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**COVER:** Figure 1. Reconstructed images, as intersection points (A), 3D models with phases (B) and textured 3D models (C). 3D Models Allow the Recovery of Information from Video Transects: A Case Study in Coral Reefs by Igor Cruz and Natália Menezes. *J Bioeng. Tech. Health* 2025;8(6):595.

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## Quality Control for Electronic Products: Implementation of a Burn-In Test for Printed Circuit Boards

Luã Malco da Conceição Souza<sup>1\*</sup>, Alan Gramacho dos Santos<sup>1</sup>, Breno Prazeres Barbosa<sup>1</sup>

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The production process of Printed Circuit Boards (PCBs) for projects that require high quality standards demands a robust Quality Control System. A product may undergo several qualification levels, with rigorous testing and high certification, and still present failures in the field, compromising customer satisfaction and, consequently, brand reputation. Considering that electronic components tend to exhibit a high probability of failure in the early stages of their useful life, this work aims to implement a Thermal Stress Screening Test Plan (Burn-in) for PCBs, anticipating the manifestation of latent defects before the product is deployed in the field, selecting those with greater durability without compromising their useful life. This test plan, necessary for implementation, must define test conditions, techniques, infrastructure, acceptance criteria, data collection procedures, and data analysis methods to ensure test standardization and reproducibility.

**Keywords:** Burn-In. PCB. Quality. Thermal Stress.

This work aims to propose a burn-in test plan applied to a real manufacturing process, as a strategy to improve the quality and reliability of printed circuit boards produced under the responsibility of SENAI CIMATEC. The test will be one of the manufacturing qualification processes that will compose the Quality Control System (QCS) of electronic component production within the same program. The use of environmental tests such as these is of crucial importance to increasing the quality level of electronic products.

A test plan is a document that must function as a “recipe”, a specific methodological procedure for a given product, so that results can be achieved under the same experimental framework. Relevant information such as test conditions, environment, test duration, initial conditions, and boundary conditions must be well defined. This document must include the applied techniques, methods, approval criteria, test parameters, analysis strategies, scope, and other relevant information necessary for test implementation.

This work is still in its initial phase and will include a future implementation stage, in which experimental results will be obtained. One of the main challenges to be overcome is the lack of Life Test data and other more comprehensive Environmental Tests from preliminary stages of product development, which hinders the development of a statistical approach. Given the difficulty in acquiring references to Burn-in test plans for PCBs in the literature that could serve as models—due to confidentiality and industrial secrecy—it is necessary to develop a proprietary approach capable of being improved and adapted to product needs.

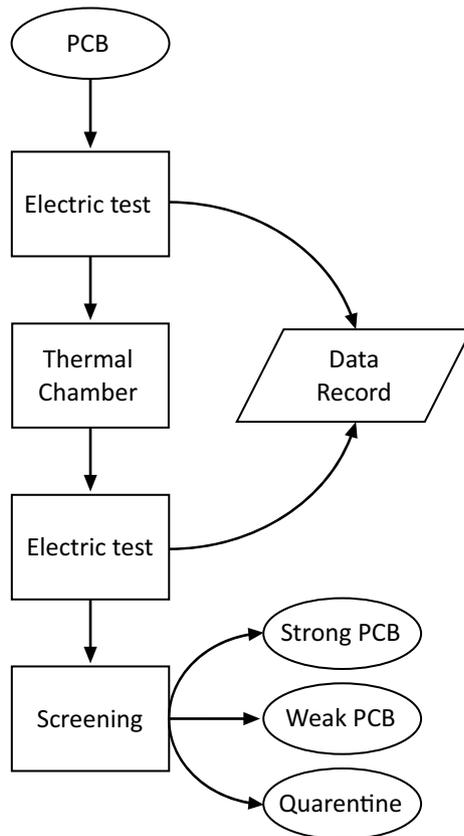
### Materials and Methods

This work is an ongoing, highly confidential research project that will soon unfold into experimental work. At present, it consists of planning the execution of the Burn-in method for the Printed Circuit Board (PCB) manufacturing process through a product-linked test plan. The Burn-in process is described by the Figure 1.

The Burn-in test plans were developed considering two main aspects in the selection of test parameters:

i) the test temperature must encompass the maximum temperature to which the Device Under

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**Figure 1.** Burn-in procedure.

Test (DUT) will be subjected in the field, including transportation, storage, and installation stages;

**ii)** the test temperature must not exceed the minimum maximum temperature rating of all individual electronic components on each PCB.

Regarding exposure time, the 96-hour parameter specified in MIL-STD-750 [1] was used as a reference. It should be noted that exposure time parameters may be modified during the execution of other tests, once trends, data patterns, or even process optimizations are identified. The key aspect is to ensure that all developed tests are properly recorded and traceable.

Standardizing test conditions is essential to ensure reproducibility and, consequently, more reliable data [2]. The tests must be carried out under the following conditions according to Table 1.

Data acquisition will be performed using test devices integrated into the Quality Control System. The DUT must undergo electrical testing before

**Table 1.** Test conditions.

Ambient temperature	25°C ± 3°C
Relative humidity	50% ± 5%
Temperature profile	70°C ± 2°C
Exposure time	96 h
DUT's condition	De-energized

being subjected to the thermal chamber. After completion of the test, the DUT must undergo a 24-hour stabilization period so that possible physicochemical reactions resulting from heating can stabilize. After this period, the DUT must again undergo electrical testing. The acceptance criteria for unit electrical tests are the same as those used by the Quality Control System.

The standard acceptance criterion will be Go/No-Go. That is, products presenting nonconformities must be removed from the population. Depending on the criticality of the changes resulting from the test, rejected products may or may not undergo remanufacturing.

The test scope must be total, meaning all products must be subjected to the Burn-in test. In the initial periods, especially during the first tests, smaller sample sizes should be used to allow adjustments and mitigation of potential losses.

All tests must be recorded, considering the test batch and the serial number of each DUT. Records must include test parameterization, test conditions, and any objections or anomalies observed. Data recording must be performed through the Quality Control System infrastructure itself.

A thermal chamber with precise temperature control must be used to ensure greater process reproducibility.

Tests must not be interrupted under any circumstances [2]. There must be no contamination, power outages, or failures in the temperature control system. Test conditions must be reproducible and inexorable [3].

The tests will result in the creation of a database to be used for future optimizations, improvements, and analyses.

## Theoretical Background

A Printed Circuit Board (PCB) has a considerable probability of failing immediately after completing the assembly process or during the early stage of its life cycle [4]. This may occur due to chemical reactions in its materials that are not yet fully stabilized, divergences in the assembly process detected by quality control mechanisms, or the presence of random effects. This behavior is described in the literature as the “bathtub curve” (Figure 2).

The use of testing methods that apply Environmental Stress Screening loads is a viable strategy to ensure the delivery of higher-quality products, mitigating the occurrence of premature failures and undesirable effects that harm brand credibility, increase customer dissatisfaction, and substantially impact product quality [5].

Burn-in is a type of thermal stress test widely used in the electronics industry [4]. Basically, a climatic chamber is used, into which a population of DUTs (Devices Under Test) is inserted and subjected to a specific stress load or combination of stresses for a defined exposure time. It is a type of non-destructive accelerated life test that moves the product from an “infant mortality” stage—where weaknesses are more frequent—to a more mature stage, where the failure rate is lower and constant.

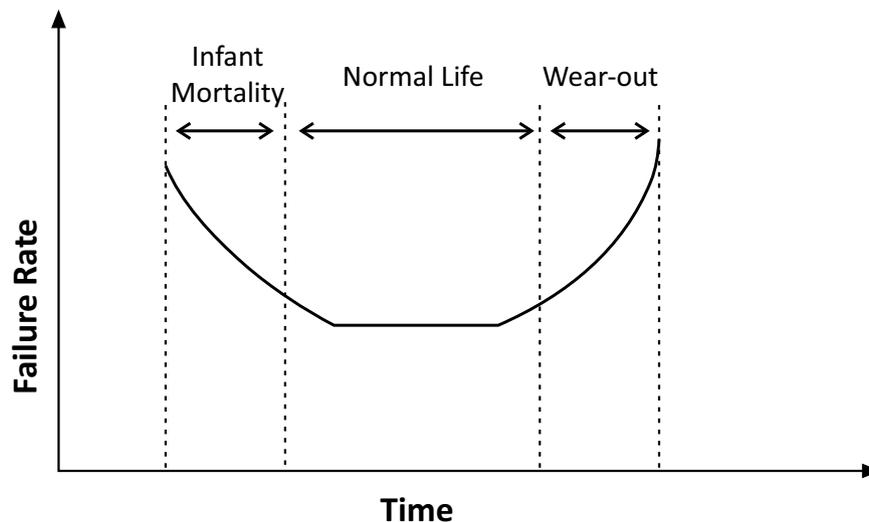
This approach is primarily used for screening purposes, separating weak products from the population that will be deployed in the field. The test is usually planned to simulate the environmental operating conditions that the DUT will face, without exceeding stress levels, in order to avoid unnecessary product aging [5]. It is typically conducted at a reasonable and constant temperature, below design operational limits, with a longer duration compared to other accelerated life tests found in the literature.

It must be considered that each product has individual characteristics in terms of design, materials, and manufacturing processes. Therefore, Burn-in is applicable only to a specific type of product. Each PCB series produced must undergo a specific Burn-in test, with its own parameters and test conditions—an exclusive “recipe.” Although widely used in the electronics industry, Burn-in test plans are kept confidential as industrial secrets and are rarely disclosed, representing a strategic advantage [6].

## Conclusion

The test plan must enable the implementation and execution of the Burn-in test in such a way that it can be reproduced, replicated, and even improved. The implementation of this test should primarily

**Figure 2.** Bathtub curve.



result in the generation of useful data, both for detecting product weaknesses and for screening stronger products.

The test plan must undergo fine-tuning of parameters such as temperature and exposure time to adapt to production needs as improvements and optimizations become necessary based on experimental results. Some losses are expected during the process, such as PCB populations that may fail due to excessive test aggressiveness rather than product weaknesses, requiring adjustments to test parameters.

The implementation of Burn-in is expected to solve the lack of product life test data, enable the detection of weaknesses, and consequently deliver products with high quality and durability.

### Acknowledgments

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## EVOLUX: A Gamified Model for Sustainable Process Innovation in the Era of Industry 5.0

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The growing complexity of production environments highlights the limitations of isolated process improvement approaches, such as Lean, Six Sigma, or Simulation. This article introduces EVOLUX, a gamified model for process innovation that integrates established methodologies with governance mechanisms (OKRs) and emerging technologies (AI, blockchain, and digital twins). The proposal seeks to overcome existing fragmentation by aligning sustainable productivity, human engagement, and the principles of Industry 5.0. Based on a systematic review and critical analysis of the literature, theoretical and practical gaps are evidenced, which justify the need for an integrative framework. The expected results include greater operational predictability, scalability of innovation practices, and strengthening of teams' intrinsic motivation. Thus, EVOLUX is positioned as an unprecedented and relevant contribution for organizations aiming to combine competitiveness, sustainability, and human focus in their transformation processes.

**Keywords:** Process Innovation. Sustainable Productivity. Gamification. Industry 5.0. Organizational Engagement.

The pursuit of sustainable productivity and continuous innovation in industrial processes takes center stage in the era of Industry 5.0. Unlike Industry 4.0, characterized by its technological focus, Industry 5.0 emphasizes the integration of production efficiency, sustainability, and the appreciation of the human factor [1,2]. This new paradigm challenges organizations to overcome fragmented approaches and to articulate, within a single model, the technical, digital, and human dimensions of innovation.

In the Brazilian context, industrial labor productivity has grown at a slower pace compared to advanced economies, representing a structural barrier to competitiveness [3]. Although consolidated methodologies such as Lean Six Sigma, discrete-event simulation (DES), and agile frameworks have been widely applied, the literature shows that their isolated adoption limits the predictability of gains and the scalability of solutions [4]. At the same time, structured gamification has emerged as an alternative to

foster motivation and collaboration in teams, but recent criticism points to risks when it is reduced to points, rankings, and extrinsic rewards, such as the weakening of intrinsic motivation, the tokenization of human effort, and team overload [5,6].

This combination of advances and gaps indicates the need for integrative frameworks. Models such as GLUX (Gamified Lean UX) exemplify the potential of combining agile practices with game elements, but their application remains restricted to the software domain [7]. There is, therefore, no methodological proposal that consolidates, on an industrial scale, the integration of gamification, emerging digital technologies, and continuous improvement methods with structured mechanisms for measuring both human and operational impact. This is the still underexplored space that grounds the present research.

This article proposes a gamified architecture designed to guide process innovation projects in industrial environments with a simultaneous focus on human engagement and sustainable productivity, called EVOLUX. Unlike existing frameworks, this architecture organizes the innovation journey into gamified macro-stages that integrate Lean Six Sigma, computational simulation, digital twins, adaptive artificial intelligence, blockchain, and OKR-based governance. It is important to

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emphasize that EVOLUX is proposed here as a conceptual architecture not yet applied, whose objective is to fill methodological gaps identified in the literature and to provide a replicable and validatable basis for future empirical studies and applications.

### **Theoretical Framework and Foundations of the EVOLUX Model**

The construction of a methodological architecture for process innovation with a focus on sustainable productivity requires a critical analysis of the approaches used in industrial environments. This section presents the foundations that support EVOLUX, highlighting contributions, limitations, and gaps of existing models in order to demonstrate the originality of the proposal.

#### Agile Methods and Organizational Sustainability

Agile methods such as Scrum, Kanban, and Lean Startup have become widely recognized for their ability to accelerate learning cycles, reduce implementation risks, and promote incremental value delivery [8]. However, their transposition to industrial contexts faces obstacles related to rigid hierarchical structures, cultural barriers, and the lack of metrics that demonstrate proven gains in productivity and sustainability [9].

Emerging models such as GLUX (Gamified Lean UX) indicate that the combination of agile practices and gamification can enhance engagement and collaboration [7]. Nevertheless, their application remains restricted to software development and does not extend to complex industrial processes. This limitation reinforces the need for a framework that unites agile flexibility, human engagement, and robust metrics in production environments.

In the context of Industry 5.0, organizational agility cannot be limited to rapid deliveries; it must be associated with sustainability, human centrality, and systemic resilience [10,11]. EVOLUX advances in this direction by incorporating agile

practices into gamified macro-stages, supported by digital governance mechanisms and metrics that balance economic, environmental, and social outcomes.

#### Gamification as a Driver of Productive Engagement

Gamification, defined as the use of game elements in non-game contexts, has become consolidated as a strategy to foster motivation and collaboration [12]. Empirical evidence points to consistent benefits: Dolly and colleagues [13] reported performance increases in gamified assembly tasks; Capponi and colleagues [14] highlighted positive effects in human-robot collaboration scenarios.

However, recent criticism warns of the risks of superficial application. Krath and colleagues [5] emphasize that gamification based solely on points, badges, and leaderboards (PBL) does not sustain intrinsic motivation, potentially generating ephemeral engagement. Leite and colleagues [15] reinforce that the uncritical use of extrinsic mechanics can result in overload, toxic competition, and burnout.

To avoid such pitfalls, EVOLUX adopts the Octalysis Framework [16] as a reference, prioritizing deeper motivational dimensions such as purpose, belonging, creativity, and curiosity, which are directly connected to Self-Determination Theory [17]. Thus, gamification in EVOLUX is not limited to superficial rewards but is structured as a methodological core capable of sustaining continuous and meaningful engagement.

#### Emerging Technologies and Continuous Improvement

Industry 4.0 introduced technologies such as artificial intelligence (AI), blockchain, digital twins, and discrete-event simulation (DES), expanding the capacity to forecast scenarios and validate solutions. However, recent studies show that their adoption is not exempt from limitations. Awasthy and colleagues [18] highlight the energy

and implementation costs of blockchain; AI may reproduce biases stemming from data quality; and DES strongly depends on the calibration of models to generate reliable results [19,20].

Despite these constraints, the integration of Lean Six Sigma (LSS) and DES has shown promising results. Goienetxea and colleagues [4] emphasized the potential of this combination but noted the absence of replicable and standardized frameworks. Recent cases confirm significant gains: Obradović and colleagues [9] documented increased productivity and cost reduction in a national industry, while Van Erp and colleagues [10] reported positive environmental impacts in logistics chains.

EVOLUX incorporates these technologies into gamified macro-stages, using DES and digital twins to validate improvement hypotheses before execution, adaptive AI for continuous adjustments, and blockchain for traceability. In this way, it combines technical robustness with human engagement, proposing a replicable path for process innovation.

### Hybrid Frameworks and Innovation Governance

The increasing complexity of industrial environments has driven the use of hybrid frameworks, which combine different methodologies to expand innovation and execution capabilities. Design Thinking (DT) contributes to collaborative and human-centered ideation but lacks mechanisms for scalability [21]. Theory of Constraints (TOC) assists in identifying critical bottlenecks but tends to restrict systemic vision [22]. Meanwhile, Objectives and Key Results (OKRs) have proven useful for strategic alignment, although many organizations face difficulties in institutionalization (Rompho, 2024).

EVOLUX proposes the structured integration of these models: Design Thinking in the ideation phase, TOC for constraint analysis, and OKRs to connect process innovation with organizational goals. This arrangement strengthens innovation governance and increases predictability of results.

### Critical Synthesis and Positioning of EVOLUX

The literature review shows that, although each approach contributes in specific ways, fragmentation still prevails: agile methodologies focus on flexibility, gamification often lacks motivational depth, emerging technologies face practical limitations, and hybrid frameworks do not consolidate integrated governance.

In this context, EVOLUX is not presented as a tested solution but as a conceptual methodological architecture. Its proposal is to fill identified gaps, such as the absence of replicable frameworks, lack of causal integration between human engagement and sustainable productivity, and the absence of robust measurement protocols in process innovation.

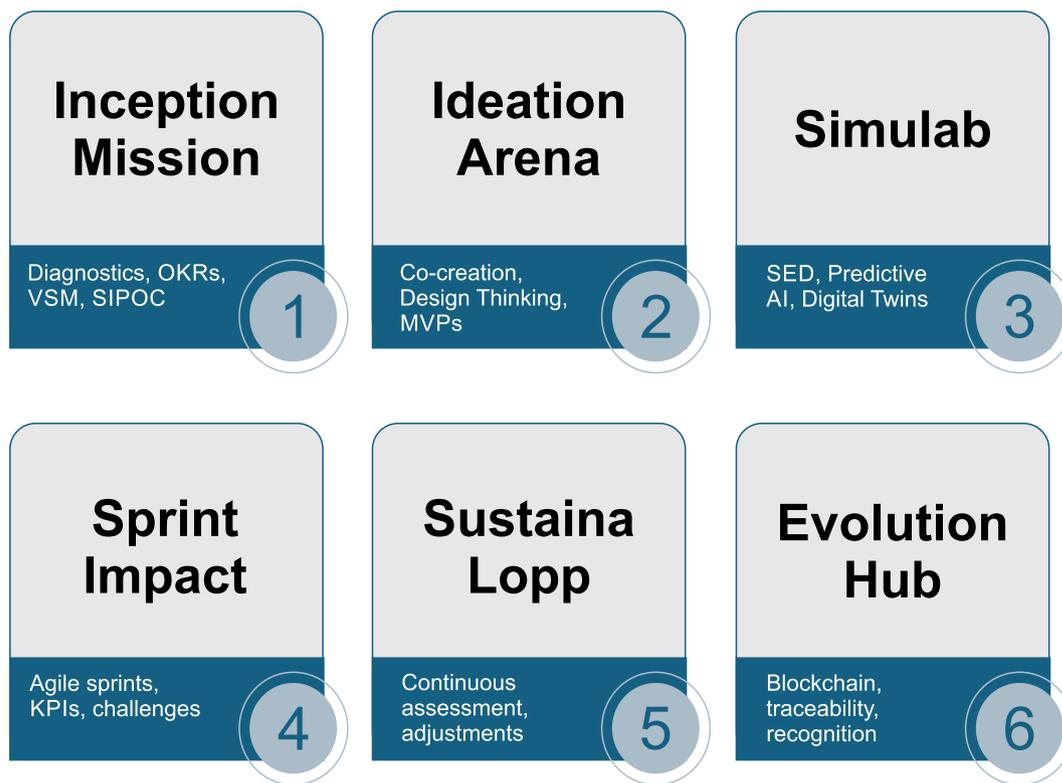
The model, therefore, offers a structured foundation for applied research and future empirical validations. As such, it positions itself as an original contribution to Industry 5.0, articulating resilience, sustainability, and human focus within a process innovation ecosystem.

### **EVOLUX Method: Architecture and Macro-Stages**

The model proposed here is organized into six evolutionary macro-stages that structure the cycle of industrial process innovation. Each macro-stage combines established tools, emerging technologies, and gamification mechanics designed to sustain motivation, collaboration, and objective measurement of results (Figure 1).

#### Inception Mission – Diagnosis and Goal Setting

The first phase of EVOLUX is dedicated to identifying bottlenecks and opportunities for innovation. It employs SIPOC, Value Stream Mapping (VSM), and Objectives and Key Results (OKRs) to map processes and align strategic objectives. Gamification occurs through rewards for accurate diagnosis, encouraging rigorous data collection and clarity in goal definition.

**Figure 1.** Steps of EVOLUX Method.

### Ideation Arena – Co-Creation of Solutions

This phase promotes collaborative idea generation using Design Thinking and TRIZ, supported by generative AI to broaden creative repertoires. Teams earn points based on the originality, feasibility, and impact of their proposals, fostering engagement and ownership. The goal is to align creativity with practical applicability, overcoming the limitation of architectures focused solely on ideation.

### Simulab – Computational Validation

Here, proposals are transformed into digital prototypes, validated through discrete-event simulation (DES) and digital twins. Metrics such as Return on Investment (ROI), cycle time, production capacity, and environmental impact are analyzed in simulated scenarios before real implementation. Gamification takes the form of performance challenges, where teams compete to propose more efficient and sustainable solutions.

### Sprint Impact – Agile Implementation

This phase conducts the application of solutions in short sprints, with KPIs monitored through digital dashboards. Blockchain ensures traceability and integrity of records. Gamification manifests itself through “Impact Challenges,” which reward efficiency, goal achievement, and innovation. In addition to motivating teams, this stage strengthens governance and organizational transparency.

### Sustaina Loop – Continuous Adjustments

This is the phase of monitoring and incremental adjustments, supported by adaptive AI that suggests improvements in real time. Gamification is incorporated into innovation leagues, with collective recognition for replicable sustainable practices. This continuous cycle ensures that improvements are not limited to punctual gains but become consolidated as part of organizational culture.

### Evolution Hub – Knowledge Management and Scalability

The final macro-stage is responsible for consolidating practices and results into digital repositories and gamified learning pathways. Blockchain guarantees innovation traceability, and internal certifications recognize teams for collective learning. This stage reinforces the evolutionary character of EVOLUX, promoting replicability and expansion across multiple sectors.

### Future Validation Protocol

Although EVOLUX has not yet been empirically applied, its architecture foresees a scientific validation protocol across four axes:

- a) **Maturity Assessment** – prior diagnosis of digital and governance readiness, guiding modular adoption of the model, from simplified stages (diagnosis, ideation, simulation) to the complete cycle;
- b) **Human Engagement** – measurement based on Self-Determination Theory (Deci & Ryan, 1985) and the Octalysis Framework (Chou, 2019), using psychometric scales of autonomy, purpose, and motivation;
- c) **Sustainable Productivity** – Lean Six Sigma and sustainability indicators (OEE, lead time, sigma level, ROI, emissions, waste);
- d) **Statistical Method** – application of Difference-in-Differences (DiD) and mixed models to isolate the effects of EVOLUX in control and intervention groups.

This protocol ensures that results are not only perceived but also supported by robust empirical evidence.

### **Expected Results and Contributions of EVOLUX**

EVOLUX distinguishes itself by integrating, within a single architecture, the technical, human, and digital dimensions of organizational innovation. It is a conceptual proposal not yet

empirically validated but structured to address recognized gaps in the literature and to guide future applications. Its contributions are distributed across three fronts: practical, theoretical, and multisectoral applicability.

### Practical Contributions

- a) **Operational Predictability** – the integration of predictive simulation and digital twins enables decision-making based on validated scenarios, reducing implementation risks and increasing the reliability of improvements.
- b) **Sustainable Human Engagement** – by adopting intrinsic motivational principles (Octalysis, SDT), EVOLUX seeks to mitigate the risks of superficial gamification and strengthen continuous motivation, fostering collaboration and overcoming cultural resistance in change processes.
- c) **Scalability and Traceability** – by adopting intrinsic motivational principles (Octalysis, SDT), EVOLUX seeks to mitigate the risks of superficial gamification and strengthen continuous motivation, fostering collaboration and overcoming cultural resistance in change processes.

### Theoretical Contributions

- a) **Original Integration** – structured connection between gamification, Lean Six Sigma, computational simulation, adaptive artificial intelligence, and governance mechanisms (OKRs, TOC, DT), articulated within a replicable architecture.
- b) **Response to Industry 5.0 demands** – aligning process innovation with three central pillars – human centricity, systemic resilience, and environmental sustainability [10,11].
- c) **Overcoming Conceptual fragmentation** – while agile methodologies, gamification frameworks, and continuous improvement approaches have advanced in isolated domains, EVOLUX proposes an architecture that

connects technical and human dimensions in a causal and validatable manner.

### Multisectoral Applicability

EVOLUX was designed to adapt to different levels of digital maturity: (a) low maturity: traditional sectors, such as textiles, may adopt simplified versions focused on diagnosis, ideation, and simulation; (b) medium maturity: discrete manufacturing can apply the complete architecture, supported by AI and OKR governance; (c) high maturity: R&D environments and technology-intensive industries may explore the full potential of the model, with advanced integration of blockchain, digital twins, and adaptive artificial intelligence. The prior assessment of maturity is a fundamental part of the methodology, functioning as a calibration stage to define which EVOLUX macro-stages can be implemented immediately and which should be incorporated gradually. In this way, the model avoids generic prescriptions and adapts to the real conditions of each organization, promoting greater predictability and suitability in the adoption process.

### **Conclusion**

EVOLUX was conceived as a gamified architecture to guide industrial process innovation projects, integrating human, technological, and operational dimensions into a single methodological ecosystem. Structured into six evolutionary macro-stages, the model organizes the journey from diagnosing bottlenecks to knowledge management, promoting continuous innovation based on established methodologies (Lean Six Sigma, agile frameworks) and emerging technologies (artificial intelligence, computational simulation, digital twins, and blockchain). This configuration differentiates itself by aligning sustainable productivity with the construction of an organizational culture that is resilient and focused on human engagement.

One of the central aspects of the model is the

emphasis on intrinsic engagement, supported by Self-Determination Theory and the Octalysis Framework, ensuring that innovation is not limited to technical gains but strengthens motivation, collaboration, and organizational resilience. In parallel, the use of operational performance metrics — such as OEE, lead time, and sigma level — ensures that the proposal goes beyond the conceptual field and can be empirically validated in terms of productive efficiency and environmental sustainability.

Methodological flexibility represents another relevant contribution of EVOLUX. The digital and governance maturity assessment, conducted prior to application, allows for calibration of adoption according to the technological and cultural readiness of each organization. This arrangement prevents generic prescriptions and makes the model scalable, adaptable, and applicable across multiple sectors, from traditional industries to high-tech environments.

Although still presented as a conceptual architecture, EVOLUX establishes a solid foundation for future validations. The proposed testing protocol combines human and productive metrics with advanced statistical methods, expanding the potential for generalization and replication across different organizational contexts. Future steps include pilot applications, the consolidation of an EVOLUX readiness index, and the deepening of human impact metrics, such as well-being, autonomy, and resilience.

In summary, the model represents an original contribution by proposing a replicable and adaptable methodology to align innovation, human engagement, and sustainable productivity, in line with the principles of Industry 5.0.

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## Assessment of Ergonomic Studies in the Design of an Off Road Vehicle

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This article presents an ergonomic assessment performed in the CL-02 prototype in the Baja Society of Automotive Engineers (SAE) Brazil competition. Using computer simulations in Computer Aided Tridimensional Interactive Application (CATIA) software and physical validations through a full-scale mockup, the project aimed to ensure comfort and safety for drivers with different body types. Postural analysis was performed using the Rapid Upper Limb Assessment (RULA) method and photogrammetry, involving drivers representing the first percentile, forty-second percentile, ninety-ninth percentile. The ergonomic evaluation determined precise spatial relationships between the driver and key vehicle components, including distances to the steering wheel, pedals, and seat reference points. These measurements highlight a layout that supports comfort and efficiency, with optimized posture through backrest inclination and steering wheel positioning. The methodology also allowed for the identification of improvement opportunities for future projects, such as fine-tuning the pedal position. The study reinforces the importance of integrating ergonomics and engineering from the early stages of design.

**Keywords:** Baja SAE. Ergonomics. RULA.

**Abbreviations:** CATIA, Computer Aided Tridimensional Interactive Application. CL-01, CalangoTec 01 Prototype. CL-02, CalangoTec 02 Prototype. PPE, Personal Protective Equipment. RULA, Rapid Upper Limb Assessment. SAE, Society of Automotive Engineers.

