in ROS2, showing its control architecture without physical modifications, as a modernization strategy compatible with current industrial applications.

This article details the retrofit of the TurtleBot2i for full integration with ROS2, aiming to modernize its software ecosystem while promoting sustainable practices through the reuse of functional hardware as a strategy aligned with contemporary needs in robotics education and research.

The remainder of this paper is organized as follows. Section 2 introduces the TurtleBot2i robotic platform. Section 3 details the methodology of the retrofit process, covering both hardware and software adaptations. Section 4 presents the results obtained with the upgraded platform, highlighting its validation in ROS2. Finally, Section 5 concludes the paper by summarizing the main contributions and outlining directions for future work.

The TurtleBot2i Robotic Platform

The TurtleBot2i platform employed in this study was originally configured with an Intel NUC6CAYH

computer, running Ubuntu 16.04 LTS and the ROS1 Kinetic framework [12]. Both software components have been officially discontinued and no longer receive security updates or technical support.

In addition to its mobile base, the platform integrates the Pincher MK3 robotic arm, featuring four degrees of freedom (DOF) [13], which enables the manipulation of small objects. For perception and visual data acquisition, the system utilizes two depth cameras: the Orbbec Astra and the RealSense SR300, as illustrated in Figure 1.

Given these characteristics, the TurtleBot2i can be classified as a legacy system, which imposes significant limitations on scalability and maintainability. The obsolescence of its software environment hinders compatibility with modern libraries, integration with emerging technologies, and adherence to current security protocols. These constraints negatively impact the platform's lifecycle and its potential for reuse in contemporary research and educational contexts.

Materials and Methods

The retrofit process of the TurtleBot2i for ROS2 involved adaptations in both the hardware and software of the platform.

The method adopted for the retrofit followed a structured process divided into three main stages.

Figure 1. TurtleBot2i operating with ROS1.



First, the limitations of the original TurtleBot2i configuration were analyzed, identifying obsolete components and opportunities for modernization. Based on this assessment, the retrofit was planned in two complementary dimensions: hardware and software. The hardware stage focused on adapting the power supply and expanding the platform's perception capabilities with additional sensors, while the software stage addressed the use in ROS2, the adaptation of robot descriptions, and the integration of drivers and communication structures. Finally, the upgraded system was validated through functional tests to ensure proper operation and compatibility with the ROS2 framework.

Hardware

The physical retrofit of the TurtleBot2i involved modifications to its base to accommodate a new power configuration. A custom support structure was designed using CAD software (Figure 2) and subsequently fabricated via 3D printing to house a lithium-ion battery (model NH2054, 14.4V), selected for its capacity to meet the energy demands of the upgraded system (Figure 3).

As previously mentioned, the Astra depth camera was originally integrated into the TurtleBot2i platform. During the retrofit process, two additional sensors were incorporated: the Velodyne VLP-16 LiDAR and the Intel RealSense D435 camera, significantly enhancing the robot's perception capabilities.

To ensure efficient communication and adequate power distribution among all components including the Intel NUC mini-PC, lithium-ion battery, Astra camera, Velodyne LiDAR, RealSense D435, and the Kobuki mobile base, the system was reconfigured with a focus on integration and reliability.

Figure 4 shows the diagram of the connections and components of the robot's new configuration.

Software

Aiming at its modernization and extension of service life, the platform was updated to run the Ubuntu 22.04 operating system, chosen for its

Figure 2. 3D design of the mount for the new battery.

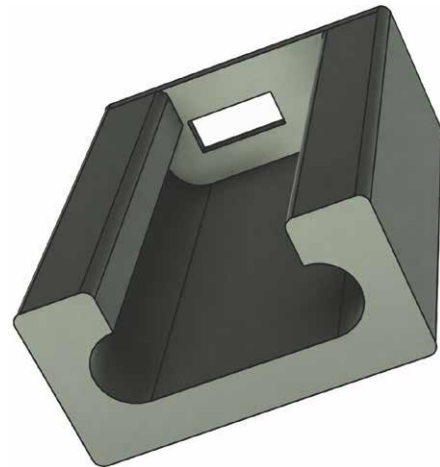


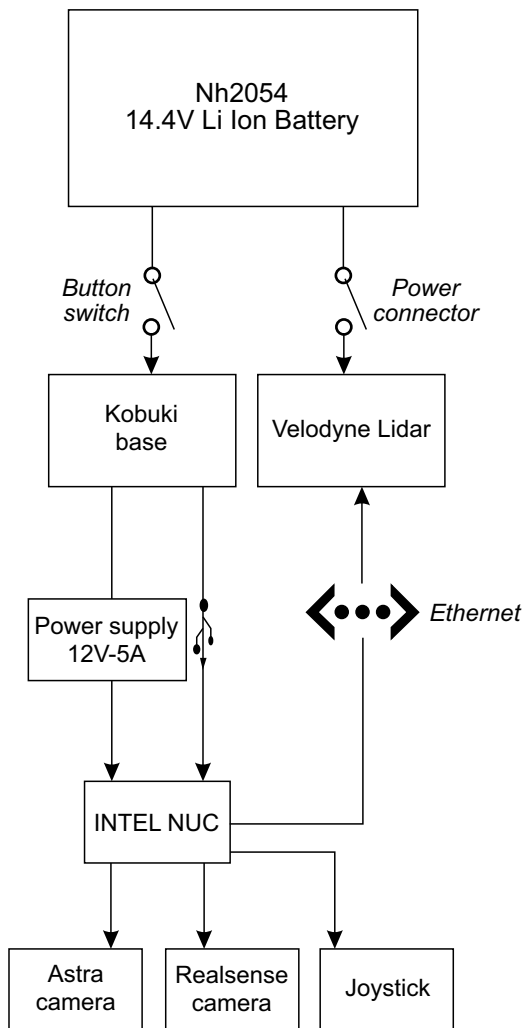
Figure 3. Battery installed in the printed mount.



stability and compatibility with ROS2, specifically the Humble distribution.

The architectural changes introduced by ROS2 were fundamental to this retrofit. While ROS1 uses a centralized system with a ROS Master, which can be a single point of failure and has limitations in communication, ROS2 adopts a decentralized, peer-to-peer communication model based on the Data Distribution Service (DDS). This architecture offers significant improvements in scalability, security, and real-time capabilities [14].

Adapting the robot's 3D model was a crucial step to enable accurate system visualization and facilitate debugging within the ROS2 environment. The old URDF (Unified Robot Description Format) model was converted to ROS2 format and updated

Figure 4. Connection diagram.

to include the new sensors, ensuring correct representation in both simulation and visualization.

During the migration, some adjustments were also required in the communication structure. One important change was the replacement of XML-based launch files used in ROS1 by Python-based launch files in ROS2. This modification allowed a more flexible configuration of nodes, parameters, and remappings, improving system maintainability, making the platform more robust for both educational and research applications compared to the previous version.

The retrofit also required the installation and configuration of new ROS2 packages to support the added sensors. For instance, Velodyne LiDAR integration relied on dedicated drivers and point

cloud processing packages, while Intel RealSense support was enabled through specific ROS2 packages maintained by the community. These additions expanded the set of published topics, especially those related to depth perception and mapping, and demanded updates in the robot's URDF description to correctly integrate the new devices. It is worth noting that the Kobuki mobile base already had ROS2-compatible drivers [15], which served as the foundation for building the TurtleBot2i software in ROS2, with the necessary configurations developed to integrate the additional hardware.

Validation

The objective of this validation was to verify whether the retrofitted TurtleBot2i could operate correctly within the ROS2 framework, ensuring the proper integration of both legacy and newly added components. The evaluation emphasized confirming sensor compatibility, consistency of published data, and the robot's ability to perform essential tasks such as perception and mapping. This stage sought to demonstrate that, after modernization, the platform remains suitable for educational and research purposes.

Rather than conducting a quantitative assessment mapping algorithm performance, the validation focused on functional aspects to confirm the readiness of the system for use in ROS2. The key objective was to ensure full interoperability of all sensors and the Kobuki mobile base within the new software architecture, thereby validating the viability of the retrofit for advanced applications. The generated map served as practical evidence of the robot's perception and modeling capabilities, reinforcing that the modernization successfully reestablished the platform's utility in contemporary research and education contexts, while also opening possibilities for more detailed investigations of precision and error in localization and mapping systems.

The validation was carried out in laboratory conditions. The procedure involved teleoperating

the robot to generate maps using SLAM algorithms, verifying the publication of sensor data, and rendering the updated URDF model in ROS2 visualization tools. Compatibility of the Kobuki base, depth cameras, and LiDAR sensor was evaluated through parameter configuration and topic monitoring to ensure proper communication in ROS2.

The robot successfully publishes data from all integrated sensors including depth cameras, the LiDAR sensor, and odometry enabling robust environment perception and modeling. These capabilities support applications such as localization, mapping, autonomous navigation, and interaction with the environment. Figure 5 illustrates the final configuration of the robot with all sensors integrated.

The system receives control inputs such as wheel speed commands and joystick-based teleoperation. Its outputs include odometry data, orientation and acceleration from the IMU, point clouds from the cameras, collision and fall detection from the Kobuki base, as well as status information from physical buttons, battery level, and general diagnostics. Ensuring compatibility of all peripherals with ROS2 required specific adaptations, including parameter reconfiguration and validation tests to confirm the consistency of data published by each device.

The robot's 3D model was successfully rendered in the ROS2 visualization environment (RViz), as shown in Figure 6. The updated model includes the robot's geometry and all embedded sensors, enabling simulation and analysis in a virtual environment. This required converting the original URDF file, correcting deprecated syntax, and incorporating the newly added sensors.

Additionally, the new configuration enabled the use of SLAM algorithms with both the original and newly integrated sensors. In laboratory tests, the robot was manually teleoperated to map an indoor environment, resulting in an accurate spatial representation, as shown in Figure 7. One of the main challenges during the retrofit was adapting all sensors to the ROS2 framework, particularly ensuring compatibility of the Astra camera,

Figure 5. Final TurtleBot2i configuration.

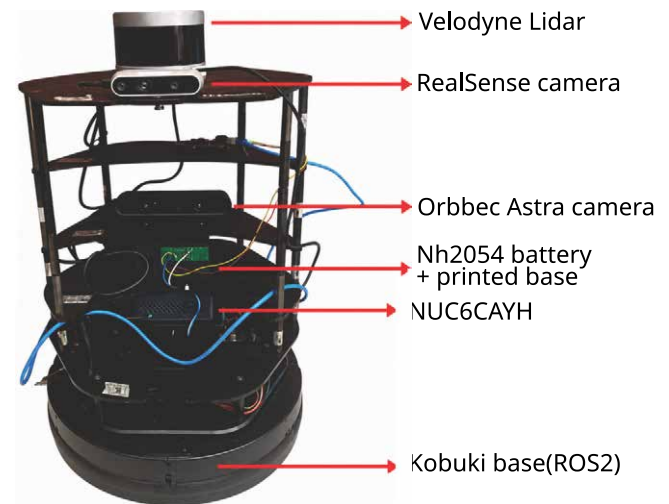


Figure 6. 3D model of the robot with integrated cameras and lidar sensor.

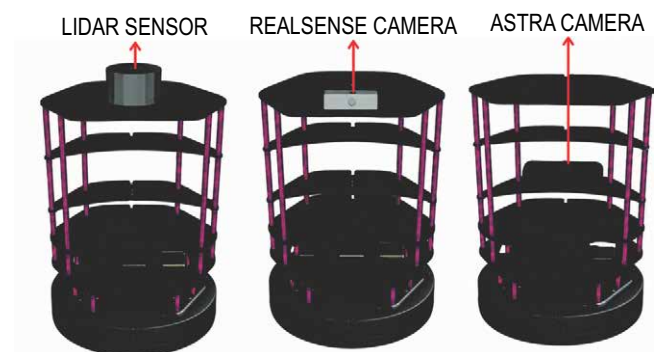
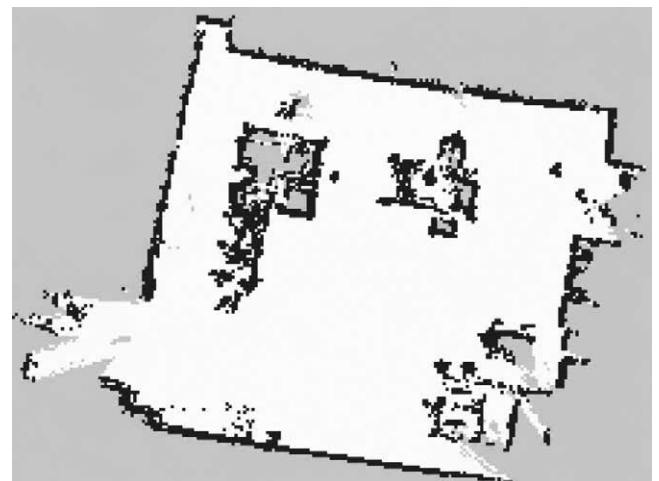


Figure 7. Environment map generated using the Velodyne LiDAR.



Velodyne LiDAR, and RealSense D435. This process involved extensive research and testing to guarantee seamless integration.

These results demonstrate that the retrofitted TurtleBot2i retains its capabilities for teleoperation, mapping, and localization, while gaining improved compatibility, scalability, and integration with modern ROS2 tools. The migration also enhances the platform's applicability in educational and research settings that demand up-to-date technologies and active community support.

Conclusion

The retrofit of the TurtleBot2i to ROS2 extended the robotic platform's lifespan and modernized its development environment, aligning it with current demands in research and education. The transition to ROS2 provided improvements in performance, security, and interoperability, while enabling the integration of additional sensors thereby enhancing its capabilities in autonomous navigation, mapping, and environmental interaction.

These advances reinforce the platform's potential to continue being used in academic and experimental contexts, even in light of the discontinuation of its original ROS1-based configuration. The update also contributes to technological sustainability by avoiding the disposal of functional hardware through the modernization of its software architecture.

As an outcome of this work, the use of the platform is proposed for experimentation with advanced techniques in perception, navigation, and coordination of mobile robots. Future research may explore its application in dynamic and unstructured environments, where safe and efficient operation is critical.

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Temperature Sensing and Modeling Based on Optical Fiber Using the OFDR Technique

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Optical Frequency Domain Reflectometry (OFDR) is a distributed sensing technique that stands out for its high spatial resolution and sensitivity, being widely applied in explosive risk environments, high temperatures, and high electromagnetic interference. The present work proposes a distributed temperature sensing system based on optical fiber using the OFDR technique, with the objective of visually modeling the thermal distribution of objects in real time. The system consisted of calibrating the sensor for the clear curve type optical fiber, which was separated into continuous segments and connected to an OFDR interrogator, allowing the collection of thermal data. A system was developed to process the data and generate a two-dimensional visual model based on the temperature distribution along the fiber. The results demonstrate that the system was able to identify thermal variations, with sensitivity and high spatial resolution, allowing the reconstruction of objects in contact with the fiber.

Keywords: OFDR. Distributed Optical Fiber Sensor. Temperature Sensor. 2D Modeling.

Abbreviations: OFDR, Optical Frequency Domain Reflectometry. RTDs, resistance temperature detectors. DTS, Distributed Temperature Sensing. FBG, Fiber Bragg Grating. EVA, Ethylene-Vinyl Acetate. LTS, Long Term Support. ROS, Robot Operating System. VRAM, Video Random Access Memory.

Precise and real-time temperature monitoring is a critical component in the operation of modern industrial systems, particularly in sectors such as energy, aerospace, advanced manufacturing, and hazardous environments like refineries and high-voltage equipment. While conventional temperature sensors, such as thermocouples and resistance temperature detectors (RTDs), remain widely used, they are often limited in their spatial resolution, electromagnetic compatibility, and ability to operate in harsh or distributed environments. Over the past four decades, fiber optic sensors have emerged as a compelling alternative, offering immunity to electromagnetic interference, chemical resistance, and the ability to be embedded within structures with minimal physical intrusion [1].

There are several techniques used for temperature sensing using optical fibers as a reliable and safe source for sensing in challenging environments, as

shown by Mihailov and colleagues 2012 [2]. The most common are those based on Raman scattering (DTS), Brillouin scattering, and Bragg gratings (FBG), each technique presenting a specific advantage in terms of range and sensitivity.

The introduction of Optical Frequency Domain Reflectometry (OFDR) marked a turning point in distributed fiber sensing. Unlike time-domain methods, OFDR utilizes Rayleigh backscattering and correlates the reflected spectral signal with a reference trace, achieving sub-millimeter spatial resolution. Its advantages over conventional techniques for distributed temperature sensing are emphasized in the study by Liang and colleagues [3], which highlights OFDR as a more promising technique.

This approach enables precise analysis of wavelength shift, spatial distribution, and attenuation characteristics along the optical fiber, as shown by Eickhoff and colleagues [4]. The present work introduces a novel method for correlating temperature variations with shape modeling, using wavelength shift data acquired through the OFDR technique. In this way, it presents an implementation of distributed temperature sensing but also broadens its applicability to complex geometric reconstructions.

Received on 18 April 2026; revised 13 July 2026.

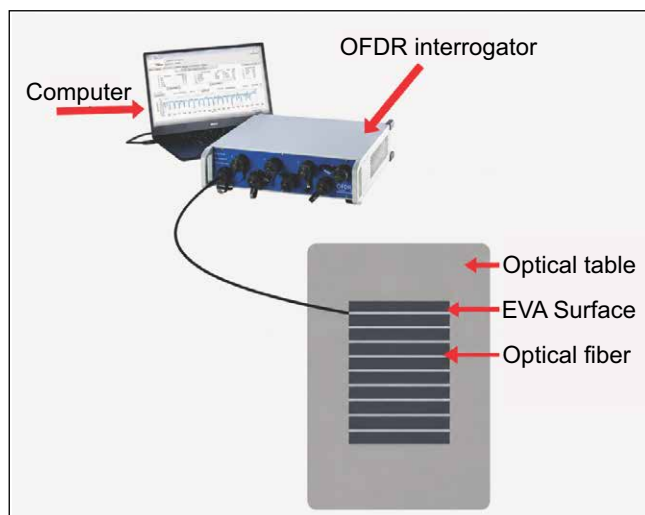
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Materials and Methods

Materials and Equipment

The development of the distributed temperature sensor integrated with a visual modeling interface, was carried out in two main stages: the calibration of the optical fiber and the implementation of a computational model in Python, designed to simultaneously reconstruct both the shape and temperature distribution of the object under analysis. For the object modeling process, the experimental set up included an OFDR interrogator (manufacturer: Luna Innovations, model: ODISI 6101) to acquiring the wavelength shift along the fiber in real time; a clear curve optical fiber (Corning Inc), selected for its low optical power attenuation under both micro and macrobending conditions; a soft EVA surface positioned beneath the fiber to minimize undesired mechanical strain. The assembly was mounted on a vibration-isolated optical table to ensure measurement stability (Figure 1). A computer running Ubuntu 22.04 LTS, chosen for its compatibility with ROS 2 Humble, and equipped with a dedicated graphics card with 2 GB of VRAM, executed the visual modeling algorithms responsible for reconstructing the object's geometry and temperature distribution.

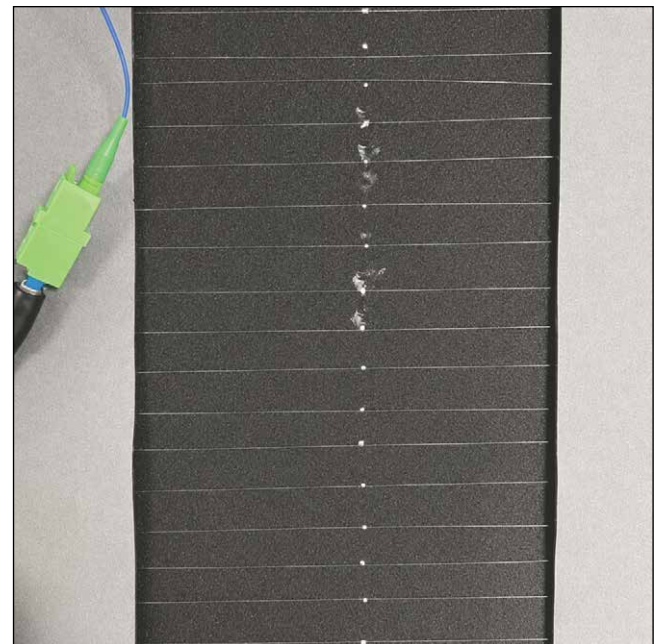
Figure 1. Schematic assembly diagram.



Experiment Setup

The experimental configuration comprised a clear curve optical fiber in a serpentine coiled arrangement, on the EVA surface, as depicted in Figure 2. This layout preserved fiber continuity and allowed its division into 20 segments of approximately 13.5cm along the horizontal axis, which results in a spatial resolution of 1cm, in the vertical axis, calculated by dividing the height of the rectangular sensing region by the number of vertical fiber sections.

Figure 2. Temperature sensor setup. Fiber divided into 20 segments.



Following the system assembly, the fiber was connected to the OFDR interrogator enabling the acquisition and real-time transmission of sensing data across a network. Spectral shift measurements were sampled at intervals of 0.65 mm, corresponding to the spatial resolution along the horizontal axis as defined by the interrogator configuration.

Fiber Optic Calibration

The optical fiber was calibrated to determine the relationship between wavelength shift and

temperature variation, ensuring reliable distributed thermal measurements. The procedure involved positioning the clear-curve optical fiber in a coil arrangement over a heated plate and applying controlled temperature increments from 20 °C to 100 °C in steps of 10 °C. A precision thermocouple monitored the surface temperature, while the OFDR interrogator simultaneously recorded Rayleigh backscattering traces. At each temperature step, multiple spectral shift datasets were collected at fixed spatial intervals. To ensure reproducibility, the calibration process was repeated three times. Data averaging was implemented through a Python algorithm to extract representative spectral shifts and perform linear regression against temperature. The resulting calibration curve defined the thermal sensitivity coefficient which directly relates temperature variation to the wavelength shift. The regression analysis yielded the following equation for the calibration line:

$$y = -0.761x + 19.7 \quad (1)$$

where y is the temperature variation (°C) and x is the spectral shift (cm^{-1}), as shown in the Figure 3.

This calibration law was adopted as the reference for all subsequent temperature measurements in this work. The methodology demonstrated robustness, reproducibility, and high spatial resolution, confirming the suitability of OFDR-

based sensing for distributed temperature monitoring. For a comprehensive description of the experimental setup, data acquisition procedures, and computational processing, readers are referred to Magalhães and colleagues 2025 [5].

Procedures

A Python code was developed to process the spectral shift data, compute distributed temperature fields, and construct the geometric and thermal model of the analyzed objects. The algorithm begins by aligning the actual centers of the fiber segments with their corresponding assumed positions along the horizontal axis. This step compensates for minor displacements introduced during the fiber's installation, typically due to variations in mechanical tension or imprecise placement, which may result in misalignment between the physical and modeled fiber positions.