Ergonomics is defined as the science that studies the interactions between humans and the elements of the systems in which they operate, using principles and data to optimize human well-being and overall system performance, as described by Iida, 2005 [1]. In the context of the development of single-seat vehicles for competitions such as Baja SAE, ergonomics became a relevant factor, since the driver remained in the driving position for extended periods, being subjected to constant vibrations, and the need for full control of the vehicle.

Design ergonomics was incorporated from the beginning stages of the prototype project of prototype, which allowed the adjustment of dimensions and geometries to different users, as described by Huet and Moraes, 2003 [2]. Rules, by Baja SAE Brazil competition, 2025 [3], required

the vehicles be capable of accommodating different drivers (different heights and weights), ensuring a minimum space for the driver equipped with all Personal Protective Equipment (PPE) (such as arm restraints, helmet, neck brace, gloves, and closed shoes), positioned in cockpit. Such regulatory requirements demand projects using structural safety, and also anthropometric and functional aspects.

During the development process of CL-02 prototype, different anthropometric profiles of the drivers were analyzed (considering body size measurements, and members proportions). The comfort during driving was evaluated, as well as mobility with the safety harness fastened, the ease of prototype access, and car operation without requiring awkward postures. Studies such as those by Guedes and colleagues (2018) [4] demonstrate the use of digital tools, such as the CATIA software, enabled the preliminary evaluation of the pilot's postural suitability and functional reach. Furthermore, Santos and colleagues (2021) [5] showed that adjustments to components such as the seat, pedals, and controls directly affected

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comfort and safety. Conversely, Huet and Moraes, 2003 [2] warned that neglecting these aspects could lead to improper postures and prolonged physical discomfort. Additionally, Walker, 2017 [6] emphasized that poorly designed ergonomic projects could impair the driver's situational awareness, thereby increasing operational risks.

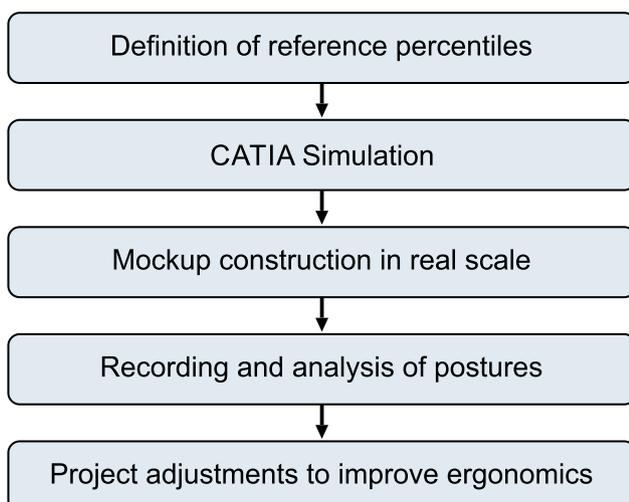
The objective of this article was to evaluate an ergonomic study applied to different individuals (covering a range between 1.59 m to 1.94 m) and weight (55 kg to 95 kg) ensuring that key joint angles such as those of the knee, hip, and elbow, were all kept within the parameters established according to Tilley, 2002 [7] and McAtamney and Corlett, 1993 [8]. The CATIA software and the RULA method were used for postural assessment.

## Materials and Methods

Several elements related to vehicle seating, essential to ensuring an ergonomic and comfortable posture, were considered as the basis for the evolution of the ergonomic design applied to the CL-01 prototype (2023), with the goal of significantly enhancing its application in the new CL-02 model, under development for the 2025 season. The approach used in this work followed the scheme observed in Figure 1.

To ensure the accommodation of drivers with different profiles, the extreme percentiles of

**Figure 1.** Visual representation of the method.



different drivers were used as reference: the ninety-ninth percentile male and the first percentile female. According to the BAJA SAE Brazil, 2025 [3], the vehicle must to accommodate drivers ranging from 1.90 m and 109 kg, to 1.45 m and 42 kg, in height and weight respectively. The profiles analyzed in this work were 1.94 m and 95 kg, 1.59 m and 55 kg, also an intermediate driver (1.75 m and 75 kg), representing the forty-second percentile. The initial analysis was carried out in CATIA software, including RULA analysis, through the simulation of driving positions, covering aspects such as range of motion of arms and legs, angle between the backrest and seat, reach of the controls, and forward visibility (Figure 2).

After the computational simulations, using the ideal measurements described by Tilley (2002) [7], it was made a full-scale physical mockup to validate the virtual prototype. This validation allowed for important adjustments to the roll cage geometry, including increased internal space, repositioning of the pedals, and changes to the seat height and inclination (Table 1).

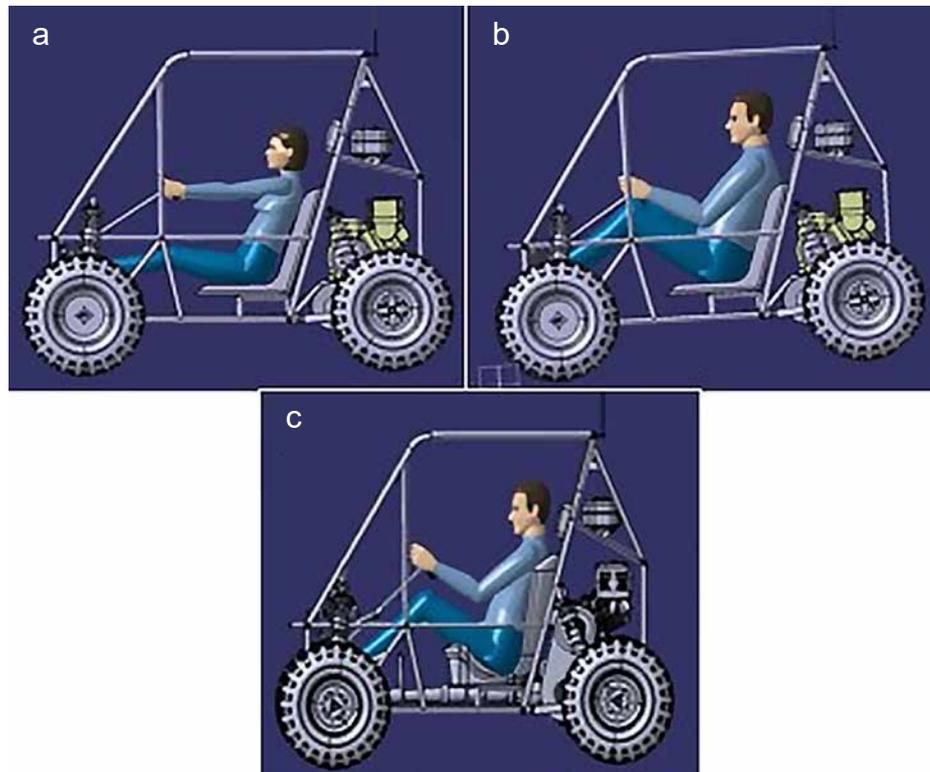
**Table 1.** Ideal measurements.

Body member	Measure
Knees	110° - 120°
Seat - Backrest	95°
Leg - Backbone	95° - 100°
Arm	115°
Ankle	100°

Source: Adapted from Tilley (2002) [7].

The RULA analysis (Table 2), is an ergonomic tool used to assess the risk of musculoskeletal injuries related to the drivers posture. It provides a score based on the position of the upper limbs, trunk, and neck during the driving. Using the final score, it is possible to determine the level of risk and, consequently, the degree of ergonomic reliability of the analyzed position, as described by McAtamney and Corlett (1993) [8].

**Figure 2.** Digital model of ergonomic simulation in CATIA with first (a), ninety-ninth (b), and forty-second (c) percentile drivers.



**Table 2.** RULA analysis.

Score	Action Level	Intervention
1 or 2	1	Acceptable posture.
3 or 4	2	An observation should be made and changes may be necessary.
5 or 6	3	An investigation must be carried out and changes must be introduced.
7	4	Changes must be introduced immediately.

Source: Adapted by McAtamney and Corlett (1993) [8].

Using information from Table 1, a photogrammetry was carried out to analyze the posture of drivers, as observed in Figures 3 and 4. The technique consisted of analyzing photographic

images to obtain measurements and body distances relevant to the project's ergonomics. These same drivers took part in the practical tests, ensuring the necessary representativeness for validation. After reaching a consensus among the users, the ergonomic modifications were incorporated into the final project, and the structure's manufacturing was initiated.

## Results and Discussion

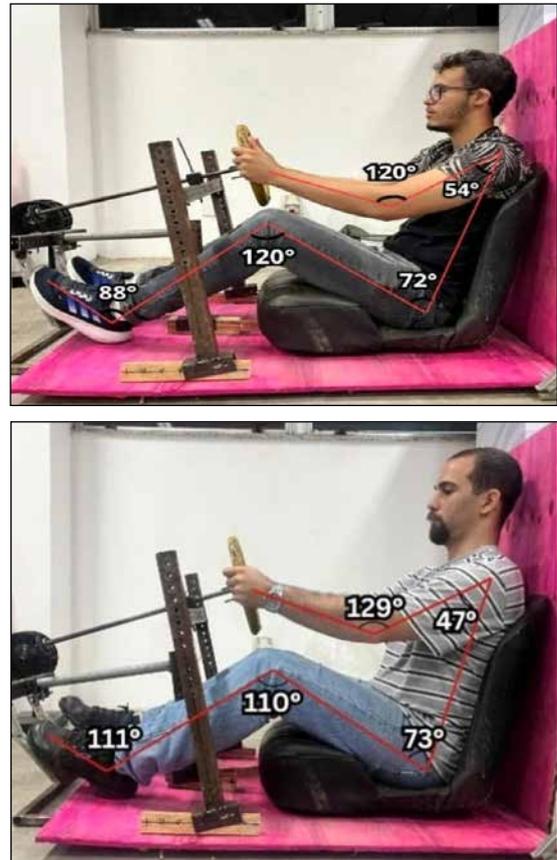
The simulations performed in the CATIA software, together with tests using a physical mockup, showed the ergonomic suitability of the CL-02 vehicle for different body types. The RULA analysis (Table 3) indicated risk levels classified low to moderate.

Photogrammetry validated the decisions made in the simulations, such as increasing interior space and repositioning the seat and pedals, ensuring comfort and proper driving posture. During the

**Figure 3.** Photogrammetry of the first percentile female and ninety-ninth percentile male in the ergonomic mockup.



**Figure 4.** Photogrammetry of the forty-second percentile male (titular drivers) in the ergonomic mockup.



**Table 3.** RULA analysis scores.

Pilot	Score
1 percentile female	3
42 percentile male	3
99 percentile male	3

tests, all evaluated percentiles reported adequate comfort, demonstrating that the design allowed efficient and safe accommodation for different body types (Figures 5 to 7).

Based on the analysis of the extreme and drivers average percentile, the main ergonomic dimensions of the CL-02 cockpit were defined to ensure a comfortable and functional driving position. The

distance between the firewall and the center of the steering wheel was determined to be 562.50 mm, while the distance to the pedals was 930 mm. The foot support plane presented a height difference of approximately 90 mm relative to the seat, and the backrest was designed with an inclination of 17° with respect to the seat base, promoting a relaxed and efficient posture. The steering wheel was positioned 518 mm above the seat base, and the horizontal distance between the backrest and the steering wheel axis was 621.50 mm.

These dimensions ensured that the joint angles of the knees, elbows, and hips remain within the ergonomic limits recommended by Tilley, 2002 [7], following the Baja SAE standards and promoting safety and comfort during driving.

**Figure 5.** Photogrammetry of the first percentile female in cockpit prototype.



**Figure 6.** Photogrammetry of the forty-second percentile male in cockpit prototype.



**Figure 7.** Photogrammetry of the ninety-ninth percentile male in cockpit prototype.



## Conclusion

The approach adopted in the CL-02 project proved effective in producing an ergonomically appropriate vehicle despite the anthropometric diversity of its drivers. The combination of simulations, postural analysis, and practical validation enabled safety and good decisions throughout prototype development.

Despite minor limitations identified for the 1% percentile, the design met the criteria for comfort and usability, particularly for the drivers average percentile.

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## Smart City Technologies: Challenges and Opportunities for Salvador-Bahia, Brazil

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**This study centers on the city of Salvador as it transitions toward becoming a smart city. It examines its main challenges: sanitation, pollution, and social inequalities, and compares these with established smart-city models. The study also presents example technologies, including the Internet of Things (IoT), artificial intelligence (AI), and cybersecurity, and outlines pathways for their application to tackle key urban problems. Conducted at a pivotal moment in Brazilian urban development, when cities face complex challenges related to governance, infrastructure, and social inclusion, the research aims to identify Salvador's priority issues and the smart-city technologies that can be applied to address them, along with the expected impacts on Sustainable Development Goals (SDG) 9 and 11 in Salvador.**

**Keywords:** Smart Cities. Salvador. Brazil. Smart-City Technologies. Intelligent Cities.

A smart city is a contemporary phenomenon that delivers social, economic, and environmental sustainability outcomes and responds to challenges such as climate change, population growth, and political and economic instability. From a broad perspective, a smart city seeks to bring together the environment, technological innovation, and human development to provide more efficient services to society. It is important to note that a smart city is not limited to the deployment of emerging and innovative information and communication technologies (ICTs). Tironi (2013) [16] explains that, to be characterized as such, the city must adhere to sustainable urban development (smart environment), incorporate information and communication technologies into the management of services (smart economy), generate participatory spaces for collaboration and innovation (smart governance), and cultivate responsible citizens (smart citizen).

The promotion of technologies that drive the development of smart cities is directly related

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to Sustainable Development Goal 9 (SDG 9) established by the United Nations, which aims to “build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation,” according to the Institute for Applied Economic Research (IPEA) [6]. In this way, smart cities play a fundamental role by integrating advanced technologies into urban management, resulting in more efficient and sustainable infrastructure.

The Connected Smart Cities Ranking is an initiative by Urban Systems that maps and compiles indicators of Brazilian cities' development with respect to the aspects of a smart city. Based on these collected data, Brazilian cities were ranked by level of development (Table 1).

Over the years, Salvador has gained increasing prominence. According to the Municipal Secretariat of Innovation and Technology (SEMIT) [9], in 2024 the city placed first among Northeastern capitals and tenth overall in the national ranking of the 100 smartest cities. In this smart-city context, Salvador stands out as the first Brazilian municipality to develop a Smart City Technology Master Plan (PDTCI). Prepared by the SEMIT, it is among the pioneers among Brazilian capitals in adopting international smart city standards. The PDTCI is aligned with standards issued by the International Organization for Standardization

**Table 1.** Connected smart cities ranking.

Rank	City - State	Rank	City - State
1°	Florianópolis - SC	6°	Balneário Camboriú - SC
2°	Vitória - ES	7°	São Caetano do Sul - SP
3°	São Paulo - SP	8°	Belo Horizonte - MG
4°	Curitiba - PR	9°	Barueri - SP
5°	Niterói - RJ	10°	Salvador - BA

Source: Adapted from the Connected Smart Cities Ranking (2024, p. 21).

(ISO) and was recently incorporated by the Brazilian Association of Technical Standards (ABNT). Salvador thus assumes a leading role by investing significantly in the transition to an integrated model of urban management, with substantial financial resources allocated both to the planning phase and to the implementation of the required technological solutions.

Although Salvador is one of Brazil's largest capitals, it faces challenges in several areas, including public security, housing, sanitation, and mobility, among others. A clear example is the situation of communities located in high-risk areas, where the lack of adequate infrastructure exacerbates existing social hardships. This underscores the need to invest in technologies that can help address these urban social problems. In the current scenario, the application of emerging technologies is crucial, since they can make Salvador a smarter city and provide residents with a better quality of life.

This research is set at a critical moment in Brazilian urban development, when cities face complex challenges related to governance, infrastructure, and social inclusion. Against this backdrop, the guiding research question is: What are Salvador's main challenges, and which smart-city technologies are applicable?

Understanding how the component technologies of a smart city can be applied is essential for improving public services, since the use of ICTs enables the mitigation of

urban problems and supports a better quality of life for the population. Accordingly, the study's overarching objective is to identify Salvador's principal challenges and the smart-city technologies that can be applied to address them, along with the expected contributions to SDG 9 and SDG 11. The specific choice of Salvador as the focus is grounded in its strategic positioning: the city has already advanced studies and municipal planning that include significant investments, with R\$ 4.5 million allocated to the initial planning phase and R\$ 60 million projected for implementation.

## Theoretical Framework

### Smart Cities

According to MDR (2021) [15], "smart cities" are those committed to sustainable urban development and digital transformation—across their economic, environmental, and sociocultural dimensions—that act in a planned, innovative, inclusive, and networked manner, promoting digital literacy as well as collaborative governance and management. In addition, they make use of technologies to solve concrete problems, create opportunities, deliver services efficiently, reduce inequalities, increase resilience, and improve the quality of life for all people, ensuring the safe and responsible use of data and information and communication technologies (ICTs).

The 17 Sustainable Development Goals (SDGs), which form part of the 2030 Agenda launched by the United Nations, aim to tackle the world's major challenges. Among these goals, SDG 9 (Industry, Innovation and Infrastructure), which seeks to promote resilient infrastructure, sustainable industrialization, and innovation, has a strong connection with the concept of smart cities by encouraging the strategic use of innovative technologies and intelligent infrastructure to address diverse needs.

There is also a connection with SDG 11 (which specifically concerns Sustainable Cities and Communities) and it seeks to make urban areas inclusive, safe, and resilient by ensuring adequate housing, basic services, and high-quality urban development by 2030. Smart city initiatives directly advance this objective through

real-time monitoring, citizen participation, smart waste management, and integrated transportation solutions, strengthening urban sustainability and social equity. In essence, smart cities are urban centers that employ advanced technologies aligned with sustainable practices to enhance citizens' quality of life and significantly reduce environmental impact. In this context, sustainability plays a fundamental role in human development, since, since the Industrial Revolution, issues such as the intensification of the greenhouse effect and the depletion of natural resources have become increasingly urgent challenges [3].

Accordingly as Elkington (1997) [17], states, sustainability is grounded in three perspectives: economic, social, and environmental (profit, people, and planet), also known as the triple bottom line (TBL) model (Table 2).

**Table 2.** Triple bottom line model - Sustainability Perspectives.

Sustainability	Definition	Benefits	References
Environmental	Environmental sustainability focuses on organizations' impacts on ecosystems and goes beyond mere regulatory compliance and recycling efforts.	Development of more efficient production systems. Environmentally sound, economically viable practices. Clean technologies.	Jamali, 2006 Genari et al., 2018 Pereira, 2009 Baum-Gartner, Ebner 2010)
Social	Social sustainability aims to ensure equal access to quality goods and services by removing the main sources of social inequality and deprivation of freedom, such as poverty, lack of economic opportunities, and neglect of public services.	Equity in living standards. Equal opportunities. Better working conditions and labor rights.	Mendes, 2009 Genari et al., 2018 Pereira, 2009 Jamali, 2006
Economic	Economic sustainability encompasses formal and informal activities that provide services to individuals and groups, increasing monetary income and raising living standards.	Economic efficiency. Greater human development. Investments across diverse areas of technological development.	Claro, Claro, Amâncio, 2008 Genari et al., 2018

## Challenges in the City of Salvador

Salvador ranks tenth among Brazil's smartest cities, and although the goal of smart cities is to promote quality of life and sustainability, the city still faces challenges and statistics that highlight the need for investments that keep pace with technological advances so that the population is effectively served. According to the Sustainable Development of Cities Index – Brazil (IDSC-BR) [5], Salvador still faces sustainability-related challenges, with medium performance in good health and well-being and reduced inequalities; low performance in quality education, gender equality, life on land, partnerships for the goals, and peace, justice and strong institutions; and very low performance in decent work and economic growth and in industry, innovation and infrastructure.

According to Bahia's Environmental and Water Resources Institute (INEMA) [7], bathing water quality refers to the condition of waters used for primary-contact recreation, meaning direct, prolonged contact where a significant amount of water may be ingested. In Salvador, Bulletin No. 16/2025 reports that 24 of the 38 sampling sites were classified as unsuitable for bathing.

Salvador also has only 39.5% of its public streets lined with trees, and a significant burden of air pollutants, as reported by the Fiocruz News Agency in the article "Air pollution in Salvador: a risk-analysis approach for decision-making": "The study, coordinated by Fiocruz Bahia researcher Nelzair Vianna, detected pollutants such as particulate matter (PM), nitrogen dioxide (NO<sub>2</sub>), and carbon dioxide (CO<sub>2</sub>) in the city's air. Specific analyses were carried out to characterize urban atmospheric particulate matter, in which metals such as cadmium, chromium, and lead were detected. These 2.5-micrometer particles (PM<sub>2.5</sub>) are so fine that they can penetrate deep into the lungs."

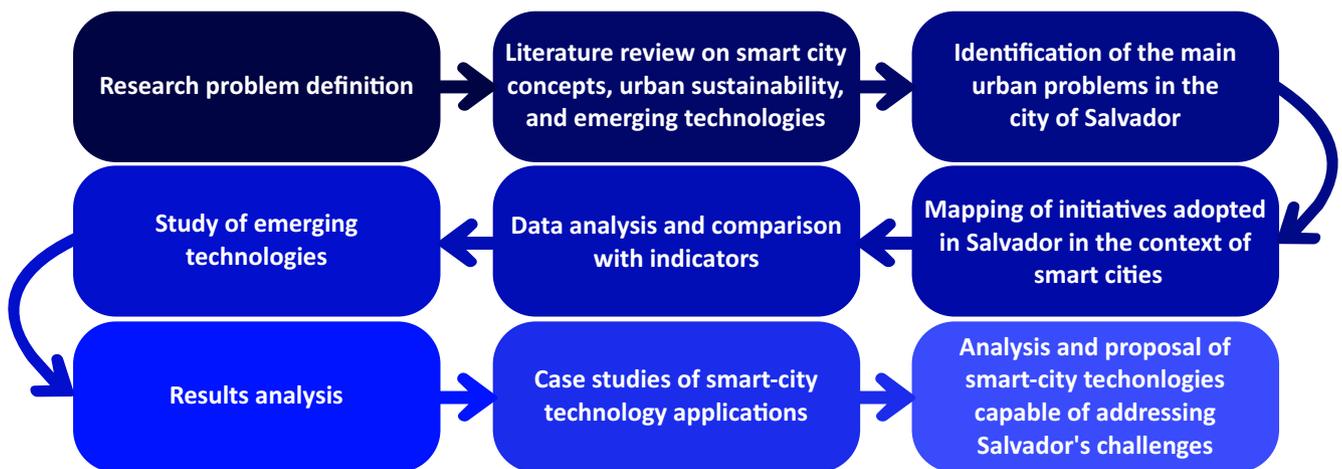
Considering the environmental dimension alongside infrastructure, a key component is basic sanitation, which, according to the National Water Agency (ANA) [1], comprises water supply; sewage collection and treatment; urban cleaning

and the collection and disposal of solid waste; and stormwater drainage and management. In this context, despite standards, oversight, and sanitation agencies, data from the National Sanitation Information System (SNIS) [13] indicate that Salvador still has residents without access to basic sanitation services: 1.24% of the population lacks access to water; 3.35% lacks solid-waste collection; 11.66% lacks adequate sewerage; and 0.1% of households are subject to flooding.

## **Materials and Methods**

This basic research, conducted between January and June 2025 with an exploratory–descriptive design and qualitative analysis, aims to expand theoretical knowledge about Salvador's challenges and potential in its transition to a smart city. The study describes urban indicators, public policies, and emerging technologies already adopted, and it explores relationships among these elements that have received little investigation. To guide this design, we adopted the procedures proposed by Gil [4]. In separately defining exploratory and descriptive research, Gil [4] characterizes them as studies whose main purposes are to develop, clarify, and refine concepts and ideas with a view to formulating more precise problem statements or hypotheses to be tested in subsequent studies, and to describe the characteristics of a given population or phenomenon or to establish relationships between variables. He also indicates that planning qualitative procedures involves defining the research objectives from a qualitative perspective, selecting the sample, and collecting and analyzing data. As for data, we examined publications (from 2020 onward) in secondary databases such as SciELO and Google Scholar, using the keywords "Smart Cities," "Challenges in the City of Salvador," and "Smart City Technologies." The study also includes a document analysis of technical reports from the Salvador municipal government and municipal legislation.

Figure 1 shows the methodological approach in nine sequential steps.

**Figure 1.** Methodological steps.

## Results and Discussion

Three cities applied different tools to address specific challenges, yielding measurable gains in energy efficiency, environmental quality, and mobility (Table 3).

The analysis of Table 3 shows that, although they differ in scope and tools, the three cases adopt complementary solutions based on sensing, automation, and green infrastructure to deliver environmental, economic, and social gains.

Helsinki and Zurich invested heavily in smart lighting and traffic-signal systems, equipped with presence, luminance, and motion sensors, to curb energy use and improve traffic flow, whereas Singapore stood out for deploying green corridors, green roofs, and rainwater harvesting, focusing on thermal regulation and air quality.

In summary, integrating renewable energy, green infrastructure, and real-time IoT solutions yields a triad of benefits: (i) environmental, through lower emissions and pollutants; (ii) economic, via optimized operating costs; and (iii) social, by improving health and mobility, providing valuable guidance for Salvador when selecting technologies best suited to its specific challenges.

The proposals presented in the Table 4 show that deploying technologies such as cybersecurity, IoT, AI, and big data can significantly help Salvador advance toward the selected SDG.

The integration between these tools and the mapped challenges outlines a strategic path for transforming the city into a smart city that meets residents' needs. The use of smart city technologies can move Salvador closer to SDG 9 and SDG 11 by directly contributing to the mitigation of social and structural problems.

Big data and AI enable precise diagnostics and can predict failures in systems and infrastructure, in addition to assisting maintenance. IoT allows sensors to provide real-time data, optimizing public management. Cybersecurity protects every technology against cyberattacks as well as citizens' data and public services. In this way, the initiatives to develop infrastructure and promote industrialization (SDG 9), and the effort to make cities safer and more sustainable (SDG 11), would be supported.

Considering the research results, our analysis of Salvador's PDTCI shows a strong convergence between the technologies identified in our study and those outlined in the municipal plan. Our study highlights IoT, AI, cybersecurity, and big data as key smart-city technologies applicable to Salvador's challenges, and offers an academic and propositional perspective, grounded in international comparisons, that can provide the municipal administration with valuable inputs to evaluate, refine, and expand planned initiatives, as well as to design new long-term actions under the

**Table 3.** Smart cities: Analysis of tool application and benefits achieved.

City	Tools	Benefits	Type of Sustainability	Technology Applied
Helsinki (Finland)	<ul style="list-style-type: none"> <li>Offshore wind farms</li> <li>Biomass plants</li> <li>Smart public lighting with presence sensors and remote control</li> </ul>	<ul style="list-style-type: none"> <li>27% reduction in CO<sub>2</sub> emissions since 1990</li> <li>Progress toward carbon neutrality by 2035</li> <li>Operational savings on the power grid through optimized lighting operation</li> </ul>	Environmental sustainability	IoT (presence sensors and remote control)
Singapore (Singapore)	<ul style="list-style-type: none"> <li>Green corridors</li> <li>Green roofs on public buildings</li> <li>Linear parks</li> <li>Rainwater capture and reuse systems</li> </ul>	<ul style="list-style-type: none"> <li>Up to 2°C temperature drop in critical neighborhoods (mitigating urban heat islands)</li> <li>Improved air quality (reduced PM<sub>2.5</sub> and NO<sub>2</sub>)</li> <li>Fewer respiratory illnesses</li> </ul>	Urban sustainability	Data and Artificial Intelligence (environmental monitoring and urban planning)
Zurich (Switzerland)	<ul style="list-style-type: none"> <li>Adaptive lighting poles with sensors</li> <li>Smart traffic lights connected to a real-time control center</li> </ul>	<ul style="list-style-type: none"> <li>Up to 70% savings in public lighting</li> <li>Reduced congestion via real-time signal timing adjustments</li> <li>Lower pollutant emissions due to fewer frequent stops</li> </ul>	Energy sustainability	IoT and Artificial Intelligence (dynamic adjustment of lighting and traffic)

Source: Adapted from Scoop Market (2024) and Earth.org (2025).

PDTCI. The plan not only mirrors these findings, it also integrates them into its structure, objectives, and supporting infrastructure.

## Conclusion

The study identified Salvador's main challenges and examined how emerging technologies, within the smart-city context, could be applied to address them, relating these applications to progress on SDG 9 and SDG 11. It also drew on smart-city

case studies from leading cities in international rankings. The central takeaway is the importance of aligning technological innovation with public policies aimed at inclusion and equity, reaffirming that the smart-city concept goes beyond service digitization and requires integrated urban planning, civic participation, and social justice.

The research objective was achieved, and through the analysis of Table 4, we showed how each proposed technology can deliver concrete and significant impacts. Moreover, this investigation

**Table 4.** Sustainability challenges in Salvador, technologies, and expected impacts.

Type of Sustainability	Challenges in the City of Salvador	Applicable Technologies	Expected Impacts
Environmental	<ul style="list-style-type: none"> <li>Air pollution</li> <li>Low urban tree cover</li> <li>Inadequate sanitation</li> </ul>	<ul style="list-style-type: none"> <li>IoT for environmental monitoring and risk prevention</li> <li>Big Data for risk and pollution analysis</li> </ul>	<ul style="list-style-type: none"> <li>Improved air and water quality</li> <li>Reduced pollution</li> <li>Increased tree coverage</li> </ul>
Social	<ul style="list-style-type: none"> <li>Social inequality</li> <li>Shortfalls in education and public health</li> </ul>	<ul style="list-style-type: none"> <li>IoT to monitor risk in vulnerable areas</li> <li>Use of AI to improve the performance of public policies</li> <li>Cybersecurity to protect population data and public services</li> </ul>	<ul style="list-style-type: none"> <li>Reduced inequalities</li> <li>Mitigation of problems in vulnerable communities</li> <li>Improved public services</li> <li>Greater speed and reliability of systems</li> </ul>
Economic	<ul style="list-style-type: none"> <li>Low infrastructure development</li> </ul>	<ul style="list-style-type: none"> <li>Apply AI to support economic development</li> <li>Big Data to support service management</li> <li>Cybersecurity to protect systems</li> </ul>	<ul style="list-style-type: none"> <li>Improved city infrastructure</li> <li>Greater speed and reliability of systems</li> </ul>

contributes not only academically, by outlining key challenges and applicable technologies, but also to municipal management by proposing solutions to the city's challenges, which may lead to revisions and improvements in its PDTCI. It can also support other Brazilian cities in advancing based on this study and new applications. This research was limited to four principal smart-city technologies, namely cybersecurity, IoT, AI, and big data, selected for their relevance and applicability to the mapped challenges. However, there are other promising technologies that warrant future exploration, such as blockchain, augmented reality, and robotics, which have the potential to contribute positively to critical areas of urban management. We therefore propose continued studies in this field to assess additional applicable technologies that can help more cities advance on SDG 9 and SDG 11, as well as on other Sustainable Development Goals.

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## Development of a Gamified Environment with AI for Aphasia Rehabilitation: A Work in Progress

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**Introduction:** Aphasia is a neurological disorder that significantly impairs communication skills, affecting speech, writing, reading, and comprehension. Current rehabilitation methods often require constant professional supervision and rely on repetitive, non-interactive exercises. **Objective:** This work proposes an innovative gamified platform to support the rehabilitation of people with aphasia through interactive, 3D environments integrated with advanced speech recognition and artificial intelligence. **Methods:** The system offers mission-based tasks in which users interact with objects and environments inspired by daily life. Voice commands, captured and transcribed via Google Cloud Speech-to-Text, are interpreted by a natural language AI to enable free-form verbal interaction, going beyond predefined commands. **Tasks include object naming, word recognition, and reading activities, with multimodal feedback (visual, verbal, and written).** **Expected Impact:** The platform enables home-based, unsupervised practice while maintaining therapeutic quality, potentially enhancing lexical retrieval, improving patient engagement, and supporting speech-language pathologists in treatment planning. This approach combines gamification, accessibility, and AI-driven personalization to deliver a more dynamic, immersive, and adaptable rehabilitation process.

**Keywords:** Gamification. Rehabilitation. Aphasia. Speech Therapy. Artificial Intelligence.

Gamified environments have been consolidating as an effective strategy in various sectors, such as education, arts, industry, and especially healthcare. By incorporating playful elements, these environments foster patient engagement in medical treatments, encouraging positive behavioral changes. Such strategies have proven effective in disease management, in motivating the adoption of healthy habits, and in improving adherence to correct medication use [1].

Aphasia is a neurological disorder that impairs communication skills, affecting speech, writing, reading, and comprehension. As illustrated in Figure 1, there are different types of aphasia, such as: Broca's, Wernicke's, conduction, anomic, global, mixed transcortical, transcortical sensory, and transcortical motor. This condition is usually caused by strokes (CVAs), although it can also result from brain tumors, head trauma, infections, or other disorders that affect brain function [2,3].

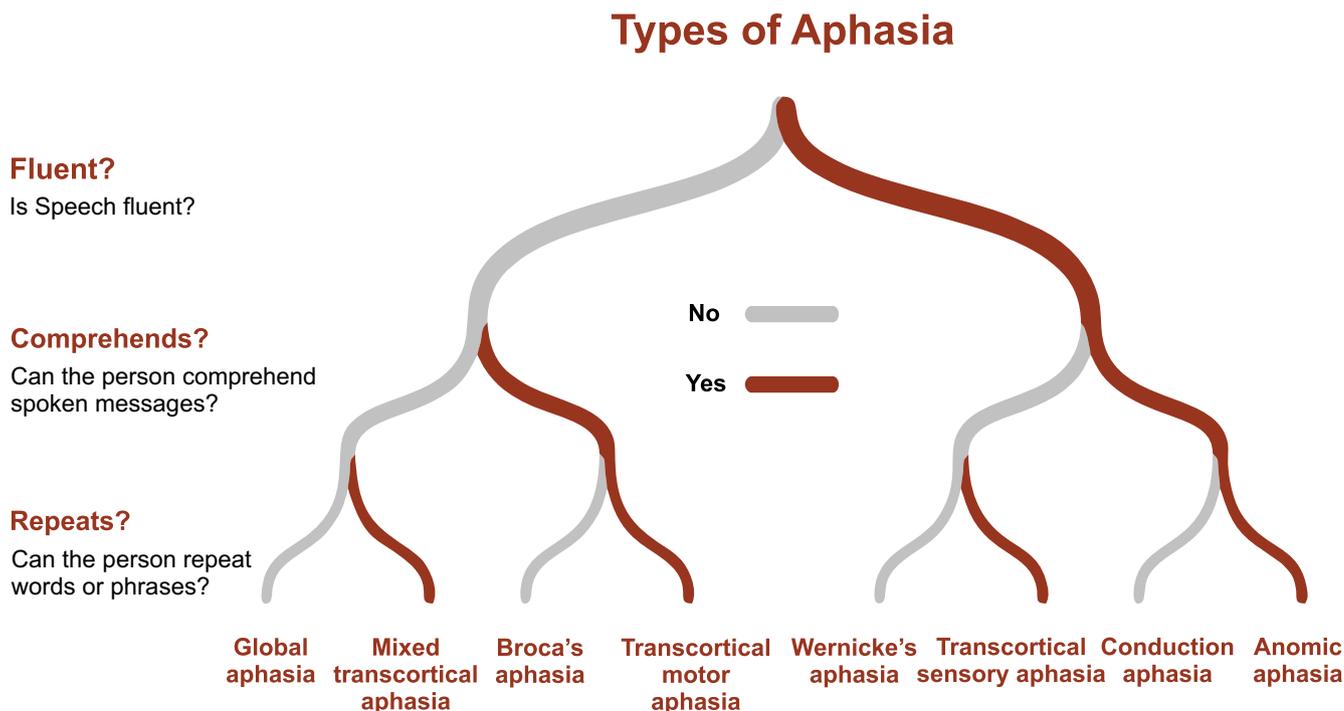
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Additionally, therapeutic training methods stand out, such as the “Look, Listen, Repeat” approach, in which the patient verbally repeats objects or phrases after seeing and hearing them. Other resources include semantic feature analysis and response elaboration training, where an image is presented to the aphasic patient, who must then identify and name the represented object [4].

Menke and colleagues 2009 [6] show that the traditional intensive naming protocol — based on figure repetition with cards and verbal correction — is effective in treating patients with chronic aphasia, as it stimulates the activation of alternative brain areas. To improve this method, authors such as Rodrigues, 2015 [7], and Rybarczyk and Gonçalves, 2016 [8], highlight the use of the three-dimensional graphic environment of the WebLisling system, which allows patients to interact with everyday items, making treatment more immersive and ecologically valid. This approach differs from conventional methods, which are traditionally based on two-dimensional figures, such as static images.

The study developed by Pereira and Debatin, 2022 [9], led to the creation of a two-dimensional (2D) digital game implemented using the Unity3D engine. The game adopts an innovative control system

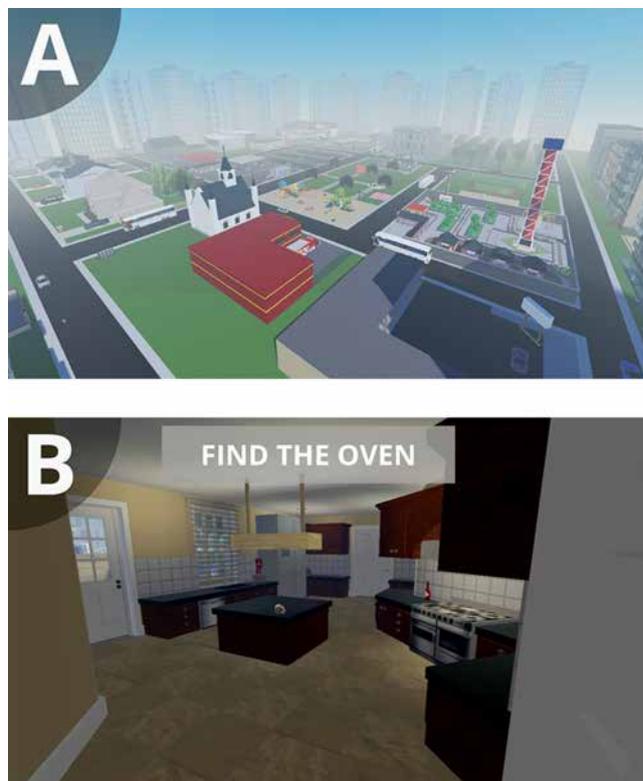
**Figure 1.** Types of aphasia from the National Aphasia Association.



through voice recognition, using the Google Cloud Speech-to-Text API. This solution was designed to provide digital accessibility for people with motor impairments, allowing them to interact with the virtual environment through predefined voice commands — such as “jump,” “right,” and “left” — carefully selected after tests to optimize response time.

In this context, the game is proposed as a complementary tool for speech therapy aimed at people with aphasia, enabling its use even without constant supervision from a speech-language pathologist. Moreover, it offers interactive environments inspired by daily life, supporting the development of naming and object recognition skills in a playful way. Players will be able to explore a city — as illustrated in Figure 2, image A — visiting places such as stores, pharmacies, museums, or supermarkets. In each of these environments, there will be a set of objects previously defined by the game; for example, in the house (Figure 2, image B), the player is expected to recognize items such as the stove. In this article, only one of the proposed scenarios will be addressed, as the project is still in the early stages of implementation.

**Figure 2.** Prototype of a city (A) and prototype of an environment (B).



## Related Works

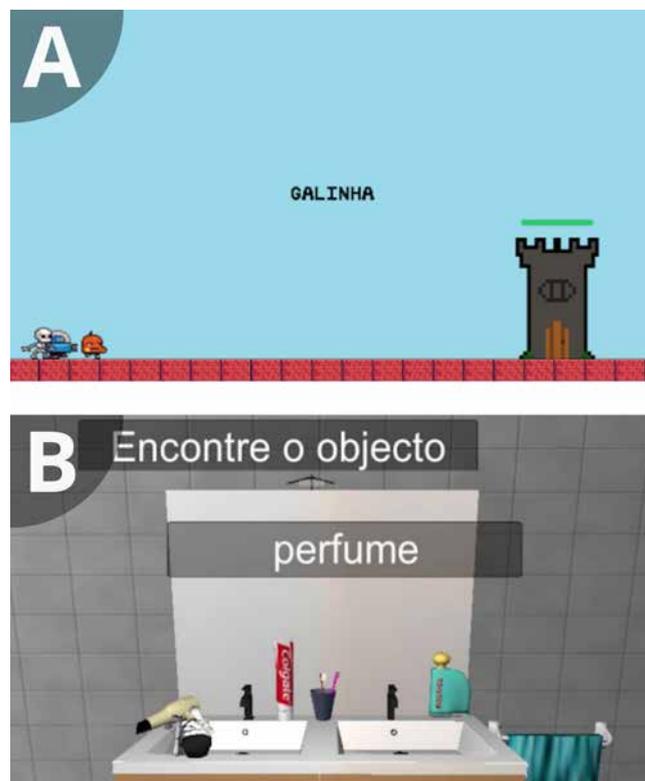
Gamification has proven to be a promising approach in supporting speech therapy treatments, particularly in the rehabilitation of patients with speech disorders. An example of this application is the Tower Defense-style game Voice Hero, developed with the intention of promoting speech training through playful activities [10]. In the game, the user must correctly pronounce the words displayed on the screen to launch attacks against enemies approaching a castle, as illustrated in Figure 3, image A. This game mechanic integrates gamified elements into the therapeutic process, fostering patient motivation and engagement.

Another relevant example is the virtual therapeutic platform WebLisling, aimed at treating Portuguese-speaking aphasic patients. Initially developed by Rodrigues, 2015 [7], and later enhanced by Rybarczyk and Gonçalves, 2016 [8], the platform uses gamification features combined with three-dimensional graphic environments to provide a more realistic and interactive therapeutic experience[7,8]. The therapeutic exercises offered by the platform are organized into four main categories: written expression, oral comprehension, written comprehension, and motor tasks. Each of these categories is contextualized within its own virtual environment, contributing to the naturalization of the learning and rehabilitation process.

In this way, the projects discussed demonstrate the potential of gamification as a support strategy in the healthcare field, particularly in speech-language pathology. By providing more interactive experiences tailored to the specific needs of patients with aphasia, gamified environments contribute significantly to the effectiveness and continuity of treatment. However, none of the reviewed works integrates all the elements that make up the present proposal.

Our project stands out by combining explorable 3D environments, voice commands interpreted by artificial intelligence to enable free verbal interactions (not limited to predefined commands), and multimodal feedback (visual, textual, and

**Figure 3.** Images of the game ‘Voice Hero’ (A) and the WebLisling platform (B).



verbal) in everyday contextualized tasks. This approach aims not only to increase patient engagement but also to make it possible to conduct high-quality therapy sessions at home, without the need for constant supervision. Thus, the proposed solution fills a gap identified in existing studies, offering an innovative and potentially more effective path for aphasia rehabilitation.

## Materials and Methods

Building on the gap identified in existing studies, the project under development incorporates elements found in other therapeutic platforms, such as WebLisling and similar solutions, but goes further by integrating additional features that enhance its potential clinical impact. Among these are the possibility of home-based practice, the provision of instant feedback, integration with voice recognition APIs, and the use of artificial intelligence to interpret free verbal interactions,

enabling more natural and contextually relevant communication within the virtual environment.

The key differentiator, however, lies in the implementation of resources capable of expanding verbal communication beyond predefined commands or patterns, through the use of artificial intelligence (AI) to interpret the content of spoken sentences. This approach aims to stimulate lexical retrieval during the exploration of the virtual environment, allowing verbalizations to occur in varied and contextually appropriate ways.

The game under development adopts an approach based on an explorable world, in which players can choose which locations in a city they wish to explore. Within these locations, there will be a set of objects, and the goal is for the person with aphasia, through missions, to be able to recognize and name such objects. These missions may involve recognizing environments — such as a kitchen, for example — and objects, with the system pronouncing or displaying their names. During the execution of each mission, the user will be shown what they must do in different ways: a three-dimensional visualization of the object (Figure 4), a written form, and a verbal form, where the player must interpret what was said. It is also possible to combine these display methods.

Character movement is controlled by voice commands processed by the Google Cloud Speech-to-Text API, allowing individuals with aphasia who have a reasonable level of comprehension and lexical retrieval — as in the case of conduction aphasia — to explore the city interactively. The captured speech is transcribed by the API and sent to a natural language AI — such as DeepSeek or ChatGPT — responsible for interpreting the utterance and converting it into specific in-game commands. This structure enables the creation of an environment where the player not only recognizes available objects but also practices naming them in a contextualized manner.

Development takes place on the Unity platform, chosen for its high adaptability to different systems, including Windows and mobile devices. Other key factors in this choice include the wide availability of assets (digital resources), the use of the C# language

**Figure 4.** Mission from the game under development.



— considered more intuitive than C++ (used in Unreal Engine) and more performant than GDScript (from Godot) — as well as good optimization for devices with less powerful hardware.

### Expected Results

The gamified environment Fala+ represents an innovative and promising proposal in the field of speech-language pathology, combining emerging technologies — such as immersive 3D environments, multimodal feedback, and natural language processing with artificial intelligence — into a therapeutic resource aimed at the rehabilitation of people with aphasia. The solution was designed to serve as a complementary tool to traditional treatment, enabling patients to make significant progress in their rehabilitation process without relying exclusively on constant mediation by the speech-language pathologist.

The therapeutic core of Fala+ is based on performing object naming and recognition tasks through different modalities — speech, writing, or visual reading — combined with verbal interactions that allow controlling movement within the virtual environments. This approach seeks, in a playful and motivating way, to stimulate cognitive and communicative skills essential to rehabilitation, while also fostering engagement and adherence to treatment.

The platform also stands out for addressing a critical gap in healthcare: the provision of high-

quality therapeutic practice conducted remotely, with professional supervision support. This feature has the potential to reduce treatment costs, improve continuity of care, and promote greater patient autonomy.

So far, development has already incorporated mission mechanics and multiple display modes—essential elements to make interaction more dynamic. However, technical challenges remain, such as improving the object recognition system—which, in its current version, identifies structural elements like floors, walls, and ceilings instead of therapeutic items—and optimizing mission displays to ensure clarity and consistency in task communication. Other critical points include creating richly detailed interiors without compromising performance, especially on mobile devices, and visually adapting objects to avoid cognitive overload or navigation blind spots.

The development plan foresees significant expansion in both content and applicability. New modalities and activities aimed at speech therapy stimulation are scheduled, such as rhyme exercises, writing practices, and matching games, all adaptable to different profiles and stages of rehabilitation. The proposal also includes expanding environments from a single setting to a set of cities with distinct characteristics—such as coastal, urban, and rural locations—to enrich sensory and narrative experiences, fostering patient immersion and motivation.

## Conclusion

The implementation of these stages will be accompanied by continuous validation with healthcare professionals, ensuring that therapeutic objectives are effectively met and that proposed activities maintain clinical relevance. If the expected results are confirmed, Fala+ could establish itself as a highly relevant technological tool, integrable into formal rehabilitation programs and scalable for treating other neurological disorders and conditions requiring cognitive and communicative stimulation. Thus, the project not only innovates in the use

of technology for therapeutic purposes but also contributes to making healthcare more accessible, dynamic, and personalized.

The project is currently in the development and refinement phase. Although it has already been validated, in terms of concept and applicability, by a speech-language pathologist as a potentially useful resource for rehabilitation support, it has not yet undergone formal clinical validation. We reinforce our commitment to conducting more in-depth studies, including trials in a real rehabilitation setting with both aphasic and non-aphasic users, to evaluate its efficacy, usability, and therapeutic impact.

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## Marine Polychaetes as Biomonitoring Tools for Total Mercury in BTS Beach Environments

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**Anthropogenic activities such as industrialization, urbanization, mining, and waste disposal release toxic metals into marine ecosystems, posing long-term threats to biodiversity and human health. These contaminants can persist, bioaccumulate in aquatic organisms, and biomagnify along the food web. Biomonitoring, using organisms capable of indicating and quantifying environmental contaminants, is essential for assessing pollution levels and guiding mitigation strategies. Polychaetes—benthic marine worms that inhabit and feed within sediments—are effective biomonitors of toxic metals, as these pollutants are often adsorbed onto sediments and accumulate in their tissues. In this study, polychaetes from the families Chaetopteridae, and Spionidae/Eunicidae were collected in Todos os Santos Bay (BTS), near Salvador, Bahia, Brazil, to monitor mercury contamination in the region.**

**Keywords: Mercury. Biomonitoring. Marine Contamination.**

**Abbreviations: BTS, Todos os Santos Bay. Hg, Mercury.**

The potential effects of anthropogenic emissions of toxic metals, along with their long-term consequences for marine ecosystems, have emerged as a key concern in environmental biomonitoring studies [1,2]. Activities such as industrialization, urbanization, municipal waste disposal, urban and agricultural runoff, mining, and sewage discharge are important sources of toxic metal release into marine ecosystems [3]. Biomonitoring studies are essential for assessing pollution levels and identifying potential risks to human health arising from daily exposure to high concentrations of toxic metals [4,5].

Among toxic metals, mercury is considered extremely harmful even at low concentrations due to its ability to bioaccumulate in different organisms [6,7]. Total mercury (THg) occurs in environmental substrates and can contaminate other organisms through dietary

intake, accumulating in their tissues and transferring through successive trophic levels via biomagnification [8].

Once introduced into marine environments, mercury can persist for long periods, bioaccumulating in aquatic organisms [9,10]. These processes threaten biodiversity and pose significant risks to human populations that rely on seafood as a dietary staple [11,12]. Understanding the pathways, accumulation patterns, and ecological effects of these contaminants is therefore crucial for developing effective mitigation strategies and guiding environmental policies [13,14].

In this context, the use of organisms—collectively referred to as biota—emerges as an effective approach for providing detailed information on the integrity of aquatic ecosystems [12,13]. According to Markert (2007), bioindicators are species capable of retaining specific contaminants; however, they lack the capacity to bioaccumulate them at levels sufficient for quantification by conventional analytical methods [14]. Thus, bioindicators can only signal the presence of a contaminant in the environment [15]. In contrast, biomonitors are capable of both indicating and quantifying contaminants to which an ecosystem is exposed [16].

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Polychaetes are marine worms widely distributed across diverse habitats, including sandy beaches near shallow waters, and exhibit remarkable morphological and ecological diversity [17]. These benthic invertebrates inhabit sediments, where they feed on stored organic matter and contribute to nutrient cycling between sediments and the water column [18]. Contaminants of anthropogenic origin, such as toxic metals, which are often adsorbed onto marine sediments, can accumulate in their tissues [19–21].

A wide range of marine organisms serve as biomonitors for aquatic pollution, including amphibians, fish, mollusks, and sea sponges, as well as microorganisms and crustaceans for monitoring soil and water parameters [22–25]. In this study, polychaetes were collected in the Todos os Santos Bay (BTS) region, near the city of Salvador, Bahia State, Brazil. Specifically, polychaetes from the families Chaetopteridae, Spionidae, and Eunicidae were used as biomonitors of mercury in the BTS region (Figure 1).

## Materials and Methods

### Site Description and Collection of Samples

The study was conducted in the BTS region, located between two zones: the North Littoral of

Bahia (LN) and the Marau Peninsula (PM) (Table 1 and Figure 2).

Polychaetes were collected from five distinct beaches within Todos os Santos Bay: Aratu (ARA), Itaparica (ITA), Madre de Deus (MD), Paripe (PAR), and Ribeira (RIB).

After verifying the optimal tide conditions (close to zero), approximately 20 individuals were collected from surface sediments at a depth of about 10 cm using aluminum sieves.

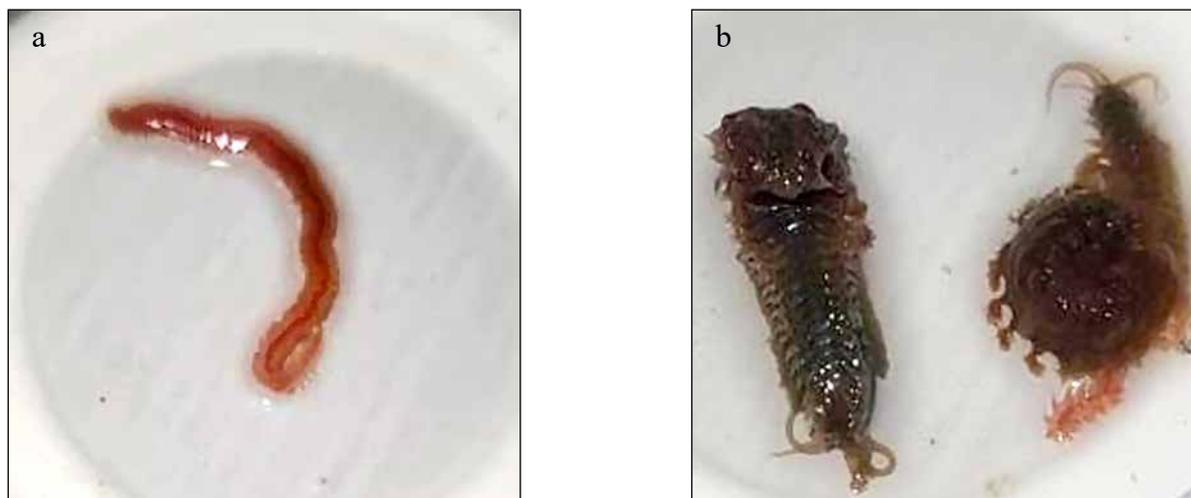
### Sample Preparation

The collected polychaetes were transferred to pre-cleaned glass recipients containing approximately 50 mL of seawater from the same region, placed in a refrigerated thermal box, and transported to the laboratory, where they were stored in a freezer at  $-20\text{ }^{\circ}\text{C}$  [29]. After that, the samples were freeze dried using an SL-404 lyophilizer (SOLAB, Brazil).

### Chemical Analysis

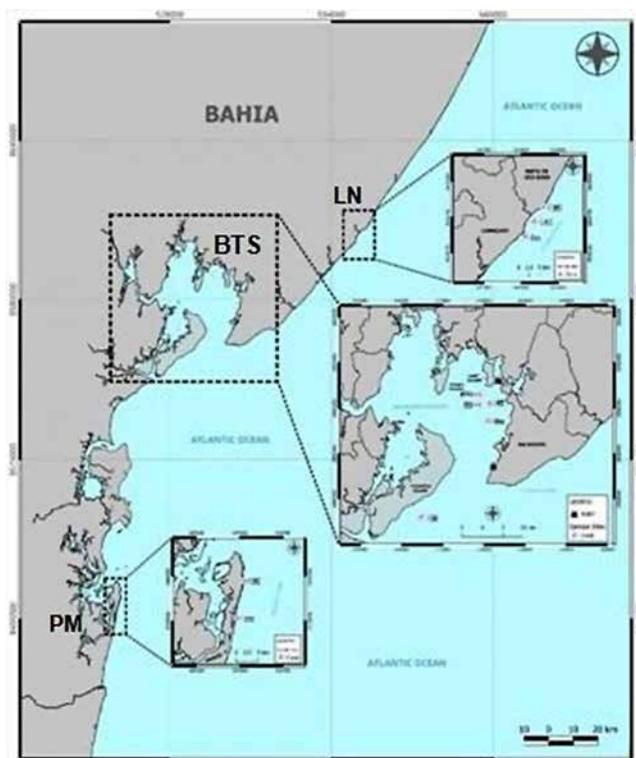
Total mercury (THg) determinations in samples from the investigated biota were performed using a DMA-80 Tri Cell Direct Mercury Analyzer (Milestone, Sorisolev (BG), Italy). This methodology was like that used by Menezes and colleagues (2023) [30]. Each biota

**Figure 1.** Polychaetes samples familys: a) *Chaetopteridae*. b) *Spionidae/Eunicidae*.



**Table 1.** Geographic coordinates of the sampling sites.

	Sites	Lat	Long
Samples	ARA	-12.911	-38.497
	ITA	-12.741	-38.606
	MD	-12.885	-38.675
	PAR	-12.814	-38.488
	RIB	-12.835	-38.476

**Figure 2.** Zones of BTS, LN and PM regions.

was analyzed directly, with approximately 20 to 100 mg of sample placed in nickel sample boats/crucibles. The boats and other metal instruments were previously cleaned in an ultrasonic bath with a 4% Extran solution for 10 minutes, washed with Milli-Q water, dried, and then subjected to a muffle furnace at 700°C for 10 minutes. For mercury determination, three calibration curves were generated, with coefficients of determination ( $R^2$ ) of 0.9994, 0.9991, and 0.9990, respectively.

Calibration was performed using three standard solutions prepared in different volumes, as instructed by the equipment manufacturer, using Table 2 as a reference.

**Table 2.** Data used to calibrate the Direct Mercury Analyzer DMA-80 Tri Cell instrument (Milestone, Sorisolev (BG), Italy).

Hg Calibration (ng)	Concentration of Hg Standard
0.5 (low range)	5 $\mu$ L of 100 PPB
1.0 (low range)	10 $\mu$ L of 100 PPB
2.0 (low range)	20 $\mu$ L of 100 PPB
3.0 (low range)	30 $\mu$ L of 100 PPB
5.0 (Medium range)	50 $\mu$ L of 100 PPB
10 (Medium range)	100 $\mu$ L of 100 PPB
20 (Medium range)	20 $\mu$ L of 1 PPM
50 (High range)	50 $\mu$ L of 1 PPM
100 (High range)	100 $\mu$ L of 1 PPM
200 (High range)	200 $\mu$ L of 1 PPM
500 (High range)	50 $\mu$ L of 10 PPM
700 (High range)	70 $\mu$ L of 10 PPM
1000 (High range)	100 $\mu$ L of 10 PPM

The limits of detection (LOD) and quantification (LOQ) were calculated based on the standard deviation of the blank replicates, using the equations [30]:

$$\text{LOD} = 3 \times (\text{SD})/\alpha \quad (1)$$

$$\text{LOQ} = 10 \times (\text{D})/\alpha \quad (2)$$

Where  $\alpha$  represents the slope of the calibration curve. The values obtained were LOD = 0.004ng and LOQ = 0.012ng. The accuracy of the method was evaluated using certified reference materials: marine sediment (MESS-3) and fish protein (DORM-4), both supplied by the National Research Council (NRCC), Canada. The certified

values were  $0.091 \pm 0.009 \text{ mg kg}^{-1}$  and  $0.410 \pm 0.055 \text{ mg kg}^{-1}$ , respectively. The results obtained by the DMA method were  $0.086 \pm 0.003 \text{ mg kg}^{-1}$  for marine sediment (95% agreement) and  $0.414 \pm 0.003 \text{ mg kg}^{-1}$  for fish protein (101% recovery).