Based on a reference ambient temperature of approximately 20 °C, the algorithm renders the temperature distribution by mapping the spectral shifts observed along the 2.7 meter fiber segment. When heat is transferred to the fiber, a wavelength shift occurs due to fiber expansion. These shifts are continuously evaluated and visualized in real-time through a dynamic color map, where cooler regions are indicated in blue and warmer areas, typically reaching 35 °C or higher, are shown in red. The algorithmic workflow and data processing scheme are illustrated in Figure 4. This visualization enables simultaneous estimation of the distributed temperature profile and geometric reconstruction of the object based on the fiber's spatially resolved thermal response.

To evaluate system performance, experimental tests were performed using three different objects: a copper wire, a roll of copper tape, and a hand (Figure 5 to Figure 7). Each object was placed unheated and heated on the sensor to evaluate its modeling capability and distributed temperature mapping.

Initially, an unheated copper wire was arranged in an "S"-shaped configuration to assess the sensor's

Figure 3. Linear regression graph between temperature and spectral shift of an optical fiber.

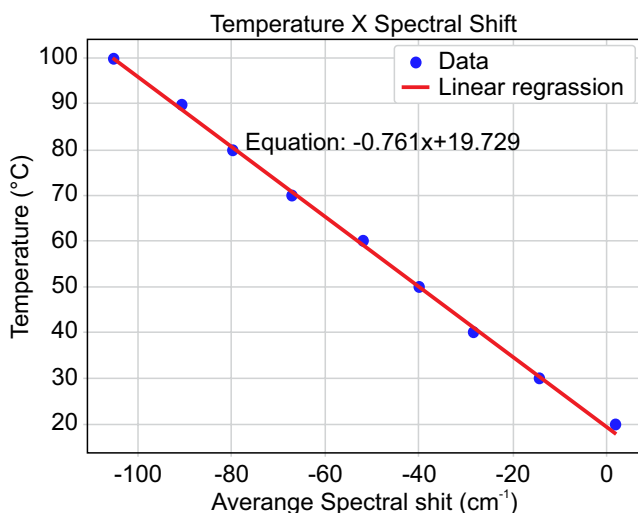
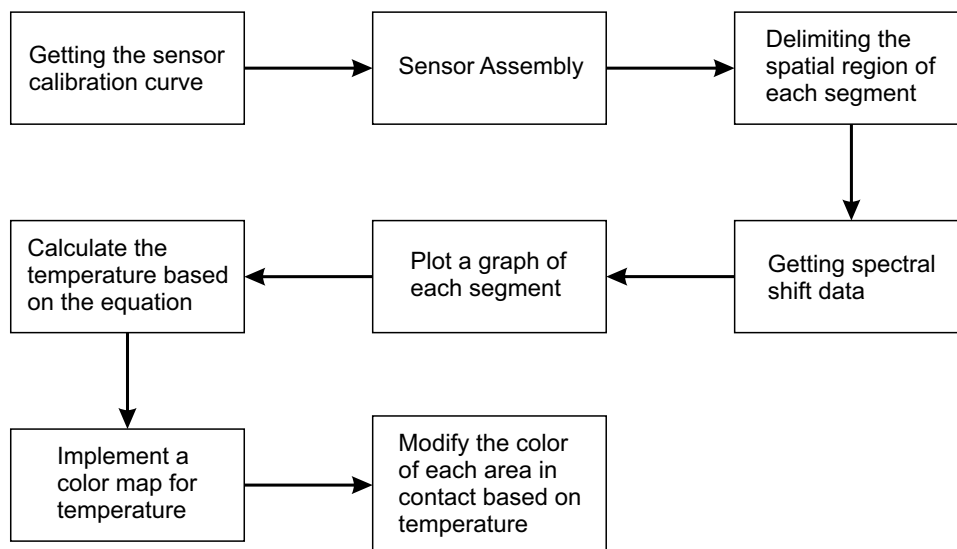


Figure 4. Block diagram of the system of the main algorithmic flows and solution structure.

sensitivity to thin objects with low temperature variation and negligible weight.

Afterwards, a copper tape roll at room temperature was placed on the sensor to assess the influence of its weight on the measurement. The same roll was later uniformly heated with a heat gun and positioned again on the fiber, allowing evaluation of the response to an object with high curvature and increased cross-sectional area.

Finally, a human hand was gently placed over the sensor without exerting pressure, in two conditions: first at room temperature and then warmed through friction. This test examined the system's ability to detect differences of temperature distribution in objects with irregular geometry and non-uniform thermal gradients.

Results and Discussion

The use of OFDR as a thermal sensing technique has been previously demonstrated in the literature by Kreger and colleagues [6]. However, unlike the approach reported in that study, the present work proposes an implementation that extends beyond distributed temperature measurement along the fiber, enabling simultaneous two-dimensional shape reconstruction and spatially resolved thermal mapping of the contacted object.

Figure 8 through Figure 11 presents the final output generated by the modeling algorithm. Upon interaction with each object, the system produces a visualization of both the object's two-dimensional shape and its corresponding temperature distribution, while also providing the average temperature across the sensor's contact area. Figure 8 and Figure 9 demonstrate the sensor's sensitivity, as evidenced by its ability to detect subtle temperature variations. When analyzing the modeling of the unheated copper wire (Figure 8) and the unheated hand (Figure 9), measurable temperature variations were observed. This occurs because the copper wire, being a good thermal conductor, even without intentional heating, acquired residual heat during handling, contributing to the sensor response. Moreover, the human body temperature is higher than the reference temperature, which is sufficient to elicit a detectable spectral shift in the fiber.

The effect of strain induced by the object's weight was negligible in the present configuration. This occurs because the OFDR interrogator was specifically calibrated for temperature measurements, which alter the sensitivity coefficients used to interpret the spectral shifts. In this calibration mode, the coefficient applied for thermal sensitivity is expressed as:

Figure 5. Unheated copper wire placed on the sensor.

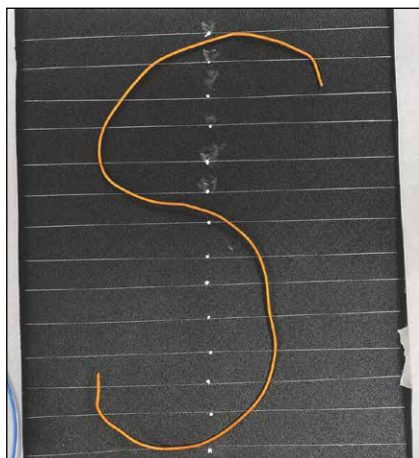


Figure 6. Heated copper tape placed on the sensor.



Figure 7. Heated hand placed on the sensor.



Figure 8. Sensor modeling with copper wire.

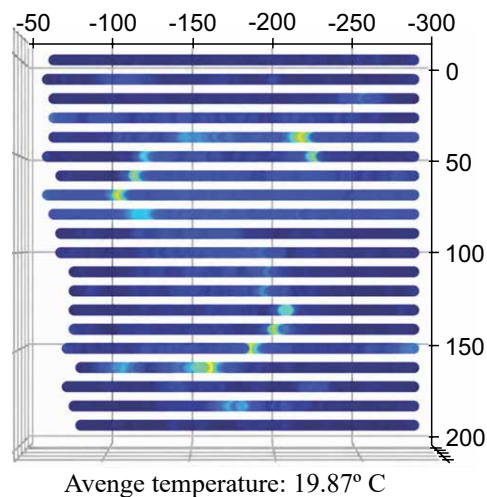


Figure 9. Sensor modeling of a non-heated hand.

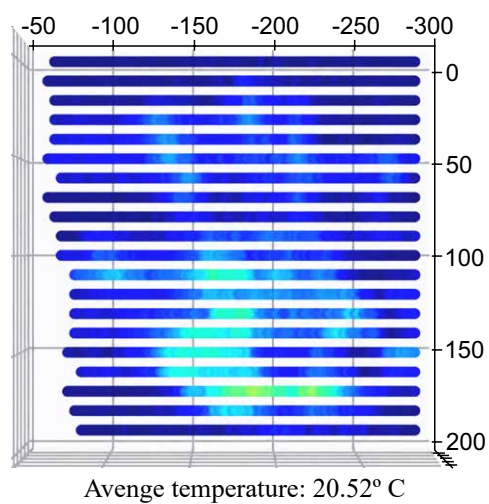


Figure 10. Sensor modeling of a hand heated by friction.

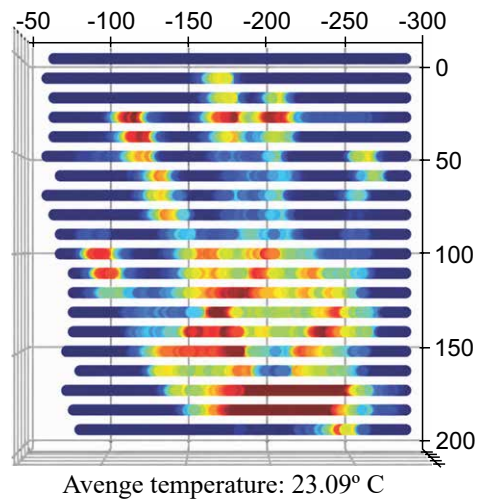
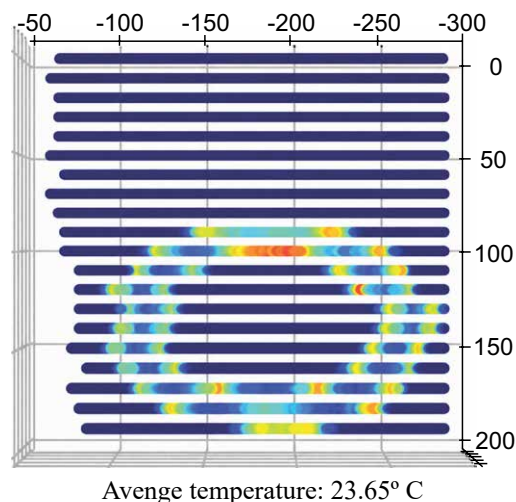


Figure 11. Sensor modeling of heated copper tape.

$$y = -0.638 x \quad (2)$$

whereas the coefficient associated with strain response is approximately ten times higher:

$$y = -6.67x \quad (3)$$

Consequently, the sensor becomes far less responsive to strain, rendering its contribution insignificant in the final output. This effect was confirmed in the case of the unheated copper tape roll, which, when placed on the fiber without prior handling, exhibited no measurable temperature variations and thus produced no detectable output. The same was observed when the copper wire was positioned without hand manipulation.

Figure 10 illustrates the high spatial resolution achieved by the proposed sensing system, demonstrating its ability to detect wavelength variations along the fiber with a sampling precision of 0.65 mm. This resolution enables accurate representation of detailed features of the object under study, facilitating the delineation of edges, contours, and subtle thermal variations.

When analyzing Figure 10, in which the human hand was heated by friction and gently placed over the sensor without applying pressure, the resulting thermal map faithfully reproduced the actual temperature distribution across the surface. Warmer regions correspond to areas of greater contact and pressure during friction, typically the more prominent parts of the hand, while cooler

regions aligned with recessed zones, confirming the system's ability to resolve complex geometry with non-uniform thermal profiles.

Additionally, the technique shows potential for enhancement. By reducing the segment spacing along the vertical axis, the spatial resolution could be significantly improved, especially for objects with pronounced curvature. This limitation is evident in Figure 11, where the thermal modelling of a heated roll of copper tape reveals a loss of detail in the curvature representation due to insufficient vertical segmentation. Increasing the number of fiber segments would improve the resolution of the circular geometries, further demonstrating the capability of the OFDR technique, especially when integrated with the modelling framework proposed in this study.

Conclusion

The development and implementation of a distributed thermal sensing system demonstrated promising results, both in terms of spatial resolution for shape modeling and thermal sensitivity. The experimental findings confirm the system's ability to simultaneously map two-dimensional object profiles and their corresponding real-time temperature distribution with considerable accuracy. Systematic testing with a copper wire, copper tape roll and human hand evidence its versatility: sensitivity to small conductive structures, ability to model bulkier curved objects, and robustness in capturing complex, non-uniform thermal fields in biological systems. The negligible contribution of strain, ensured by the calibration mode adopted, further reinforces the reliability of thermal measurements. The proposed approach expands the potential applications of sensing techniques, contributing to the advancement of OFDR-based technologies and establishing a foundation for future developments and enhancements.

Acknowledgement

The authors would like to thank CNPq, Shell Brazil Petróleo LTDA, the Brazilian Company for Industrial Research and Innovation (EMBRAPII),

the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP), and Senai CIMATEC for their support and investments in Research, Development, and Innovation (R&D&I).

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Evaluation of the Physicochemical and Microbiological Stability of Cocoa Honey-Flavored Mate Tea under Different Storage Conditions

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Cocoa is a versatile fruit, used by the food industry mainly for the production of chocolate, and cocoa honey, liquid extracted during the fermentation or pressing of cocoa, when combined with mate tea, results in a drink with remarkable sensory and commercial appeal. This study aimed to evaluate the physicochemical, microbiological and sensory stability of cocoa honey mate tea stored under two temperature conditions: ambient (CM1) and refrigerated (CM2), over 45 days. The results showed that the microbiological indices remained within acceptable limits throughout the storage period, ensuring food safety. The physicochemical analysis showed stability of titratable acidity in CM2, while CM1 presented slight reduction. The pH remained stable in both samples, similar to previous studies with mate tea-based beverages. There was a reduction in °Brix values in both conditions. The vitamin C content decreased in CM2 and increased in CM1. Sensory analysis indicated high acceptance in all attributes, without significant differences between the samples over time. In the face of this, it is important to continue the study to assess whether stability is maintained.

Keywords: Stability. Cocoa Honey. Mate Tea.

Cocoa (*Theobroma cacao* L.) is a tropical fruit of high economic and cultural value, with wide use in the food industry, cosmetics and pharmaceuticals [1]. According to the International Cocoa Organization [2], Brazil stands out among the seven countries that produce most cocoa, with Bahia and Pará being the states with the highest production quantities.

Among the by-products of the fruit is cocoa honey, a liqueur extracted by pressing or during fermentation. Just like cocoa, cocoa honey can be used in different ways, for example as a base for jellies, fermented drinks, sweetener or juices. One of the ways to use it is combined with mate tea, which, according to Portaria N° 519 of June 26, 1998, are products used in the preparation of food beverages, resulting from different technological processes and consisting of parts of vegetables, whole, fragmented or ground [3].

It should also be mentioned that, according to the 2017-2018 IBGE Family Budget Survey (POF), only 7.4% of the Brazilian population consumes tea daily [4]. The association between mate tea and cocoa honey represents an innovative alternative for increasing consumption and adding value to regional ingredients, after all, the combination results in a refreshing drink with sensory and commercial acceptance.

However, its greatest challenge is the short shelf life, due to the high microbial load present in the fruit and the post-harvest conditions. These factors make cocoa honey and, consequently, beverages that have it in their formulation, highly perishable [1].

Being a promising product, the physical-chemical, microbiological and sensory study of cocoa honey allows to develop methods that extend its shelf life and expand industrial applications. Analyzing samples periodically and under different conditions contributes both to the diversification of the market, as for quality assurance and product safety [5].

This study goes beyond the proposal of using cocoa honey, by directing to the development of a functional drink from this by-product, in order

Received on 15 April 2026; revised 22 July 2026.

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J Bioeng. Tech. Health 2026;9(8):831-835
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to expand consumption alternatives, promote the appreciation of regional biodiversity and add value to an ingredient still underused in the food industry. In this sense, it is essential to evaluate the influence of different storage conditions, at room temperature (CM1) and refrigerated (CM2), on the physico-chemical, microbiological and sensory stability of the formulation over time. Thus, it becomes necessary to evaluate the effects of different storage temperatures, tea mate cocoa honey flavor CM1 and CM2 over a period.

This study aimed to evaluate the stability of cocoa honey mate tea, stored at room temperature (CM1) and refrigerated (CM2), over 45 days, through physical-chemical, microbiological and sensory analysis.

Materials and Methods

To determine the stability of cocoa honey mate tea (CM1 and CM2), this study evaluated two samples of the product over 45 days under different storage conditions. The samples were kept at room temperature and refrigerated, being analyzed over 45 days. The microbiological characterization evaluated the presence or absence of fungi, molds and yeasts, according to the limits established by the Normative Instruction no 161/2021 of Brazilian Health Regulatory Agency (ANVISA) [6], ensuring that the product complies with the quality and safety standards required for ready-to-drink beverages. The physicochemical analyses were pH, using digital pHmeter (PHS3BW, Bel Engineering), portable digital refractometer (SPINLAB/SPIN104-D) for measurement of °Brix and official methods for determination of vitamin C (EN 014 FQA - MAPA IN 24, 2005 [7]) and titratable acidity (EN

019 FQA - IAL 312/IV [8]). These tests allowed to evaluate the influence of physical-chemical parameters on the stability and shelf life of the product, ensuring quality, standardization and compliance with regulatory requirements. Finally, the sensory analysis was carried out according to ABNT NBR ISO 11136:2022 [9], by means of hedonic tests in a controlled environment, to verify the sensory acceptance and the purchase intention, comparing the newly produced with those stored under different conditions during the study period.

Results and Discussion

The results of the microbiological analyses (Table 1) performed in CM1 and CM2 tests were considered satisfactory, since they are within the limits established by RDC no 724 and by Normative Instruction no 161, both dated July 1, 2022 (Brazil, 2022 [10]).

Food contamination can occur through the environment, water, utensils, containers, raw materials and carelessness of handlers, and it impacts the shelf life of foods [11]. Therefore, to evaluate this shelf life, microbiological analyses are essential. Due to the presence of cocoa honey as one of the ingredients, which has a high microbial load [1], product perishability was taken into account. In view of this, the previous heat treatment of cocoa honey allowed the preservation of its properties. In addition, the incorporation of additives and preservatives in the formulation of cocoa honey mate tea did not negatively affect the sensory acceptance of the product by consumers, on the other hand, contributed to a significant increase in shelf life, extending the period in which the product can be marketed without loss of quality.

Table 1. Result of microbiological analysis in the different storage times of tea mate cocoa honey flavor at room temperature and chilled.

Microrganism	Sample	T0	T45
Fungus, Molds, and Yeast (mL/g)	CM1	<1.0 X 10 est.	<1.0 X 10 est.
	CM2	<1.0 X 10 est.	<1.0 X 10 est.

The levels of fungi, molds and yeasts remained within the limits allowed by IN N° 161 [6] at all different times. This compliance with microbiological standards guarantees the safety of the food for the consumer and product quality recognized in the market. Thus, good manufacturing practices, together with the use of additives and preservatives, played a crucial role in the results of cocoa honey mate tea, even after 45 days stored at room temperature or refrigerated.

Table 2 presents the physico-chemical results of CM1 and CM2 samples, observed during this period. It is observed that the titratable acidity presented similar values in T0 and T45 at refrigerated temperature, while the ambient temperature decreased, varying 0.66%. At ambient temperature, the observed variability may have occurred due to the chemical alteration of the CM2, caused by the action of microorganisms that degrade the organic acids present, reducing the acidity over time. On the other hand, due to the more effective storage conditions in refrigeration, the drink kept its acidity stable. Santos Filho (2018) [12], in his article on the influence of temperature in cocoa juice over 42 days, highlights the low variance of organic acids during the study. This highlights the impact of time and temperature on product stability.

At ambient and refrigerated temperature, the pH difference in CM1 and CM2 was minimal, which can be attributed to natural degradation processes or interactions between the ingredients of the prototype. In the study of Koop (2014) [13] with

bubble tea based on mate tea and pitanga pulp at room temperature, pH values remained stable for 30 days, also presenting low variations.

With regard to the soluble solids content (°Brix), in CM1 and CM2 there was a reduction. This decrease can be attributed to different physicochemical and microbiological factors. Among the main causes, spontaneous fermentation of simple sugars by yeasts and bacteria naturally present in the product may result in the conversion of these sugars into ethanol and organic acids, directly reducing the °Brix, or action of endogenous enzymes, that promote the hydrolysis of oligosaccharides, altering the profile of soluble sugars [14,15].

As for the percentage of vitamin C, there was a reduction in CM1 and an increase in CM2. The increase may have occurred because the analysis has accounted for antioxidant compounds of cocoa honey. The reduction, which normally occurs, was a factor in the sensitivity of vitamin C to storage time. The ideal scenario, which did not occur, would be that this decrease was in CM2, since vitamin C degrades faster at room temperature. Nakilcioğlu-Taş and Ötleş (2020) [16] address in their article on vitamin C and the degradation time in citrus juices, highlighting factors such as storage temperature, light and presence of oxygen influence this loss.

Although present, the identified vitamin C content is below the limit required by legislation for the product to be considered a source of this nutrient. According to the Resolution no 269 of

Table 2. Result of the physico-chemical analyses in the different storage times of cocoa honey mate tea at room temperature and refrigerated.

Sample	CM1		CM2	
Physical-Chemical Analysis	T0	T45	T0	T45
°Brix (%)	7.9	7.5	8.03	7.4
Titratable Acidity (m/v)	2.83	2.17	2.53	2.5
Vitamin C (mg/100g)	1.37	1.71	1.71	1.03
pH	3.3	3.1	3.24	3.1

September 22, 2005 [7], the Dietary Reference Intake (DRI) must be 45 mg for adults, and the result is below the recommended. However, it is necessary to consider that the drinks in question are combinations of mate tea with cocoa honey, which interferes with the value found. Then, one possibility is to potentialize them with ingredients that add value to the nutritional profile of this product.

Finally, the sensory analysis was performed with untrained tasters, evaluating the attributes of aroma, color, flavor and texture of teas CM1 and CM2. For both samples, the results showed that the tasters did not notice a significant difference in up to 45 days of conducting the study, presenting an excellent acceptance in all attributes and a promising potential for the market.

Conclusion

The cocoa honey mate teas demonstrated that the products maintained their microbiological safety and physico-chemical and sensory stability throughout the period analyzed, indicating that the processing and storage conditions were adequate. We observed a longer conservation in CM2, however, this difference was not very expressive in relation to CM1, especially regarding the microbiological and sensory results, which remained stable.

Certainly, the heat treatment of cocoa honey, and the use of additives and preservatives, contributed to extending the shelf life of cocoa honey tea. The continuity of the study will allow to verify if the stability, quality and shelf life of teas are maintained for a longer period.

Acknowledgement

To SENAI CIMATEC, for the support to the realization of the project, providing its facilities, equipment and a highly qualified technical team. To COOPERMATA, for partnership and direct collaboration in the development of activities. To

EMBRAPII and SEBRAE, for institutional support and encouragement of innovation.