Intraand interday precision was assessed by analyzing the certified reference materials. Approximately 40 samples were processed per day, with calibration checks performed every 10 measurements. Intraday precision was estimated with four replicates on the same day, while interday precision was calculated over four consecutive days, with four replicates per day, all performed under the same experimental conditions. The coefficient of variation (CV) found was 1.1% for marine sediment and 2.3% for fish protein (intraday) and 5.6% and 5.3% for sediment and fish protein, respectively (interday) [31,32].

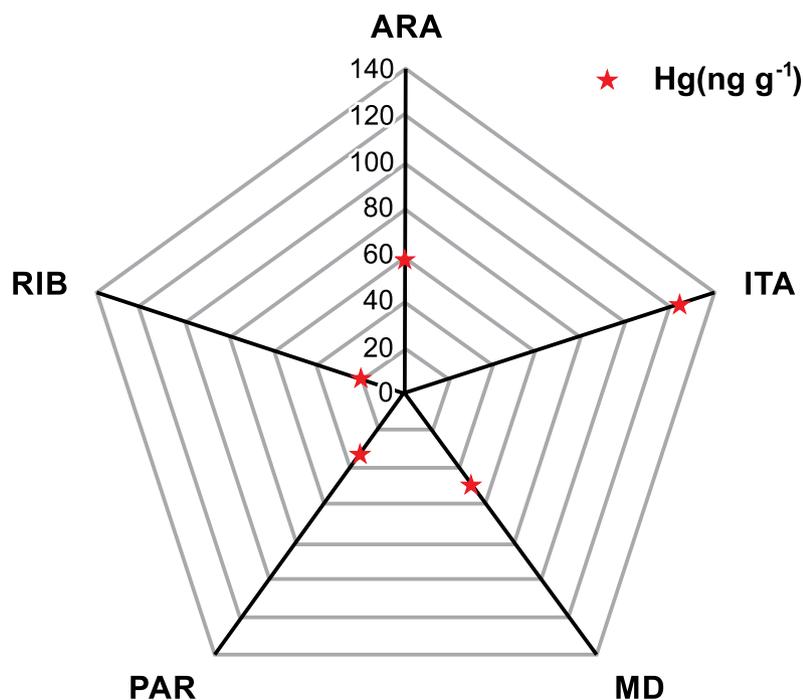
## Results and Discussion

From the results, polychaetes collected at the ITA site exhibited the highest Hg concentration, exceeding  $130 \text{ ng g}^{-1}$ , which may indicate a

stronger influence of anthropogenic sources such as boating activity, fishing, or nearby urban discharge [26]. ARA (Aratu) showed intermediate concentrations (around  $60 \text{ ng g}^{-1}$ ), consistent with its proximity to industrial and port areas, which are known potential contributors of mercury to aquatic ecosystems. PAR (Paripe) and MD (Madre de Deus) presented lower values, between 20 and  $40 \text{ ng g}^{-1}$ , suggesting reduced contamination compared to ITA and ARA. The lowest concentration was recorded at RIB (Ribeira), near  $10 \text{ ng g}^{-1}$ , possibly due to less direct exposure to Hg sources or more favorable environmental conditions for mercury dispersion and dilution (Figure 3).

Overall, the radar plot illustrates the spatial distribution of mercury concentrations in polychaetes at the five sampled sites, revealing marked spatial variability, particularly at ITA ( $125 \text{ ng g}^{-1}$ ), while the other sites displayed values below  $60 \text{ ng g}^{-1}$ . Such variability may be related to differences in local contamination sources, hydrodynamics, and sediment characteristics influencing the bioavailability and bioaccumulation of Hg in polychaetes.

**Figure 3.** Mean mercury (Hg) concentrations ( $\text{ng g}^{-1}$ ).



In the study conducted by Sola and colleagues (2022), eight polychaetes species were collected in BTS, with mean Hg concentrations ranging from 46.1 to 740 ng g<sup>-1</sup>, indicating a strong potential for Hg bioaccumulation in these organisms (Figure 4).

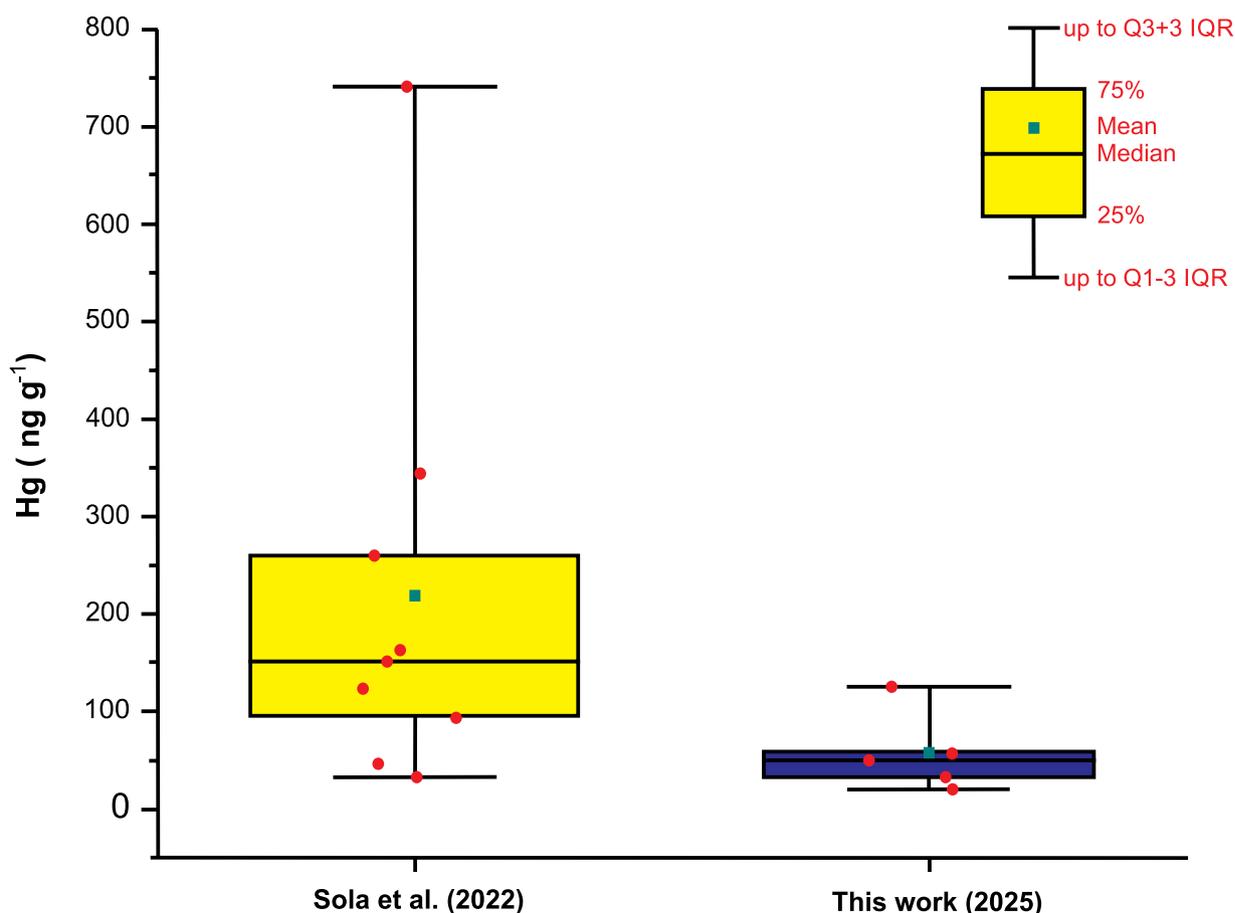
A comparison between the mercury (Hg) concentrations reported by Sola and colleagues (2022) and those obtained in this study reveals significant differences in both central tendency and dispersion. The Hg levels reported by Sola and colleagues present a notably higher median and a much wider range, with values reaching approximately 740 ng g<sup>-1</sup>, indicating substantial variability and possibly high contamination in the environment or in the sampled organisms. In contrast, the data from this work show considerably lower median Hg concentrations, with a narrower interquartile range and fewer extreme values, suggesting lower contamination levels.

These marked differences between the two studies may be attributed to several factors, including variations in the polychaetes species analyzed, differences in collection sites, or seasonal variations in sampling. The greater dispersion and higher outliers in the Sola and colleagues (2022) dataset may also reflect localized pollution hotspots or episodic contamination events. Conversely, the data from the present study were more constrained, with lower maximum values than those observed by Sola and colleagues (2022), which may indicate that the studied area was less impacted by Hg contamination.

## Conclusion

Anthropogenic activities such as industrialization, urbanization, mining, and waste disposal release toxic metals into

**Figure 4.** Comparison between studies.



marine ecosystems, posing long-term threats to biodiversity and human health. These contaminants can persist, bioaccumulate in aquatic organisms, and biomagnify along the food web. Biomonitoring, using organisms capable of indicating and quantifying environmental contaminants, is essential for assessing pollution levels and guiding mitigation strategies. Polychaetes—benthic marine worms that inhabit and feed within sediments—are effective biomonitors of toxic metals, as these pollutants are often adsorbed onto sediments and accumulate in their tissues. In this study, polychaetes from the families Chaetopteridae, Spionidae, and Eunicidae were collected in Todos os Santos Bay (BTS), near Salvador, Bahia, Brazil, to monitor mercury contamination in the region.

Although mercury detection in marine ecosystems has been previously reported, continuous monitoring remains of paramount importance. The values reported by Sola et al. were considerably higher, reinforcing the need for frequent biomonitoring to track variations in this toxic metal. Such monitoring enables timely alerts to the competent regulatory authorities and supports the development of public policies aimed at mitigating the deleterious effects of mercury on ecosystems, biota, and human health.

## Acknowledgement

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## Development of Processing Strategies to Enable 3D Printing of LLDPE With Sisal Fiber Reinforcement

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Linear low-density polyethylene (LLDPE) is a packaging material with superior properties compared to conventional low-density polyethylene. However, due to its low thermal stability, it cannot yet be used in high-performance applications. Due to its use as single-use packaging and low natural degradation in nature, the continued use of this material may delay the achievement of the UN's sustainable development goals. Therefore, sisal fibers can be used in LLDPE, reducing the carbon footprint of this material and utilizing agro-industrial residue. However, the use of these fibers reduces the processing temperature to approximately 200 °C due to their degradation and therefore brings even more challenges to the application of this material in 3D printing. This polymer exhibits significant thermal shrinkage due to crystallization, which hinders its application in 3D printing. To this end, this work aims to develop new techniques for printing a novel LLDPE/ sisal fiber composite. Printing temperatures between 175 and 190 °C were tested, and it was observed that temperatures below 190 °C caused problems due to the low polymer fluidity in the 3D printer's small extruder nozzle. However, this temperature was enough to guarantee the completion of the printing. Three substrate materials were analyzed: polyethylene terephthalate glycol (PETG), high-impact polystyrene (HIPS), and polylactic acid (PLA), at a printing bed temperature of 80 to 123 °C. The experiments enabled the printing of good-quality test specimens using HIPS and PETG as substrates, but only at a bed temperature of 123 °C. The test specimens produced enabled the feasibility of future mechanical characterization of the material, and the methods developed will enable the development of LLDPE in the literature. As future research, the generation of a customized g-code will be studied that will allow the use of the same substrate to manufacture multiple test specimens, thus reducing process waste.

**Keywords:** LLDPE. 3D printing. Composite. Sisal fibers.

Linear low-density polyethylene (LLDPE) is a semi-crystalline and flexible polymer used in packaging, cable sheathing, among other applications. Although LLDPE exhibits superior properties compared to non-linear LDPE, the low heat deflection temperature and limited mechanical strength of both materials hinder their use in structural applications [1,2].

The use of PE and its variations as single-use packaging exacerbate environmental problems and hinders companies' progress toward the sustainable development goals (SDGs) proposed by the UN [3] due to the low degradation rate in nature. To mitigate the environmental impact

of using this polymer, the incorporation of sisal fibers into LLDPE can enhance sustainability by reducing its carbon footprint, in addition to providing a destination for industrial waste from fiber processing [4]. Because of this, 3D printing can provide applications with high added value to LLDPE, and possibly recycled LLDPE, such as automotive parts, in which its high toughness, low density, and low cost can favor the reduction of vehicle weight and manufacturing costs [5]. These benefits can be increased with the addition of sisal fibers due to their low cost, high production volume, and growing environmental disposal concern. The use of these fibers can provide an alternative to agro-industrial residues that would otherwise be used as biomass [6].

However, the addition of sisal fibers poses challenges for printing this material due to the decrease in thermal stability [7], in addition to the difficulties caused by high thermal shrinkage, which is amplified by the effects of crystallization due to

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the polymer's high crystallinity (above 50%) [8]. To enable printing of LLDPE, the literature has resorted to the manufacture of blends with other polymers such as polyolefin elastomers [9], but 3D printing the polymer in pure form remains a challenge.

Aiming to open a new research avenue for 3D printing of LLDPE with sisal fibers, this work aims to develop new techniques for printing a novel LLDPE/ sisal fiber composite based on the following guiding questions: (1) What are the problems observed when printing with LLDPE? (2) Which are the printing requirements considering the addition of fibers? (3) Which are the best substrate materials to prevent detachment from the print bed? (4) Which are the best printing parameters for LLDPE?

## Materials and Methods

The materials used were LLDPE grade ML3602U from Braskem in the formulations (Table 1) described in Table 1. For incorporation of sisal fibers, the twin-screw extruder L/D = 40 mm, AXPlásticos (model DR1640, Brazil) using a temperature profile of 100/ 150/ 170/ 180/ 190/ 190/ 195/ 200/ 195 °C and 120 rpm was used. For filament production was used the Filmaq3D CV Model single-screw Extruder at the temperature of 185 °C. The substrate materials used were high-impact polystyrene (HIPS) filaments and natural-colored polylactic acid PLA from 3DFILA, in addition to black Polyethylene terephthalate glycol (PETG) from Prusa.

To print the test specimens, the Prusa MK3s+ 3D printer with a smooth PEI table was used, using the printing parameters described in Table 2. The G-code was generated through the Prusa

**Table 1.** Formulations used in this study.

Formulation ID	LLDPE (%)	Sisal Fibers (%)
F0	100	0
F1	95	5

Slicer software. For printing, test specimens were printed in accordance with ASTM D638 type 4.

## Results and Discussion

**Table 2.** 3D printing parameters used in this study.

Printing parameter	Value
Nozzle diameter	0.6 mm
Extrusion width	0.6 mm
Layer height	0.3 mm
Printing temperature PETG, HIPS	255 °C
Printing temperature PLA	210 °C
Printing temperature LLDPE	190 °C
Bed temperature	80-123 °C
N° of substrate layers	3
Type of substrate	Raft

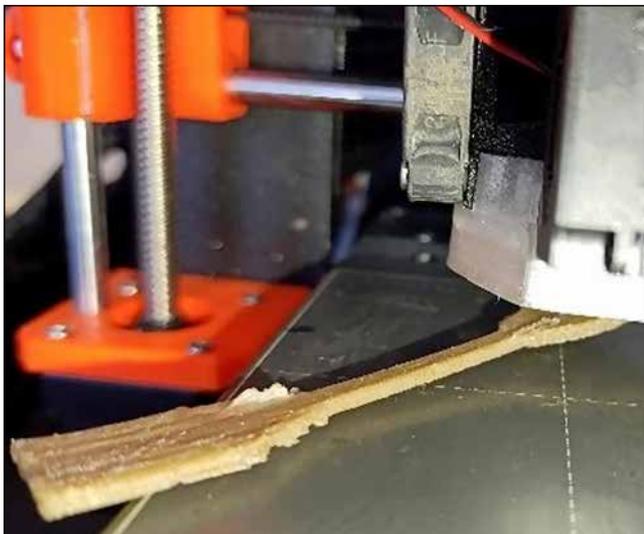
### Observation of Printing Problems with LLDPE With Sisal Fibers

It was observed that under processing conditions of 190 °C and printing bed temperature of 80 °C, it was not possible to guarantee adhesion. Figure 1 shows a test specimen with 5% sisal fibers content that detached from the printing bed during production, and which inspired this study.

### Analysis of Printing Requirements Considering LLDPE Composite with 5% Sisal Fibers

Although the use of sisal fibers as reinforcement reduces the environmental impact of this plastic and, consequently, its carbon footprint, their addition limits the processing temperature to approximately 195 °C due to fiber degradation at high temperatures. Based on this, a printing test was performed with pure LLDPE (F0) to determine the lower possible printing temperature of the material

**Figure 1.** Detachment of the printing bed caused by the sample warping in composition with LLDPE with 5% sisal fibers.



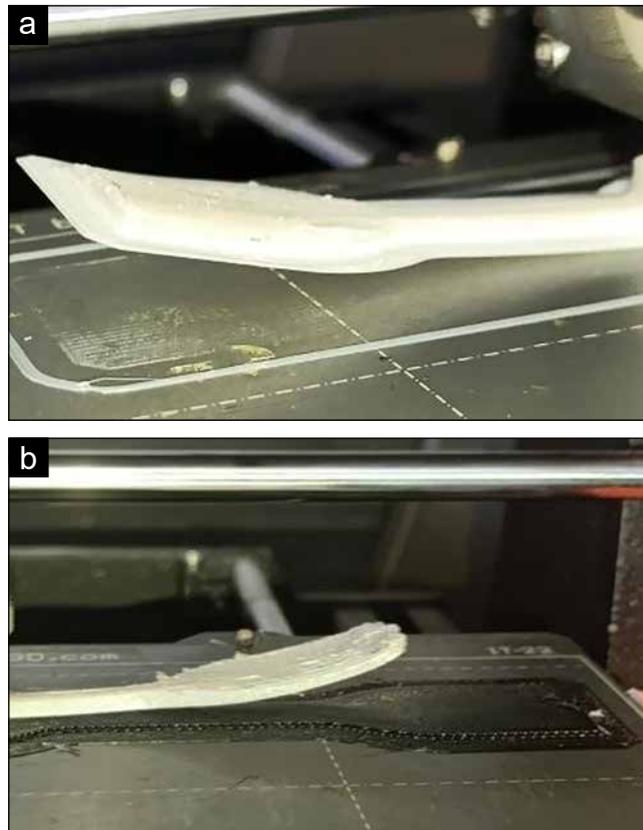
within the 190 °C limit. To this end, temperatures of 175, 180, 185, and 190 °C were tested. At 175 °C, the test specimens exhibited voids in their first layers due to the low fluidity of the polymer in the extruder nozzle, indicating that the material did not melt properly. Tests at 180 and 185 °C showed few voids in the first layers but still did not melt properly, resulting in extruder motor stalling with a characteristic clicking sound and the failure of the print. From this, it was defined that the best printing temperature that maintains the integrity of the fibers and guarantees the completion of the print is 190 °C, also been in agreement with the literature [4].

#### Analysis of the Best Suitable Substrate Material

For the analysis, a raft-type interface was created with the bed temperature set at 80, 100 and 123 °C (maximum possible temperature) to reduce printing defects due to thermal contraction. Figure 2a shows that the HIPS substrate peeled off along with the sample at 80 °C, while with the PETG substrate (Figure 2b), the sample peeled off, but the substrate remained in full contact with the print bed.

To evaluate the 100 °C printing bed temperature, tests were also performed with PLA. It was expected that, due to the material's lower melting

**Figure 2.** Printing LLDPE with different substrate materials at a bed temperature of 80 °C [(A) HIPS (B) PETG].

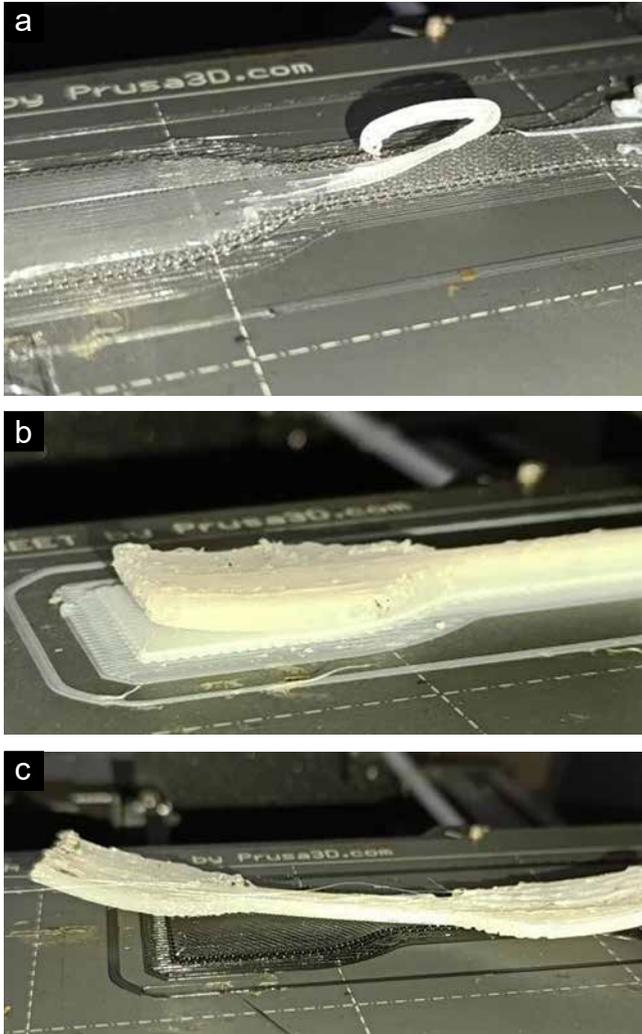


temperature and higher print bed temperature, LLDPE would be able to melt the substrate material and achieve better adhesion.

However, as can be seen in Figure 3a, LLDPE did not adhere satisfactorily to PLA, and testing with this substrate material was discontinued. Figure 3b shows the test with HIPS. Although the substrate material remained adhered to the print bed, the extruder nozzle lost its position due to thermal contraction of the specimen, and the print could not be completed.

To understand the behavior of polymers at the highest possible bed printing temperature with the intention of mitigating the thermal gradient between the printing layers and consequently the thermal contraction of the part, tests were carried out with a bed temperature of 123 °C. In Figure 4, it was observed that the HIPS material had satisfactory adhesion and was able to complete the

**Figure 3.** Printing LLDPE with different substrate materials at 100 °C bed temperature [(a) PLA (b) HIPS (c) PETG].

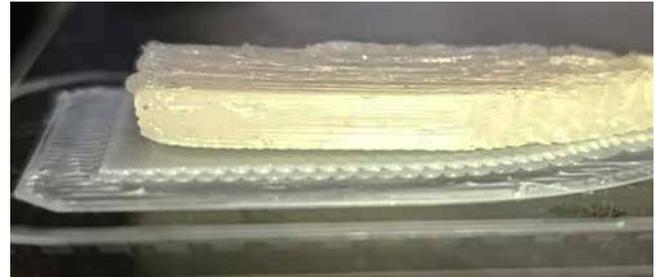


printing with low warping compared to previous tests, a result that allowed the production of test specimens for mechanical evaluation.

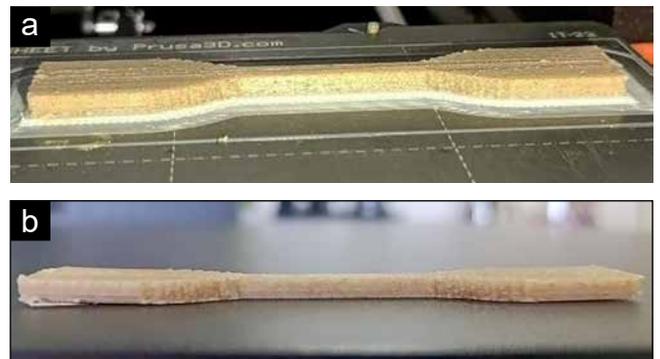
To validate this result with the addition of sisal fibers, Figure 5a shows the specimen printed with the HIPS substrate, and Figure 5b shows the specimen produced after cooling and removal of the substrate. The substrate had satisfactory adhesion to the specimen and was able to complete the printing.

Figure 6a shows the specimen produced with the PETG substrate with slight warping, but much lower than that of specimens produced with a lower bed temperature. Figure 6b shows the specimen after cooling and removal of the substrate.

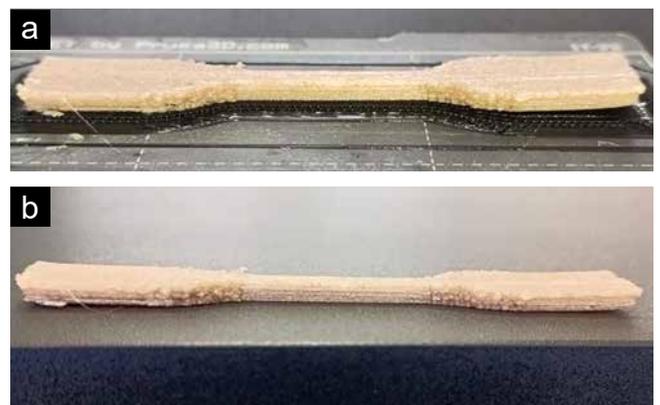
**Figure 4.** Printing LLDPE with HIPS substrate at a bed temperature of 123 °C.



**Figure 5.** Printing LLDPE composite with HIPS substrate at 123 °C bed temperature (A) after printing (B) after cooling and detachment from substrate.



**Figure 6.** Printing of LLDPE with 5% sisal fibers with PETG substrate.



The feasibility of printing at such a high bed temperature can be explained by the high polymer temperature (above the cold crystallization temperature) [6], which neutralizes the thermal contraction caused by this phenomenon, in addition to reducing the effects of thermal contraction on the material due to the smaller temperature gradient

between the print nozzle and the bed. After printing is complete, the entire part is cooled uniformly by natural convection. This is to ensure that all layers cool evenly after printing, and the crystallization process occurs gradually throughout the part, increasing its dimensional stability.

Based on the tests, it can be concluded that both HIPS and PETG polymers serve as suitable substrates for LLDPE printing maintaining good adhesion even with composite material, but only at 123 °C bed temperature.

## Conclusion

After analyzing the technical requirements for 3D printing of pure LLDPE and a novel LLDPE with 5% sisal fibers composite, it was possible to determine that a printing temperature of 190 °C is the most suitable as it guarantees adequate fluidity for printing without compromising the integrity of the sisal fibers. Furthermore, three interface materials were tested, two of which successfully printed tensile specimens. Printing was possible using HIPS and PETG substrates using a raft support pattern, but only at a bed temperature of 123 °C. The developed printing method proved to be an important step forward in enabling literature experimentation with this material with 3D printing. Future research will develop custom G-code for substrate reuse between prints, thus reducing material waste.

## Acknowledgement

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## A Foundational Framework for Substation Fault Diagnosis from Imbalanced Thermal Data Using Transfer Learning

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A key component of predictive maintenance for vital electrical substation equipment is thermographic inspection, which makes it possible to identify thermal abnormalities early on before they cause failures. Maintenance workflows suffer by the subjective, time-consuming, and human error-prone manual interpretation of the resulting thermal images. Although deep learning offers an efficient automation solution, a significant real-world obstacle to its widespread use is the extreme scarcity and class imbalance of available fault data. In order to close this gap, a comprehensive methodological framework for creating a reliable baseline diagnostic model is proposed and described in this paper. The strategy is based on transfer learning, which involves optimizing strong, pre-trained Convolutional Neural Network (CNN) architectures to take advantage of their acquired features and lessen the impact of sparse data. From data preparation and aggressive minority fault class augmentation to the use of a weighted loss function during training, the framework describes the complete pipeline. The experimental pipeline was validated after this methodology was put into practice. The model's anticipated initial bias towards the prevalent "Normal" class—a direct result of the data imbalance—was validated by preliminary observations. The main result of this work is this procedural validation, which provides a strong, repeatable basis for further investigation. While conclusive performance analysis and the investigation of explainability techniques remain open for future work, this study offers a practical route for creating trustworthy diagnostic tools under practical data constraints.

**Keywords:** Artificial Intelligence. Thermography. Deep Learning. Fault Detection. Electrical Substations.

**Abbreviations:** CNN, Convolutional Neural Network. AI, Artificial Intelligence. MLP, Multilayer Perceptron. SVM, Support Vector Machine. GANs, Generative Adversarial Networks. GAP, Global Average Pooling. XAI, Explainable Artificial Intelligence.

Reliability of power systems is something modern society takes for granted but is reliant on flawless working of vital infrastructure, most notably electrical substations. These units are head of the grid, and collapse of one component of it (a transformer, a circuit breaker, or simply a connection) can result in mass power cuts with dire economic as well as social consequences. To prevent this, utilities rely heavily on predictive patterns of maintenance, and of available tools, infrared-based thermography has been useful. It offers a non-intrusive, in real-time means of "seeing" heat, being thus extremely good at detecting the tell-tale signs of a potential failure,

such as an overheated joint, method well-tested in industry standards [1].

Despite thermography, power is ultimately limited by the human eye and brain. Each of these thermal images must be manually inspected by a skilled technician, which can be a slow and subjective process. What in one expert's eyes is an essential fault, in another's is nothing but solar reflection or normal variability in operations. An acute risk and a challenge of scalability are present. A central consideration guiding this effort is the need to automate the inspection process to ensure it is quick, objective, and scalable.

The easy solution lies in Artificial Intelligence (AI), with deep learning structures like Convolutional Neural Networks (CNNs), which have significantly impacted the field of image processing [2]. It is not news to train a model to recognize thermal fault patterns. Most research works, however, overlooks the most crucial in-the-field limitation: data. Faults in a well-maintenance

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substation happen rarely. This creates a familiar machine learning problem: a small, highly imbalanced set, making it extremely difficult to train a trustworthy model from scratch.

This work targets just such problem at first principles. It provides an elaborate methodological framework towards the first stage of an automated diagnosis program. The contribution of this work is designing, in fine detail, a baseline experiment using transfer learning to leverage ideas learned under large datasets as well as data augmentation to virtually supplement a sparse set of fault images. This work clearly defines architecture, data processing strategies, as well as evaluation measures, of a model, once in working, will serve as a baseline reference point to justify as well as guide subsequent research in next-level-data generation as well as explainability strategies.

## Related Work

This project is founded on two pillars of research: applying thermography in predictive maintenance as well as using deep learning in image classification.

The infrared thermography theory and application to electrical equipment are well-documented. Usamentiaga and colleagues [3] define in detail heat transfer physics, emissivity, as well as reading thermal patterns of likely failure, as defined in standards by National Fire Protection Association and NETA MTS-2019 [1,4]. These patterns, most of them being hotspots or unknown thermal gradients, are precisely those on which was trained the AI model herein proposed.

Early efforts at automating this activity used traditional machine learning strategies. For instance, Ullah and colleagues [5] built a predictive maintenance framework with a Multilayer Perceptron (MLP), a classical neural network structure. It relied on feature extraction of eleven hand-designed statistical features (e.g., mean, variance, skewness) in thermal images to differentiate equipment as "defect" or "non-defect" with 84% accuracy, with subsequent graph-cut-

based refinement. This work demonstrated possible automation of diagnostics but identified manual feature engineering as an essential condition.

Subsequent research involved using CNNs to automatically learn image features through deep learning. [6] provided a novel method of using a special CNN with a Support Vector Machine (SVM) classification method. A key part of their research involved complex preprocessing to locate and extract temperature values from the scale bar of the thermal image, using extracted characters to build a training set.

More recently, focus has moved on to current state-of-the-art object detection architectures. Liu, Li and Gao [7] used a YOLOv4-based approach to fault diagnosis of some substation equipment, including insulators, cables, and transformers. It locates equipment along with any abnormal heating areas, calculates spatial overlap between them to determine a fault status. Performance reported average precision of 92.2% and confirmed the potential of current object detection architectures for this task.

The weakness of most of this presented research is the assumption of a large, balanced dataset. In most cases, this most severe of challenges, the scarcity of data, is handled superficially. Transfer learning has been an extremely useful means of making up for this. As illustrated by Mahmoud and colleagues [8] and Elgohary and colleagues [9], learned features such as edges, textures, and shapes of a model pre-trained with a large dataset such as ImageNet [10], can be transferred in a new domain, such as images of electrical equipment under thermal imaging, with much less data as a fine-tuning set. This approach has been successful in some medical and industrial imaging applications with limited data. This research is placed firmly within the context of pragmatic studies, with a focus on an exacting use of transfer learning as being the most realistic first step towards this specific problem, as it opens towards further advanced solutions such as Generative Adversarial Networks (GANs) towards synthetic data generation in due course [11,12].

## Materials and Methods

We detailed the proposed framework for developing and evaluating the baseline fault diagnosis model.

### Dataset and Preprocessing

This work's first dataset is composed of thermal images acquired using active substation equipment. It is composed of diverse equipment, including bushings, connections, transformers, circuit breakers, relay and surge arresters, with varied operational as well as environmental conditions. In this first task, images will be grouped into two main groups: “Normal” and “Anomaly” as the base of a binary classification problem.

Before being presented to the model, they go through a standardized preprocessing pipeline:

1. Resizing: All images were resized with a fixed size of (224×224 pixels) to meet the input condition of our adopted pre-trained CNN architecture.
2. Normalization: The values of pixel intensity were normalized such that they remain in the interval [0, 1], inviting stability and acceleration of training in models.

### Data Augmentation

Given the anticipated class imbalance, where “Anomaly” images are expected to be significantly fewer than “Normal” ones, data augmentation plays a critical role. To enhance the representation and variability of the minority class, a series of geometric and photometric transformations will be selectively applied to the “Anomaly” images. This strategy helps reduce model bias toward the majority class and improves generalization.

The augmentation techniques applied were:

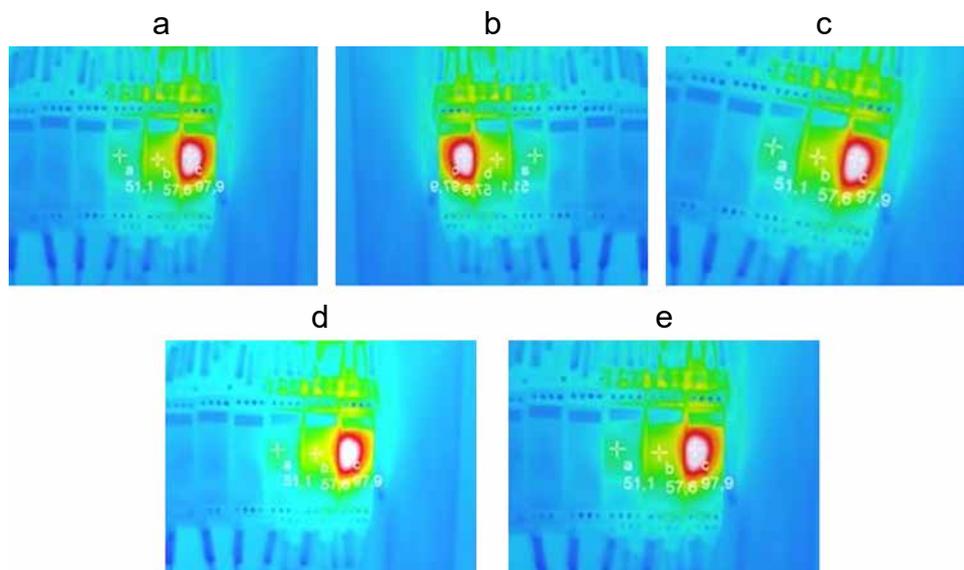
- Horizontal flips.
- Random rotations (within a range of -15 to +15 degrees).
- Random adjustments to brightness and contrast.
- Random scaling or zoom (90-110% of the original size).

Figure 1 illustrates the effect of these transformations (a) Original; (b) Flipped; (c) Rotated; d) Brightness adjusted; (e) Scaled.

### Transfer Learning Model Architecture

This framework utilizes a transfer learning approach with the architecture of ResNet50 [13],

**Figure 1.** An example of original thermal image of a fault, and 4 augmented versions.



a highly regarded and potent CNN pre-trained with the ImageNet dataset. The reasoning is to build upon the rich low-level features learned in ResNet50, rather than attempting to learn them from a limited dataset.

The execution of the training was as follows:

- 1. Load Pre-trained Base:** The ResNet50 was initialized with its ImageNet weights, while ignoring its final classification layer.
- 2. Freeze the Base Layers:** The weights of the base convolutional layers were "frozen," meaning they were not updated during the initial training phase. This helped preserve the valuable features already learned.
- 3. Add a Custom Classifier Head:** A fresh stack of layers was added atop the "frozen" base model. This head included a Global Average Pooling (GAP) layer, followed by a Dropout layer for regularization purposes. Ultimately, there was a dense layer featuring a Sigmoid activation function to generate a probability score for binary classification.
- 4. Train and Fine-Tune:** The model underwent two training stages. Initially, only the new classifier head was trained. After it converged, some upper layers of ResNet50 were unfrozen for fine-tuning with a low learning rate, allowing the pre-trained features to better adapt to the thermal imagery.

#### Validation of the Framework and Behavioral Analysis

The evaluation in this early phase of research is not concerned with optimizing performance metrics, but rather with two main goals: (1) verifying the overall experimental framework's functional integrity, and (2) conducting a preliminary behavioral analysis of the model when it is exposed to the highly imbalanced dataset.

To make sure that the evaluation is objective, the dataset will be split into standard training, validation, and testing sets. The main sign that the basic model is learning will be that the training loss function is going down over the first few

epochs. This shows that the model can extract features from the data.

The preliminary analysis will be based on a qualitative assessment of the predictive effectiveness of the model. The main goal is to explain why the model initially favors the "Normal" class, which is a common and expected result from the data distribution. The goal of this analysis is not to determine precise performance scores. Rather, it examines how the model's predictions evolve over time by testing them on the validation set. Making qualitative observations and verifying procedures are among the objectives of this study's first section. The behavioral analysis will yield preliminary findings that will be used to empirically support the next steps in the research process, which will center on systematic hyperparameter tuning and the application of more sophisticated techniques to address the observed class imbalance.

## **Results and Discussion**

### Experimental Setup and Preliminary Process Validation

The primary aim of this initial stage was not to produce a fully optimized model, but rather to construct and validate the entire experimental pipeline, ensuring the robustness of the data processing, model training, and evaluation process.

### Execution of the Proposed Method

The workflow was carried out exactly as the methodology specified. A typical 70-15-15 split was used to divide the small dataset into training, validation, and testing sets. Using a custom data loader, the data augmentation techniques, such as random rotations, flips, and brightness adjustments, were successfully applied in real-time to the training batch. The experiment's main component involved loading a pre-trained ResNet50 model, freezing its convolutional base

layers, and swapping out the final classification layer for a new head designed specifically for the binary classification task ("Normal" vs. "Anomaly").

The training script was developed to execute the two-stage training process: initial training of only the new classifier head, followed by a fine-tuning phase with a low learning rate. The process was monitored using standard metrics, such as training and validation loss and accuracy, which were logged after each epoch.

### Preliminary Observations

The initial training epochs were primarily used to confirm that the experimental pipeline was functioning as planned. A distinct and illuminating performance trend emerged from these early runs: the model performed significantly better at correctly classifying images in the "Normal" class while struggling to identify images in the "Anomaly" class.

The inherent structure of the training dataset is the direct cause of this behavior. The "Normal" class gives the model a rich and varied collection of examples by supplying a large number of thermal images from a wide range of equipment types. Because of the data's richness, the network can learn a reliable and broadly applicable feature representation of what constitutes typical equipment operation in various settings. As a result, the model gains the ability to recognize new, undetectable examples of equipment that is healthy.

The "Anomaly" class, on the other hand, is incredibly sparse, covering only a few types of equipment and making up a very small portion of the entire dataset. This gives the model a very small feature space to learn from. Insufficient variation significantly impairs the model's capacity to generalize the appearance of an "anomaly," which results in a high rate of misclassification for this crucial class. The model rapidly discovers that creating a strong bias towards the majority "Normal" class is the best way to reduce the overall error.

This observation, while predictable, is a crucial preliminary finding. It verifies empirically that the main obstacles to overcoming are the stark class disparity and the lack of diversity in the fault data. The pipeline's successful deployment, together with this diagnostic of the model's initial behavior, confirms the research direction and emphasizes the need for the suggested methodological focus on new strategies to generate synthetic data and weighted loss functions that are intended to address this imbalance.

### **Conclusion**

A thorough and practical methodological framework for creating a fundamental AI model for substation fault diagnosis using thermal images was provided in this paper. The suggested method makes use of transfer learning and data augmentation to establish a strong baseline while acknowledging the practical limitation of data scarcity. The creation and procedural validation of this framework, which verifies that every step is operational and appropriately configured, constitutes the main contribution of this study.

The first crucial step in a larger research agenda is the effective application of this framework. To fully develop the diagnostic capabilities of the model, future work will involve the thorough execution of the training and hyperparameter tuning process. The final performance outcomes from that thorough process will be saved for a later publication that will include a detailed evaluation of the model's efficacy as well as research into explainability strategies to increase confidence and real-world adoption.

The future research will proceed along three general paths:

- 1. Improvement of the Transfer Learning Technique:** Evaluating the use of thermal image datasets from similar equipment to augment the current dataset, as well as testing other pre-trained networks.
- 2. Generation of Advanced Data:** Based on the baseline output, studies and implementation of

advanced artificial data generation schemes will be under consideration, using likely Generative Adversarial Networks (GANs), aimed at narrowing down and refining the dataset with rare fault examples as well as severe ones.

**3. Explainable AI (XAI):** Explainability models, such as Grad-CAM, will be integrated to have graphical evidence of the model's predictions. That is necessary to build confidence and change the model from being a “black box” to an explainable and reliable maintenance engineer tool.

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## Automated Testing for Constrained Embedded Systems: A Maturity-Oriented Approach

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The increasing complexity of embedded systems, especially in critical environments, demands reliable and scalable validation methodologies. This work presents an automated testing framework based on Python to validate embedded systems through acoustic and serial communication. The tool executes protocol-defined commands, logs responses, and generates reports with quantifiable metrics. Through this structured approach, the system enables proactive identification of edge-case failures and aligns with Capability Maturity Model Integration (CMMI) and Technology Readiness Level (TRL) frameworks. Results indicate improved test coverage, reduced post-deployment bugs, and process standardization, even in resource-constrained environments.

**Keywords:** Automated Testing, System Maturity, Embedded Systems, Protocol Validation, CMMI.

**Abbreviations:** CMMI, Capability Maturity Model Integration, TRL, Technology Readiness Level, ISTQB, International Software Testing Qualifications Board, UART, Universal Asynchronous Receiver-Transmitter, TTL, Transistor-Transistor Logic.

The increasing complexity of embedded systems demands structured, automated validation techniques that contribute directly to the system's maturity and reliability. As noted by Humble and Farley [1], continuous, automated testing plays an important role in enhancing system resilience and reducing time-to-deployment. This paper examines how automated testing frameworks, such as the Python-based tool developed here, enhance the maturity of complex systems by standardizing validation processes, reducing human error, and generating structured reports with detailed outcome metrics.

The proposed solution leverages acoustic and serial communication to interface with a controller board, executing all protocol-defined commands while generating reports with success/failure rates and operational responses. By supporting programmable test scenarios, the tool validates functionality and identifies edge-

case vulnerabilities. This aligns with Capability Maturity Model Integration (CMMI) principles, where automated testing elevates maturity from ad hoc routines to quantitatively managed processes. Prior studies highlight that automation accelerates development and strengthens resilience [1], but gaps remain in adapting these methods to constrained embedded environments. This work demonstrates how a lightweight, protocol-aware tool enforces rigorous standards while contributing to maturity metrics such as process predictability and defect density [2].

### Theoretical Framework

To assess the impact of automated testing on embedded system development, this section introduces two evaluation frameworks: the CMMI and the Technology Readiness Levels (TRL). CMMI provides a model for assessing process maturity across five levels, from initial (Level 1) to optimizing (Level 5), emphasizing process standardization, measurement, and continuous improvement [2]. TRL, on the other hand, evaluates technological development stages, from conceptual research (TRL 1) to full operational deployment (TRL 7). This study focuses on

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how the proposed testing framework supports progression across these levels, particularly through repeatability, traceability, and data-driven feedback.

Given the remote and unassisted nature of the Device Under Test (DUT), which operates in environments such as sealed enclosures or underwater conditions, the approach follows black-box testing principles. The DUT cannot be instrumented internally during operation and therefore must be evaluated based solely on its external responses to predefined commands [6]. This justifies the choice of protocol-centric and interface-aware testing, especially considering the constraints in accessibility, power cycling, and communication.

### Automated Testing as a Maturity Catalyst

Automated testing plays an important role in promoting system maturity, as defined by the CMMI framework [2]. As systems evolve, their validation processes should transition from ad hoc routines to structured, repeatable, and quantitatively managed workflows. Crucially, CMMI is not limited to testing but integrates all organizational processes, from requirements through deployment. Automated validation contributes to maturity when embedded in this wider cycle, where results inform requirements, design corrections, and deployment readiness.

The DUT includes a microcontroller-based system with sensors, control, and communication functions that must respond deterministically under diverse conditions. Manual testing is inefficient, error-prone, and inadequate for ensuring long-term reliability. Automated testing simulates operational conditions, validates protocol coverage, and generates structured reports that support both system validation and organization-wide process improvement.

This scenario justifies the development of an automated testing framework that can simulate real operational conditions, validate complete protocol coverage, and generate structured performance

reports. Automated build-test-deploy pipelines accelerate feedback loops [1], a principle applied here through acoustic/serial communication with embedded systems.

Compared to existing tools such as Robot Framework and Latch [6], which are typically tailored to either high-level system APIs or desktop-class embedded platforms, the proposed framework addresses low-level, protocol-specific testing in highly constrained environments.

Unlike Robot Framework, which requires OS-level support, or Latch, which focuses on constrained systems without domain-specific interfaces, the proposed framework combines lightweight execution with protocol-centric testing for remote and inaccessible environments. Its integration of acoustic communication and maturity-oriented reporting distinguishes it from existing tools, which typically validate functionality without linking outcomes to organizational improvement.

### Protocol-Centric Testing in Constrained Environments

Embedded systems face validation challenges due to resource limitations. As prior research shows [7], lightweight, protocol-aware approaches are essential. The paradigm of protocol-centric validation enables testing in inaccessible conditions, such as underwater deployments, where traditional wired methods fail. Configurable test logic reflects agile testing principles, supporting scenario simulation. Compliance with international guidelines ensures behavioral consistency and deterministic validation.

### Structured Reporting and Maturity Benchmarking

Structured reporting transforms raw test data into maturity indicators. Standardized metrics such as success/failure rates, response times, and defect density underpin statistical process control, supporting CMMI progression from Level 3 to Level 4 [2]. These measurements also benchmark

TRL advancement, from laboratory validation (TRL 4–5) to operational readiness (TRL 6–7) [4]. Liu and Mei [7], and Wang and colleagues [8] show structured reporting generates transparency, root-cause analysis capability, and historical data for risk modeling. As formalized by CMMI [2] and ISTQB [3], automated reporting functions as a maturity accelerator by converting reactive testing into proactive, data-driven practice.

Transparency through auditable command-response records eliminates informational gaps in validation processes [4]. Temporal and decoded logs enable root-cause failure analysis rather than symptomatic troubleshooting [8]. Historical data standardization supports probabilistic risk modeling essential for predictability [1].

Theoretical frameworks synthesize structured reporting's role as a maturity catalyst. As formalized by CMMI [2] and ISTQB standards [3]: "Automated reporting functions as a maturity accelerator, converting reactive practices into data-driven proactivity". This evolution materializes when quantitative indicators support CMMI Level 4 decision-making, structured logs enable continuous optimization (Level 5), and traceability validates higher TRLs ( $\geq 6$ ) for operational deployment [4].

## Materials and Methods

This study adopts an applied engineering methodology grounded in experimental observation and measurement. The hypothesis is that a lightweight, protocol-aware framework improves maturity, reliability, and efficiency in constrained embedded systems. The methodological path followed five stages: (1) requirements and constraints definition, (2) framework design, (3) implementation on DUT hardware, (4) systematic test execution via UART and acoustic channels, and (5) analysis through predefined metrics.

The proposed framework integrates hardware and software elements to establish a fully automated testing pipeline.

## Materials and Parameters

The DUT was an ARM Cortex-M4 controller with FreeRTOS, acoustic modem, UART interface, and peripheral modules. The host machine ran Python 3.12 with PySerial and ReportLab. Evaluation metrics included protocol coverage, success/failure ratio, execution time, repeatability, and defect detection. These parameters ensure reproducibility and transparency.

## Application Layer

Developed using the pyserial library [10], the application layer is responsible for the automated execution of all commands defined in the embedded system's communication protocol. Such as power on and off modules, measure and acquire sensors data.

The application is modular and configurable, allowing users to define test sequences, edge-case scenarios, and expected responses for each command.

## DUT Embedded System Layer

The device under test (DUT) is based on a real-time operating system (FreeRTOS), executed on an ARM Cortex-M4 microcontroller. It supports multiple communication interfaces and peripherals such as an acoustic transmission module, MODBUS-compliant communication, and various sensors.

The firmware is structured around a deterministic command-response protocol, ensuring traceability across the testing process.

By supporting both acoustic and TTL-level serial communication interfaces, the framework overcomes the inherent limitations of inaccessible or remote systems, such as underwater or sealed devices, where traditional wired validation is not feasible [7].

## Reporting Engine

A dedicated module within the Python application generates structured reports using

the ReportLab library [10]. These reports include a complete command execution log, a decoded FreeRTOS protocol response with human-readable descriptions, a success/failure status for each test step, and temporal data to correlate commands and environmental variables.

The system's ability to generate detailed reports, including success/failure metrics and decoded response logs, directly contributes to CMMI Level 4 ("Quantitatively Managed") by enabling performance measurement, repeatability, traceability, auditability of all test campaigns and statistical control [6].

### Dual-Channel Communication Strategy

Given the constraints of embedded environments, such as limited physical access and low-level hardware interfaces. The framework implements two types of communication channels. The serial for bit level in-lab validation and acoustic for underwater environments. This feature extends test coverage into operationally relevant environments, enhancing realism and robustness.

### Protocol Execution and Response Decoding

Each protocol command is executed in isolation and sequence. The system records raw responses from the controller, decoded interpretations of each response (e.g., translating 0x0B to "Measure Clock Error"), and execution timestamps to enable performance profiling.

This level of detail supports the identification of behavioral inconsistencies and the early detection of defects in both firmware and hardware components.

The inclusion of user-configurable testing logic enables simulation of a wide range of operational conditions, including edge cases. This approach follows best practices in agile software testing, which emphasize adaptability and iterative feedback; this supports auditability and facilitates root-cause analysis [8,9].

### Tool Limitations

Although designed to maximize coverage and repeatability, the tool has certain operational constraints. Its operation depends on strict adherence of the DUT to the defined protocol sequence and states. Test scenarios must be preconfigured manually, as there is no dynamic case generation yet. In addition, the tool runs externally to the DUT, requiring intermediate hardware for interfacing and power. These constraints do not compromise their practical use but influence the interpretation of metrics and the generalization of results.

### **Results and Discussion**

#### Test Bench and Execution Workflow

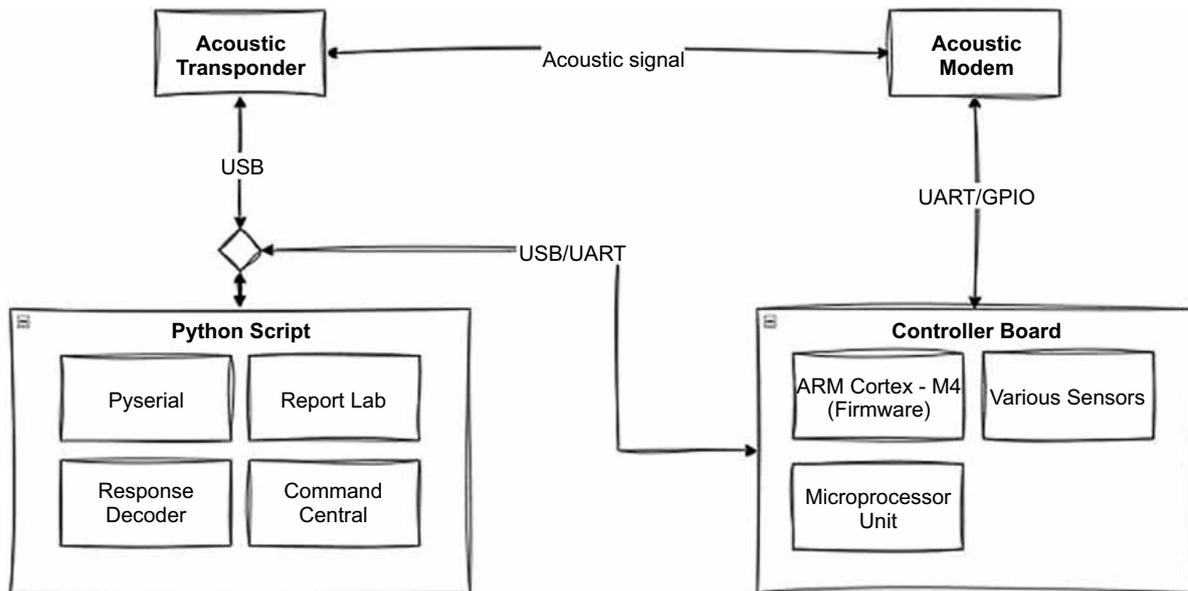
Figure 1 shows the block diagram of the dedicated test bench assembled to validate the effectiveness of the proposed automated testing framework, simulating real-world operational conditions for the embedded system.

#### Test Environment Setup

The test bench consisted of a controller board featuring an ARM Cortex-M4 microcontroller running FreeRTOS, connected to the test system via UART and acoustic interfaces. Peripheral Modules, including various sensors, an acoustic transducer, and MODBUS-based communication modules.

The Host Machine is a computer running the Python-based automation tool, responsible for managing all test procedures, capturing responses, and generating reports.

Power supply and interface adapters are used to ensure the reliable operation of modules under test. Verifying the integrity of command-response behavior across different operational states and environments, the tool has compliance with the ISTQB guidelines [2], ensuring that protocol validation adheres to internationally recognized standards.

**Figure 1.** System comms.

### Execution Procedure

The test execution followed a systematic approach to ensure full protocol coverage and reproducibility of results. First, all modules were powered on and initialized through predefined commands issued via the application layer. Initial status checks were performed to validate firmware readiness and confirm proper interface activation. Then the entire set of protocol-defined commands was executed in sequence, covering operations such as power cycling modules, triggering measurements, reading memory blocks, and querying sensor data. Testing all operational cases of the DUT 50 times to evaluate the expected response and the consistency of the firmware protocol and the DUT functionalities. Each command was sent through both the UART and acoustic interfaces to compare results across communication channels.

The system responses were recorded in real time, and the raw outputs were logged alongside decoded messages, timestamps, and status classifications (e.g., success, failure, timeout).

The framework validated that command responses were identical across both modes, confirming functional equivalence and interface robustness. However, it is important to note that

acoustic communication takes approximately four times longer than serial communication to receive a response from the module.

### Empirical Validation

To assess the effectiveness of the proposed automated testing framework, a series of in-lab tests was executed using the complete set of protocol-defined commands across multiple operational scenarios. The goal was to evaluate improvements in test coverage, system reliability, and post-deployment defect rates.

At each new firmware release the tests were re-executed to validate the quality and reliability of the development. At each error reported a new firmware version was released and evaluated on the same premises. Executing all firmware commands systematically aligns with CMMI's Defined (Level 3) stage, where processes are documented, standardized, and integrated across the organization [2].

### Coverage and Automation Metrics

The tool successfully achieved 100% coverage of the system's communication protocol,

validating every command in both acoustic and UART modes. This comprehensive coverage enabled a full protocol compliance verification across interfaces, a detection of undocumented or unexpected behaviors, and consistent execution of edge-case scenarios.

The automation capabilities allowed repeated execution of test suites with no manual intervention, reducing human error and accelerating validation cycles. The integration of programmable testing, hardware-aware communication, and structured reporting creates a feedback loop that elevates system maturity from reactive to proactive — a critical advancement for safety-critical embedded applications [2,3].

### Defect Reduction and Reliability Gains

Comparative analysis of firmware versions before and after integrating the automated testing framework demonstrated that numerous errors were identified and resolved pre-deployment. This proactive correction substantially reduced field failure rates. The increased frequency of firmware update versions following test implementation provides empirical evidence of these corrective actions. Key observations include the early detection of issues that caused power-saving failures, the elimination of misconfigured responses related to sensor modules and the identification of firmware inconsistencies in the module's integration.

### Process Efficiency and Repeatability

The adoption of the framework also improved overall test efficiency and traceability. Test execution time per module decreased by ~90%, thanks to batch automation and pre-defined test profiles, as the average test cycle reduced from 180 minutes (manual) to 15 minutes (automated), with minimal deviation across repeated sessions.

The reports enabled traceability across validation sessions, with version control and serial number signatures. Repeatability was validated

by executing the same test suite under different environmental and hardware configurations with consistent results.

### Maturity Impact Assessment

The integration of automated testing and structured reporting contributed to measurable improvements in software process maturity, aligned with CMMI and TRL frameworks.

This alignment positions the tool as a maturity accelerator, transforming embedded system validation from isolated checks into a lifecycle-oriented process.

The automated tests enable the system's evolution by enforcing consistency, accelerating feedback cycles, and reducing the incidence of human-induced errors. The tool records success rates, failure diagnostics, and timing data, aligning with the TRL framework [4]. These outcomes confirm that the framework is not only a test tool but also a maturity accelerator, capable of advancing embedded systems validation into quantifiable, repeatable, and improvement-oriented processes.