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Improvement of the Reliability of Anesthesia Machines Through the Application of the FMEA Methodology

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This work proposed the application of the FMEA (Fail-ure Mode and Effects Analysis) methodology to the anesthesia carriage, for which a case study was carried out in a group of nine equipments, using the FMEA tool. The purpose of this research was to evaluate the reliability of the anesthesia machine, demonstrating through daily and semiannual data analysis, proving that preventive maintenance focused on reliability enables greater safe-ty, both for the patient and for the hospital's multidisciplinary team. The methodology was developed with the purpose of analyzing failure indicators, to assist in the development of hospital maintenance strategies, exemplifying its application through the FMEA tool, seeking solutions with innovations in maintenance management, in order to reduce costs, through the speed in the analysis of results for health units.

Keyword: Clinical Engineering. FMEA. Anesthesia Machine.

According to Akao (1990) [1], there are three main items of reliability: (1) durability, related to the useful life of the product; (2) safety, and (3) maintenance. In data collection, it is possible to characterize parameters of a component, equipment or program, giving importance to different operating circumstances.

To implement a maintenance management method for medical devices, according to the Ministry of Health (2002) [2], it is crucial to understand the history of the equipment in the context of the Health Care Establishment (EAS), including its group or family, useful life, obsolescence, construction and the possibility of replacement during maintenance. These details support maintenance, ensuring safety and quality. This information guides the technician in the analysis of failures, urgency of the service, implementation of preventive maintenance and in the search for the level of reliability necessary to avoid risks to the patient's life.

In this context, this research work used failure parameters, generating reliability indicators, at the

Received on 8 April 2026; revised 25 July 2026.

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same time that it is possible to evaluate the conditions of use of the equipment, and consequently, direct maintenance actions through the characteristics of the failures, providing improvement in the quality of health services and generating conditions for Clinical Engineering to consolidate its integration into the technological process in health.

The objective of this study was to apply the FMEA (Failure Mode and Effects Analysis) methodology based on the reliability of the anesthesia carriage, using data analysis, with the main focus on the study of failures and a point of view on maintenance centered on reliability, using a case study carried out from a health unit.

Materials and Methods

To carry out this study, the authors performed a retrospective data collection of data on the history of corrective maintenance services, performed in a medical anesthesia cart, from January 1, 2021 to December 13, 2023, in a public hospital in the city of Salvador, Bahia, Brazil. The hospital under study has 120 beds, 30 of which are intensive care units, 8 operating rooms and 1 magnetic resonance room, performing 9,000 surgeries per year, justifying the high demand for the anesthesia cart and its criticality in the operating room.

The hospital has a team that carries out daily inspections of high-complexity equipment,

testing, before the first surgeries, in order to avoid inconveniences and delays during the day. Verification is carried out on all functional parts of the equipment such as: gas system, ventilatory modes, canister and anesthetic agents.

In this work we will introduce the concepts of reliability, time of intervention, probability of failure and MTBF (Mean Time Between Failures). According to Kardec [3], MTBF are the periods that are lost in the operation of a machine, and its average can be performed by means of Equation 1. We need to calculate the total fail-free operation time over a specific period and compare it to the number of errors that occurred during that interval. Then, the MTBF and failure rate as a function of time (λ) were calculated from Equations 1 and 2, respectively below, where N_f is the number of recurrent failures in the study time.

$$MTBF = \frac{(Total\ Time\ Available - Time\ Lost)}{(Number\ of\ stops)} = \frac{1}{\lambda} \quad (1)$$

Based on this conclusion, it is possible to develop approaches to gradually deal with equipment-related issues.

It is crucial for the maintenance manager to determine the possibility of failure of an item or equipment. In this regard, we have the reliability calculation. According to the NBR-5462 [4] standard, reliability refers to the percentage or probability of correct operation of machines, systems and/or items included in the production chain, as specified, during a specific period. Thus, it is up to the Engineering professional to measure how much it is possible to trust a piece of equipment and ensure that the production will have its production flow planned.

To calculate reliability, we first need to calculate the failure rate (λ) which is the inverse of MTBF:

$$\lambda = \frac{1}{MTBF} = \frac{Number\ of\ stops}{(Unit\ x\ Time)} = \frac{N_f}{t} \quad (2)$$

With these values, we can calculate the reliability of the equipment for a given time. Then, reliability was calculated in equation 3, respectively below, where R is Reliability; t time to be measured, be a certain period or life cycle of the equipment (t 1);

(e) basis of the Neperian algorithms and is worth 2.71 and λ failure rate.

$$R(t) = e - (\lambda).t.100 \quad (3)$$

Given the cost associated with the occurrence of failures and taking into account the current capacity of the internal team, as it is an equipment with a high degree of criticality of the equipment, risks involved for employees and patients, it was established that each component must have a minimum reliability of 95%. The maximum time allowed for equipment intervention ($t_{0.95}$) is determined using Equation 4. [5]

$$t_{0.95} = - \frac{\ln(0.95)}{\lambda} \quad (4)$$

According to Piazzzi [6], reliability can be calculated from a given time interval, with this premise we can calculate the probability of failure (Q) of components for a life cycle, equal to the failure density $F(t)$, shown by Equation 5.

$$F(t) = Q = 1 - R(t) \quad (5)$$

Being sure of the reliability of the equipment is essential to ensure that the processes achieve the desired results within a stipulated timeframe. It is an essential maintenance indicator for competitiveness when combined with predictive maintenance and its computational analysis. Mainly to save on equipment maintenance costs and make more assertive strategic decisions. The data were collected from work orders, and the analysis was based on the maintenance process and the observations made by the Clinical Engineering team.

In accordance with the IEC 60812:2018 [7] standard, and based on the calculations, it was possible to use the FMEA tool, increasing the reliability of the equipment, suggesting maintenance based on a plan according to the failures analyzed in the study interval. The FMEA methodology uses the Risk Priority Number (RPN), multiplying from numerical indices of Severity (G), Occurrence (O) and Probability of Detection (D) of each failure, for a critical analysis of failure modes. By assigning values from 1 to 10, the most critical failure modes are assigned larger values, indicating higher

frequency or lower detection. Control actions are determined by RPN, helping the maintenance team identify the most important faults. In addition, shown in equation 6 we have, RPN combines semi-quantitative assessments of severity, occurrence, and detectability. Its value varies depending on the measurement scales, usually from 1 to 1000.

$$RPN = G \times O \times D \quad (6)$$

Results and Discussion

The study was carried out on 86 service orders, however 7 work orders will not be included in the calculation, (1 failure inconsistency, 1 failure not found, 1 failure due to assembly in manufacturing, 2 preventive, 1 installation and 1 uninstallation).

Operational Failures are related to the team not knowing how to operate the equipment or having doubts about its perfect functioning, but without causing damage to the equipment, these mistakes had 19.05% called.

Table 1 shows the number of failures during the analyzed period, together with the failure rate, the MTBF and the time required for intervention, considering a reliability of 95% ($t_{0.95}$), the reliability for each failure, in the period of 180 days, having performed the semiannual preventive test.

Table 2, similar to the Table 1, shows the reliability at 365 days, with annual maintenance and a mean difference of 17.01% between Tables 1 and 2. In Table 2, we consider the period of 365 days for the actual reliability of the components.

Table 3, similar to the previous ones, portrays the reliability in the period of 1 day, with inspections performed daily and the probability of failure for each component is completely non-existent, consequently making the reliability very high, approaching 100%.

They analyzed the work orders, and had some observations. For the CCI-0001 equipment, two occurrences were observed: in one of them, the medical team noticed that the equipment failed and considered it safe to continue the surgery, while at another time no failure was found, support was requested from the manufacturer.

In the case of the CCI-0002 equipment, there was an error in the assembly during the manufacturing process and was identified in the first days of use by the team, the nurse opened the call, but no failure was found, and the administrative staff was asked to pay attention to the equipment.

For the CCI-0003 equipment, a work order was linked to the balloon support arm, connected to the lung ventilator and anesthesia cart. However, there

Table 1. Failure rate, mean time between failures (MTBF), intervention time, and reliability over a 180-day period.

Failure Mode	Average No. of Failure (Nf)	Failure rate (λ)	MTBF (days)	Intervention time ($t_{0.95}$)	Reliability (t_{180} days)	Probability of failure
O2 Button Failure	2.20	2.01E-03	497.7	25.5	69.65%	30.35%
Uncalibrated O2 sensor	1.80	1.64E-03	608.3	31.2	74.39%	25.61%
Flow Sensor Failure	1.80	1.64E-03	608.3	31.2	74.39%	25.61%
Patient Circuit Failure/Leakage	1.40	1.28E-03	782.1	40.1	79.44%	20.56%
Uncalibrated flux sensor	1.20	1.10E-03	912.5	46.8	82.10%	17.90%
Power supply or battery	1.67	1.52E-03	657.0	33.7	76.04%	23.96%
Damaged O2 sensor failure	1.00	9.13E-04	1095.0	56.2	84.84%	15.16%
Fault in the front control display	2.00	1.83E-03	547.5	28.1	71.98%	28.02%
Uncalibrated vaporizer	1.00	9.13E-04	1095.0	56.2	84.84%	15.16%
Poor contact	1.00	9.13E-04	1095.0	56.2	84.84%	15.16%
Average	1.51	1.38E-03	789.9	40.5	78.25%	21.75%
Total	15.07	1.38E-02	72.7	3.7	8.40%	91.60%

Table 2. Failure rate, mean time between failures (MTBF), intervention time, and reliability over a 365-day period.

Failure Mode	Average No. of Failure (Nf)	Failure rate (λ)	MTBF (days)	Intervention time (t0.95)	Reliability (t365 days)	Probability of failure
O2 Button Failure	2.20	6.03E-03	165.9	8.5	11.08%	88.92%
Uncalibrated O2 sensor	1.80	4.93E-03	202.8	10.4	16.53%	83.47%
Flow Sensor Failure	1.80	4.93E-03	202.8	10.4	16.53%	83.47%
Patient Circuit Failure/Leakage	1.40	3.84E-03	260.7	13.4	24.66%	75.34%
Uncalibrated flux sensor	1.20	3.29E-03	304.2	15.6	30.12%	69.88%
Power supply or battery	1.67	4.57E-03	219.0	11.2	18.89%	81.11%
Damaged O2 sensor failure	1.00	2.74E-03	365.0	18.7	36.79%	63.21%
Fault in the front control display	2.00	5.48E-03	182.5	9.4	13.53%	86.47%
Uncalibrated vaporizer	1.00	2.74E-03	365.0	18.7	36.79%	63.21%
Poor contact	1.00	2.74E-03	365.0	18.7	36.79%	63.21%
Average	1.51	4.13E-03	263.3	13.5	24.17%	75.83%
Total	15.07	4.13E-02	24.2	1.2	0.00%	100.00%

Table 3. Failure rate, mean time between failures (MTBF), intervention time, and reliability over a 1-day period.

Failure Mode	Average No. of Failure (Nf)	Failure rate (λ)	MTBF (days)	Intervention time (t0.95)	Reliability (t365 days)	Probability of failure
O2 Button Failure	2.20	2.01E-03	497,7	25,5	99,80%	0,20%
Uncalibrated O2 sensor	1.80	1.64E-03	608,3	31,2	99,84%	0,16%
Flow Sensor Failure	1.80	1.64E-03	608,3	31,2	99,84%	0,16%
Patient Circuit Failure/Leakage	1.40	1.28E-03	782,1	40,1	99,87%	0,13%
Uncalibrated flux sensor	1.20	1.10E-03	912,5	46,8	99,89%	0,11%
Power supply or battery	1.67	1.52E-03	657,0	33,7	99,85%	0,15%
Damaged O2 sensor failure	1.00	9.13E-04	1095,0	56,2	99,91%	0,09%
Fault in the front control display	2.00	1.83E-03	547,5	28,1	99,82%	0,18%
Uncalibrated vaporizer	1.00	9.13E-04	1095,0	56,2	99,91%	0,09%
Poor contact	1.00	9.13E-04	1095,0	56,2	99,91%	0,09%
Average	1.51	1.38E-03	789,9	40,5	99,86%	0,14%
Total	15.07	1.38E-02	72,7	3,7	98,63%	1,37%

was an alarm indicating low flow in the anesthesia carriage, but the surgery continued, and it was later found that the equipment was working properly.

For the CCI-0005 equipment, faults were identified, such as leakage in the CO2 line and repair in the support system hose, although no errors were found after the tests were carried out.

In the case of the CCI-0006 equipment, there was the replacement of an unspecified part, and despite

an occurrence reporting the non-functioning of the flowmeter, the surgery continued.

For the HOD-0011 equipment, the anesthesia carriage was uninstalled for air conditioning maintenance, and a new work order was opened for installation in the original room, with a clinical engineering technician waiting for the equipment to be released by the operating room team to resolve the work order request.

Table 4 shows the FMEA that was calculated, highlighting the most common failure modes, organized according to the highest RPN calculated. The value of RPN helps us prioritize maintenance actions, with the goal of increasing equipment reliability. The time intervals for the maintenance procedures are determined according to the calculated t0.95, as it is a high-risk equipment, its failure can generate serious losses for the hospital, comparing them with the frequency indicated in the preventive maintenance plan established by the outsourced team.

Cleaning the Plate

In anesthesia practice, some of the most critical components of equipment are the internal pipes, which over time can dry out, rupture, or develop

cracks. A common fault occurs in the patient circuit, dried out pipes due to repeated sterilization processes. The flow sensor is subject to misuse by the patient in the course of movements. Battery replacement is also an essential consideration, it is recommended to do annual testing, although this period may vary by manufacturer. Another important aspect is the bellows and sealing rings, which require lubrication and replacement to ensure perfect sealing.

The analysis of work orders revealed significant operational failures, with impacts in terms of working hours. Lack of technical knowledge accounted for 19% of the cases, while misuse of equipment resulting in damage corresponded to 11% of occurrences. The implementation of regular training and awareness are essential measures. These actions are carried out monthly by the technical team, which employs a rigorous

Table 4. FMEA developed for anesthesia carriage failure analysis.

Component	Function	Failure Mode	Crash Effects	Severity	Cause of Failure	Occurrence	%	Forms of detection	Detection	RPN	Corrective / Preventive maintenance
Button Circuit	Release O2 to the patient	O2 Button Failure	Stuck	5	Natural wear of plastic and button mechanism	8	13	Visual	2	80	Replace the button
Fluxo sensor	Measures gas flow	Flow sensor failure	Failure to control/monitor O2 flow in ventilation	1	Natural wear and tear	7	11	Alarm	5	35	Calibration or replacement
Sensor de O2	O2 concentration	Uncalibrated O2 sensor	Failure to control/monitor O2 in ventilation	1	Natural wear and tear	7	11	Alarm	5	35	Calibration or replacement
Patient Circuit	Bring the gases to the patient	Patient Circuit Failure/Leakage	No piece on the line	6	Natural wear and tear caused by stress	6	8	Alarm	3	108	Patient Circuit Exchange
Fluxo sensor	Measures gas flow	Uncalibrated flux sensor	Failure to control/monitor O2 flow in ventilation	1	Natural wear and tear	5	7	Alarm	5	25	Calibration or replacement
Power supply system	Provides and adjusts electrical voltage	Power supply or battery	Won't turn on/risk of shutdown	7	Wear and tear and no connection at the source	4	6	Without turning on the equipment	3	84	Change the battery and check if it is connected to the network
Sensor de O2	Check Expected O2	Damaged O2 sensor failure	Out of proper parameters	1	Natural wear and tear	4	6	Alarm	5	20	Calibration or replacement
Dashboard	View patient information	Fault in the front control display	Be parameter	8	Wear and tear of the internal component of the screen	3	5	Operator	2	48	Panel replacement
Vaporizer	Controls anesthetic gas mixed into fresh gas	Uncalibrated vaporizer	Incorrect anesthetic delivery parameters	9	Natural wear and tear	2	2	Technician & Operator	4	72	Calibration or replacement
Circuits & Electronic Components	Componente control and data handling	Poor contact	General equipment failure	3	Oxidation, natural wear and tear	1	1	Checking the connection of the equipment	3	9	Cleaning the plate

checklist of competencies before accessing the operating room, thus ensuring the maintenance of the necessary skills and the safety of the operations.

Conclusion

The results highlight the importance of reliability engineering tools in the analysis of maintenance plans for anesthesia carts in hospitals. They point to the need to review the preventive maintenance plan to reduce failures and ensure reliability above 98% for each component. The FMEA tool proved to be efficient in improving the operational reliability of the equipment.

The reliability and probability of failure analysis revealed that the most critical failure mode is operational failures, general maintenance, and O2 button failure, largely caused by natural wear and tear. This data highlights the urgent need to enhance maintenance procedures and review action plans to mitigate risks.

In practice, anesthesia equipment is composed of several critical parts, such as internal piping, patient circuit, and sensors, which are susceptible to natural wear and tear. However, calibration of the

components and annual replacement of the batteries are necessary to ensure the desired performance. Even with the high demand in public hospitals and the limitation of resources, it is possible to maintain the perfect functioning of the anesthesia equipment, ensuring patient safety.

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Incorporation of Constraints in Optimization Problems via Normalization Condition in Hilbert Space

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In this work, we introduce a technique for incorporating constraints into the structure of quantum mechanics through the normalization condition of quantum states. We present a method for constructing Hamiltonians for optimization problems directly from the problem's own constraints, eliminating the need to insert penalty terms into the Hamiltonian and ensuring that the search space matches the feasible solution space of the problem. We demonstrate the validity of the proposal with a theoretical proof of concept, discuss its possibilities and limitations, and explore potential applications.

Keywords: Quantum Computing. Optimization. Embedding Constraints.

Quantum computing has emerged as a promising alternative for solving classes of problems that exhibit intractable complexity on classical architectures, particularly in combinatorial optimization tasks. Several quantum algorithms have been proposed to leverage this advantage, such as the Quantum Approximate Optimization Algorithm (QAOA)[1] and the Variational Quantum Eigensolver (VQE)[2], whose efficiency critically depends on how the problem is encoded into the system's Hamiltonian.

However, a recurring challenge in variational approaches is the imposition of constraints on the parameters of the quantum state. Often, these constraints must be enforced through artificial penalty terms in the Hamiltonian, which can hinder convergence, introduce unwanted degeneracy, or compromise the interpretability of the solution.

In this work, we propose an alternative theoretical approach: to incorporate linear constraints directly into the normalization condition of the quantum state, leveraging the structure of Hilbert space itself to guide the problem's solution. The objective

is to show how this technique allows us to pre-serve quantum coherence and explore the geometry of the system in a more natural way, avoiding the need for auxiliary penalty terms.

To illustrate the proposal, we consider an optimization problem with a limited resource constraint and a minimum investment per asset constraint, for a portfolio balancing task. The formulation is presented in general terms and tested through a proof of concept, demonstrating its theoretical feasibility.

Related Works

The incorporation of constraints in variational quantum algorithms began with approaches based on classical penalty terms added to the Hamiltonian, especially in QUBO and QAOA models. These strategies assign quadratic penalties to constraint violations but require fine-tuning of the penalty coefficient, resulting in distorted energy landscapes, increased circuit depth, and vulnerability to noise — limitations that hinder practical scalability on NISQ hardware [3].

In Drieb-Schön and colleagues [4], the authors present an innovative approach — the parity mapping — as an alternative to traditional energy penalty methods used to handle constraints in quantum optimization problems. Instead of introducing penalty terms and extra qubits, the

Received on 16 April 2026; revised 20 July 2026.

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J Bioeng. Tech. Health 2026;9(8):842-846
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technique represents products of binary variables as parity variables, enabling the direct encoding of constraints involving arbitrary sums and products (up to k -body) within a two-dimensional architecture. The inclusion of exchange and spin-flip interactions between parity qubits ensures that numerically valid states preserve the constraints without the overhead of additional penalties or circuit depth, maintaining physical locality and enabling implementations on hardware-limited platforms.

The article by Zheng and colleagues [5] proposes an innovative hybrid strategy that associates constrained optimization problems with generalized eigenvalue problems through the use of Unitary Coupled Cluster (UCC) excitation generators, leveraging the generator coordinate method. Instead of applying heuristic penalties typical of algorithms such as VQE, they construct non-orthogonal, overcomplete many-body generator functions based on canonical transformations, projecting the system's Hamiltonian into an effective subspace and reducing the problem to a generalized eigenvalue problem. This formulation guarantees rigorous lower bounds on the energy, avoiding barren plateaus and the failures of traditional optimizers. The method also introduces an adaptive scheme to iteratively select the set of UCC generators, leading to the hierarchical construction of an ADAPT ansatz that balances subspace expansion and ansatz optimization — resulting in highly efficient and accurate simulations of strongly correlated systems.

In Viet Le and Kekatos [6], the authors extend VQE to directly handle constraints using a Lagrangian with Lagrange multipliers, optimized via a primal dual method adapted to the parameter-shift rule. This approach avoids heuristic penalties and provides theoretical guarantees of optimality, applying to problems such as QCBO, mean probabilistic constraints, and linear programs. Simulations show high-quality solutions with shallow circuits, overcoming the limitations of penalized VQE.

In Hao and colleagues [7], the authors propose an innovative approach to solving constrained

optimization problems using simple quantum ansatzes. Instead of applying penalty terms to the Hamiltonian, which tend to compromise solution quality, the method introduces as the objective the so-called energy within the feasible region—that is, the expectation of the Hamiltonian restricted to samples that satisfy the constraints—and imposes a lower bound on the probability of being within this feasible region (in-constraint probability) directly in the optimizer. This formulation significantly improves solution quality compared to traditional penalty methods and is implemented in the QVoice package, integrated with Qiskit for rapid prototyping on simulators and quantum hardware.

Theoretical Proposal

The technique proposed in this work consists of structuring the problem's Hamiltonian by incorporating the problem's constraints into the quantum-state normalization condition. In this way, the Hilbert space structure itself is utilized to confine the search space to the space of feasible solutions, eliminating the need for penalties in the Hamiltonians and ensuring that any parameterized state of the system is a feasible solution, which also eliminates any need for restrictions on parameters of the ansatz of the variational algorithm. We did this by interpreting the state probabilities as values dependent on constants and variables of the problem.

Equations (1) and (2) represent the simplest case, where the weights and variables are positive.

$$\sum_i w_i \cdot x_i = k \quad (1)$$

$$\sum_i p_i = \sum_i \frac{x_i \cdot w_i}{k} = 1 \quad (2)$$

With this expression, we can obtain the value of the variable in terms of the normalization condition.

$$x_i = \frac{p_i \cdot k}{w_i} \quad (3)$$

where $\lambda_i = \frac{k}{w_i}$. In this way, we obtain the eigenvalue associated with the state of probability p_i ,

making it possible to construct a diagonal Hamiltonian with well-defined eigenvalues, whose expected value corresponds to the sum of the variables for example.

$$\langle A \rangle = \sum_i \langle \Psi(\theta) | A | \Psi(\theta) \rangle \quad (4)$$

$$= \sum_i c_i(\theta)^* c_i(\theta) \cdot \lambda_i \langle \psi_i | \psi_i \rangle \quad (5)$$

$$= \sum_i |c_i(\theta)|^2 \cdot \lambda_i \quad (6)$$

$$= \sum_i p_i \cdot \lambda_i \quad (7)$$

$$= \sum_i \left(\frac{x_i \cdot w_i}{k} \right) \cdot \left(\frac{k}{w_i} \right) \quad (8)$$

$$= \sum_i x_i \quad (9)$$

Note, however, that the condition of positivity of the probabilities is also imposed. This means that for the given example, the product of the i -th variable by its respective weight is necessarily positive.