### **Conclusion**

This study presented the design, implementation, and empirical validation of a protocol-aware automated testing framework aimed at increasing the maturity of embedded systems, particularly those operating in constrained environments. By integrating acoustic and serial communication, structured reporting, and programmable test scenarios, the framework effectively bridges the gap between informal validation routines and quantitatively managed test processes.

The results demonstrate that automated testing not only enhances protocol compliance and reduces human error but also significantly improves defect detection, test coverage, and execution efficiency. The use of structured reports and decoded protocol responses provides transparency and auditability, enabling traceable and reproducible validation cycles aligned with CMMI and TRL frameworks.

The role of the CMMI here is to coordinate the organizational process model of testing as an integrated element of the software development lifecycle. The framework's outputs feed back into requirements refinement, design validation, and deployment assurance, ensuring that automated testing accelerates maturity across all process domains. Furthermore, the framework's lightweight design ensures compatibility with resource-constrained embedded systems, extending its applicability to real-world, mission-critical deployments. As a result, it serves not only as a testing utility but also as a strategic asset for advancing the reliability, maintainability, and process maturity of complex embedded solutions, as shown in Table 1.

**Table 1.** Bridging theory and practice.

Concept	Implementation in this Work
CMMI Maturity [2]	Integrated into the organizational development lifecycle
Agile-Testing Integration [7]	Programmable test scenarios for diverse conditions

Future work may include integration with continuous integration (CI) pipelines, graphical dashboards for monitoring test metrics, and expansion to support additional communication protocols and hardware platforms.

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## Structural Sizing for EDP Valve Body for HPHT Wellhead

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The reduction in production from active oil wells in Brazil and the depletion of reservoirs have driven research into deep-sea reservoirs, especially on the Brazilian equatorial margin and in projects such as Sergipe-Águas-Profundas. This work aims to design an EDP valve for intervention in HPHT (High Pressure, High Temperature) offshore wells. API and ASME standards, in addition to technical literature, were used to define the appropriate material and mechanical properties, and to calculate allowable stresses, as well as the stresses acting on the body and its components, using stress criterion to ensure equipment integrity. Stress concentrations were applied in regions with geometric alterations, as these are more critical. Finite element analysis more accurately assessed the equipment's behavior under the established conditions. Both calculation models were within the allowable design limits and demonstrate that the extreme conditions of HPHT wells require a thorough analysis of the design parameters.

**Keywords:** Oil and Gas. High-Pressure-High-Temperature. Intervention. Emergency Disconnect Package. Structural Analysis.

Brazil seeks to reduce oil imports and explore deep-water reservoirs, such as the projects of Sergipe Águas Profundas and the equatorial margin, aiming for self-sufficiency, due to their high production potencial [1,2]. Those projects must also align with current ecological demands, ensuring the protection of the ocean environment, amid contemporary environmental and climate challenges [3]. In HPHT deep wells, conditions can reach 103.5 MPa and 177 °C, which require intervention operations to ensure functionality [4].

These operations support equipment repair, maintenance, and fluid injection, extending service life and ensuring integrity, which boosts production and prevent accidents, such as oil leaks, that may harm the environment [5-8]. For this, subsea systems between the wellhead and intervention riser are used: the Lower Riser Package (LRP) for well control and the Emergency Disconnection Package (EDP) for cutting the intervention string and sealing the well (Figure 1) [9–11].

Figure 1 represents these systems, with accumulators and intervention panels; the EDP, located at the top, functions as an additional pressure barrier, while the LRP serves as the primary barrier, containing two main valves for wireline and coiled tubing cutting [12,13]. These systems, exposed to adverse conditions that may lead to failures, are essential for operational safety [14,16]. Efforts focus on improving efficiency and simplifying intervention system design to reduce costs and support deep-water oil production [17].

This study presents the initial phase of a structural sizing project for a forged EDP valve body for offshore HPHT wellheads, covering material selection, stress and dimension calculations, and a preliminary fatigue life analysis and finite element verification.

### Theoretical Basis

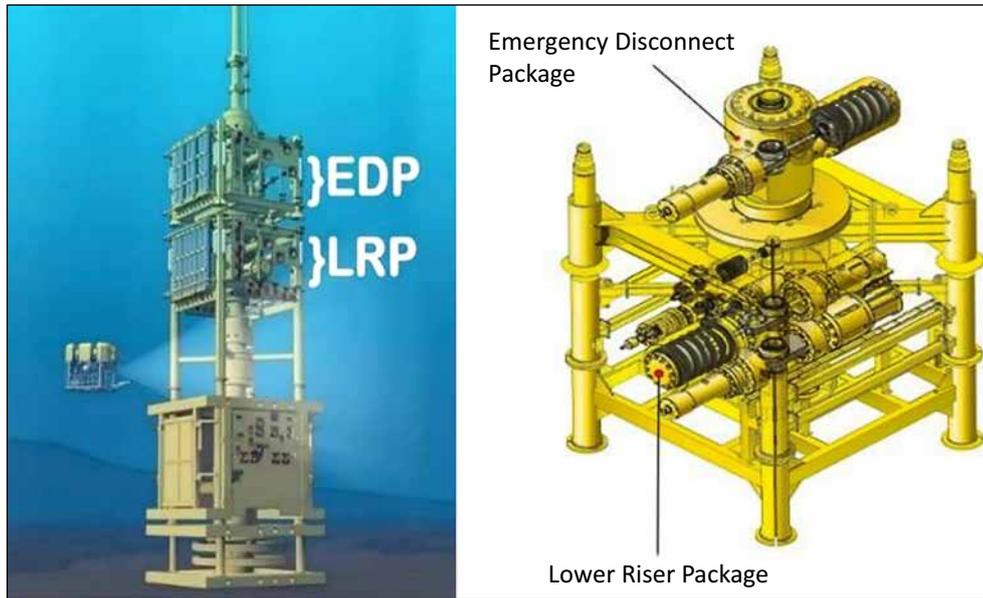
The EDP may adopt various structural configurations, differing in cavity layout, shape, or shearing valve type. Figure 2 shows a linear-actuated valve for well sealing in operations up to 137.9 MPa, suitable for HPHT use. Its forged, unified structure protects internal components and mechanisms. Forging minimizes defects and

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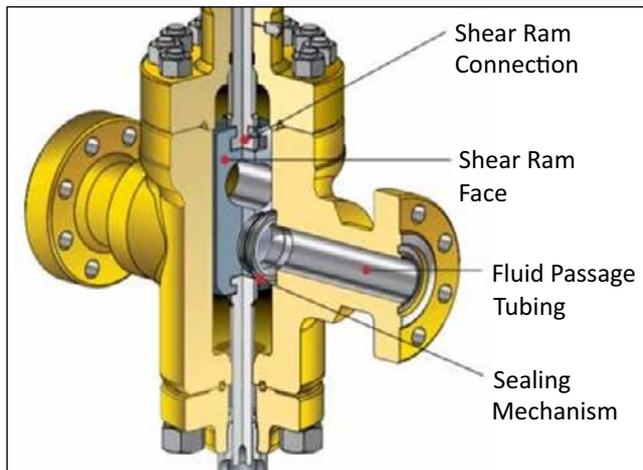
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**Figure 1.** Positioning and structure of intervention systems [11,12].



**Figure 2.** EDP valve body structure for intervention operations [17].



increases strength, with materials chosen for high mechanical and corrosion resistance [18-20]. Proper sizing is essential for safe interventions and to maintain production under critical conditions [4,13,18,21].

For HPHT analysis, API 17TR8 outlines key design and construction guidelines, addressing corrosion, fatigue, and plastic collapse [22–26].

Table 1 defines corrosion failure criteria, setting minimum H<sub>2</sub>S concentrations for sulfide stress corrosion based on pressure [27]. At 103.5 MPa, H<sub>2</sub>S above 2.5 ppm classifies the environment as sour, requiring metallurgical evaluation for operational viability [24].

At high temperatures, steels lose yield strength, requiring reduction factors in the design of bodies, flanges, and bolts [28–31]. Subsea equipment must comply with structural integrity standards [23]. This study applies API 17TR8’s flowchart for 103.5–137.9 MPa and ASME VIII Divisions 2 and 3 [22]. Stress analysis follows Lamé’s method for thick-walled cylinders [32], with allowable stresses from ASME II-D and VIII-2, and sizing features per API 6A [33-35].

**Table 1.** Minimum H<sub>2</sub>S concentration for acidic environment classification [22].

Rated Working Pressure	69 MPa	103 MPa	138 MPa	172 MPa	207 MPa
Concentration of H <sub>2</sub> S (ppm)	5	3.3	2.5	2	1.7

Fatigue is analyzed via stress cycling and fracture mechanics, crucial for HPHT conditions, supported by tests and statistical models [33,36–38]. Plastic collapse considers linear or elastoplastic behavior, focusing on stress concentrators [33,39–41]. Testing validates designs but is costly, so modeling and simulations are used [19,25,33,42–45].

The Finite Elements Method (FEM), endorsed by API 17TR8, enables accurate, cost-effective simulations of complex geometries [22,26,40,46,47].

The aforementioned standards, despite being written by international organizations, are recognized by Brazilian corporations and agencies, being used and referenced for projects in the national territory [48–50].

**Materials and Methods**

The method defined design conditions, developed an analytical model for load, stress, and fatigue life, and applied FEM.

Design Conditions

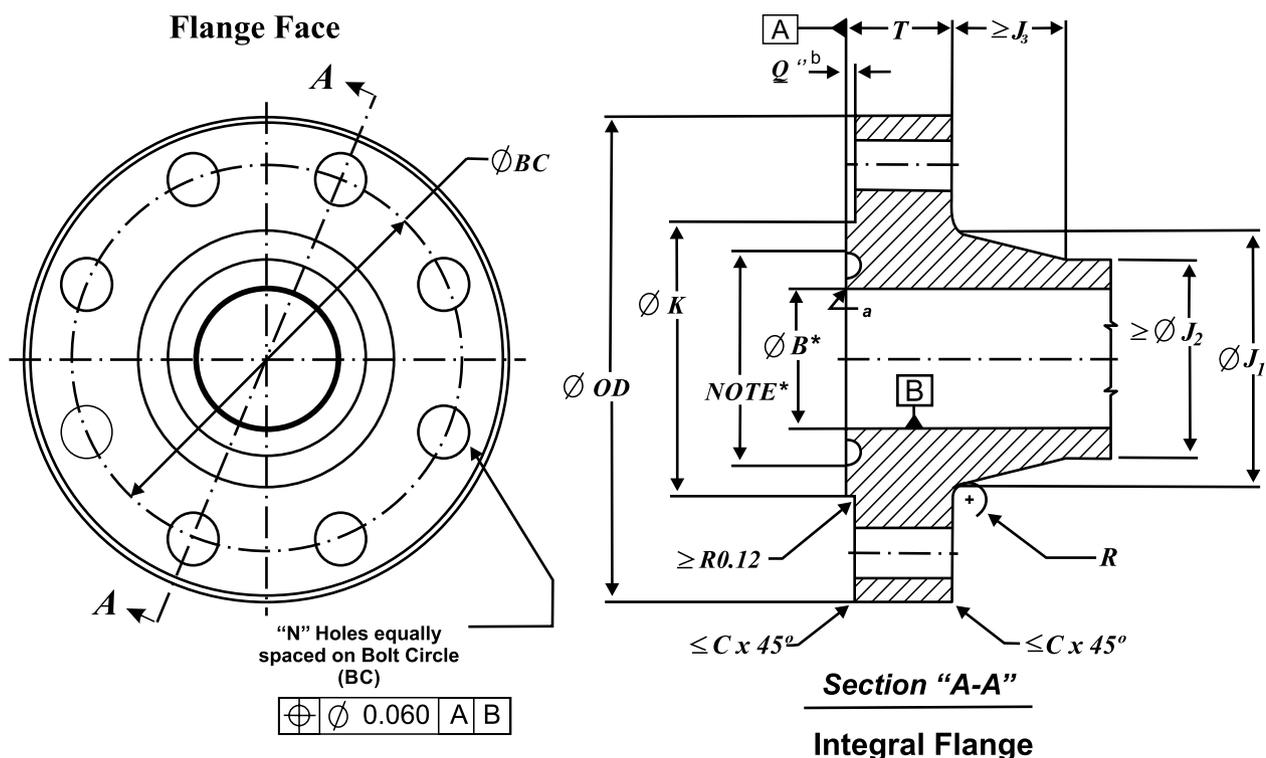
Design pressure was 103.5 MPa, operating 51.8 MPa, and temperature 176.7 °C. based on 3000 m HPHT wells in Potiguar and Sergipe-Alagoas basins [1,51–55]. The analyses covered stress, deformation, fatigue, and hydrostatic tests [22,33].

An 11" cylindrical shear valve body with two lateral holes (Figure 2) was sized analytically and numerically. Forged AISI 4145H steel, quenched and tempered, was the chosen material, for its acceptable hardness, nickel content, and corrosion resistance [27,56]. Its ambient yield strength is 862 MPa [57,58], reduced to 90% for high temperature, per API 6MET [28]. An API 6A integral flange (Figure 3), was selected based on the proposed pressure and dimensions [35,59].

The hub’s vertical flange nominal diameter was set at 11”, and the side flange was 13 5/8”, to fit the shear ram. Tables 2 and 3 detailed flange and bolt sizes [35,59].

For fasteners, SA-320 Grade L7 material was chosen for subsea use, with required properties in

**Figure 3.** Flange 6A with BX seal for 103.5 MPa operating pressure [35].



**Table 2.** Dimensions for API 6BX integral flanges to 103.5 MPa [35].

Normal size and Bore of Flange		Basic Flange Dimensions							
		Maximum bore	Outside diameter of flange		Maximum chamfer	Diameter of raised face	Total Thickness of flange	Large diameter of hub	Small-diameter of hub
(in)	(mm)	$B$	$OD$	tol.	$C$	$K \pm 1.6$	$T$ +3 0	$J_1$ 0 -3	$J_2$
11	279	280.2	815	$\pm 3$	6	454	187.4	584.2	427.0
13 $\frac{5}{8}$	346	346.9	885	$\pm 3$	6	451	204.8	595.3	528.6

**Table 3.** Bolt dimensions for API 6BX flanges to 103.5 MPa [35].

Normal size and Bore of Flange		Bolting Dimensions								
		Length of hub	Radius of hub	Diameter of bolt circle	Number of bolts	Diameter of bolt	Diameter of bolt holes		Minimum length of stud bolts	Ring number
(in)	(mm)	$J_3$	$R$	$BC$		(in)	tol. <sup>e</sup>		$L_{ssb}$	$BX$
11	279	235.7	16	711.2	20	2	54	+ 2.5	490	158
13 $\frac{5}{8}$	346	114.3	25	711.5	20	2 $\frac{1}{4}$	61	+ 2.5	540	159

**Table 4.** Mechanical properties of ferritic materials for high-alloy fasteners [61].

Class and Grade, Diameter, in [mm]	Heat Treatment	Minimum Tempering Temperature, °F [°C]	Tensile Strength, min, ksi [MPa]	Yield Strength, min, ksi [MPa] (0.2 offset)	Elongation in 2 in. or 50 mm, min, %	Reduction of Area, min, %	Handness, max
Ferritic Steels							
L7, L7A, L7B, LTC,L70, L71, L72, L73			125	105	16	50	321 HBW or 35 HAC
21/2 [65] and under <sup>A</sup>	quenched and tempered	1100 [593]	[860]	[725]			

Table 4 [29,60]. Suitable for bolts up to 2,5" (65 mm), heat treated by quenching and tempering, it has 35 HRC hardness, 724 MPa yield strength, and 861,85 MPa tensile strength. A safety factor of 2.0 was applied, considered acceptable [33,34,60].

#### Allowable Stresses and Loads Calculation

Allowable stresses were set as the minimum yield or rupture ratio, with its respective factors, as shown in Equation 1 [32].

$$S_{adm} = \min\left(\frac{S_y}{1.5}; \frac{S_u}{2.4}\right) \quad (1)$$

Loads were estimated from body-fixing bolts and flange forces under pressure and sea current moments, according to Equations 2 and 3 [33].

$$M_o = abs(((H_D * h_D + H_T * h_T + H_G * h_G) * B_{SC} + M_{oe}) * F_s) \quad (2)$$

$$M_g = W_g * (C + G) * B_{SC} * F_s) * 0,5 \quad (3)$$

These body stresses was defined accounting for stress concentrators and secondary stresses, and

safety factors [33,34,62]. The stiffness index was calculated per Equation 4 [33].

$$J = \frac{52,14 * V * M}{L * E * K_R * h_o} \quad (4)$$

### Analysis of Lamé and Secondary Stresses

Lamé stress analysis, using defined dimensions and corrosion allowance, computed wall thickness and stresses by Equations 5–7 [32].

$$\sigma_{rr} = \frac{(p_1 * R_1^2)}{R_2^2 - R_1^2} - \frac{R_1^2 * R_2^2}{r^2 * (R_2^2 - R_1^2)} * (p_1) \quad (5)$$

$$\sigma_{\theta\theta} = \frac{(p_1 * R_1^2)}{R_2^2 - R_1^2} + \frac{R_1^2 * R_2^2}{r^2 * (R_2^2 - R_1^2)} * (p_1) \quad (6)$$

$$\sigma_{zz} = \frac{(p_1 * R_1^2)}{R_2^2 - R_1^2} + \frac{F}{\pi * (R_2^2 - R_1^2)} \quad (7)$$

Equivalent stresses by von Mises criterion (Equation 8) included self-weight, thermal effects, and concentration factors [33,41,61].

$$\sigma'_{eq\_\theta max} = \sqrt{\frac{(\sigma'_{\theta\theta} - \sigma'_{rr})^2 + (\sigma'_{rr} - \sigma'_{zz})^2 + (\sigma'_{zz} - \sigma'_{\theta\theta})^2}{2}} \quad (8)$$

### Fatigue Life Analysis

Fatigue life followed the modified Goodman criterion, with resistance limits, factors and stresses (Equation) 9 [40].

$$\frac{\sigma'_m}{S_{ut}} + \frac{\sigma'_a}{S_f} = 1 \quad (9)$$

### Finite Elements Method

FEM model evaluated stress–strain response under complex loading and geometry, complementing analytical results [22,33].

## **Results and Discussions**

The EDP was designed per load and dimensional requirements. Figures 4 and 5 show the main body and a full 3D CAD model, with external structure and an internal sealing section. The design features a vertical bore, for coiled tubing, and a horizontal chamber, with a ram that shears the tube and seals the system via O-rings.

To verify structural integrity, stresses in the nozzle opening regions were analyzed.

Allowable stresses for flanges, bolts, and the EDP body at design (177 °C) and sealing (ambient) temperatures are presented in Table 5, with body and flange stresses being identical due to its material equivalence. The stress reduction due to temperature is responsible for the difference in stresses between the two temperature conditions.

Flange load calculations considered the bending moments induced by sea current forces, which increase stresses acting on the body, as calculated previously. Table 6 presents the resulting loads for each designed flange. Stress concentrators were then accounted for, and flange integrity was assessed.

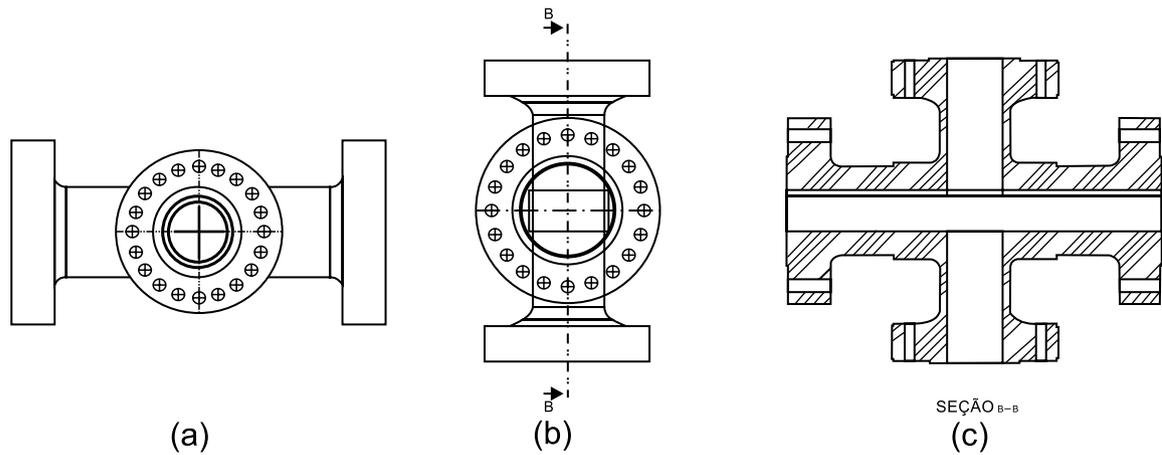
Table 7 lists the safety factors for operating, sealing, hydrostatic test, and combined Table 4. Safety Factors for EDP Flange Design stress conditions for both flanges, calculated by dividing the material's allowable stress by the acting stresses, following ASME VII-2 criteria, also shown in Table 7. This standard considers the unit as the minimum value to ensure equipment integrity, applying safety parameters as constants in the calculations, being a usual practice at the oil and gas sector. Therefore, all safety factors calculated below were acceptable, above the recommended minimum limit of 1, indicating that the equipment, with the calculated dimensions and chose materials, can withstand the forces and stresses acting on it [33].

A flange stiffness index analysis also confirmed compliance, with values below 1 for both sealing and operating conditions.

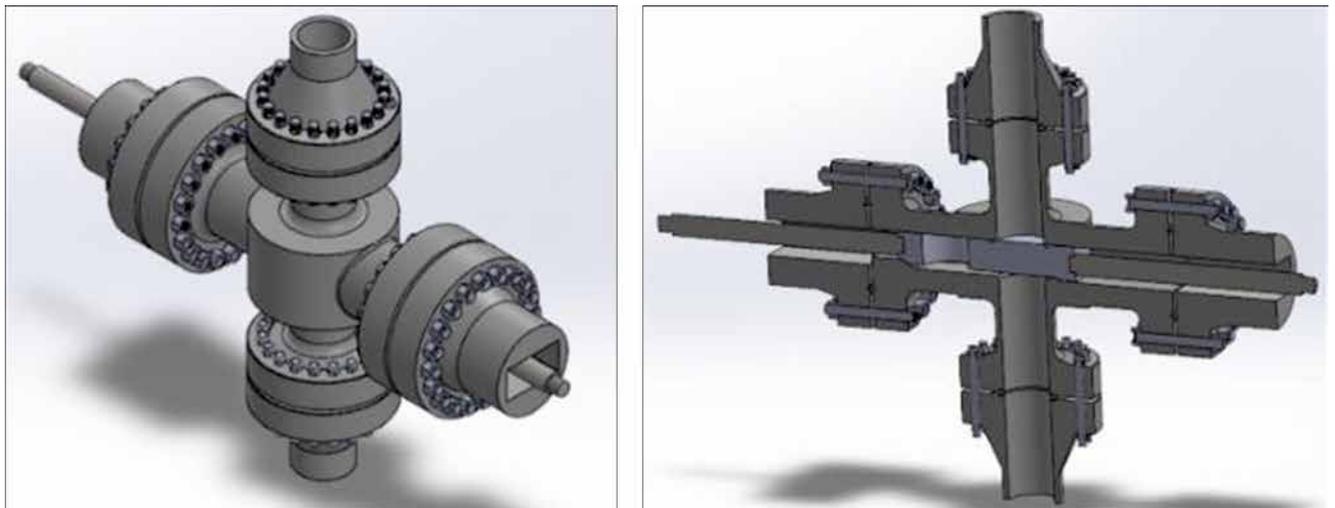
In the Lamé stress analysis with the Von Mises criterion, considering secondary stresses, it was found that wall holes created stress concentrators exceeding design limits. To mitigate this, lateral projections were added to the hole region (Figure 8), sized so that their external surface extended beyond the stress concentration zone, preventing overload on the necks between projections and flanges.

The local thickness increase preserved structural integrity while reducing material and financial costs compared to increasing the overall body thickness. Table 8 presents the safety coefficients

**Figure 4.** Top (a), side (b) and front view with section cut (c) of the EDP body.



**Figure 5.** EDP CAD assembly.



**Table 5.** Allowable stress for flanges and bolts.

Equipment Component	Allowable Stress at Design Temperature (MPa)	Allowable Stress at Sealing Temperature (MPa)
Body and Flanges	415,50	458.33
Flange Bolts	337.55	358.33

**Table 6.** Bending moment at flanges caused by current force.

Internal Diameter (In.)	Normal Force (N)	Shear Force (N)	Bending Moment (J)
11''	650	1166.8	1.4E+5
13 5/8''	650	1798.3	2.2E+5

**Table 7.** Safety factors for EDP flange design.

Component	Analyzed Condition	Calculation Method	Safety Coefficient
<b>Axial Flange</b>	Operation (With concentrator)	$\frac{1,5 * \sigma_{adm\_op}}{\sigma_{axial\_op} * K'_t}$	7,72
	Sealing (With concentrator)	$\frac{1,5 * \sigma_{adm\_sg}}{\sigma_{axial\_sg} * K'_t}$	5,80
	Hydrostatic Test (With concentrator)	$\frac{0,9 * S_{y\_Aço\_4145}}{\frac{P_{TH}}{P_i} * \sigma_{axial\_op} * K'_t}$	6,45
	Combination of Sealing Stresses (Axial + Tangential)	$\frac{2 * \sigma_{adm\_sg}}{\sigma_{axial\_sg} + \sigma_{tan\_sg}}$	8,57
	Combination of Sealing Stresses (Axial + Radial)	$\frac{2 * \sigma_{adm\_sg}}{\sigma_{axial\_sg} + \sigma_{radial\_sg}}$	4,75
	Combination of Stresses in Operation (Axial + Tangential)	$\frac{2 * \sigma_{adm\_op}}{\sigma_{axial\_op} + \sigma_{tan\_op}}$	11,40
	Combination of Stresses in Operation (Axial + Radial)	$\frac{2 * \sigma_{adm\_op}}{\sigma_{axial\_op} + \sigma_{radial\_op}}$	6,22
<b>Side Flange</b>	Operation (With concentrator)	$\frac{1,5 * \sigma_{adm\_op}}{\sigma_{axial\_op} * K'_t}$	9,03
	Sealing (With concentrator)	$\frac{1,5 * \sigma_{adm\_sg}}{\sigma_{axial\_sg} * K'_t}$	9,52
	Hydrostatic Test (With concentrator)	$\frac{0,9 * S_{y\_Aço\_4145}}{\frac{P_{TH}}{P_i} * \sigma_{axial\_op} * K'_t}$	7,55
	Combination of Sealing Stresses (Axial + Tangential)	$\frac{2 * \sigma_{adm\_sg}}{\sigma_{axial\_sg} + \sigma_{tan\_sg}}$	14,58
	Combination of Sealing Stresses (Axial + Radial)	$\frac{2 * \sigma_{adm\_sg}}{\sigma_{axial\_sg} + \sigma_{radial\_sg}}$	5,56
	Combination of Stresses in Operation (Axial + Tangential)	$\frac{2 * \sigma_{adm\_op}}{\sigma_{axial\_op} + \sigma_{tan\_op}}$	13,83

for regions with and without stress concentration, calculated as the ratio between the material strength and the acting equivalent stresses.

Structural modifications ensured the equipment body met acceptance criteria under internal pressure and secondary loads, being suitable for the proposed operating conditions.

Simplified finite element analysis using  $\frac{1}{8}$  symmetry and three mesh sizes (20 mm, 5 mm, 2 mm) showed satisfactory mesh quality (Figure 6). The Jacobian criterion, ideally near unity,

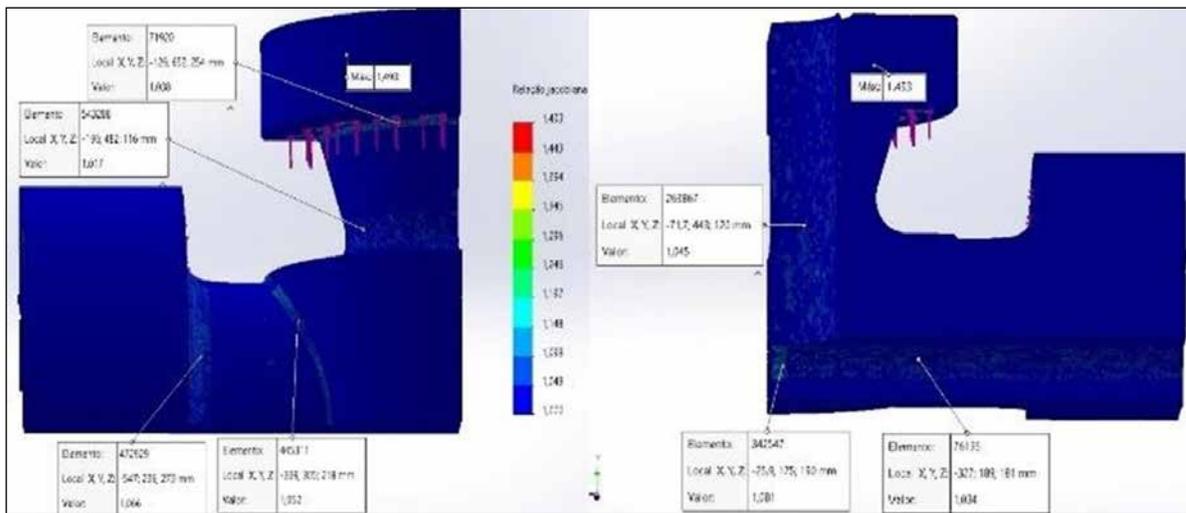
ranged from 1.0 to 1.16 in critical regions like the internal nozzle surface, nozzle necks, and ram sliding nozzle concentrator, being within the 20% tolerance [63] and validating the mesh quality.