In addition to equality constraints, it is possible to incorporate constraints of the type: $\sum_i^n w_i \cdot x_i \leq k$. This condition can be accessed through slack variables in Equation (1).

Proof of Concept

We present a minimal portfolio example that uses the proposed mechanism to enforce constraints via state normalization. Consider $n = 3$ assets with expected (normalized) excess returns $\mu = (\mu_1, \mu_2, \mu_3) = (0.10, 0.07, 0.15)$, positive costs $w = (w_1, w_2, w_3) = (2, 1, 3)$, minimal values to x_i , $Q = (0.1, 0.05, 0.12)$ and a budget $k = 1$. The classical constraint is exactly Equation (1). But in this case x_i has a minimum value, $x_i = Q_i + y_i$. We use Equations 2–3 to encode it into the state normalization,

$$p_i = \frac{w_i y_i}{k - \sum_i^n w_i \cdot Q_i} \quad (11)$$

so feasibility holds identically for any variational parameters that produce a normalized probability vector p .

The payoff is given by:

$$\sum_i^3 \mu_i \cdot (Q_i + y_i) = \sum_i^3 \mu_i \cdot Q_i + \sum_i^3 \mu_i \cdot y_i \quad (12)$$

where is necessary to optimize only the term of y_i . Then we define the payoff operator by replacing y_i from Equation 6 in Equation 7 which is given in terms of the probability p_i of the computational basis state $|i\rangle$,

$$B = \sum_{i=1}^3 \frac{\mu_i \cdot (k - \sum_i^3 w_i \cdot Q_i)}{w_i} \cdot |i\rangle\langle i| \quad (13)$$

for which

$$\lambda_i = \frac{\mu_i \cdot (k - \sum_i^n w_i \cdot Q_i)}{w_i} \quad (14)$$

so

$$\begin{aligned} \langle B \rangle &= \sum_{i=1}^3 \lambda_i p_i = \sum_{i=1}^3 \frac{\mu_i \cdot (k - \sum_i^3 w_i \cdot Q_i)}{w_i} \cdot p_i \\ &= \sum_{i=1}^3 \mu_i y_i \end{aligned} \quad (15)$$

We prepare a parameterized state $|\Psi(\theta)\rangle = \sum_{i=1}^3 \sqrt{p_i(\theta)} |i\rangle$ with $\sum_i p_i(\theta) = 1$ by construction and maximize $\langle B \rangle$ over θ . Because $\sum_i p_i = 1$, this is equivalent to maximizing the convex combination of the three numbers $\{\lambda_i\}_{i=1}^3$, hence the optimum is attained by concentrating all probability on the index with the largest eigenvalue λ_i (no penalty terms are needed, and feasibility is exact at every step).

For the chosen data, the adjusted scores are $\lambda_1 = 0.0195$, $\lambda_2 = 0.027$, $\lambda_3 = 0.0195$, so the maximizer is $i^* = 2$. The variational optimum is therefore

$$p^* = (0, 1, 0), x^* = (0.1, 0.44, 0.12), \quad (16)$$

which satisfies the constraint exactly, $\sum_i w_i x_i^* = 2 \cdot 0.1 + 1 \cdot 0.44 + 3 \cdot 0.12 = 1 = k$, and achieves the objective value

$$\langle B \rangle_{\Psi^*} = \mu \cdot x^* = \mu_2 = 0.07 \quad (17)$$

Operationally, the algorithm prepares $|\Psi(\theta)\rangle$, measures in the computational basis to estimate $p(\theta)$ (and thus $x(\theta) = \lambda \odot p(\theta)$ with $\lambda_i = k/w_i$), and updates θ to increase $\langle B \rangle$. At all iterations $\sum_i p_i(\theta) = 1$ by construction, which enforces $\sum_i w_i x_i = k$

identically; the Hamiltonian remains diagonal and shallow, and no artificial penalty co-efficients are introduced.

Discussion

The proof of concept demonstrated that the proposed normalization-based formulation can enforce portfolio constraints exactly, without the need for auxiliary penalty terms or additional circuit depth. In the long-only budget-constrained example, the quantum variational approach produced the optimal allocation by concentrating the probability amplitude on the asset with the highest adjusted return μ_i/w_i , with the budget constraint satisfied identically at every iteration due to the state normalization. This property eliminates the need for manual tuning of penalty coefficients and ensures that infeasible solutions are never explored during the optimization.

The classical benchmark, solved in closed form, yielded the same optimal allocation and objective value for this linear instance. This agreement is expected for convex linear problems without additional constraints, as both formulations effectively reduce to maximizing a convex combination of adjusted returns. While the classical method is trivial to apply for such problems, the proposed quantum approach generalizes naturally to more complex scenarios—such as non-linear objectives, additional coupled constraints, or structured Hamiltonians—without altering the constraint-handling mechanism. In these situations, classical solvers may require more elaborate formulations or penalty parameter calibration, whereas the normalization-based method preserves feasibility by construction.

However, despite its generalizability, this technique has limitations. The normalization condition requires all probabilities to be positive, which restricts the expressibility of variables, as well as the impossibility of working with binary variables. Imposing individual constraints on the variables of the lower and upper bound problem can also make the incorporation of constraints unfeasible. Finally,

although probabilities can represent powers of variables in a hypothetical case, and linear combinations of powers are representable by Hamiltonians, modeling nonlinear problems in general remains unclear and can be challenging or even in-feasible depending on the problem.

It is important to note that the present work represents a small-scale validation of the method, intended primarily to verify its theoretical soundness and illustrate its basic application. The example chosen was deliberately simple to allow analytical verification against a classical benchmark.

Conclusion

The proposed method provides an elegant and physically consistent mechanism for incorporating linear constraints into the rhythms of variational quantum algorithms, leveraging Hilbert space normalization to define intrinsically feasible regions. The proof-of-concept confirms its equivalence to the classically optimal solution in simple cases, while its conceptual generality suggests potential advantages for more complex constrained optimization problems. By ensuring feasibility at the state-preparation level, the approach can improve convergence behavior and robustness in noisy intermediate-scale quantum (NISQ) devices, avoiding the drawbacks of penalty-based strategies.

Since this study is a preliminary validation, future work will focus on formalizing and applying the formulation to a broader class of problems, including nonlinear objectives, multi-constrained systems, the use of off-diagonal Hamiltonians, and domain-specific optimization tasks such as dollar-neutral portfolios and risk-adjusted returns. We also plan to conduct more comprehensive performance analyses, including comparisons with realistic noise models and larger problem instances, to fully assess the scalability and practical benefits of the method.

Acknowledgement

This work has been partially supported by QuIN - EMBRAP II CIMATEC Competence Center in

Quantum Technologies, with financial resources from the PPI IoT/Manufatura 4.0 of the MCTI grant number 053/2023, signed with EMBRAPPII.

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Is Eve listening? An Interactive Learning Tool Designed to Teach Quantum Communication

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This study proposes an alternative approach to foster student engagement in the educational process by encouraging autonomy and active participation. Game-based elements are employed to introduce topics in modern physics to basic education students, with a focus on fundamental concepts of quantum cryptography. Specifically, the didactic material developed presents the core principles and operation of the BB84 protocol. To facilitate understanding, a board game was created simulating the initial steps of the protocol, including the presence of an eavesdropper attempting to intercept the message.

Keywords: Active Learning Methodologies. Gamification. Board Game. Quantum Cryptography. BB84. **Abbreviations:** Active Learning Methodologies, ALMs. Quantum Computing, QC. Quantum Information, QI. Quantum Key Distribution, QKD.

In Brazil, education is regarded as a fundamental human right, with access and free provision guaranteed by the Federal Constitution [1] and recognized by the Universal Declaration of Human Rights [2]. Nevertheless, low levels of school learning underscore the challenges of promoting transformative, free, and high-quality education in contemporary society. Although essential, investments in public policies aimed at the structural improvement of educational institutions alone are not sufficient to ensure quality education [3]. Reforms in basic education involve developing students' interest in content, and to this end, adaptations in teaching methodologies are necessary, along with a curriculum overhaul [4].

Active learning methodologies (ALMs) position the teacher as a facilitator, fostering collaboration, autonomy, and problem-based knowledge building [5]. As a new paradigm of educational quality, they integrate real-world situations and innovations into the learning process [6]. Common approaches include project-based learning, the flipped

classroom, and gamification [5].

However, developing approaches that encourage students to take responsibility for their learning can become a fruitless endeavor if the content taught in the classroom is presented in an isolated or fragmented manner—disconnected from its social and productive context [7]. In this scenario, it is essential to highlight the need for a comprehensive curriculum reform in the context of physics education. This need arises from the fact that the current curriculum is predominantly composed of concepts developed before the 20th century [4], placing greater emphasis on classical physics while neglecting modern and contemporary physics [8]. Such an approach is unwarranted, as excluding theories like relativity and quantum mechanics [9] deprives students of the opportunity to understand the technologies and societal debates that shape their everyday lives [8].

In the field of technology, the pursuit of greater computational processing power has driven the development of quantum computing (QC) and quantum information (QI) [10], which (alongside advances in artificial intelligence) is reshaping industrial processes and contributing to the emergence of the Fourth Industrial Revolution [9].

As scientific and commercial interest in these technologies grows, the media has become saturated with concepts that often appear abstract

Received on 6 April 2026; revised 22 July 2026.

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J Bioeng. Tech. Health 2026;9(8):847-853
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to the general public [4]. In the case of QC and QI, it is common to find articles and news reports discussing the impact of quantum technologies on strategic sectors of society, such as healthcare, cryptography, and data security [9].

In this context, the relevance of technological literacy has once again come to the forefront, giving rise to a new educational movement focused on fostering scientific literacy in the field of quantum science. Intending to engage students and prepare them to understand the technologies underlying the second quantum revolution, we have developed an educational resource grounded in gamification and centered on concepts from modern physics.

Assuming that Generation Alpha consists of digital natives [5], this study proposes the creation of a card game based on the BB84 quantum cryptography protocol. The objective is to use an active learning methodology to make these complex concepts more accessible to students, encouraging collaborative problem-solving through peer interaction. As a result, we aim to foster the development of cognitive skills, such as analysis and synthesis, rather than merely memorizing content [6]. In the following sections of this article, gamification will be presented as an active pedagogical approach, and both the BB84 protocol and the mechanics of the developed game will be discussed in detail.

Materials and Methods

With the growing search for alternatives to the traditional teaching model and based on the remarkable ability of games to capture and sustain participants' attention, both the demand for and the development of research on gamification in educational settings have increased, highlighting it as an effective strategy in the teaching and learning process [8,11,12]. By definition, gamification involves adopting a game-like mindset, applying game mechanics and aesthetics in educational and non-playful contexts [5,8,11]. The purpose of this approach is clear: to motivate students, sustain their attention, and foster problem-solving skills, thereby reframing the learning process [5,8,11].

The use of educational games can also be understood as a simulation of a real-world situation, in which the student (while perceiving themselves as playing) is actively appropriating concepts. For such activities to be effective, certain fundamental game components, such as objectives and rules, must be clearly and precisely defined. It is essential to note that a poorly formulated or overly complex objective may compromise the activity's success; in such cases, it should be broken down into smaller, more manageable parts [11]. Similar care must be taken when defining the rules, as they determine the procedures to be followed by players and structure the actions required to complete the challenge [11,12].

In the following subsection, we provide a brief explanation of the importance of cryptography for human development and the BB84 protocol, to support educators responsible for implementing the activity, helping them understand both its development context and its fundamental concepts.

A Brief Review of Cryptography

One of the earliest pieces of evidence of cryptography in human history was found in Egypt, where unconventional hieroglyphs were used in place of the usual symbols and carved on the walls of a tomb in 1900 BC [13]. Cryptography, from Greek, means hidden writing. The origin of the word is attributed to the Spartans, who used a wooden baton, also known as scytale, to conceal their messages [14]. Only those who had the scytale of the correct dimension and format were able to decipher the message.

Another well-known record dates back to 100 BC, when the Roman emperor Julius Caesar, to communicate securely with the Roman army, used a cryptographic system in which each character of the message was replaced by another, based on a key. This type of encryption technique became known as the Caesar Cipher [15], a monoalphabetic rotation whereby each letter of the alphabet was replaced by the third successive letter. That is, A became D,

B became E, and so on. As an example, the word CRYPTOGRAPHY, using this logic, would become FUBSWRJUDSKB.

In contemporary history, World War I opened new doors for the development of modern cipher systems, which advanced with the rise of military communication via radio [15]. The ease of intercepting radio signals made encryption essential, but ciphers like the Caesar Cipher were relatively easy to break due to the high message volume.

In the post-war period, the Enigma cryptographic machine was developed by the German engineer Arthur Scherbius and was later used by the Nazi regime during World War II [15]. Enigma's daily reconfigurable rotor made it hard to break, with Alan Turing's work on its code aiding the Allies and paving the way for modern computing. As communication technology advances, cryptography must evolve to protect data, a challenge heightened by the rise of quantum computers. With a quantum computer, classical cryptography could be easily broken due to the significantly higher processing power compared to today's computers [14].

As a result, new quantum cryptography protocols have begun to appear, protocols that would remain secure even against cyberattacks using a quantum computer. These protocols are based on the laws of quantum mechanics, unlike post-quantum cryptography, which is based on classical physics but is designed to be resistant to both classical and quantum computers [13].

Quantum cryptography, rooted in modern physics, can be taught in physics, mathematics, history, and ethics, linking quantum mechanics, probability, historical uses of cryptography, and debates on privacy in the technological era.

BB84 Protocol

Originally proposed in 1984 by Charles Bennett and Gilles Brassard, the BB84 protocol (named after its creators and the year of its conception) is currently one of the most well-known quantum key distribution (QKD) protocols [16]. It is

characterized by the use of quantum properties (specifically, the polarization states of photons) to enable cryptographic key exchanges that are theoretically unbreakable [17, 18]. The protocol involves three main actors: Alice, Bob, and Eve (short for eaves-dropper) [18]. For clarity, this paper will present the operation of the BB84 protocol in a series of distinct stages.

In the first stage, Alice transmits information to Bob through a quantum channel. To achieve this, she sends a sequence of individually polarized photons, each randomly prepared in one of two bases: the orthogonal basis (+), or the diagonal basis ($\times$). In the orthogonal basis, photons are polarized at either 0° or 90° , while in the diagonal basis, they are polarized at $\pm 45^\circ$ [18]. Bits are then encoded by arbitrarily associating logical values with the polarization states of the photons [17,18]. To visualize the photon transmission and measurement bases. In this work, we adopt the convention of assigning bit 0 to photons polarized at 0° or $+45^\circ$, and bit 1 to photons polarized at 90° or -45° .

Bob then randomly selects the basis on which to measure the received photons [17]. If the measurement basis matches the transmission basis, Bob retrieves the correct bit; otherwise, the result is entirely random [18]. The sequences of bits sent by Alice and received by Bob form what is known as the raw key [18]. Due to the random basis selection, an intrinsic error rate of approximately 25% is expected even in the absence of eavesdropping, which leads to discrepancies between Alice's and Bob's raw keys [18].

The second stage of the protocol, referred to as the reconciliation phase, occurs over a classical public channel. At this stage, Alice reveals the polarization bases used for each photon, without disclosing the corresponding bit values [18,17]. Based on this information, Bob compares the sequence of bases he used and discards all bits resulting from measurements made with mismatched bases. The key formed from the remaining, correctly measured bits is referred to as the sifted key [18, 17].

The final three stages of the BB84 protocol focus on Eve detection and error correction. In the third

stage, Alice and Bob compare a random subset of the bits that were sent and measured to estimate the error rate. The quantum bit error rate (QBER) serves as an indicator of the presence or absence of an eavesdropper [17,18]. Because the bits sent by Alice may undergo rotation during transmission or be incorrectly measured by Bob due to basis misalignment, an intrinsic error rate related to channel quality is expected [17]. Error rates exceeding this expected threshold are interpreted as additional errors introduced in the transmission, typically attributed to Eve attempt to intercept information.

If Alice and Bob obtain results that indicate the presence of a third party in the process, they must terminate the key transmission to ensure the security of the transmitted information. Alice must then generate a new sequence of polarized photons using random bases, effectively restarting the protocol. Otherwise, if the communication is considered sufficiently secure, the bits used during verification are discarded, and both the sender and the receiver proceed to the final two steps of the protocol [17].

Steps four and five of the BB84 protocol involve the application of algorithms designed to minimize noise originating from the communication channel and equipment (thus reducing the error rate in the bits received by Bob), as well as to amplify privacy. It is important to note that these final three steps result in a significant reduction in key size, that is, the number of photons emitted by Alice must be substantially greater than the final desired key length [18].

Results and Discussion

The proposal to develop a board game (Figure 1) focused on teaching quantum communication is justified by the difficulty in finding educational materials specifically tailored to this subject. Although several games address concepts related to quantum mechanics, QC, and QI [19], few are specifically designed for classroom application. When searching is limited to games available

in Portuguese, this gap becomes even more pronounced, with a significant reduction in the availability of accessible resources. Given Brazil's educational inequalities and limited Internet access in many schools [20], board games offer an affordable and accessible alternative to digital resources that align with curricular objectives. The proposed game simulates the initial stages of the BB84 quantum key distribution protocol, using custom dice to represent quantum states, measurement bases, and intercept attempts. This playful approach helps students grasp core quantum concepts like randomness and probability by immersing them in a dynamic, hands-on experience.

To be able to play, we need the following items, 60 States Cards (bits 0 or 1); 40 cards of bases base (0° , -45° , 45° and 90°); 20 Alice's Base Cards - 05 per base (0° , 90° , -45° , 45°); 6 dice of base and states (the faces show + or $\times$, and 0 or 1); 1 dice of "intercept or not intercept"; 3 card board of States and Bases and player's shield.

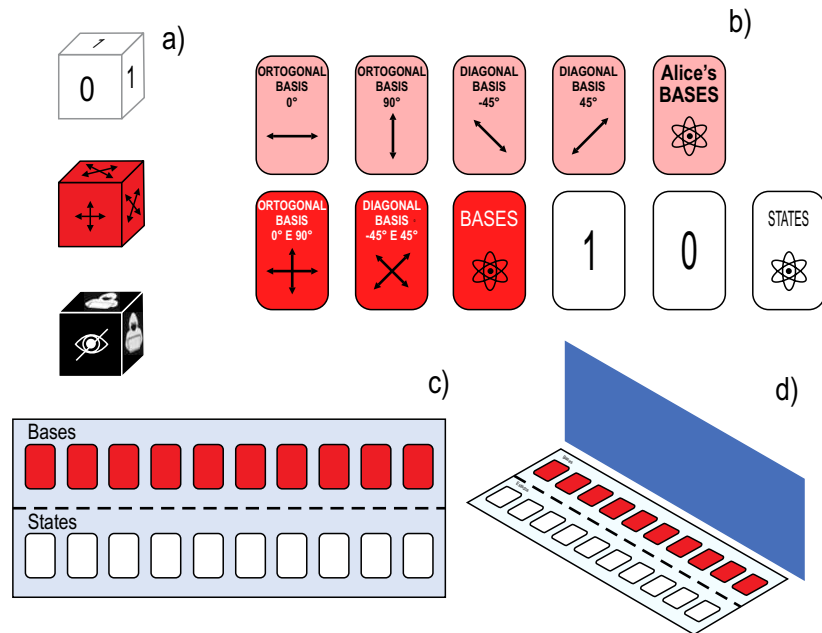
Game Rules

With the kit in Figure 1, two game modes can be implemented. The first, with Alice and Bob, demonstrates the protocol's basic operation, similar to a didactic computer simulation but using game elements. The second, with Alice, Bob, and Eve, assigns different goals: Alice and Bob aim to transmit a secure key, while Eve tries to intercept it.

Each player chooses who will be Alice, Bob, and Eve. Everyone gets a board and a shield to hide it, plus a state die and a basis die (Eve also gets an extra interception success die). Each player has 10 bit-0 cards and 10 bit-1 cards; Alice receives special state cards, while Bob and Eve get 5 cards for each basis (orthogonal and diagonal).

Alice starts by creating the sequence to be transmitted, rolling the two dice (basis and state) to determine the basis and state for each round. This repeats for 10 rounds, where Alice selects one basis card and one compatible state card, placing on their respective boards. Although the state dice are identical, Alice has four possible state card choices

Figure 1. Game Elements: a) The white die is the states' dice, the red die is the bases dice, and the black die is the interception success die. b) The status cards are in red, differentiating those used by Alice and the others by Bob and Eve. c) The board. d) The player's shield.



(two per basis) and must select one compatible with the die's basis. As established in section II.B, some combinations cannot be transmitted. This limitation can help detect intruders, serve as a discussion topic, or be addressed beforehand with transmission guidelines, at the instructor's discretion.

Next, Eve tries to intercept the message: she secretly rolls two dice (basis and interception success) and reveals the result only to Alice. If Eve gets "intercept" and the basis matches Alice's, she obtains the bit and Alice reveals the value. Otherwise, Eve rolls the state die and records a random value.

Bob now receives the data. He rolls the basis die. For rounds without Eve's interception, Alice checks if bases match; if states also match, she tells Bob to place bit-1 or bit-0. Otherwise, Bob rolls the state die to set the bit. In intercepted rounds, Eve decides Bob's basis and state. After 10 rounds, verification begins. Shields are removed, cards revealed. Alice and Bob keep only bits where bases match; Eve keeps only bits she successfully intercepted. If Eve forwarded the state to Bob without detection in at least three rounds, she wins. If Alice and

Bob communicate securely or detect and discard the compromised protocol, they win. In the initial rules, re-transmission and eavesdropping detection are left out to encourage players to create their own security strategies and better understand how the protocol works. Just like in real protocols, if the error rate reaches 25% or more, the channel is considered compromised. In the game, this means Eva must successfully intercept at least three out of ten rounds, equivalent to 30% of the key. The choice of 10 rounds makes percentage calculations easier, and the teacher can decide whether all rounds are played by each player at once or if turns alternate bit by bit.

Students should understand that the computational process requires more formalism than the game dynamic, which aims only to give a general intuition of the BB84 protocol. In the actual protocol, Alice and Bob communicate via an authenticated classical channel: Alice informs the bases used, Bob compares results and discards discrepancies, while Eve only intercepts and resends photons. If the error rate exceeds the limit, the channel is deemed compromised.

To enrich the activity, steps can include converting the final key from binary to text to decrypt a message, creating a narrative context, or varying key lengths to analyze the difficulty of detecting an eavesdropper, enabling interdisciplinary discussions.

In the mode game with Alice and Bob only, Eve's mechanics are removed. Both cover their boards, keep the same base/state cards and dice. Alice rolls both dice, records the results, and Bob rolls the base die. If bases match, Alice tells Bob the state; otherwise, he rolls the state die. At the end, unmatched bases are discarded and remaining states analyzed for possible intrusion.

The dynamic can be simplified by change custom dice with regular dice or coins, defining 'heads' and 'tails' for each parameter, or by using playing cards with rules based on suits, parity, or other rules, while preserving the proposal's simplicity and focus on playful concept building.

Conclusion

This work represents a starting point for future didactic applications involving quantum technologies in basic education, proposing a board game to simulate the BB84 protocol, highlighting gamification as an effective tool to engage students through playful and didactic methods. Given the growing global demand for quantum professionals, introducing these topics early in schooling is both relevant and strategic, especially for exact sciences with low enrollment and high dropout rates. Besides enhancing student learning, the proposal supports curriculum updates and teacher development. Next, we plan to implement this resource in classrooms to gather data on the effectiveness of gamification in teaching quantum technology concepts.

Acknowledgments

This work has been fully funded by the project "iNOVATeQ Lato Senso Especialização em Computação Quântica - Pesquisador - QIN-FCRH-2024-1-2-2" in supported by QuIIN - Quantum Industrial Innovation, EMBRAPII

CIMATEC Competence Center in Quantum Technologies, with financial resources from the PPI IoT/Manufatura 4.0 of the MCTI grant number 053/2023, signed with EMBRAPII.

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Mitigating Pipeline Hazards in RISC-V: Forwarding vs. Stalling in the Context of Continuous-Variable Quantum Key Distribution

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The viability of continuous variable quantum key distribution (CV-QKD) systems critically depends on the performance of a computationally intensive digital signal processing (DSP) and post-processing sequence, including reconciliation, privacy amplification, and authentication. These operations require low-latency processing to sustain viable key rates, making the processor a key limiting factor in overall key generation. Application-specific instruction set processor (ASIP) accelerators offer a promising approach to address these limitations; however, their development relies on a base instruction set architecture (ISA). The open and modular nature of the fifth-generation Reduced Instruction Set Computing (RISC-V) standard makes it a strong alternative to proprietary designs, which often face customization and intellectual property barriers. This work presents an early-stage investigation into programmable accelerator microarchitectures, evolving from a single-cycle processor to a 5-stage pipeline. Both stall and forwarding mechanisms were implemented and compared to handle pipeline hazards. To validate the design, the central processing unit (CPU) was synthesized and deployed on a Xilinx Kintex-7 field programmable gate array (FPGA) using Vivado. Simulations revealed that, while both approaches were functionally equivalent and had similar hardware usage, the forwarding implementation executed in 25 cycles, a 57.6% reduction compared to the 59 cycles of the stalling version, resulting in shorter simulation time (255.0 ns vs. 590.0 ns). However, forwarding consumed more power due to extra control logic, whereas stalling delivered better timing performance and more robust margins under constraints. In conclusion, forwarding improves throughput, while stalling enhances timing robustness, guiding efficient RISC-V optimization for CV-QKD systems. **Keywords:** RISC-V. Pipeline. Forwarding. Stalling. Continuous-Variable Quantum Key Distribution.

Advances in quantum technologies, particularly CV-QKD, offer new possibilities for secure communication. However, the practical viability of these systems depends on a performance bottleneck: a computationally intensive post-processing sequence that demands low-latency processing to sustain viable key rates [1,2]. This makes the processor a significant limiting factor in the overall key generation.

Overcoming this challenge requires dedicated hardware acceleration. The open and modular nature of the RISC-V architecture presents a robust alternative to proprietary designs [3], which are often hindered by customization restrictions.

To maximize performance, pipelining is a fundamental technique [4], but it introduces challenges known as hazards [5] that must be managed. This work addresses these challenges through early-stage investigation by implementing and comparing techniques like forwarding and stalling [6].

This paper presents the development of a 5-stage pipelined RISC-V processor from a single-cycle design [7]. We detail the CPU's architecture, its support for a comprehensive subset of the RV32I instruction set, and the implemented hazard-handling mechanisms. The findings of this study offer a crucial contribution to the optimization of RISC-V processors, aiming to meet the rigorous speed and performance requirements of high-demand applications like post-processing in CV-QKD systems.

The structure of this paper is organized as follows: Section 2 provides an overview of CV-QKD. Section 3 discusses the role of FPGAs

Received on 22 April 2026; revised 27 June 2026.

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J Bioeng. Tech. Health 2026;9(8):854-860
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in accelerating CV-QKD processing. Section 4 details the model and methods, including the RV32I architecture, pipelining strategy, and hazard types. Section 5 describes the design of the 5-stage pipelined RISC-V processor and its hazard mitigation units. Section 6 presents synthesis results, resource utilization, timing analysis, and power for both stalling and forwarding implementations. Section 7 describes the conclusion of the work and future research directions.

CV-QKD Systems

The core of CV-QKD systems is the secure distribution of symmetric cryptographic keys. This process relies on transmitting and detecting quantum states to create a raw key. However, the protocols require significant DSP operations.

A typical QKD system, including CV-QKD, follows main steps to establish a secret key: Preparation, Distribution, and Measurement of Quantum States. During this phase, a sender (Alice) encodes keys into quantum states and sends them to a receiver (Bob) through a quantum channel. Bob then measures these received states using random or in both quadratures. In CV-QKD, the information is encoded into the amplitude and phase quadratures of the electric field in the optical phase space of the quantum states, which allows the use of high-sensitivity coherent detection techniques and DSP techniques to improve the information correlation.

Data Sifting: During the sifting phase, raw data corresponding to mismatched quadrature measurements is discarded. This process only takes place with random quadrature selection in homodyne detection.

Parameter Estimation: Subsequently, channel parameters (transmittance T and excess noise ξ) are estimated to bound the information accessible to an eavesdropper (Eve).

Information reconciliation (IR): This is one of the crucial steps in post-processing, where error-

correcting codes are used to obtain identical keys. Privacy Amplification (PA): Finally, it reduces leaked information through hash functions to generate shorter, information-theoretically secure secret keys.

Field-Programmable Gate Arrays

FPGAs have proven promising due to their superior parallel processing capabilities and lower power consumption compared to Graphics Processing Units (GPUs) [8, 9]. The challenge lies in optimizing the utilization of FPGA resources and effectively mitigating pipeline hazards within the processor design to meet the rigorous speed and performance requirements of these systems.

In CV-QKD systems, the post-processing computation speed, which includes IR and PA, is a critical factor that affects the practical secret key rate [10]. By enabling the creation of specialized modules, FPGAs can perform these complex and computationally demanding DSP operations efficiently, thereby accelerating performance in terms of both distance and secret key rate.

Materials and Models

Developing the RISC-V processor requires a clear methodological approach, which will be described in this section. To achieve the project's objectives, this work was divided into three main phases: (1) selecting and adapting the RV32I architecture; (2) applying pipelining to optimize instruction execution; and (3) implementing hazard mitigation strategies (stalling and forwarding).

RV32I Architecture

The RISC-V RV32I architecture, designed to be an efficient compiler target and to support modern operating systems [11], stands out for its base instruction set. This Instruction Set Architecture (ISA), which is standard in all RISC-V implementations, has a total of 47 instructions, as established in the manual [12]. In this work, we

focus on the successful implementation of 37 of these instructions, Figure 1, seeking a balance between functionality and minimal hardware requirements.

The execution of an instruction follows a well-defined flow: the program counter (PC) points to the address of the instruction to be fetched from instruction memory. The instruction is then decoded to identify the operation and the source registers. The necessary values are then read from the register file, if necessary. The arithmetic and logic unit (ALU) performs the operation, and the final result is either saved to data memory or written back to the register file, depending on the instruction type.

Pipelining

As shown in Figure 2, the pipelining technique is classically divided into five stages: instruction fetch (IF), instruction decode (ID), execute (EX), memory access (MA) and write-back (WB). This approach offers substantial advantages in optimizing processor utilization and resolving performance bottlenecks [13-15]. By implementing overlapped instruction execution through pipeline registers between sub-processes, the instruction throughput [16] is improved, and the program execution time is reduced, enhancing overall processor performance.

Hazards

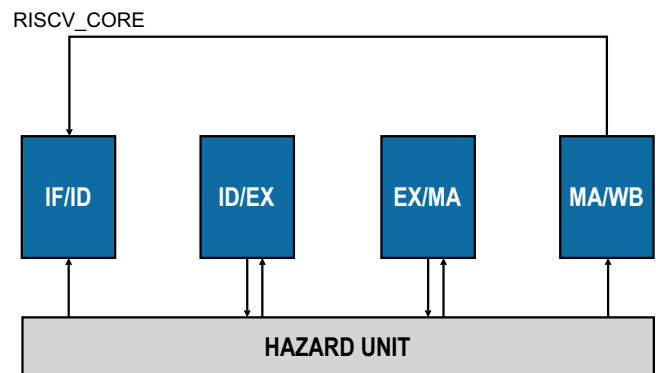
When implementing pipelining, challenges known as hazards arise, which can compromise the efficient and correct execution of instructions. A hazard occurs when a dependency or resource conflict could cause an incorrect result during execution.

A pipeline can face three main types of hazards: structural hazards, which occur when two instructions try to use the same hardware resource at the same time; data hazards, which happen when an instruction needs the result of a prior instruction that hasn't finished yet; and control hazards, which arise with branch or jump instructions because the next instruction to fetch isn't known until the branch decision is made.

Figure 1. Implemented instructions.



Figure 2. Architecture RISC-V processor.



When forwarding is not feasible, the processor implements stalling, which inserts a delay cycle—commonly referred to as a “bubble”—into the pipeline to ensure that correct data is used. The strategic application of these two techniques optimizes processor performance, minimizes latency, and preserves the integrity of the RISC-V pipeline.

Stalling is particularly crucial for resolving load-use hazards. This occurs when an instruction attempts to use the value of a register that has just been updated by a load instruction.

The Figure 3 illustrates the execution flow of instructions within a RISC-V processor pipeline, specifically demonstrating the occurrence and resolution of a control hazard in a 5-Stage pipelined RISC-V processor. The hazard is caused by the branch instruction `beq x2, x6, 12`, whose decision is finalized only during the EX stage at clock cycle 6T. Prior to this, the subsequent instruction, and `x11`,

Figure 3. Stalling example.

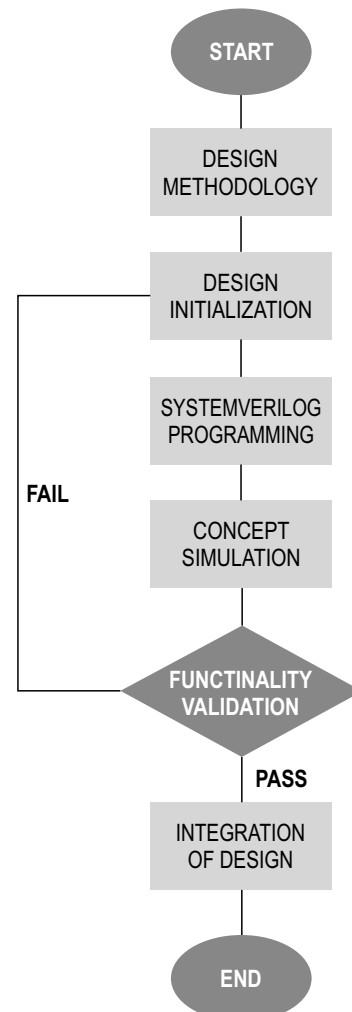
Clock Pulse/ Instruction	T	2T	3T	4T	5T	6T	7T	8T	N(T)	N+1(T)	N+2(T)	N+3(T)	N+4(T)
addi x1,x0,5	IF	ID	EX	MA	WB								
or x5,x3,x2		IF	ID	EX	MA	WB							
and x5,x3,x2			IF	ID	EX	MA	WB						
beq x2,x6,12				IF	ID	EX	MA	WB					
and x11,x3,x7					IF	NOP	NOP	NOP					
									IF	ID	EX	MA	WB

x3, x7, is fetched speculatively in the IF stage at cycle 5T. To prevent the execution of a potentially incorrect instruction, the pipeline implements a stalling mechanism. This stall is explicitly shown by the insertion of no operation (NOP) instructions for the and x11, x3, x7 instruction during clock cycles 6T, 7T, and 8T. This delay ensures that the pipeline waits for the branch outcome to be resolved before proceeding with the correct instruction flow, thereby maintaining program correctness.

RISC-V Processor Design

To implement a processor with both architectures, a rigorous design process is essential. As shown in Figure 4, the design process begins with methodology definition. Next, SystemVerilog coding is performed, followed by simulation for functional validation. If the design passes validation, it proceeds to integration. Otherwise, the process returns to the design initialization phase for optimizations and adjustments, creating an iterative refinement cycle until all requirements are met.

The five-stage pipelined processor shown in Figure 2 is designed to allow instruction operations to overlap, which significantly increases throughput and processing efficiency. The Hazard Unit, shown at the bottom of the diagram, is the crucial control

Figure 4. Implementation flowchart.

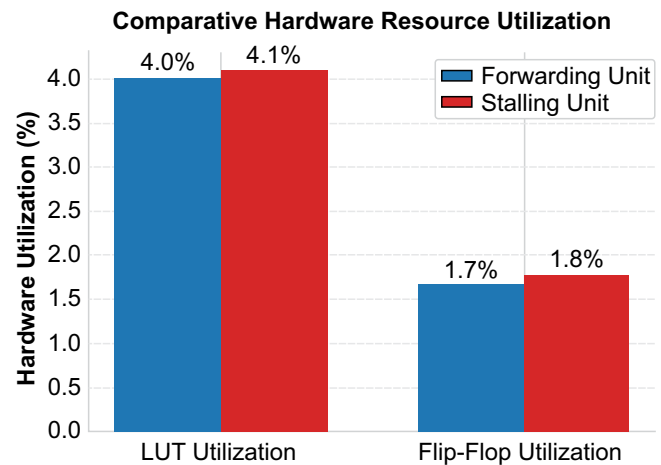
logic for detecting and mitigating hazards in the pipeline. Its function is to ensure correct and timely instruction execution by applying mechanisms such as forwarding and stalling to resolve data and control conflicts.

From that groundwork, two distinct CPU implementations were developed, each adopting a different hazard-handling strategy. The first implementation uses a full stall policy, where pipeline execution halts entirely upon hazard detection, prioritizing design simplicity and predictability. The second implementation incorporates forwarding logic. A comparative analysis between the two CPU implementations will be conducted using the Vivado synthesis analysis tool, enabling informed assumptions regarding the impact of each hazard-handling strategy on performance, resource utilization, and design complexity.

Results

The design was synthesized and implemented on a Xilinx Kintex-7 FPGA (XC7K70T-FBV676-1) using Vivado. Resource utilization—particularly look-up table (LUT) and flip-flop (FF) consumption—was analyzed as a critical factor for embedded CV-QKD deployments, where cost-efficiency and power constraints are key

Figure 5. Percentage of hardware resources.

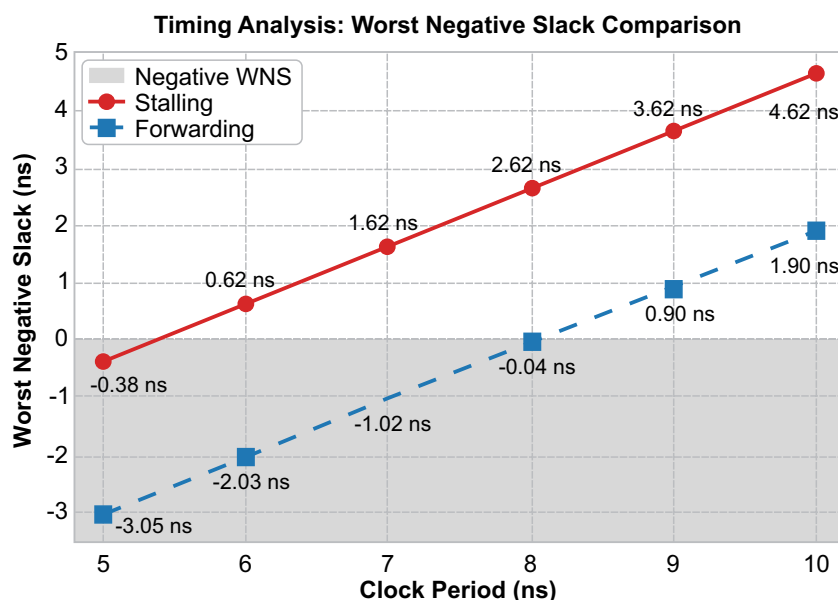


considerations in hardware selection. A comparison between the stall and forward methods is shown in Figure 5.

The results indicate that both architectures exhibit similar resource usage in terms of look-up tables (LUTs) and Flip-Flops, with the forward method demonstrating a slight advantage over the stall method. Figure 6 illustrates the worst negative slack (WNS) observed across varying clock periods for both the stalling and forwarding architectures, as obtained from static timing analysis (STA) reports.

As shown in Figure 6, the forwarding architecture exhibits a consistently negative slack at lower clock periods, indicating poorer timing performance

Figure 6. Contrast between different clock periods.



under aggressive timing constraints. However, its slack improves linearly with relaxed clock periods, eventually meeting timing requirements at 8 ns and beyond. In contrast, the stalling architecture demonstrates superior timing characteristics throughout, achieving positive slack as early as 6 ns clock period and reaching slack of 4.62 ns at 10 ns. This suggests that, while forwarding may offer marginally better resource efficiency, stalling provides more robust timing margins under tighter constraints.

Figure 7 presents the power consumption comparison between forwarding and stalling architectures across varying clock periods, based on post-implementation power analysis performed in Vivado. The results show that the forwarding implementation consistently consumes more power than the stalling counterpart across all evaluated clock periods. This is primarily due to increased dynamic power driven by the additional control logic inherent in forwarding.

To evaluate functional behavior and cycle performance, both the stalling and forwarding architectures were simulated using the RISC-V code example provided in Harris's textbook, as previously referenced. The simulation results are summarized in Table 1. Both implementations produced the correct final value at memory address

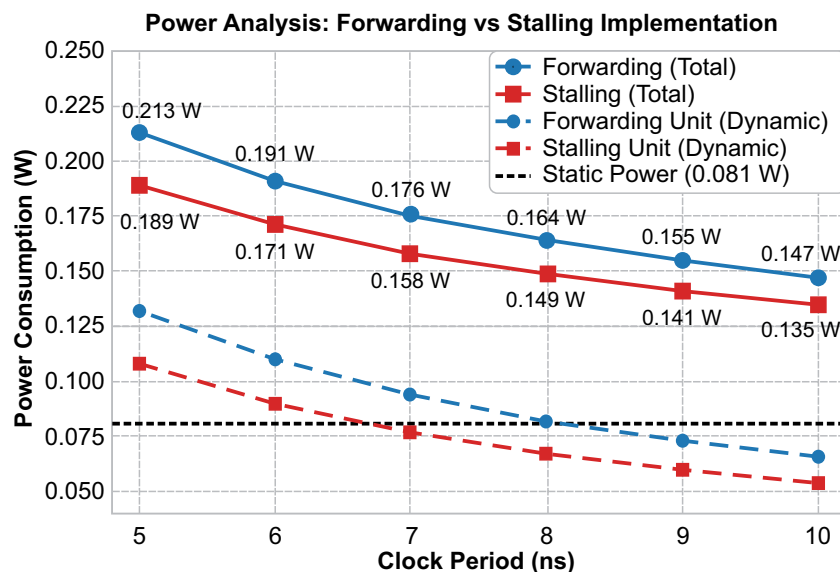
Table 1. Stalling vs Forwarding.

Metric	Stalling	Forwarding
Total Cycles	59	25
Simulation Time (ns)	590	255

100, confirming functional equivalence. However, the forwarding architecture completed execution in only 25 cycles, compared to 59 cycles for the stalling design, representing a 57.6% reduction in cycle count. Consequently, the total simulation time was significantly lower for the forwarding implementation (255.0 ns vs. 590.0 ns), clearly demonstrating its performance advantage due to reduced pipeline hazards and improved instruction throughput.

As shown, the forwarding-based design significantly reduced execution cycles and simulation time, enhancing throughput, which is critical for the time-sensitive post-processing operations in CV-QKD. However, this gain came at the cost of increased power consumption and reduced timing margins under tight constraints. In contrast, the stalling approach showed better performance in timing analysis and lower dynamic power usage, making it a more stable choice for resource-constrained environments.

Figure 7. Comparison between clock periods.



Conclusion

This work explored the development and evaluation of a pipelined RISC-V processor aimed at supporting CV-QKD systems. By implementing and comparing two key hazard mitigation strategies: stalling and forwarding, the study demonstrated the trade-offs involved in optimizing performance, timing robustness, and power efficiency. The forwarding design boosted through-put at the cost of higher power consumption and reduced timing margins, making it preferable for a CV-QKD system ASIP. In contrast, the stalling approach was more power-efficient and stable, making it better for resource-constrained systems.

These findings lay the groundwork for future research focused on refining processor architectures for quantum communication applications, with the goal of achieving optimal trade-offs between speed, efficiency, and reliability.

Acknowledgements

This work was funded by the HW DSP project: Development and Prototyping of a Multicore SoC with Dedicated Accelerators and a DSP RISC-V Processor with Dedicated Instructions for CV-QKD Applications on FPGA, supported by QuIIN – Quantum Industrial Innovation, the EMBRAP II CIMATEC Competence Center in Quantum Technologies, with financial resources from the MCTI IoT/Industry 4.0 Priority Program (PPI), through Cooperation Agreement No. 053/2023 established with EMBRAP II. The authors also acknowledge CAPES (Coordination for the Improvement of Higher Education Personnel) for the financial support provided under Finance Code 001.