The FEM analysis identified the highest stress concentrations in the thinnest regions and areas with geometric changes, confirming these as critical structural points. Figure 7 presents the maximum stress values under the most demanding load case, the Hydrostatic Test, which remain below the material's yield strength.

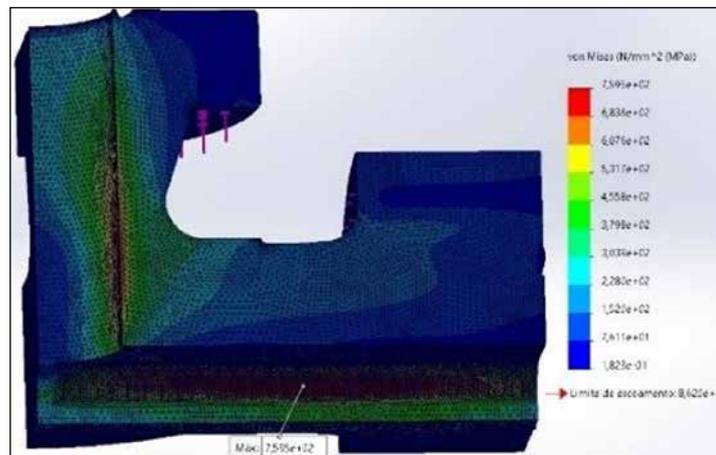
**Table 8.** Safety coefficients for equipment pressure conditions.

Load Condition	Radial Stress (MPa)	Circumferential Stress (Mpa)	Axial Stress (MPa)	Von Mises Stress (MPa)	Calculation Method	Safety Coef.
Operation, away from the concentrator	103,4	238,6	76,9	296,4	$\frac{Y_f * S_y}{\sigma_{eq}}$	2,17
Hydrostatic Test away from the concentrator	155,1	330,0	87,4	420,1	$\frac{0,9 * S_y}{\sigma_{eq}}$	1,47
Operation with concentrator	103,4	476,3	21,1	528,6	$\frac{Y_f * S_y}{\sigma_{eq}}$	1,41
Hydrostatic Test with concentrator	155,1	609,4	3,4	698,8	$\frac{0,9 * S_y}{\sigma_{eq}}$	1,11

**Figure 6.** Division and mesh quality in the analyzed element.



**Figure 7.** Von mises stress (hydrostatic test) on CAD model by FEM.



The analysis considered torque and bolt stress values recommended by API 6A for the respective types of flanges and bolts used in the equipment design [35]. Maximum stress zones extended along the flange necks, highlighting significant bending effects. Increasing thickness in these regions is a possible design optimization, to reduce those stresses and improve stiffness.

Based on the FEM results, safety coefficients were calculated for each analyzed scenario using the corresponding Von Mises stress values, as shown in Table 9. Differences between the numerical and analytical model results are attributed to FEM's consideration of complex factors excluded in the pressure vessel calculations, such as detailed geometric features, like angles, surfaces and cuts for ram movement.

**Table 9.** Safety coefficients based on stresses obtained by FEM.

Load Condition	Von Mises Stress (MPa)	Safety Coefficient
Operation	255.4	2.94
Project	507.6	1.54
Hydrostatic Test	759.5	1.02

Despite increased stress during the hydrostatic test, all safety coefficients remained within acceptable limits, corroborating the analytical results and indicating the equipment's suitability for the intended operations. However, both analytical and numerical results approached critical values under hydrostatic conditions, suggesting the need for structural optimization, particularly increasing wall thickness at the nozzle necks.

Additionally, membrane stresses on the equipment wall were analysed and compared between analytical and numerical methods using Von Mises stress at average wall thickness. Table 10 presents these stress values and corresponding safety coefficients, calculated as the ratio of membrane stress to the material's allowable stress.

**Table 10.** Safety coefficients based on membrane stresses obtained in FEM.

Type of Analysis	Load Condition	Membrane Stress (MPa)	Safety Coefficient
Analytical	Project	239.5	1.72
	Hydrostatic Test	353.3	1.30
Numerical (FEM)	Project	240.2	1.72
	Hydrostatic Test	363.2	1.27

The stress values obtained for this criterion were within acceptable limits and showed close between the analytical and numerical methods. Thermal stresses acting on the body under design conditions were also evaluated, combined with pressure effects, to assess combined stresses via FEM. Results, presented in Table 11, remained within acceptance limits, with higher maximum stresses compared to the pressure-only case due to the additional thermal loading.

**Table 11.** Combined stresses analysis by FEM.

Combined Stresses Case	Stress Value (MPa)	Safety Coef.
Von Mises Stresses	549.1	1.43
Maximum Stresses	571.3	1.43

The fatigue life analysis, yielded a safety factor of approximately 0.4, indicating that the equipment has a finite service life, operating up to 42756 cycles. This indicates less operating time than usual for those equipments and a need for earlier replacement. This is a topic that requires further analysis and refinement in later stages of this project, considering a change in materials or the changes in well pressure levels at different

stages of its life cycle, since production declines are natural in these structures, and these reduce pressure levels during operation [64].

The design assumptions and simplifications applied in the analyses effectively optimized computational resources and reduced calculation complexity without compromising result quality. The outcomes were consistent with each other and aligned with the theoretical framework, adequately representing the functionality of the modelled mechanisms and the structural integrity of the components.

## Conclusions

The equipment was sized according to manufacturing and dimensional specifications, utilizing 11" and 13½" API 6BX flanges made from AISI 4145H steel. The objectives were successfully met, with both analytical and finite element analyses showing compliance within acceptable design limits. In the hydrostatic test, safety coefficients values are close to 1, indicating the need to increase wall thickness, in order to ensure integrity under critical conditions.

As expected, stresses during the hydrostatic test were notably higher than design stresses, due to increased pressure, and stress concentrators significantly amplified these stresses, which justifies careful consideration of this aspect in future design phases.

Fatigue life analysis indicated that the designed EDP valve operates over a finite life cycle, which is not recommended for this type of equipment. Therefore, a more detailed analysis, considering well pressure variations throughout its service life and material optimization, should be performed to achieve more appropriate results.

The development of such equipment is vital for advancing the oil and gas industry, ensuring well integrity and sustained production, particularly at the national level.

Results highlight the importance of accurately determining operating conditions to assess structural integrity, especially for subsea HPHT

equipment where pressure is a critical factor influencing stresses.

Another potential improvement includes refining the CAD model with structural optimization and running FEM analysis in other software, as Ansys or Abaqus, to verify and confirm the results.

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## Exploring the Use of Nonconventional Receivers for Quantum Communications

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Standard protocols in optical communication systems employ coherent states of light as the information carriers. The quantum nature inherent to these states introduces a fundamental complexity into the decoding process. In particular, when dealing with attenuated signals, the overlap between different states precludes the possibility of perfectly discriminate them. In this study, we investigate the performance of conventional and nonconventional quantum discrimination strategies under different informational metrics. We focus our analysis on binary coherent states within the ideal case of a lossless channel. The usual homodyne receiver was studied in comparison with the Kennedy and the optimized displacement receiver. We find that nonconventional strategies employing non-Gaussian measurements surpass the conventional homodyne discrimination scheme according to measurement error probability and mutual information.

**Keywords:** Quantum Communications. Quantum State Discrimination. Mutual Information. Non-Gaussian Measurement.

**Abbreviations:** POVM, Positive Operator-Valued Measure. BPSK, Binary Phase-Shift-Keying.

In general terms, the main objective of any communication system is to transmit information reliably from a transmitter to a receiver [1]. In optical quantum communication, it becomes necessary to employ the mathematical framework of quantum mechanics to adequately describe the transmission and reception of optical fields under various conditions [2]. This quantum description becomes essential in the photon-starved-regime, where the quantum shot noise fundamentally limits signal discrimination capabilities [3]. Under such circumstances, the detection process becomes a discrimination problem, and the theoretical framework of quantum state discrimination must be employed at the receiver's end of the communication protocol.

In this study, we aim to investigate different quantum state discrimination strategies by employing two distinct criteria: measurement error probability and mutual information. Our objective is to compare conventional and nonconventional

reception strategies. We focus on binary coherent state modulation within the ideal case of a lossless channel.

### Fundamentals of Quantum Detection and Communication

In quantum theory, a physical system is represented by a positive semidefinite unit trace operator  $\hat{\rho}_i$  on the system's Hilbert space  $\mathcal{H}_s$ , called a density operator [4]. When only pure states are assumed, its description is given by state vectors  $\{|\psi_i\rangle\}$  as

$$\hat{\rho}_i = |\psi_i\rangle\langle\psi_i|. \quad (1)$$

For a quantum communication protocol, the transmitter, Alice, encodes a classical symbol  $a_0$  or  $a_1$  into two quantum states  $|\psi_0\rangle$  and  $|\psi_1\rangle$  with a priori probabilities  $p_0$  and  $p_1$ , respectively. In the case of quantum optical communication, the usual information carrier are optical signals described by coherent states [1]. Here, we consider pure coherent states of the form

$$|v\rangle = \hat{D}(v)|0\rangle, \quad (2)$$

where  $\hat{D}(v)$  is the displacement operator and  $|0\rangle$  is the vacuum state [5,6]. In particular, our focus will be on analyzing a binary phase-shift-keying

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(BPSK) configuration, characterized by the two quantum coherent states  $|\alpha\rangle$  and  $|\alpha\rangle$ . These states possess an identical amplitude magnitude  $|\alpha|$ ; however, they are differentiated by a phase shift of  $\pi$ .

Once the signal is encoded, it is propagated through a quantum channel, described by a completely positive trace preserving map  $\hat{G}$  [7], until it reaches the receiver, Bob, in the form of an altered state  $\hat{G}(|\alpha_i\rangle)$ . At this point, Bob infers by the incoming signal whether the transmitted symbol was  $a_0$  or  $a_1$ . This inference is realized by performing a quantum measurement process, denoted by a positive-operator valued measurement (POVM)  $\{\hat{\Pi}_{b_i}\}$

$$\sum \hat{\Pi}_{b_i} = \mathbb{1}, \quad \hat{\Pi}_{b_i} \geq 0, \quad (3)$$

which retrieves an outcome  $b_i$  correlated with the variables  $\{a_0, a_1\}$  [4].

Hereafter we consider only the ideal case of a lossless channel, i.e.  $\hat{G} = \mathbb{1}$ , such that  $\hat{G}(|\alpha_i\rangle) = |\alpha_i\rangle$ . In this case, the communication procedure is depicted schematically on Figure 1.

**Figure 1.** Alice encodes symbol  $a_0(a_1)$  into state  $|\alpha\rangle(|\alpha\rangle)$ , which is then transmitted to Bob. Afterwards, Bob performs a measurement  $\Pi_0(\Pi_1)$  that yields an outcome  $b_0(b_1)$ , which is correlated with the symbols encoded by Alice.

$$\begin{array}{ccccccc} a_0 & \longrightarrow & |\alpha\rangle & \longrightarrow & \hat{\Pi}_0 & \longrightarrow & b_0 \\ a_1 & \longrightarrow & |\alpha\rangle & \longrightarrow & \hat{\Pi}_1 & \longrightarrow & b_1 \end{array}$$

With that, the conditional probability that Bob measures a result  $b_i$  given that Alice sent a signal  $a_j$  is given by the Born rule:

$$p(b_i|a_j) = \text{Tr}(\hat{\Pi}_i|\alpha_j\rangle\langle\alpha_j|), \quad i = 0, 1; \quad (4)$$

with  $|\alpha_0\rangle = |\alpha\rangle$  and  $|\alpha_1\rangle = |\alpha\rangle$ .

Two general metrics are often used to evaluate the efficiency of a communication system [8]; one is the error probability defined, in our case, as Weedbrook and colleagues [9]:

$$P_{\text{err}} = p_0 \text{Tr}(\hat{\Pi}_1|\alpha_0\rangle\langle\alpha_0|) + p_1 \text{Tr}(\hat{\Pi}_0|\alpha_1\rangle\langle\alpha_1|). \quad (5)$$

The other is the mutual information defined as Helstrom [10]:

$$I(A : B) = H(A) - H(A|B), \quad (6)$$

which measures the amount of information about Alice's variable extracted by Bob for a particular measurement [11]. In that expression  $H(A) = -\sum_a p(a) \log_2(a)$  and  $H(A|B) = \sum_b p(b) H(A|B = b)$  are the usual and conditional Shannon entropies.

## Coherent State Discrimination

Because of the nature of the quantum states used in quantum communication protocols, the classical values decoded by Bob can differ from the ones encoded by Alice, even for a lossless channel. This limitation arises from the quantum trace of those states, and it is related to the impossibility of perfectly distinguishing between two non-orthogonal states [12]. For the case of coherent states, this non-orthogonality is closely associated with the inherent quantum shot noise characteristic of such states. This relationship manifests as an overlap in the probability regions within the phase-space representation (Figure 2).

This quantum state discrimination problem is ultimately a measurement optimization issue, that is, the best strategy for determining the state received must be given by the POVM that minimizes the probability of error of equation (5). The minimum error probability allowed by the quantum theory is given by the Helstrom limit, which for binary signals of equal a priori probabilities is given by [9]

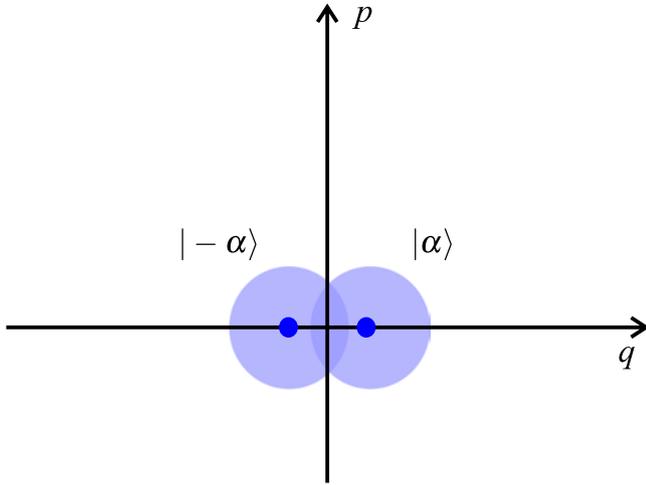
$$P_{\text{Hel}} = \frac{1}{2} \left[ 1 - \sqrt{1 - e^{-4|\alpha|^2}} \right]. \quad (7)$$

Implementing the optimal POVM as proposed by Helstrom presents substantial complexity when applied to coherent states [13]. Nevertheless, there exist feasible discrimination techniques that can approximate the optimal POVM, which brings us closer to achieving the Helstrom limit.

## Conventional and Non-Conventional Receivers

In the literature on quantum state discrimination, each discrimination scheme defines a receiver.

**Figure 2.** Representation of states  $|\alpha\rangle$  and  $|\alpha\rangle$  in phase space. The intrinsic quantum noise is responsible for overlap between states.



Generally speaking, the structure of a receiver comprises an unitary operation, which is succeeded by a detection process [14]. The usual schemes applied for coherent state discrimination are based on Gaussian detections, that is, the possible outcomes follows a gaussian distribution [15]. In the context of optical communication with BPSK modulation, these detections are centered on the measurement of field quadrature components through a homodyne detection technique [9, 16].

Nonetheless, non-Gaussian measurements hold considerable significance in specific protocols, as they have the potential to surpass conventional detection methods concerning figures of merit that are pertinent to the field of quantum communication [17-19]. In particular, non-Gaussian on/off detections have been used as an essential tool in the context of coherent state discrimination [20-23]. In the following, we shall examine two main discrimination schemes that implement non-Gaussian detection, referred to as non-conventional receivers, and conduct a comparative analysis with the conventional homodyne receiver.

### Discrimination Strategies

A homodyne receiver is a discrimination strategy based on the homodyne detection,

consisting exclusively of Gaussian operations. The POVM characterizing this receiver is formulated as

$$\hat{\Pi}_0 = \int_{-\infty}^0 |x\rangle\langle x| dx, \quad \hat{\Pi}_1 = \mathbb{1} - \hat{\Pi}_0. \quad (8)$$

Here,  $(|x\rangle\langle x|)$  denotes a projection operator that projects onto the eigenstates of the quadrature operator  $\hat{x}$ . Consequently, when a measurement of the quadrature  $x$  yields a positive outcome, it is indicative of the state  $|\alpha\rangle$ . In contrast, negative results identify the state  $|\alpha\rangle$ .

The equation (5) together with the POVM elements above gives the error probability of the homodyne receiver:

$$P_H = \frac{1}{2} \left[ 1 - \text{erf}(\sqrt{2}|\alpha|) \right], \quad (9)$$

where  $\text{erf}(x)$  is the error function. This error probability is also known as the *Gaussian limit*. This is due to the fact that among all Gaussian measurements, homodyne detection represents the optimal approach for the discrimination of binary coherent states [17]. This approach approximates the Helstrom limit, being nearly optimal, for coherent states characterized by a very low mean photon number  $|\alpha|^2$ . However, the effectiveness of this strategy diminishes, as  $|\alpha|^2$  increases.

The first proposal for a practical discrimination scheme of binary coherent states considered near-optimum, was formulated by R. Kennedy [20]. Its receiver, also known as nulling-displacement receiver, consists first of applying a displacement operation with amplitude  $\alpha$  in both states such that

$$|\alpha\rangle \longrightarrow |0\rangle \quad |\alpha\rangle \longrightarrow |2\alpha\rangle. \quad (10)$$

Then, its applied an on/off detection on the displaced state to measure the presence of any photons. This detection is represented by the operators

$$\hat{\Pi}_0 = |0\rangle\langle 0|; \quad \hat{\Pi}_1 = \mathbb{1} - \hat{\Pi}_0 = \sum_{n=1}^{\infty} |n\rangle\langle n|, \quad (11)$$

where  $|n\rangle\langle n|$  are projectors into Fock states, i.e., states of a well-defined number of photons [5].

The principle here is to map the problem of discriminating between  $|\alpha\rangle$  and  $|\alpha\rangle$  into

discriminating between vacuum  $|0\rangle$  and state  $|2\alpha\rangle$ . This strategy minimizes the first term of equation (5) and the error probability is given by

$$P_K = \frac{1}{2}e^{-4\alpha^2}. \quad (12)$$

Although we have a value higher than the Helstrom limit,  $P_K > P_{\text{Hel}}$ , the Kennedy receiver is classified as *near-optimum*, since in the high-energy regime we have  $P_K \approx 2P_{\text{Hel}}$  [24]. Consequently, this strategy surpasses the performance of the homodyne receiver for most of the energy values of the coherent states. However, when dealing with highly attenuated signals, the homodyne receiver constitutes a more effective method of discrimination. This behavior is illustrated in Figure 3, which presents the error probabilities associated with the homodyne and Kennedy receivers against the Helstrom limit, depicted as a function of the mean photon number.

An optimized the displacement parameter of the Kennedy receiver can overcome the advantage a homodyne receiver holds in scenarios characterized by low-amplitude signals. This strategy, first proposed by Takeoka and colleagues

[17], is known as optimized displacement receiver and consists of determining the displacement parameter  $\beta$  that minimizes the error probability for each amplitude of the coherent state. In this case, before on/off detection, both states are displaced by an optimized factor  $\beta$  such that

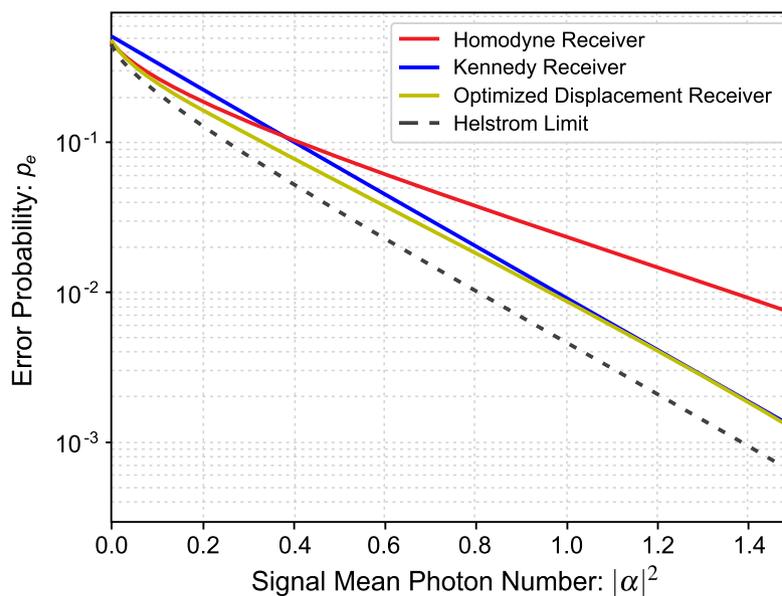
$$|\pm\alpha\rangle \longrightarrow \hat{D}(\beta)|\pm\alpha\rangle = |\pm\alpha + \beta\rangle. \quad (13)$$

The error probability for this receiver is given by

$$P_\beta = \frac{1}{2} \left( e^{-(\beta+\alpha)^2} - e^{-(\beta-\alpha)^2} + 1 \right). \quad (14)$$

As shown in Figure 3, the displacement optimization reduces the probability of error compared to the homodyne receiver for any intensity value, including, in particular, signals with a low mean photon number. For high energy values, we have an expected convergence  $P_\beta \rightarrow P_K$ . The practical implementation of this receiver has been demonstrated experimentally through different studies [22,25]. Furthermore, this strategy presents possible applications in quantum key distribution, where it has been shown to increase the secret key rate compared to that of a simple homodyne detection [18].

**Figure 3.** Logarithmic plot of error probability as a function of  $|\alpha|^2$  for the optimized displacement receiver (solid yellow curve), Kennedy receiver (solid blue curve), homodyne receiver (solid red curve), and the Helstrom limit (dashed black curve).



## Mutual Information and Discrimination Strategies

Another fundamental criterion for evaluating the performance of a communication system is the mutual information between the random variables associated with the transmitter and the receiver. Here we describe the behavior of mutual information for the different receivers presented in the last section. When considering a lossless channel and a priori probabilities  $p(a_j) = 1/2$ , the equation (6) can be worked on to become a function of the conditional probabilities:

$$I(A : B) = 1 + \frac{1}{2} \sum_{k=0}^1 \sum_{j=0}^1 p(b_k|a_j) \log_2 \frac{p(b_k|a_j)}{\sum_l p(b_k|a_l)}. \quad (15)$$

With this equation, we can directly evaluate the mutual information through the POVM associated with each receiver and the Born rule equation (4).

The numerical results obtained for the different receivers are presented in Figure 4 as a function of the mean number of photons of the signal. For comparison is also plotted the accessible information for the BPSK modulation, obtained

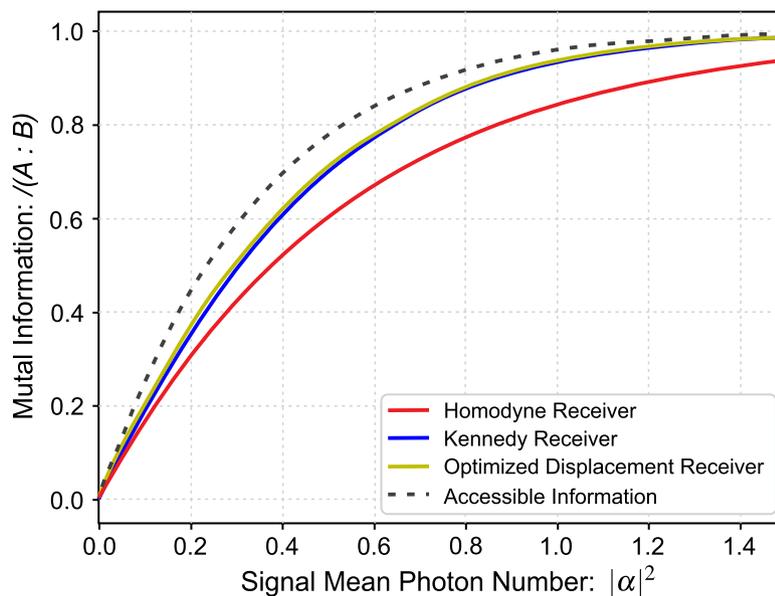
by the maximization of the mutual information over all possible POVM's:  $\max_{\hat{\Pi}_b} I(A : B)$ .

In Figure 4, it is easily seen how both nonconventional receivers outperform simple homodyne detection, even for low-intensity signals. In addition, the mutual information of the nonconventional receivers saturates more rapidly than the homodyne one that demands a higher signal energy to reach the maximum. However, when comparing both nonconventional receivers, significantly less contrast is observed. Although the optimized displacement receiver demonstrates a similar trend to the error probability — exceeding the performance of the Kennedy receiver for attenuated signals and converging at higher energy values — the distinction is subtle, evidencing only a slight advantage for low-energy signals. For higher energy both strategies saturates equally and in general the mutual information is comparable.

## Conclusion

In this work, we calculated the error probability and mutual information considering different

**Figure 4.** Plot of the mutual information as a function of  $|\alpha|^2$  for the optimized displacement receiver (solid yellow curve), Kennedy receiver (solid blue curve), homodyne receiver (solid red curve). For comparison the accessible information (dashed black curve) is also plotted.



discrimination strategies for binary coherent states. As a result, we show that, in particular, the optimized displacement receiver outperformed the homodyne receiver for both criteria considered. The Kennedy receiver surpasses the mutual information achieved by the conventional discrimination strategy across all energy levels; however, when analyzing the error probability, it is demonstrated to be a less effective strategy for highly attenuated signals. Furthermore, Kennedy receiver shows considerable improvement in the error probability when optimized displacement is implemented. However, the mutual information derived from these two strategies remains comparable at all energy levels.

The gap between the error probabilities and the Helstrom limit, as well as the discrepancy between the calculated mutual information and the accessible information, indicates the potential for further development. In addition, the analysis of discrimination state strategies through communication metrics opens the possibility of further studies of applications in fields related to quantum information processing. In particular, improvement of the mutual information between trusted parties is a critical aspect in quantum key distribution, such that a direct problem related to the optimization of measurements can be explored from the standpoint of the secret-key rate.

## Acknowledgement

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## Bench Tests in Digital Signal Modulation as Preparation for CV-QKD Setup Creation

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Nowadays, quantum key distribution cryptography using continuous variables (CV-QKD) has emerged as a promising approach for the telecommunications industry, owing to its enhanced security and ease of integration with the coherent communication systems currently in use. In this context, this work presents the construction of a classical communication system for testing, with a future goal of transitioning to the quantum regime, focusing on the manipulation of equipment for signal modulation.

**Keywords:** Modulation. CV-QKD. Setup. Python.

Quantum key distribution (QKD) cryptography is a method of secret key transmission that enables secure communication between two authenticated parties, commonly referred to in the literature as Alice and Bob, without the risk of information being intercepted by an unauthenticated party [1]. The great advantage presented by QKD protocols, in contrast to classical cryptography methods, is that their security is tied to the properties of quantum mechanics—such as Heisenberg's uncertainty principle and the no-cloning theorem—whereas classical methods like RSA rely on computational complexity; this implies that QKD protocols possess stronger security against technological advances such as quantum computing [1,2].

QKD communication protocols are divided into two types: discrete-variable QKD (DV), such as BB84, which utilizes single photons for information transmission, and continuous-variable QKD (CV), which employs light properties, including position and momentum, to encode information. A major advantage of CV-QKD is its similarity to commercially used coherent communication systems, which facilitates its implementation in current transmission networks [3,4].

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Following the principles of coherent communication, it is possible to implement and use digital modulation methods—such as BPSK, QPSK, and QAM—to perform cryptography using CV-QKD [5,6].

This work aims to demonstrate the creation of a test bench for cryptographic systems using CV-QKD, focusing on the control of equipment used for the modulation of classical optical signals, ultimately preparing them for the assembly of a CV-QKD system.

### Materials and Methods

Considering the focus of this work on the previously mentioned digital modulations, it is helpful to analyze their operation. The constellations are based on two sinusoidal signals, referred to as I (In-line) and Q (Quadrature), with a phase difference of  $\pi/2$  between them, which are then combined to obtain the final signal. PSK (Phase-Shift Keying) modulations use phase shifts to represent symbols, with the shift value depending on the PSK type: BPSK (Binary PSK) manipulates only the I wave, with phase shifts of 0 and  $\pi$  rad; QPSK (Quadrature PSK), on the other hand, divides the key between the I and Q waves, applying respective phase shifts to obtain phases of 0,  $\pi/2$ ,  $\pi$ , and  $3\pi/2$  rad [5]. Unlike PSK modulations, QAM constellations vary the amplitudes of the I and Q signals to encode each symbol, with normalized amplitudes in 16QAM ranging between 0.33 and 1 V [6].