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Eps Monolithic Panel System: A Sustainable Alternative in Construction

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The civil construction sector in Brazil is still marked by the predominant use of the conventional masonry method, which has become established due to its reliability, but presents challenges such as material waste and considerable environmental impact. In this scenario, the industry seeks more efficient and sustainable alternatives, such as monolithic EPS panels. These panels offer benefits in terms of thermal and acoustic performance, execution speed, waste reduction, and cost-effectiveness. EPS panels are made of expanded polystyrene, reinforced with galvanized steel mesh and coated with mortar, presenting lightness, versatility, high durability, and, additionally, being a recyclable material. Thus, this study was carried out to analyze the use of monolithic EPS panels as a replacement for the conventional block masonry system, through a literature review and a survey of case studies. To assess the competitiveness of monolithic and conventional construction techniques, a comparative cost analysis was developed based on data presented in indirect studies, making it evident that, regardless of the size of the residence, the monolithic EPS panel system presents a superior cost-benefit ratio compared to the ceramic block system. Furthermore, EPS stands out as a 100% recyclable, odorless, and low environmental impact material, significantly reducing waste generation on construction sites. Another important aspect is that, being prefabricated, the system eliminates waste and optimizes the use of resources, contributing to more sustainable practices. In medium-sized projects, the use of monolithic EPS panels has also been associated with cost reductions of up to 38% when compared to traditional masonry, mainly due to faster execution and lower labor demand. Standardization by ABNT, through standards such as NBR 16866:2022, ensures technical safety and consistency for its application, reinforcing its viability as a modern and efficient alternative.

Keywords: Construction. Monolithic EPS Panels. Expanded Polystyrene. Conventional Masonry.

Brazil's construction sector relies heavily on ceramic masonry and reinforced concrete, traditional methods known for their reliability. However, they pose environmental challenges, including high resource use and waste generation. Sustainable alternatives—like steel framing, drywall, precast concrete, and monolithic EPS (Expanded Polystyrene) panels—offer solutions but face low adoption due to professional resistance and limited information.

Developed in 1980s Italy for earthquake safety, monolithic EPS panels combine EPS cores with galvanized steel mesh and structural mortar. They allow faster construction, thermal and acoustic efficiency, and reduced structural load, enabling flexible architectural design.

Introduced in Brazil in the 1990s and approved by IPT São Paulo, this system remains underutilized due to lack of awareness and hesitation to replace conventional methods. This article evaluates the feasibility of EPS panels as an alternative to traditional systems, considering execution time and cost.

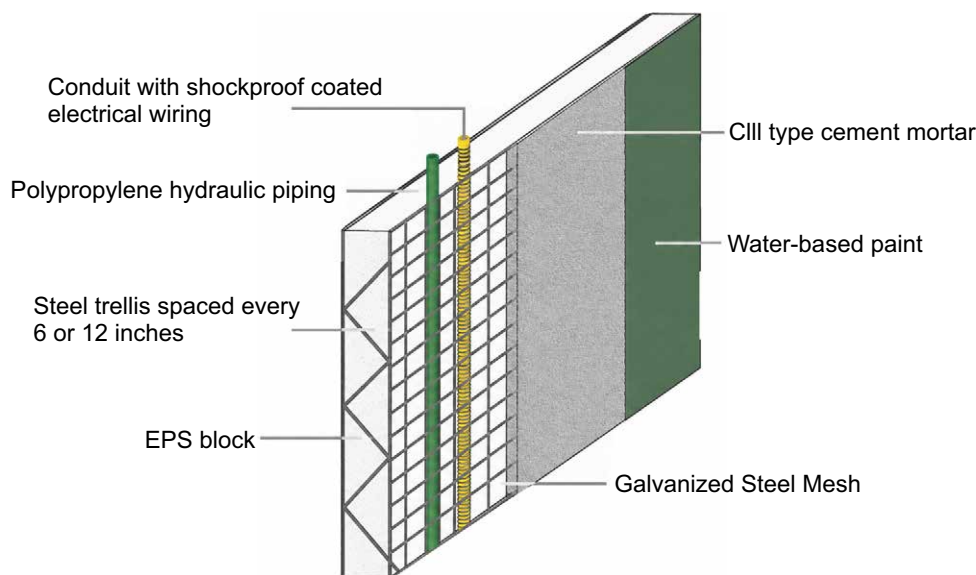
Monolithic Eps Panel System

EPS (Expanded Polystyrene), commercially known as Styrofoam®, is a vapor-expanded plastic composed of 98% air and 2% polystyrene, offering lightweight properties and thermal insulation [1] The system integrates modular panels with structural and closure functions. These monolithic panels feature flat or contoured EPS cores, reinforced with low-carbon steel mesh and galvanized wires. Panels are interconnected with galvanized steel trusses and coated on both sides with micro-concrete ($f_{ck} = 25$ MPa, minimum 3.5 cm thickness), custom-cut per project (Figure 1).

Received on 20 April 2026; revised 25 July 2026.

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J Bioeng. Tech. Health 2026;9(8):861-866
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Figure 1. Structure of the panels.

Source: Barreto [2].

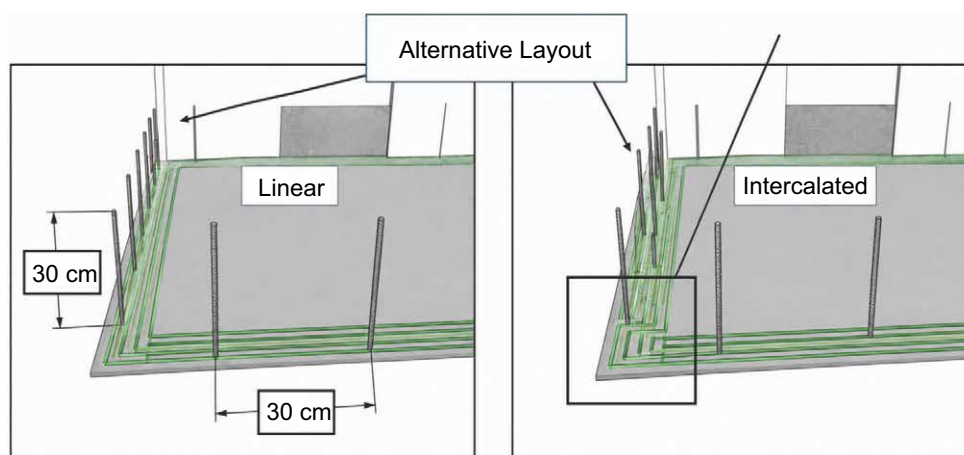
There are different types of panels: basic ones, used for walls and enclosures; double panels, which consist of two panels joined by a concrete core for added strength; curved panels, which are flexible and adaptable to complex architectural designs; and special panels, which include additional insulating materials such as rock wool and cork to enhance thermal and acoustic performance [2].

The construction process using monolithic EPS panels begins with the foundation, typically a raft type, which distributes loads evenly over the soil. Next comes the wall assembly, where panels are secured with steel bars and reinforced at corners and openings (Figure 2). To ensure alignment, braces are used prior to applying the coating [3]. According to Medeiros [4], electrical and plumbing installations are carried out after the wall assembly, with grooves for pipes created using heat blowers (Figure 3). The coating is applied through mechanically sprayed mortar, forming a resistant layer. Slabs and roof structures use special panels reinforced with metal frames to ensure structural stability.

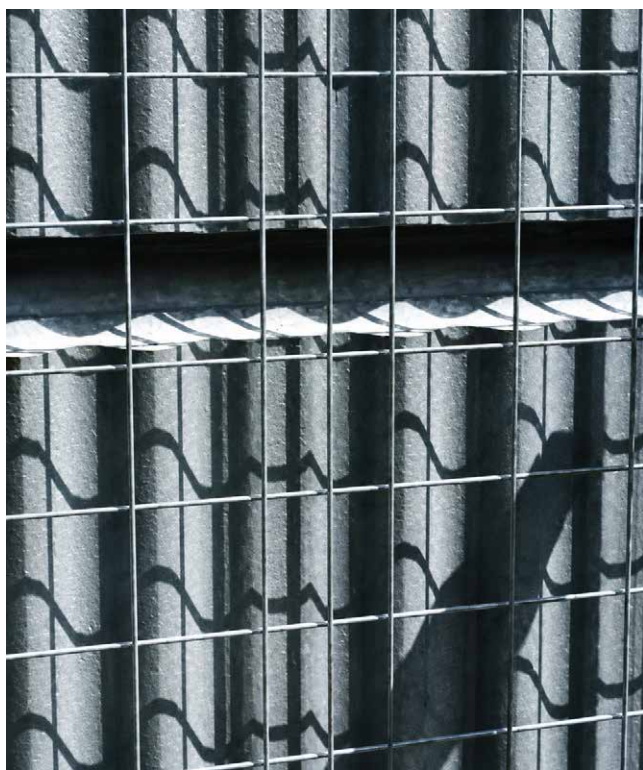
To guarantee quality and safety, the system adheres to technical standards from the Brazilian Association of Technical Standards (ABNT), such as NBR 16866 [5], which defines testing methods for EPS; NBR 11949 [6], which specifies criteria

for apparent density; and NBR 7973 [7], which addresses water of absorption. EPS stands out for its lightness, ease transport and assembly, durability, impermeability, and sustainability. It also offers thermal and acoustics insulation, improving energy efficiency and indoor comfort, while providing high strength—able to bear structural loads without significant deformation. Based on these qualities, this construction system presents an innovative solution for buildings up to six stories high, enabling cost reduction, increased efficiency, and lower environmental impact [2]. Time is a crucial factor in civil construction, affecting cost, planning, and client satisfaction. The traditional method involves a rigid sequence of steps that cannot be expedited, with each phase depending on the completion of the previous one, often resulting in delays. Stages such as site layout, masonry, installations, and finishes take considerable time, usually leading to higher expenses due to labor and equipment rentals. Innovations like concrete 3D printing can help reduce time but do not eliminate the sequential nature of the process.

In contrast, the EPS system allows for fast assembly, with prefabricated panels that can be installed in just a few days. Installations, such as plumbing and electrical systems, are more

Figure 2. Configuration of anchoring rods.

Source: CASSAFORMA [3].

Figure 3. Groove cutting for auxiliary installations.

efficient with minimal cutting, and finishes like mortar application are also quicker—reducing total construction time and consequently labor and equipment costs. However, the installation of additional systems, such as insulation or sealing, may require extra time depending on the design.

While EPS offers a more agile and economical solution, choosing between the two methods depends on the type of project, budget, and client requirements. The traditional method remains preferred for builds requiring greater robustness and customization, while EPS is ideal for faster, more efficient construction. Table 1 summarizes the characteristics of both methods.

Materials and Methods

This qualitative and exploratory study compares monolithic EPS panels with conventional masonry systems over a 15-year period (2009–2024), emphasizing the last five years. The research followed three main stages:

Literature Review: Identified key concepts, technical characteristics, construction processes, and regulations related to EPS panels and traditional masonry. Sources included CAPES Journals Portal, SciELO, and ABNT standards such as NBR 16866 [5].

Case Study Analysis: Examined execution time and cost data from two projects—Casa A (low-income housing in Paraíba) and Casa B (high-end residence in Camaçari-BA) both utilizing EPS panels, allowing direct structural and financial comparisons.

Table 1. Comparison between traditional and EPS construction methods.

Aspect	Traditional Method	EPS Method
Rental Time	Long (weeks to months)	Short (days to weeks)
Installation and Assembly	Sequentially, with several steps requiring more time and coordination between teams.	Fast installation of prefabricated panels, reducing assembly time.
Utilities Installation	Deep and detailed grooves for electrical and hydraulic piping, requiring more time and possibly leading to rework.	Minimal cuts to embed piping, speed up the process and reduce wall impact.
Finishes	Time-consuming steps such as roughcast, base coat, and plaster, requiring additional drying and curing time.	Fast application of projected mortar, with shorter drying times.
Total Time	High (months, depending on project and conditions).	Low (weeks, with significant total time reduction).
Labor Costs	Generally higher due to the need for more workers and time-consuming steps.	Lower labor costs, as the work is faster and requires fewer professionals.
Equipment Costs	Higher, due to prolonged use of heavy equipment and tools.	Lower equipment costs, assembling prefabricated panels requires fewer heavy tools.
Adaptability to Site	High flexibility, allowing adjustments according to local conditions and project requirements.	Lower flexibility, as the system is more standardized and may not adapt well to certain types of projects.
Durability and Maintenance	Lower needs for maintenance over time, especially in stable climates.	May require specific care in certain climates, such as protection against excessive moisture.
Sustainability	Higher waste generation and material waste during construction.	Less material waste and better resource utilization, contributing to more sustainable practices.
Execution Complexity	More complex processes, with more steps and greater chances of execution errors.	Simpler and more direct execution, with lower chances of mistakes and rework.

Comparative Evaluation: Synthesized findings into tables to assess cost-benefit, environmental impact, and waste generation. The analysis highlights the advantages and challenges of adopting EPS panel systems in Brazilian construction.

Results and Discussion

Two case studies demonstrate the technical, economic, and sustainable feasibility of the monolithic EPS system in Brazilian civil construction.

House A, analyzed by Balbino [1], is a low-income single-family home of 46.80 m² with thermal-acoustic roofing and basic rooms. Based on SINAP data from June 2020 (Paraíba), EPS construction resulted in a 29.13% cost reduction compared to the conventional method, totaling R\$35,022.43 versus R\$49,421.77 for traditional masonry. This reduction is attributed to lower infrastructure demand and efficient planning of electrical and hydraulic systems. In addition, the panel assembly requires significantly less time than building walls and structures.

House B, studied by Garcia [8] is a 361.66 m² two-story residence with leisure areas, kitchen, and a kiosk. Built using the monolite method, it demonstrated lower material costs and faster execution, according to SINAPI [9, 10] data from the second half of 2009. The lightweight nature of the panels reduced structural reinforcement needs, positively impacting foundation costs. Although the study didn't specify labor hours, it emphasized reduced labor demand.

Both buildings reinforce the technical and economic advantages of EPS, which also stands out for its sustainability, being recyclable and environmentally viable. The findings suggest that EPS is a strategic alternative, especially for affordable housing, offering cost savings, faster construction, and ecological responsibility.

Comparative analysis has shown that the monolithic EPS system is economically advantageous, with cost reductions of 29.13% in House A and 38.42% in House B (Table 2).

Larger projects present even more significant savings, making EPS an efficient alternative. In addition to cost reduction, sustainability stands out, as conventional masonry consumes more natural resources and generates greater waste. EPS also offers constructive efficiency by enabling swift assembly and the pre-planned integration of plumbing and electrical systems, reducing the need for rework.

By contrast, conventional masonry involves more time-consuming procedures. However, challenges such as limited access to suppliers and a shortage of specialized labor hinder its adoption, especially in less developed areas. The results show that in larger constructions, proportional savings with EPS are even greater. Its feasibility for low-income housing is promising, as it reduces costs and accelerates construction without compromising structural quality. Thus, expanding the use of EPS can contribute to a more efficient and sustainable sector, aligned with the contemporary demands construction in Brazil.

Table 2. Case study summary.

PROJECT		HOUSE A		HOUSE B	
		[1]		[8]	
Description	Location	Paraíba		Busca Vida, Camaçari - BA	
	Typology	Low-income		High-end	
	Built Area	46.80 m ²		361.66m ²	
Space Program	Program	Living/dining room, two bedrooms, kitchen, circulation, bathroom, and service area		2 Living rooms, 3 suites, 2 bathrooms, leisure area, 1 kitchen, and 1 kiosk	
	No. of floors	1		2	
Structural System	Foundation	Pile		Pile	
	Structural System	EPS monolithic panels	Reinforced concrete	EPS monolithic panels	Reinforced concrete
	Partition System	EPS monolithic panels	Ceramic blocks	EPS monolithic panels	Ceramic blocks
Total Cost	Total Cost	R\$ 35.022,43	R\$ 49.421,77	R\$ 100.491,36	R\$ 163.199,47
	Cost reduction (%)	29.13%		38.42%	

Conclusion

Monolithic EPS panels emerge as an innovative and sustainable alternative to conventional masonry, significantly reducing material waste, environmental impact, and execution time. Lightweight, versatile, and offering thermal and acoustic efficiency, these panels allow for fast assembly and reduced demand for specialized labor.

Cost analysis revealed substantial savings: a 29.13% reduction in the smaller house and 38.42% in the larger one, highlighting the economic viability of the system. Moreover, EPS required fewer natural resources and less time, underscoring its superiority in terms of sustainability.

In the context of Brazil's construction sector, broader adoption of EPS panels could modernize the industry and align it with current demands for resource optimization and sustainable practices. However, overcoming cultural and technical barriers remains essential. This includes promoting public policies, professional training, and reliable information dissemination on EPS applications.

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Exploring Evidence of Presence in Gamified Virtual Reality Training to Empower Construction Professionals

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The construction sector is inherently complex, dynamic, and hazardous, ranking among the industries with the highest rates of occupational accidents. Even experienced professionals, despite prior training, often struggle to effectively recognize and manage risks. The construction industry is one of the sectors that employs the most people in the country, and has a high rate of accidents and deaths, with working at heights being one of the main causes of this. The lack of training and awareness among workers so that they can recognize risk situations is one of the factors that appear to cause this situation. To obtain positive rates regarding the minimization of accidents, responsibilities must be met, through Regulatory Standards NR18 and NR35. This study aims to evaluate the effectiveness of virtual reality training for work at heights by analyzing users' sense of presence through both subjective and physiological measures. The study presents findings from a VR simulation conducted in a laboratory setting with 14 participants, all with no prior experience in such activities. Data was collected during and after the experiment to assess signs of presence. The results indicate that the practical application of VR generates a strong sense of presence among participants, suggesting that virtual reality may be a promising solution for training professionals in high-risk construction tasks. The contribution of this study is, in addition to advancing research on the practical use of virtual reality for training construction professionals, to prove the effectiveness of VR for training the target audience without risk to life.

Keywords: Virtual Reality. Gamification. Construction. Working at Height. Safety Training.

The construction industry is considered complex, dynamic, and dangerous [1]. Worldwide, it is one of the leading sectors for accidents at work, causing substantial economic losses, according to the International Labor Organization. Despite regulations and ongoing efforts, the incidence of accidents remains unacceptably high, indicating a persistent gap in current training approaches. Human factors, such as inattention and negligence, are responsible for many of the disasters that occur on construction sites. The interactions between human beings, the working environment, and working conditions mean that errors are a consequence when minimum safety standards are not applied. In Brazil, working at

heights in construction has explicit requirements in Regulatory Norms NR18 [2] and NR35 [3].

Estremote and Oliveira [4] analyzed accident prevention measures in activities at height and noted that they occur mainly due to three factors: poor training, which in itself has an impact on workers' lack of awareness so that they can recognize risk situations and on the incorrect use of protective equipment; lack of inspection and monitoring by professionals in the relevant area, which has an impact on the degree of pre-existing risk; and negligence, especially in the safekeeping and conservation of equipment. Few studies combine physiological and experiential data to evaluate training realism and user engagement. Thus, the need for more effective training is evident.

In this context, virtual reality (VR) and gamification have emerged as allies in training for more conscious work at height. VR immerses users in a realistic, computer-generated simulation [5],

Received on 15 April 2026; revised 26 July 2026.

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J Bioeng. Tech. Health 2026;9(8):867-873
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while gamification applies game-design elements to non-gaming contexts to enhance motivation and engagement. When combined, these approaches can create highly effective and safe learning experiences [6]. Slater and colleagues [7] state that immersion and presence are distinct concepts and clarify that high technological immersion is necessary but not sufficient for effective participant presence; it also requires appropriate experiential design.

The results of a VR simulation with 14 participants with no experience of working at height are presented to verify the level of presence evidence of these individuals by analyzing the data collected during and after the experiment.

Therefore, this study aims to evaluate the effectiveness of virtual reality training for work at heights by analyzing users' sense of presence through both subjective and physiological measures.

This article is organized as follows: Section 2 describes the methods used; Section 3 presents the experiment; Section 4 analyzes the results and discussions; and Section 5 provides our final considerations.

Materials and Methods

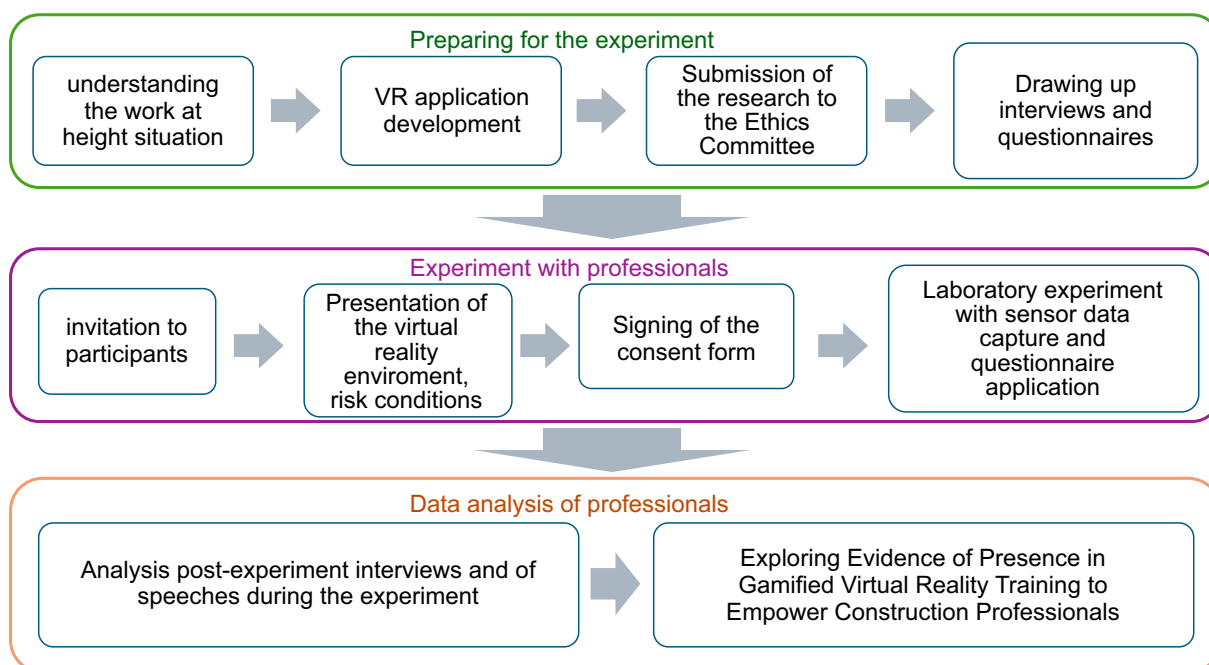
The methodological approach adopted is experimental, conducted in a laboratory without a control group. The aim is to refine the device for evaluation by experienced workers at heights. Figure 1 details the protocol for this experiment.

After understanding the situation, the experiment was prepared in detail, consisting of analyzing the reactions and perceptions of participants using headsets programmed for working at height in construction. The experiment used a Meta Quest 3 headset and a Samsung Galaxy Watch 7 to measure heart rate, which will be evaluated later. This article focuses on the analysis of the speeches collected during and after the experiment.

The research was submitted to the ethics committee for working with human beings in accordance with current legislation, Resolutions No. 466/12 and 510/16, and approved under opinion number 7.247.106. To carry out the research, the Terms of Free Consent for the participating public were used.

The target audience was made up of 8 building technician students over the age of 18 and 6 civil

Figure 1. Research flowchart.



construction teachers, who are therefore professionals without prior knowledge of working at height but who are aware of the requirements imposed by the regulatory realism of environmental elements [8].

The sources of evidence were the researchers' observations, audio data, and semi-structured questionnaires applied after the experiment.

All participants particularly enjoyed the weather changes and visual effects, which contributed to the authenticity of the experience. However, two mentioned that the lack of platform movement and the simulated wind detracted from the potential for immersion. Both wanted to feel, in addition to the visual and audio effects, the platform moving underfoot and the sensation of the wind against their skin.

This article presents and discusses the evidence of presence collected during the experiment. To this end, the following constructs will be observed:

(a) Adaptation/Immersion refers to the extent to which participants naturally feel integrated into the virtual environment, considering factors such as ease of adaptation and the perceived;

(b) Engagement measures the cognitive and emotional involvement of participants, with a focus on their attention to the tasks and emotional responses during the simulation [8].

(c) Interface quality assesses the usability and responsiveness of the tools and controls within the virtual environment, influencing user interaction and comfort [8].

(d) Sensory fidelity refers to the perceived accuracy and realism of sensory stimuli, including visual, auditory, and tactile feedback provided by the virtual system [8].

The Experiment.

The experiment used virtual reality to simulate the task of painting a 33-meter building facade from a suspended platform, aiming to assess user responses in a high-risk, immersive scenario.

The simulation goes through 4 stages that reflect real-world tasks: Application of Personal Protective Equipment (PPE), Workplace Assessment, Platform Operation, and Surface Preparation and Painting. Figures 2 and 3 show scenarios from this simulation.

To increase realism, dynamic environmental factors, such as changes in weather from clear skies to thunderstorms, were simulated using a specialized Unreal Engine 5 plugin. Realistic sound signals, including thunder and rain, accompanied these situations.

Figure 2. Platform on the ground.



Figure 3. Platform at a height of 33 meters.



The session began with a narrative approach to working at height, highlighting the importance of the tasks to be carried out and the time constraints. The four phases of the simulation were explained: the choice of PPE, how to operate the ascent and descent of the platform, the need to observe the weather conditions, and the washing, sanding, and painting work to be carried out.

The participant was then taken to the location to put on the Meta Quest 3 headset, and the simulation began with audio recording during the experiment and heartbeat capture (Figure 4).

Gamification elements were introduced by creating decision-making scenarios under pressure, requiring participants to choose between adhering to safety protocols or maximizing task efficiency in adverse weather conditions.

For example, they could stop working and lower the platform if the weather conditions became unfavorable, generating different simulated results. After the simulation, Meta Quest 3 and watches were collected, and questionnaires were administered.

Results and Discussion

Evidence of immersion was collected during the experiment. We selected the feedback from

Figure 4. The experiment VR.



some of the participants. Table 1 presents the participants' statements during the simulation and responses to interviews.

All the participants found the simulation immersive or realistic. Many were unfamiliar with virtual reality, which made them very focused on carrying out the tasks. After a short learning period, the participants were able to use the interface. Nonetheless, all participants reported initial difficulties with understanding the controls. Many felt confused by unclear progress indicators and suggested improvements to enhance guidance during the simulation.

All the participants particularly enjoyed the weather changes and the visual effects, which contributed to the authenticity of the experience. However, two of them mentioned that the absence of platform movement and wind simulation hindered the full potential of immersion. The introduction of these elements could make the environment even more dynamic and realistic.

This analysis is conducted through the lens of existing literature:

Immersion and Realism

Phrases like “Wow! It’s high.” and “I’m not even going to look down there” reflect a strong spatial and emotional response, which aligns with Slater’s definition of place illusion, the sensation of “being there” in a virtual environment. According to Slater, presence emerges when users respond to virtual stimuli as if they were real, regardless of knowing they are not [9]. Slater [10] highlights that presence intensifies when users emotionally respond to the virtual environment as though it were real.

Engagement with the Task

The sequence: “I started sanding... It’s almost finished... Now I’ll apply the paint” illustrates how users internalize the virtual task flow. Slater [10] suggests that presence is reinforced when the environment allows coherent, goal-oriented behavior that mirrors real-world logic.

Lamas [11] suggests that engaging in specific tasks within VR strengthens the sense of being “in” the experience.

Interface and Interaction

Although technical issues like “I know I don’t know how to paint, but this is too much” may seem outside the scope of presence, Slater argues that sensorimotor consistency and plausibility are essential for maintaining presence. When system responses break expected patterns, the illusion of presence can be disrupted.

McMahan [12] argues that interface glitches can interrupt presence, while smooth, intuitive interactions help sustain it.

Sensory and Emotional Reactions

Heightened Emotions and Disorientation: Reactions such as “Guys, did I die then?” and “Osh, did I fall?” demonstrate behavioral realism, a key indicator of presence. Slater emphasizes that presence is not merely engagement, but a psychological state where users behave in VR as they would in real life situations.

Curiosity and Exploration Attempts: The question “What is this button for?” reflects active engagement with the environment. Slater notes that presence is enhanced when the virtual world responds appropriately to user actions, reinforcing the illusion that their behavior has meaningful consequences.

Spontaneous narratives and environmental integration: Weather-related remarks such as “Man, it’s going to rain.” or “...just when I started painting there was a thunderstorm...” illustrate how participants assign narrative meaning to their experience. This reflects the concept of contextualized comprehension, which is aligned with situated learning theory.

Strong emotional reactions have been recognized as core indicators of presence in virtual environments, especially in high-risk simulations where users respond to the virtual context as if

Table 1. Participants' statements during the simulation and responses to interviews.

	Speeches During the Experiment	Interview Responses
Adaptation/ Immersion	“Wow! It’s high.” (P11) “It’s going up. That’s crazy.”	“At first, I was very scared, because I’m afraid of heights, but I also found it difficult when I thought about the worker who actually does this every day, how dangerous it is” (P11).
	“I’m not even going to look down there. Okay. Oh, okay. Now I get it.” (P10) What a scare. I think so. Mercy! (P10)	“Walking on the platform. Because it swayed. Even though I knew it was secured by the steel bars, right? It still swayed and was a little scary, especially when turning to pick up the equipment.” (P11).
Involvement	“I started sanding. ... It’s halfway done. ... It’s almost finished It’s finished. Now I’ll apply the paint. It’s started.” (P1) “Oh no, man. Oh no. I don’t believe it. How slow of me. The weather is starting to get dark, and I’m working there.” (P10)	“It involves that challenge where you have to face the altitude and you have to, yeah... simulate the work, which is you sanding, cleaning, and, yeah, managing to do your job properly.” (P9) You forget about the environment around you. You, you’re there on the construction site” (P6)
Interface Quality	“What is this button for?” (P10) “It’s not loading. I’m fully inside the paint bucket and the red bar is... It keeps saying ‘preparing painting material,’ and it stays red the whole time. I can’t make any progress with this... And here on the wall, it doesn’t do anything either. I know I don’t know how to paint, but this is too much. I should at least be able to splatter something here.” (P4)	“I noticed some difficulty with certain mechanics, for example, the painting one, which I think is more about fine details to help improve the experience, you know? Like when it was time to prepare the paint, I wasn’t really sure what to do. You had to put the brush in and pull...” (P3)
Sensory Fidelity	“Everything is black, a simulated serious accident, you were the victim of a serious accident. Thank you... Did I die? I didn’t die, right?” (P1) “Wow! What happened?” (P2) “Osh, did I fall?” (P5) “Guys, did I die then?” (P12) “Simulated serious accident. You were the victim of a serious accident because you continued working in conditions... Oh, no. I didn’t notice.” (P4) “Wow! It’s all dark in here, you, see? (P7) It’s cloudy! (P11) “Man, man, it’s going to rain. It can’t be. Man, the weather here looks like it’s going to be a downpour. (P10) “Oh no, man. Oh no. I don’t believe it. How slow of me. The weather was starting to get dark, and I was working.” (P10) “..just when I started painting there was a thunderstorm... (P4)	“It’s a new experience, because I’ve never done anything like that. And it gave me a little adrenaline rush, like, it was a bit nerve-wracking and stuff.” (P12) “And I believe that it is also important to pay more attention to the weather, right? Because at first it was just cloudy and then it started raining out of nowhere.... And then there was this accident.” (P11)

it were real, an idea supported by both Maples-Keller et al. [13] and Slater [14], who emphasizes that authentic emotional engagement reflects the plausibility and immersive quality of the scenario.

Conclusion

This article presents the first results of a larger experiment involving professionals with no experience of working at height. In this research, it is believed that immersive technologies, when combined with elements such as gamification, physical objects, and storytelling, can improve the quality of the height training usually provided to construction workers. The aim is to further evaluate this technology to improve the model used.

The analysis reveals multiple types of presence that go beyond visual perception, including emotional immersion and task engagement. Key considerations include the importance of intuitive interfaces and environments enriched with realistic stimuli.

It is suggested that future VR experiences optimize sensory and narrative elements to enhance their formative and emotional impact. As a limitation, the study involved 14 participants with no experience working at heights and no experience with VR.

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A Bibliometrics of the Analysis Methods of 3D Printed Concrete Structures

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3D concrete printing (3DCP) has revolutionized the construction industry, allowing for the production of complex geometries with greater efficiency and sustainability. This is despite ongoing challenges with structural reliability and long-term performance, which are due to the material's anisotropic properties and layer interfaces. This study performed a bibliometric analysis of the literature on the structural analysis of 3DCP, using VOSviewer to identify research trends and gaps. The methodology included a keyword search in the Scopus database, which resulted in 108 selected articles after a rigorous screening process. The results indicate a significant increase in 3DCP research since 2018, with a projected peak of 40 articles published in 2025. A co-occurrence analysis of keywords revealed a concentration on "concretes," "concrete printings," and "finite element method," highlighting research into material failure and behavior. The 108 works, authored by 374 individuals, were distributed across 8 clusters, with 23 papers showing co-authorship. Maximiliano Cremonesi, Liberato Ferrara, and Giacomo Rizzieri had the strongest collaborations between 2024 and 2025. China and the United States lead in publications, with 37 and 12 articles, respectively, and China also leads in collaborations with 14. The Journal of Building Engineering was the most relevant journal, with 11 publications. Despite these advancements, the study points to significant gaps, such as the need for more sophisticated numerical models to simulate interlayer and multi-scale interactions. The integration of structural reinforcements and a better understanding of the long-term durability of 3DCP are also critical challenges. Furthermore, there is a major opportunity for research in multifunctional materials and the application of artificial intelligence and machine learning to optimize design and predict performance, thereby boosting sustainability in 3DCP.

Keywords: 3D Concrete Printing, Structural Analysis, Finite Element Method, Bibliometrics.

The civil construction industry has witnessed a significant transformation with the advent of 3D concrete printing (3DCP), an additive manufacturing technology that offers the potential to revolutionize how structures are designed and built [1-3]. By enabling the production of complex geometries with greater efficiency and sustainability, 3DCP represents a promising advance compared to conventional construction methods [4,5]. This innovation not only accelerates the construction process but also minimizes material waste and can reduce labor costs, making it an area of growing interest in global research and development [6-8]. However, the widespread implementation of 3D-

printed concrete structures still faces challenges, particularly regarding their structural reliability and long-term performance [9-11].

Unlike traditional cast concrete, 3DCP exhibits distinct characteristics due to the layer-by-layer deposition process, such as the anisotropy of mechanical properties and the presence of interfaces between printed layers [12,13]. Structural analysis, therefore, plays a crucial role, providing the necessary tools to predict performance under different loading conditions and to optimize design and printing parameters. Numerical modeling, and in particular the finite element method (FEM), emerges as an indispensable tool for investigating the behavior of 3D-printed concrete structures [10,14-17].

Methods like FEM allow for the simulation of the layer extrusion and deposition process, the evaluation of the hardened properties of printed concrete [18], and even rheological and fresh-state properties [14,19]. Recent studies have explored various approaches to model the anisotropic

Received on 28 April 2026; revised 21 July 2026.

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J Bioeng. Tech. Health 2025;9(8):874-881

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behavior and the phenomena of damage and plasticity in 3D-printed materials [20-24].

In this context, this research aimed to conduct a bibliometrics of the literature on the structural analysis of 3D-printed concrete, strictly following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [25] to ensure the transparency and reproducibility of the methodology. The VOSviewer software [26] was used to map research trends, identify the main areas of investigation, the most influential authors and journals, and the existing collaboration networks in the scientific community.

Materials and Methods

To conduct the research, the PRISMA guidelines were strictly followed [25]. This three-phase approach—search, selection, and data analysis—allowed not only for the identification and critical selection of research literature but also for the evaluation and generation of new perspectives on the analysis of 3D-printed concrete structures.

Initially, the data search phase, conducted in June 2025, used a keyword search in the Scopus database by evaluating titles, abstracts, and finally, reading the full text.

The search terms were selected to cover the main areas of interest for the review and were combined using Boolean operators (AND, OR) to maximize the scope and relevance of the results. The combination of keywords and Boolean operators adopted was "3D Concrete Printing" AND "Finite element" AND ("structural analysis" OR "experimental testing" OR "experimental program" OR "numerical simulation" OR "numerical modeling"), to identify relevant articles in the Title, Abstract, or Keywords fields.

The articles resulting from this search were then analyzed and selected based on the PRISMA criteria for subsequent evaluation. The publication period was not defined, allowing all articles related to the topic to be searched up to the present.

The metadata of the eligible articles included, such as authors, keywords, citations, and co-

citations, were collected and processed. The VOSviewer software (version 1.6.15) [25] was the central tool for visualizing and analyzing these bibliometric relationships.

VOSviewer enabled the creation of maps based on keyword co-occurrence, which is fundamental for identifying emerging themes and key research areas.

Additionally, co-authorship analysis was employed to map the collaboration networks among researchers and institutions. This allowed for the identification of prominent research groups and the extent of collaborations in the field.

Another crucial aspect was the analysis of author co-citation, a sociographic analysis of the countries of origin of the research, and journals. By examining which authors or publications are frequently cited together, VOSviewer helped identify the most influential works and high-impact journals that have shaped the development of the field.

Finally, VOSviewer's ability to visualize the evolution of research clusters over time was explored. This allowed for tracking the emergence of new sub-areas, the decline of others, and changes in research priorities, providing a dynamic understanding of the progress in the study of structural analysis of 3D-printed concrete.

Results and Discussion

The results of the bibliometric analysis offered a synthesis of the current state of research and are critically presented and discussed in this section, highlighting emerging trends, main topics of investigation, and existing knowledge gaps.

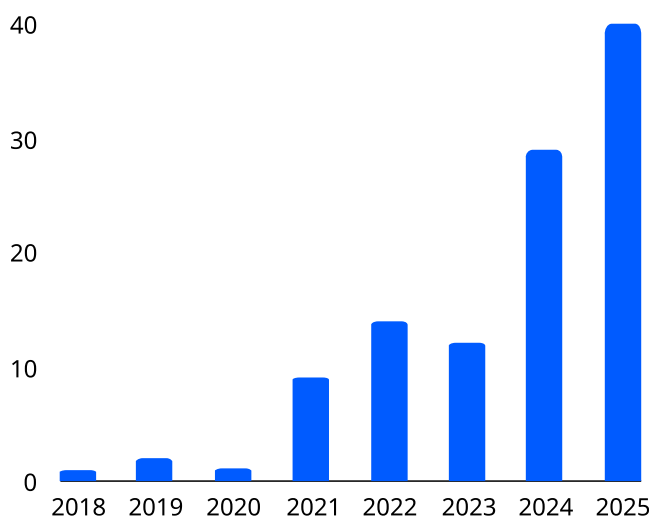
Descriptive Analysis

After applying the PRISMA protocol, 108 articles were included for the bibliometric analysis. This analysis reveals that research on the structural behavior of 3DCP began in 2018, as shown in Figure 1. This first paper presented a numerical and experimental analysis of the mechanical

behavior of fresh 3D-printed concrete [27]. It is important to note that older studies involving 3DCP are found in the literature, but under a broader approach involving 3D printers and printing systems, material research, equipment and technology, design, and impacts on the civil construction sector [28].

Research involving structural analysis, whether experimental, numerical, or combined, has intensified over the last five years, with a maximum of 40 articles published in 2025.

Figure 1. Descriptive analysis of publications.



Keyword Co-occurrence

The mapping of keyword co-occurrence allowed for the identification of distinct clusters, indicating the main areas of investigation. In total, 1033 keywords were used, and 62 reached a minimum volume of five occurrences. Figure 2 presents the sociogram of this analysis. Table 1 shows the top 15 keywords analyzed.

The 62 items presented in the sociogram in Figure 2 contain 662 links and a total link strength of 4474. For example, "concretes" appears in the center of Figure 2, with the largest number of links (329).

The colors in this figure indicate the research periods, with yellow signifying more recent research (2024) and purple indicating older research (2022).

Co-authorship Analysis

The co-authorship analysis allowed for the identification of various groups of authors researching a common theme. The 108 analyzed works were written by 374 authors. Considering a minimum of 3 works written by each author, 23 works were distributed into 8 clusters, as shown in Figure 3. Additionally, 85 links were observed between the authors with a total link strength of 104. The strongest links were from authors Maximiliano Cremonesi, Liberato Ferrara, and Giacomo Rizzieri, with a total link strength of 8 each, and their works were published between 2024 and 2025.

Sociographic Analysis of Countries

The analyzed works originate from 35 different countries, with China and the United States having the highest number of publications, at 37 and 12, respectively. The countries with the most collaborations were China, with 14, and Australia, with 13. Figure 4 shows the results of the sociographic analysis between countries.

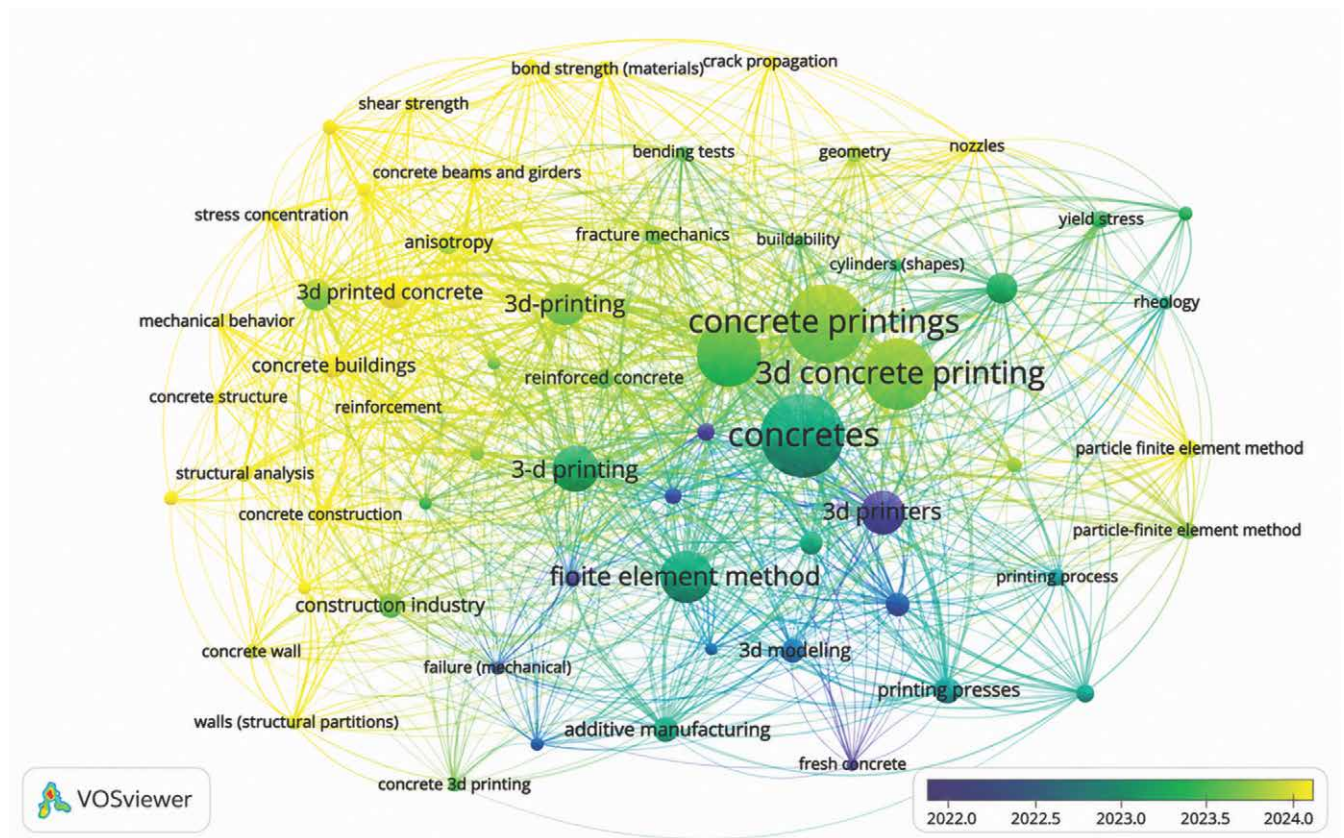
Sociographic Analysis of Sources

This analysis made it possible to identify the most relevant journals on 3DCP structural analysis. The articles were published in a total of 41 journals, and by considering a minimum of 2 articles and one citation per journal, this sample was reduced to 19 and is presented in Figure 5.

The most relevant journal was the Journal of Building Engineering, with 11 publications, 315 citations, and a total link strength of 7.

Research Gaps and Future Directions

The bibliometric investigation identified growing advances in research as well as the main gaps related to 3DCP structural analysis. The keyword analysis found a concentration in research related to the failure analysis of 3DCP

Figure 2. Sociogram of co-occurrence of keywords.**Table 1.** Co-occurrence of keywords.

S n°	Keyword	Occurrences	Total Link Strength
1	Concretes	48	329
2	Concrete printings	45	283
3	3d concrete printing	40	222
4	3d printing	36	249
5	Finite element method	28	219
6	3-d printing	24	175
7	3d printers	23	155
8	3d-printing	22	152
9	3d printing concrete	17	90
10	Extrusion	15	121
11	Compressive strength	15	95
12	Printing presses	13	104
13	Additive manufacturing	12	85
14	Numerical model	11	93
15	Construntion industry	11	82

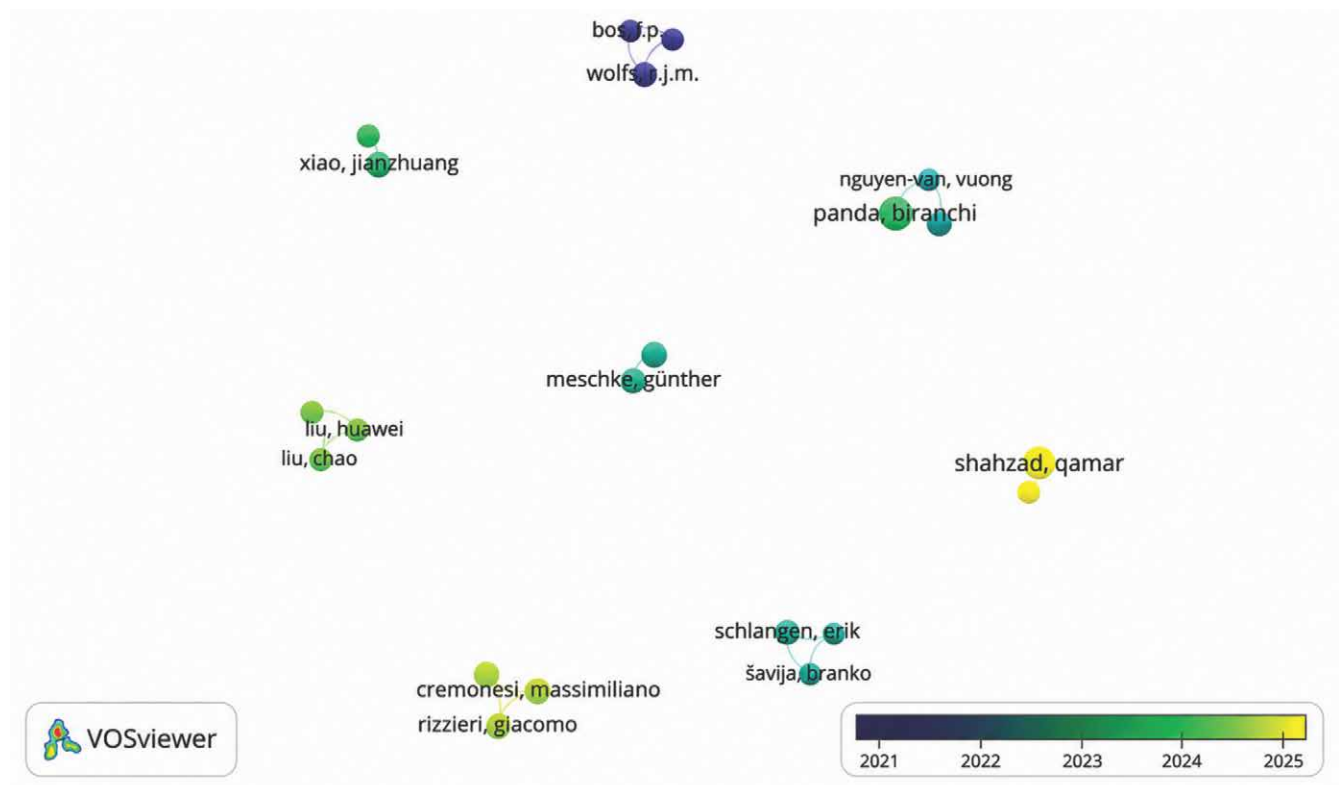
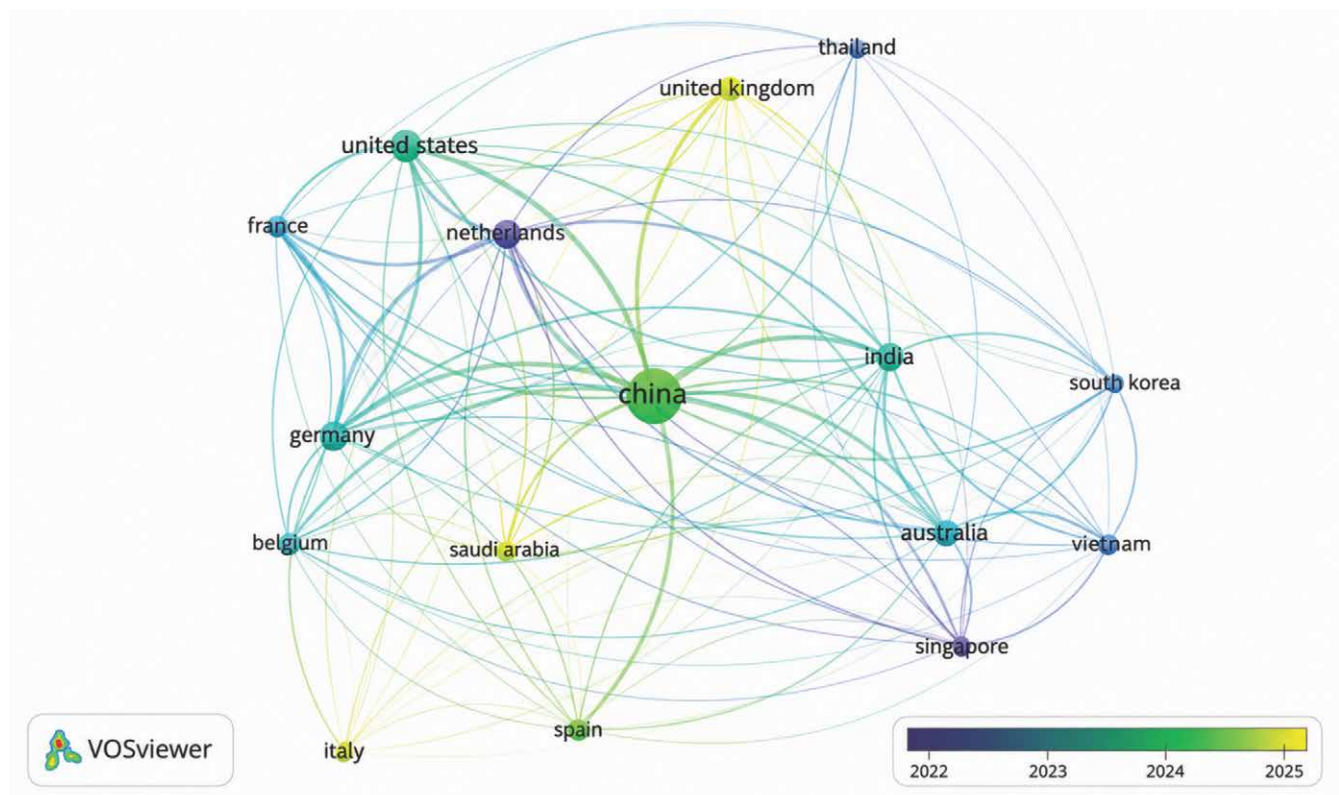
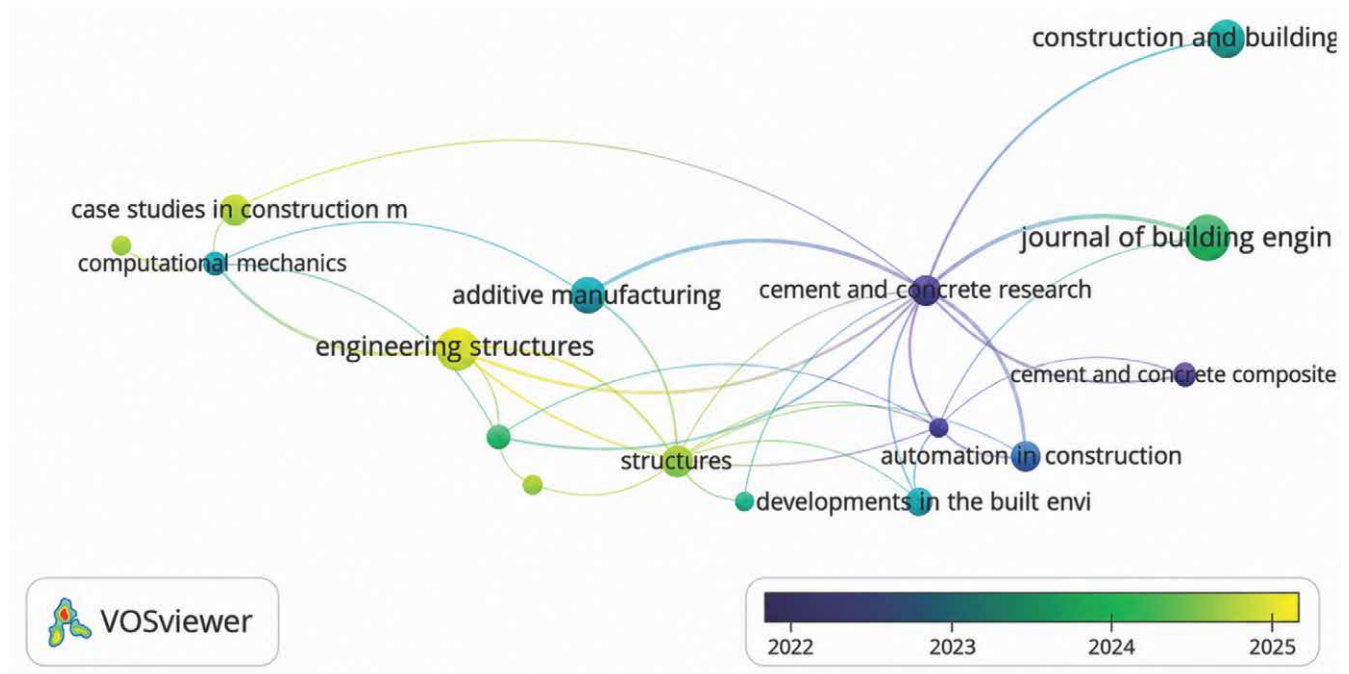
Figure 3. Sociogram of co-authorship.**Figure 4.** Sociogram of co-authorship.

Figure 5. Sociogram of the sources.

in its hardened state and methods based on fluid dynamics for the fresh state.

The development of more sophisticated numerical models that better simulate interlayer interactions and multiple length scales (micro, meso, macro) is a promising future direction.

Models based on Smoothed Particle Hydrodynamics (SPH) [29] and the Particle Finite Element Method (PFEM) [14, 19] are being developed to simulate the flow and deformation behavior of cement paste during 3D printing, considering the material's rheological behavior and properties.

Integrating structural reinforcement into 3D-printed concrete is a significant challenge due to the anisotropy and interfaces created by layer-by-layer deposition. This makes it difficult to incorporate conventional steel bars and properly orient fibers [24, 29-30]. Optimized reinforcement designs aim to improve the structural performance and ductility of 3DPC.

There is a knowledge gap regarding the long-term performance and durability of 3DPC structures, despite the contribution of numerical simulation to understanding failure mechanisms.

It is essential to investigate how the properties of 3D-printed materials evolve over time and the impact of environmental factors on structural integrity.

The bibliometric analysis also identified a gap in the integration of artificial intelligence (AI) and machine learning (ML). Such tools offer transformative potential for predicting performance and optimizing printing processes.

Conclusion

This study performed a bibliometric analysis on the structural analysis of 3D-printed concrete (3DCP). Research in the field has grown significantly since 2018, with a peak in 2025, demonstrating the importance of 3DCP in construction.

Keyword analyses focused on "concretes," "concrete printing," and "finite element method," indicating advances in the study of failure and material behavior. Co-authorship, country, and journal analyses confirm international collaboration and the influence of publications like the Journal of Building Engineering.

Despite the progress, the study points to several gaps. More sophisticated numerical models are needed for interlayer and multi-scale interactions, with methods like peridynamics and SPH showing promise. There is also a significant opportunity for multifunctional materials and the application of AI and ML to optimize design and predict performance, which would drive sustainability in 3DCP.

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A Review of Computational Vision Applied to Materials Selection

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This bibliographic review shows the crescent works in the field of computational vision applied to materials selection within the framework yolo. The results obtained with the search present studies from the years of 2021 to 2025, published in the patforms Dimensions, Google Scholar and WebofScience. It was observed that studies in that field are crescent, have increased from 2023. Researches in that field indicate that solutions for defects, classification and material properties are the most common fields of study. Architectures of Deep Learning and Convolutional Neural Networks are the most common used techniques, together with framework Yolo for integration in already built-in solutions.

Keywords: Material Selection. Material Identification. Artificial Intelligence. Computer Vision. Yolo.

Currently the development of intelligent systems tends to use the generation of images and Artificial Intelligence (AI) elements of machine vision and computer vision [1] to raise the relevance in the field, since the task uses a lot of computer resources and needs a lot of data. That technology has been applied in material selection field, for example, recycling, for classification and sorting waste [2]. Other solutions consist of analyzing materials properties, using scanning electron microscopy (SEM) analysis, to identify microstructure degradation [3], but most of the solutions used currently are related to materials shortage, another related area is the solid waste identification, with Machine Learning (ML) algorithms that can identify metals, non-metals and plastic [4]. A tool identified in that bibliographic research for materials selection using AI is the YOLO framework, for its practicality and an already built-in interface for system integration and easily usage [5-7]. It has a CNN architecture build in its structure, and make easier for defining and changing hyperparameters, besides it has a wide benchmark of increased performance and resource usage. YOLO is an open source tool which enables its use and improvement by the community,

It has an advantage of using pre-trained models and databases for an existing weight-model creation, which improves the accuracy of new models [8]. Models are influenced by the environment of the scene, when light is stronger or darker, some characteristics may be affected, dropping accuracy [9,10], depending on the model architecture and tools used to create it, for that frameworks like YOLO within built in models are used for a wide range of applications strengthening their accuracy [11].

Yolo framework uses, Deep Learning (DL) architectures, that are suitable and used for crack detection in roads, as an example of applicable solution in traffic policies outperforming traditional techniques [12], and Convolutional Neural Networks (CNN) architectures that are derived from DL. CNNs are used for segmentation tasks and more detailed information from images.

Another field of study and application are the automotive industry, being enhanced by YOLO's, techniques like data augmentation, and the use of CNN layer architectures are capable of identifying car damage better [13]. Another classification solution with the current methods are identifying variances in the same material, as plastic for example, it has transparent plastic, which is a hard task for humans, together with some systems it can complete those tasks [5].

Computational Vision can be integrated with robot systems, either for helping human tasks, or

Received on 20 April 2026; revised 17 July 2026.

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J Bioeng. Tech. Health 2026;9(8):882-886
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to improve them. Waste collection is a delicate activity, with challenges within sorting objects, not only from inorganic but from organic source [4,14]. Health and Industry activities in that field may affect people constantly, for that solutions using AI with object detection and segmentation are applied, together with frameworks like YOLO [15].

In that context this work has the objective of searching studies in the field of AI and materials selection

Materials and Methods

This literature review has the objective to summarize the fields of Computer Vision applied to the materials selection, with the most recent and discussed techniques and approaches. Therefore the research was done using scientific platforms like “Google Scholar”, “Dimensions” and “Web of Science” in the period of 2021 - 2025.

The research was made in the month of July of 2025, it involved a carefully key-word search to cover the main interest areas, they words were

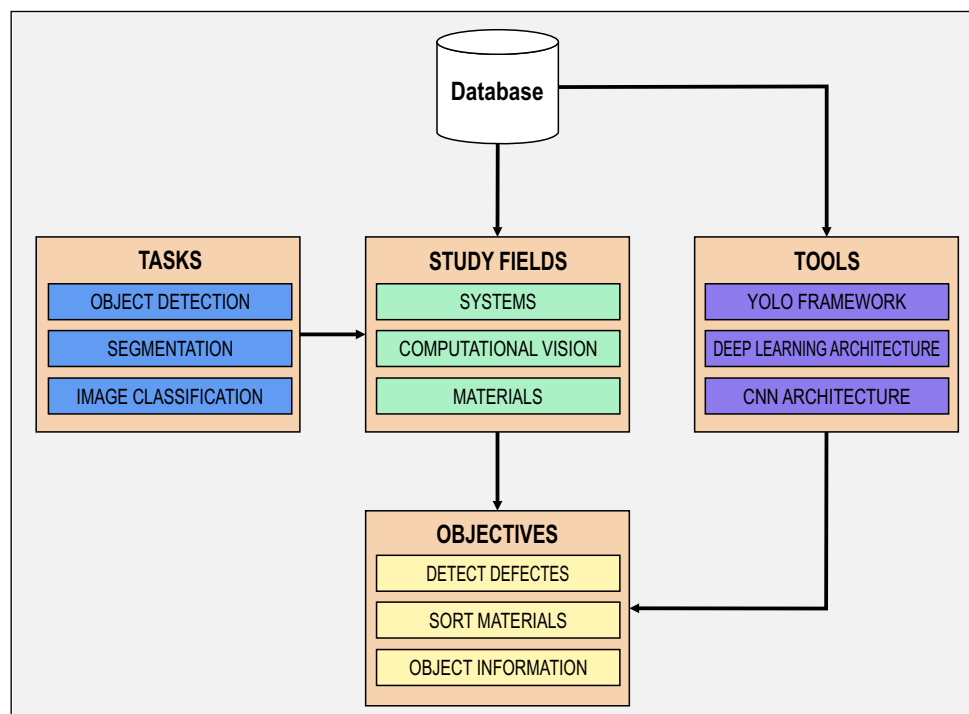
combined using boolean operators (AND, OR) to maximize the scope and the results relevance. The specific key-words combination was (“Material selection” OR “Material identification”) AND (“Artificial intelligence” OR “Computer vision”) AND "yolo" .

Results and Discussion

The results observed in the search appoint that there are many useful cases for applying object detection in current solutions, the most common cases are referred to identify materials patterns in 2D images [16], within the help of Deep Learning and Convolutional Neural Network techniques. There are many researches in quality control of materials, as defects are subject of many studies and are hard to detect [17].

The works and solutions available follow a pattern shown in Figure 1, most common tasks are Object Detection, Segmentation and Image Classification [2,4,6,17]. Many of the works in the field have a challenge of using specific database for their needs, also there are ways of maximizing

Figure 1. Standard workflow of Computational Vision solutions and the tools used.

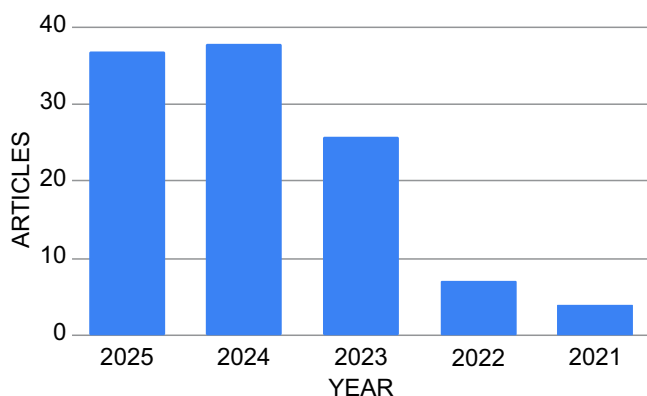


the efficiency of already existing tools [18], for instance in inspection systems, with the aid of CNN techniques.

The search using keywords and their combinations resulted in a total of 146 publications. The quantitative of the studies is presented in Figure 2, showing an increase from 2023 indicating an interest of the subject and its use.

Figure 2. Summary of the articles found researching through platforms, Dimensions, Google Academic, Web of Science.

Articles produced per year



The main papers obtained as result of the search, those that used YOLO as a tool for AI with or without help of other techniques were highlighted.

Adetunji and colleagues (2025) [2] used YOLO, integrated with CNNs. The main objective of the work was the identification of plastic transparent bags inside an industrial environment, and the models generated through that architecture presented superior results even with different light conditions.

The influence of light conditions were evaluated in YOLO's application to identify materials in civil construction field. This approach had the improvement of models and architectures by combining data from cameras and millimetric wave radars, that showed being necessary to raise the accuracy and recognition of materials in low contrast scenarios. The results indicate that it is possible to develop efficient and effective models, despite the image conditions,

knowing that those parameters affect the model directly [9].

In the field of materials sorting for waste recognition, Hegde and colleagues (2024) [4], CNN models were used to classify the materials through collected images by treadmill cameras. The authors indicate that the applied methodology can be useful for cities and companies, in the waste management area, with the intention of adjusting trial practices applied, with reuse or recycling of materials. The results obtained through the models used were compared by their recognition capacity and identification, in terms of accuracy and inference. It was possible to classify the residues using the images, though the classification of materials in metals/non-metals, the results obtained were near 98%, according to the experiments the authors report some challenges within the application of tools, for example, the image quality depends on the physical state of the material, overlap of objects and if there is a proper light in the environment.

Applying YOLO for waste management, Sumathy and colleagues (2025) [18], combined that architecture with Vision Transformers (ViTs). The proposed method tried to surpass the limitations in traditional segregation processes, that require a long time to be completed and depends on intensive work, offering a faster and more efficient solution with less computational resource usage. To increase robustness of the model, specialized databases were used, that allowed a better adaptation in different visual conditions. The results indicate high precision for materials like glass (90%) and plastic PET (85%), despite the electronic waste classification still presents a lower performance (45%), highlighting an opening challenge.

Yolo combined with Neural Architecture Search (NAS) was used to identify materials with defects in the manufacturing process. The tool was applied in the injection process of plastic parts, with the idea of optimizing the workflow, reducing production of defect parts and directing the material for reprocessing. The inspection system (IMIS)

captures the image logo after the press opening process and decides if there is a defect. If a defect is detected a control circuit sends a command to the machine before the next injection [17]. Another study by Dunli and colleagues (2022) [8], compared the YOLOv5 algorithm to the NVIDIA GeForce RTX 2080 Ti, for material detection in pallets through and automated mounting production line, the results indicated a significant reduction in the time needed for training the tool, showing viability to fast implementation in automated industrial scenarios.

Outside the industrial environment, the Scaled-YOLOv4 was used to detect materials in objects thrown in Pasig River, Philippines. The greatest challenge for applying the tool, according to the authors, was the presence of deformations, occlusions and variations in light conditions. The model achieved a precision in materials identification of 63%, from that total, 67% precision for plastic identification and 59% for paper identification [7].

A comparative study between the models (1) CNN e ResNet50 and (2) YOLO v3 and YOLOv4 was developed to classification and trial of medical wastes during the phase post-pandemic of Covid-19. The applied training in tools focused in objects like facial mask, gloves and syringes. The result shows that from 2207 medical waste images, CNN e ResNet achieved 89.35 and 85.75% of precision, while YOLOv3 and YOLOv4 used 3073 images for training and achieved 84.86 and 89.21% of medical precision. The limitations verified in the work are from wrong detections in real time using camera, similar shape objects of medical waste [19].

In summary the revised studies appoint YOLO as one of the most important AI architectures for detection and materials classification in industrial and environmental scenarios. Challenges as light, occlusion, visual similarity, between objects, still delimitates the accuracy in some of the cases, the results shows expressive improvements in efficiency, processing time and practical implementation.

Conclusion

The works from the search show that solutions used in the materials field are related to object segmentation, object detection and image classification, most of them are related to shortage of materials and identifying materials property, either for defects or quality control quantification. Deep Learning and Convolutional Neural Networks are the architecture approaches used for modeling Computational Vision Solutions. They have better accuracy and response to modeling creation than other techniques.

YOLO is a well-known and solution integrated framework used in most cases. It enables the creation of faster and resource optimized models that can be used in many different cases and scenarios.

Acknowledgement

Thanks to the SENAI - CIMATEC University institution, this work was possible to be done and the support of the PP-GTEC (Post Graduation Program of Management and Industrial Technology) with all the available resources.

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