Figure 1 illustrates the configuration of components adopted for the practical realization of these modulations, in which a laser was connected to an I/Q modulator via an optical fiber through a polarization controller. The arbitrary waveform generator (AWG) was connected to the I/Q modulator via an RF cable, and the bias voltage controller (BIAS CTRL) was connected via optical fibers with electrical feedback. Finally, the bias voltage controller used an optical fiber to connect to the photodetector, which in turn was connected to an oscilloscope.

For efficient control of the equipment, a Python code library was developed, primarily utilizing the PyVISA library to connect to instruments, model them, and communicate with them to control test parameters as desired [7]. Each device had its own code model and complexity—for instance, the laser received commands for activation and deactivation, while the oscilloscope could automatically save the obtained results.

Among the instruments modeled by the library, the AWG stood out for its greater functional complexity compared to the others, such as codes for generating modulated waveforms. These functions were implemented to receive the secret key and generate a sinusoidal wave according to the requested modulation type, in a file format compatible with the AWG. Afterward, the library provided commands to send the signal to the AWG, select the desired output channel, activate that channel, and enable the equipment's operation.

The creation and use of the code library allowed precise and synchronized control of the equipment, establishing a functional system for testing. For each generated signal and obtained

result, a low-pass filter was applied to reduce noise. These procedures were implemented to enhance the quality of the tests and improve the visualization and validation of the results.

## Results and Discussion

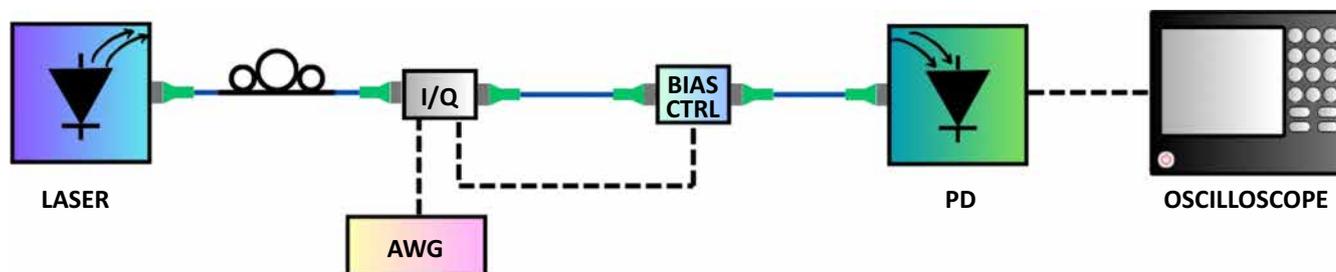
As discussed, fine control of the instruments in the system produced concrete results. The data obtained by the oscilloscope were first processed, as previously mentioned, to generate graphical representations of their quadratures, allowing for the retrieval of the original key. The results are illustrated in the following figures: the BPSK constellation is shown in Figure 2, the QPSK in Figure 3, and the 16QAM in Figure 4.

The results show that the symbol detection points are correctly positioned within the decision intervals, indicating no ambiguity or errors during signal generation, transmission, detection, or processing. The positioning of these points enabled the retrieval of the original symbol set and the reconstruction of the initial key, confirming the validity of the system built during the project. From these results, the feasibility of generating quantum signals for key transmission is validated through signal attenuation and the introduction of a local oscillator for phase recovery [8].

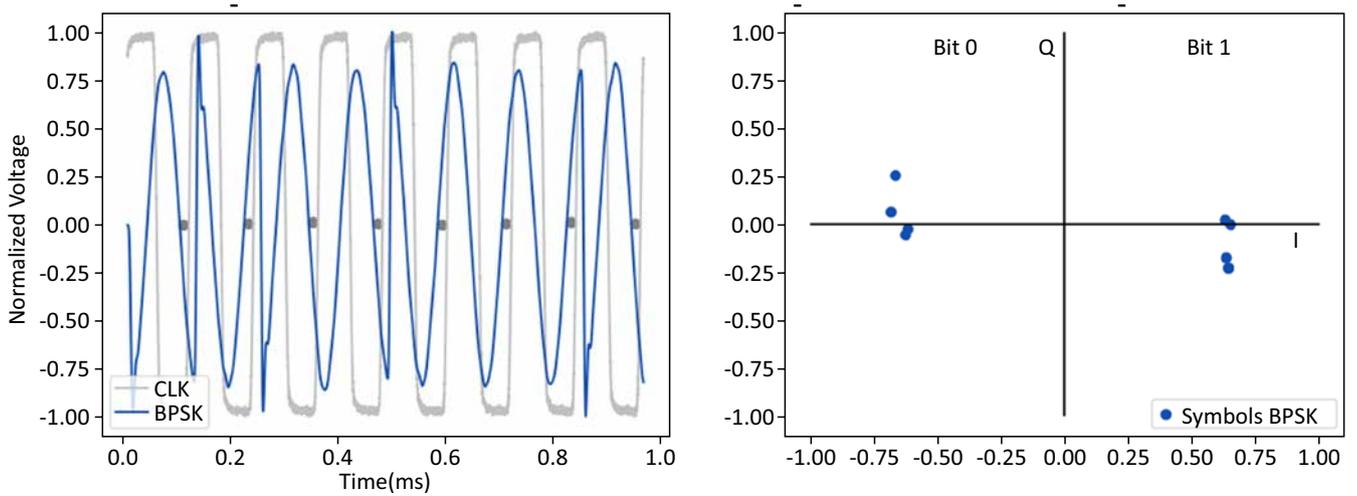
## Conclusion

This work demonstrated the capability of the developed system to transmit information through modulated signals, thereby preparing it for the transition from a classical system to a quantum system using CV-QKD. An improvement in the

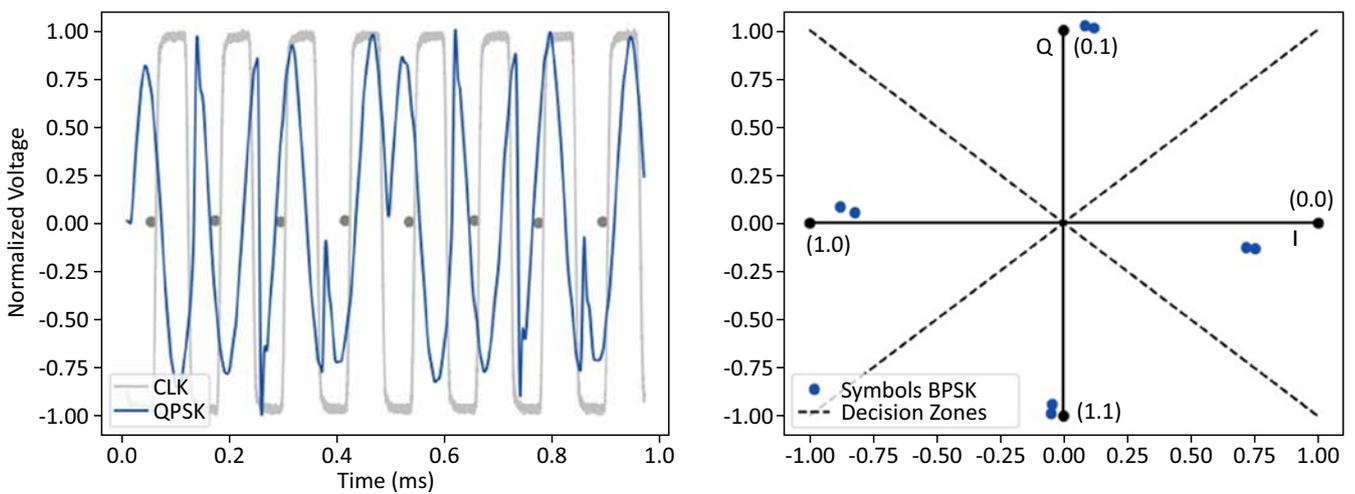
**Figure 1.** Configuration of the signal generation, transmission, and reception system.



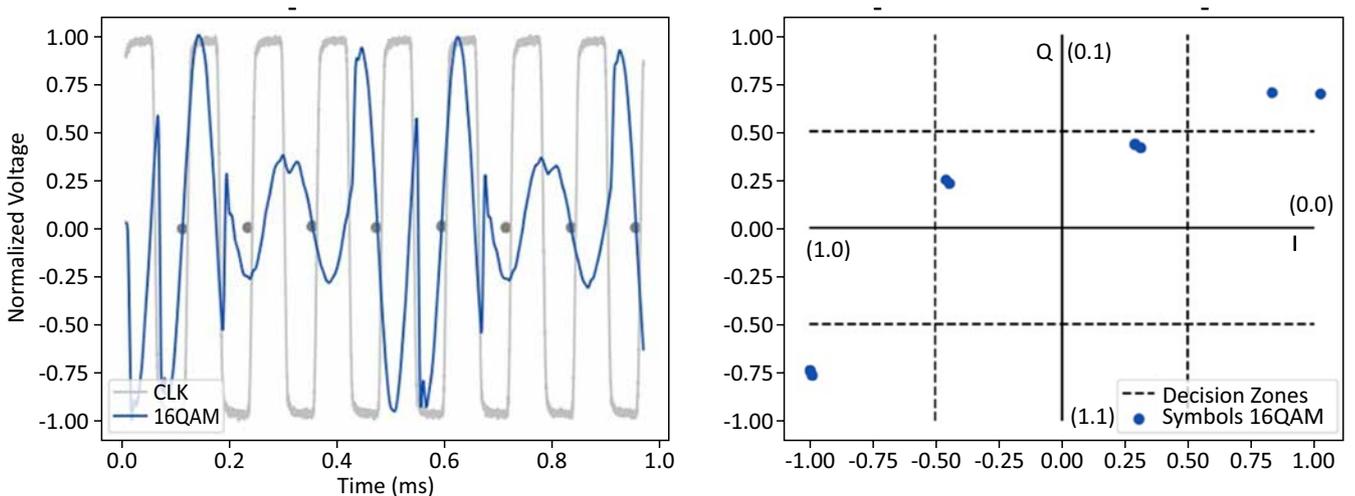
**Figure 2.** BPSK signal and its constellation diagram.



**Figure 3.** QPSK signal and its constellation diagram.



**Figure 4.** 16QAM signal and its constellation diagram.



precision of the obtained constellation diagrams is also expected in the future, bringing them closer to the ideal decision-zone points as the transmission and modulation system is updated and optimized. Future steps for the project include transitioning from the classical to the quantum domain, testing additional modulation types—such as higher-order QAM constellations (e.g., 64QAM)—conducting free-space optical tests, and studying which variables most affect the constellation diagram.

### Acknowledgments

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## Implementing Immersive and Biometric Technologies to Prevent Psychosocial Risks in Industrial Settings: Evidence-Based Guidance for Occupational Health and Safety

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Preventing psychosocial risks in industrial environments, such as occupational stress, burnout, and harassment, remains a challenge for Occupational Health and Safety (OHS) teams and organizational management. This study synthesizes consolidated evidence on how virtual reality (VR), augmented reality (AR), and biometric technologies (wearables, biofeedback, and eye tracking) can be used by organizations to prevent and mitigate psychosocial risks, aiming for healthier work environments aligned with OHS practices, standards, and current laws. An umbrella review was conducted, following the PRISMA guidelines, focusing on studies from the last five years that used immersive technologies and physiological sensors in organizational contexts. The analysis highlighted significant interventions for industrial training and prevention programs, such as the use of scenarios for the development of socio-emotional skills and the objective monitoring of stress-related responses. Evidence shows that immersive experiences can safely replicate situations of escalating conflict and abusive behavior, while biofeedback and eye tracking provide complementary, near real-time information on cognitive and emotional overload. When combined, these strategies aid in the early detection of psychological distress and allow for more focused and personalized interventions. As a practical contribution, the results guide industry-oriented design decisions towards applicable solutions, indicating what should be simulated, measured, and how to translate these results into actions to mitigate psychosocial risks. This strengthens preventive strategies, training effectiveness, and continuous improvement in the management of these risks. Future research should prioritize empirical validation in industrial contexts, cost-benefit assessments, and feasibility for large-scale implementation.

**Keywords:** Virtual Reality. Psychosocial Risks. NR-01. Biometric Sensors. Mental Health at Work.

With growing global concern about psychosocial risks in the workplace, Occupational Health and Safety (OHS) regulations have undergone significant changes. In 2019, the WHO estimated that 15% of the working-age population suffered from a mental disorder, with depression and anxiety leading to 12 billion lost workdays annually, costing the global economy US\$1 trillion [1]. These risks are intrinsically linked to work practices, environments, and interpersonal relationships, contributing to anxiety, depression, chronic stress, insomnia, and even suicide attempts [2]. In Brazil, Regulatory Standard No. 5

(NR-05), updated in 2022, requires organizations with an Internal Commission for the Prevention of Accidents and Harassment (CIPA) to adopt measures against harassment and workplace violence [3]. Regulatory Standard No. 1 (NR 01), updated in 2024, mandates the identification, assessment, and control of psychosocial risks in the Risk Management Program (PGR) [4]. Internationally, ISO 45003:2021 offers guidelines for managing psychosocial risks, including prevention, intervention, and rehabilitation [5].

ILO estimates indicate that 1 in 5 workers worldwide (23%) have experienced violence or harassment at work, though underreporting remains high [6]. In Brazil, data from the Occupational Health and Safety Observatory show that between 2019 and 2024, mental and behavioral disorders ranked third among causes of both occupational and non-occupational leave. For occupational origin (B91), these accounted for 6.17%, and for

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non-occupational origin (B31), 12.5%. Combined (B91+B31), benefits granted due to mental health conditions more than doubled, from 224,647 in 2019 to 471,649 in 2024. The main causes were anxiety disorders, severe stress reactions, adjustment disorders, and depressive episodes. According to the Brazilian Classification of Occupations (CBO), the occupation most affected by non-occupational mental health leave (B31) was “production line feeder,” representing 3.16% of cases (48,530 leave requests) [7].

In response, innovative technologies such as virtual reality (VR) and augmented reality (AR) have been used in immersive training to address harassment, neglect, and hierarchical pressure, fostering socioemotional skills like empathy, self control, and ethical decision-making [8–10]. Eye tracking and biometric sensors, including heart rate variability (HRV) and galvanic skin response (GSR), enable real-time assessment of stress, attention, and emotional discomfort [11,12].

Industry 4.0 has further integrated these technologies into production, allowing the collection and analysis of physiological and behavioral data for preventive, personalized interventions [13]. With rising mental health concerns, these tools also facilitate early detection of psychological distress and promote inclusive, evidence-based practices [14]. However, there is still limited research combining VR, AR, eye tracking, biometric sensors, and biofeedback for psychosocial risk mitigation within regulatory frameworks.

This study aims to provide evidence-based guidance for Occupational Health and Safety by synthesizing consolidated evidence on how immersive and biometric technologies can be implemented to prevent and mitigate psychosocial risks in industrial environments.

## Materials and Methods

This study is exploratory in nature, as investigations into the combined use of immersive and biometric technologies in the management of

psychosocial risks in the workplace still represent an emerging and constantly evolving field. Therefore, a qualitative approach was chosen, which is suitable for studies in underexplored areas that require in-depth interpretative analysis [15].

In order to consolidate existing knowledge in the scientific literature, an umbrella review was conducted with the following objectives: (i) to identify studies addressing the application of technologies such as virtual reality, augmented reality, biometric sensors, and eye tracking in organizational contexts; (ii) to analyze the evidence regarding the effectiveness of these technologies in preventing and mitigating psychosocial risks in industrial environments; (iii) to verify the alignment of these interventions with the guidelines of NR-01 and ISO 45003 standards; and (iv) to propose recommendations for the development of technological solutions aimed at promoting mental health in the workplace.

To ensure transparency, methodological rigor, and reproducibility, the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was adopted [16]. The review followed established methodological guidelines and structured the process into four main stages: planning, search, analysis of the evidence base, and synthesis of results. The following subsections describe each step adopted in this study.

### Planning

The planning stage involved defining the thematic scope of the research and selecting relevant scientific databases to ensure the breadth and quality of the sources consulted. The search was conducted in the Scopus, PubMed, and Web of Science databases, chosen for their broad international coverage, peer-reviewed content, and strong citation metrics, making them suitable for systematic reviews in interdisciplinary fields [17]. Google Scholar was used as a complementary source to broaden the identification of relevant studies and track cited references. The focus was

on identifying secondary studies investigating the application of immersive and biometric technologies in mitigating psychosocial risks in occupational settings. The methodological protocol was prepared in advance and submitted for review by experts in the fields of virtual reality, workplace mental health, and systematic review, ensuring conceptual alignment and scientific rigor.

### Literature Search

A comprehensive search was conducted using a structured search string aligned with the research question, targeting the databases identified during the planning phase [17]. The following descriptors and Boolean combinations were used: ("realidade virtual" OR "virtual reality") AND ("realidade aumentada" OR "augmented reality") AND ("rastreamento ocular" OR "eye tracking") AND ("sensores biométricos" OR "biometric sensors") AND ("riscos psicossociais" OR "psychosocial risks") AND ("revisão sistemática" OR "systematic review") AND "biofeedback". Only peer reviewed articles published between 2019 and 2024 were considered. For methodological and theoretical grounding, additional relevant sources were also included regardless of publication year. The results were exported to spreadsheets, where records were organized and initially screened.

### Evidence Base Assessment

In this stage, the previously defined eligibility criteria were applied. Included were systematic reviews or meta-analyses that presented interventions based on VR, AR, biometric sensors, or eye tracking, provided they were applied in occupational contexts focused on mental health or psychosocial risks. Excluded were narrative reviews, conceptual or exploratory studies, and articles that did not directly address the context of workplace mental health.

Initially, 312 records were identified. After removing 87 duplicates, 225 articles remained

for title and abstract screening. In this stage, 183 records were excluded for not meeting the eligibility criteria. The remaining 42 articles were read in full, resulting in the inclusion of 10 systematic reviews, 2 national regulatory standards (NR-01 and NR-05), and 1 international standard (ISO 45003). To enrich the scientific evidence base of this review, additional secondary sources were included, such as specialized book chapters and recognized institutional platforms. Specific book chapters were used to deepen the methodological approach related to the integration of biofeedback with immersive technologies, biosensors, and user perception. Furthermore, statistical data and indicators were obtained from official and updated sources, including the Occupational Health and Safety Observatory of the SmartLab MPT-ILO platform, as well as reports from the International Labour Organization (ILO) and the World Health Organization (WHO). The use of these sources aims to enrich the understanding of psychosocial risks by aligning empirical data with the theoretical analysis presented in this study.

### Synthesis and Analysis of Results

The results were organized in a spreadsheet containing the following information: author/year, type of technology used (VR, AR, biometric sensors, eye tracking), psychosocial topic addressed, application sector, type of review (narrative or meta-analysis), and main findings. The information was systematized into thematic categories to facilitate qualitative analysis of patterns, gaps, and recommendations found in the selected reviews.

### **Results and Discussion**

This section presents the main findings of the umbrella review, emphasizing their implications for practical implementation in industrial Occupational Health and Safety contexts. The results are discussed based on evidence extracted from the systematic reviews analyzed, with a focus

on the practical application of these tools across different industrial sectors, the psychosocial variables investigated, the methodologies adopted, and the challenges associated with their implementation.

### Immersive and Biometric Technologies: State of the Art and Applications

Virtual reality remains the most prominent technology, widely used in immersive training to simulate complex situations, foster empathy, and address sensitive ethical issues [8,9,18]. Augmented reality is often employed to reinforce training and safety regulations, including in on site environments [10,18]. Biometric devices such as HRV and GSR use biofeedback techniques to monitor stress levels in real time, while eye tracking helps identify behavioral patterns related to attention and emotional shifts [11,12].

The combined use of biofeedback with these technologies enables objective evaluation of the user's experience in immersive environments. In addition to measuring stress levels, engagement, emotional discomfort, and fatigue during training and simulations, these devices provide additional parameters for validating scenario effectiveness and tailoring interventions. For example, visual avoidance behaviors detected through eye tracking may be associated with greater personal discomfort, suggesting their potential as early indicators of emotional distress. Integrating this information into analytical platforms allows for individualized interventions and reports that anticipate trends, supporting decision-making in Occupational Health and Safety (OHS) and Human Resources Management [19].

### Psychosocial Focus, Evaluated Variables, and Application Contexts

The main variables investigated included harassment perception, empathy, workplace stress, emotional self-regulation, anxiety, burnout, and attentional deviation. These technologies

enabled objective and personalized assessment and intervention on these factors [8–11, 18].

Although most studies focused on clinical and educational settings, there has been growing research in industrial environments such as logistics, continuous manufacturing, and heavy engineering [10,18]. Case studies in the automotive and construction industries indicate reduced anxiety, improved communication, and greater adherence to safety protocols after immersive training.

### Methodological Synthesis of Systematic Reviews

The reviews included provided narrative summaries or quantitative meta-analyses using validated psychometric scales and PRISMA guidelines. Main challenges were the lack of long term data, limited sample diversity, and replication difficulties across industrial sectors. Methodological differences among reviews hinder result comparisons. Some applied the AMSTAR 2 checklist for rigor, while others did not clearly state inclusion and exclusion criteria.

There is a growing number of interdisciplinary reviews combining occupational health and behavioral sciences, highlighting the complexity of psychosocial risks and the need for integrated solutions.

### Challenges and Perspectives on Technology Adoption

The use of immersive and biometric technologies to prevent psychosocial risks in industry is growing despite ongoing obstacles. VR and AR effectively promote empathy, emotional intelligence, and address workplace harassment and stress, enabling safe exposure to adverse situations and ethical reflection.

Biometric sensors (HRV, GSR, respiratory monitoring, eye tracking) offer precise emotional and fatigue monitoring, supporting evidence based interventions aligned with standards like NR-01 and ISO 45003.

Challenges include high costs, infrastructure needs, training, and integration with OHS systems requiring standardized solutions. Ethical concerns over data privacy, consent, and security also affect acceptance.

Longitudinal studies are lacking, limiting generalization, and methodological issues like sensor calibration and data privacy need resolution to standardize biofeedback in OHS.

Cultural resistance and fears of surveillance persist, but transparent communication and employee involvement foster trust and innovation. Ethics committees and dialogue forums help align practices with local contexts.

Despite difficulties, VR, AR, biometric sensors, and biofeedback trends point to personalized, data-driven psychosocial risk management.

Collaboration among science, technology, management, and policy, with partnerships and research investment, is vital to prioritize workplace mental health responsibly.

Table 1 provides a practical mapping between immersive and biometric technologies, specific psychosocial risks, measurable indicators, and outcomes for decision-making in Occupational Health and Safety (OHS) and Human Resources

(HR), translating the analyzed evidence into practical guidance for industry stakeholders. This mapping aligns technological applications with the regulatory requirements of NR-01 and ISO 45003 standards, facilitating implementation in industrial environments.

Minimum viable pilot project in an industrial context (6 to 8 weeks):

- Establish the priority psychosocial risk based on the PGR (NR-01).
- Choose the type of situation (harassment, pressure, conflict, high-demand task).
- Select the degree of monitoring (none → wearable → wearable + eye tracking).
- Ensure informed consent and data governance (privacy, access and retention).
- Use baseline and post-intervention metrics (a validated scale + an objective indicator).
- Establish the decision standard for intervention or referral.
- Communicate the results to the OHS committee and the CIPA.

From a regulatory perspective, the incorporation of immersive and biometric technologies directly

**Table 1.** Actionable mapping: Technology → Psychosocial risk goal → Measurement → OHS/HR decision.

Technology	Psychosocial Risk Target	Practical Metric	Output for OHS / HR	Regulatory Alignment
VR / AR immersive scenarios	Harassment prevention, ethical conflict, empathy	Scenario performance, validated self-report scales	Targeted training, behavioral feedback	NR-01 (risk identification), ISO 45003 (prevention)
HRV / GSR (biofeedback)	Stress, anxiety, emotional overload	HRV indices, EDA peaks	Early risk flagging, referral criteria	NR-01 (risk monitoring)
Eye tracking	Emotional discomfort, attentional avoidance	Gaze fixation, avoidance patterns	Training adaptation, scenario redesign	ISO 45003 (work design)
Integrated biofeedback platforms	Burnout, emotional dysregulation	Physiological trends across sessions	Personalized intervention plans	NR-01 + ISO 45003

facilitates the workflow established by NR-01, especially in the phases of identification, assessment, and control of psychosocial risks within the Risk Management Program (PGR). Simulated scenarios and biometric monitoring assist in the proactive identification of risks, while interventions based on biofeedback favor constant monitoring and prevention. At the same time, ISO 45003 highlights a cyclical approach to the management of psychosocial risks, encompassing job design, leadership practices, and employee engagement. The technological applications synthesized in this review are in line with these guidelines, allowing for evidence-based interventions, constant feedback, and organizational learning, as demonstrated in the mapping presented in Table 1.

From an industrial implementation perspective, pilot programs using these technologies can track practical key performance indicators (KPIs) such as: (i) a decrease in reported psychosocial incidents or an improvement in the quality of reports; (ii) changes in scores on validated stress or burnout scales before and after the intervention; (iii) training completion rates associated with behavioral indicators observed during the scenarios; and (iv) physiological patterns that signal reduced stress reactivity in repeated sessions.

The adoption of immersive and biometric technologies in the workplace still depends on ethical considerations. To ensure that physiological and behavioral data is collected solely to promote health and prevent risks, it is essential to adopt principles such as data minimization and purpose limitation. To preserve trust, transparent governance, restricted access, and well-defined data retention policies are fundamental. Furthermore, employee participation in scenario creation and the provision of clear feedback reports on collective results can reduce feelings of monitoring and encourage the acceptance of these technologies as supportive rather than punitive tools.

## Conclusion

This umbrella review provides evidence-based guidance showing that integrating immersive

technologies (VR, AR) with biometric sensors and eye tracking offers promising solutions to prevent psychosocial risks in industrial workplaces. Recent studies highlight their role in identifying, assessing, and intervening in harassment, stress, anxiety, and burnout, promoting healthier and more inclusive work environments [9,18,20].

VR and AR training simulate critical situations and develop socio-emotional skills like empathy and ethical decision-making in safe settings. Biometric sensors and eye tracking provide real time, objective data on workers' emotional states, enabling early psychological distress detection and personalized interventions [8,10,11].

Challenges for wide adoption include costs, infrastructure, training, data privacy, and adapting solutions to diverse industrial and cultural contexts. Longitudinal studies and real-world protocol validations are lacking, especially in developing countries [18,20].

These technologies align with NR-01 and ISO 45003 standards, supporting occupational health and safety and fostering organizational cultures open to mental health dialogue. Expected benefits include reduced harassment, improved well being and productivity, and enhanced data-driven decision-making [18,20].

Recommendations include investing in applied research, longitudinal monitoring, standardizing protocols for VR, AR, biometric and eye tracking tools, ongoing professional training, and adapting to laws and organizational policies. Public policies should encourage pilot projects and partnerships among academia, industry, and regulators for ethical and technical viability.

Biofeedback combining biometric sensors and eye tracking advances objective user experience assessment, measuring stress and engagement in real time for personalized interventions. Methodological challenges remain, such as sensor calibration, privacy, consent, and industrial context adaptation to establish biofeedback in OHS and psychosocial risk prevention [19].

In summary, these technologies meet regulatory demands and can transform organizational culture,

creating safer, healthier, and more innovative workplaces benefiting employees, companies, and society.

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## Integration of Industry 4.0 Technologies in Environmental Sanitation: A Systematic Review

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Environmental sanitation faces challenges arising from uncontrolled urban growth, increased pollution, inadequate monitoring methods, increased demand for clean water, insufficient sewage treatment capacity, and lack of maintenance on aging systems. Industry 4.0, through technological innovations such as the Internet of Things (IoT), microcontrollers, and sensors, seeks to solve problems related to sewage management, given the increased demand for water resources and the poor performance of existing treatment plants. Therefore, this study aims to explore the scientific literature on the application of Industry 4.0 principles in the context of sanitation, with a specific focus on optimizing sewage network monitoring through IoT and technologies aimed at automation and process improvement. To this end, a string search strategy was adopted to select articles related to the topic. Initially, a set of approximately seventy articles was analyzed based on keywords, of which thirty-seven presented contents aligned with the proposed application of Industry 4.0 in environmental sanitation. After detailed analysis, ten articles were selected as the basis for this study. Thus, the article seeks to propose solutions, using emerging technologies, to address the shortcomings still present in the urban sanitation sector. Through this, it aims to reduce damage to infrastructure and public health, optimize operational costs, improve the efficiency of treatment plants, and enhance water infrastructure management with artificial intelligence. **Keywords:** Industry 4.0. Environmental Sanitation. Internet of Things (IoT). Sewage Network Monitoring. Process Automation.

Water is an extremely important resource for life and socioeconomic development, serving as a source for irrigation, industry, and human and animal consumption [1]. However, population growth and increasing demand raise concerns about limited resources and water scarcity [2]. Among the Sustainable Development Goals (SDGs), SDG 6 advocates for universal access to water and sanitation, with targets to manage water resources, improve water quality, and reduce untreated water.

According to Chavhan and colleagues [1] and Alprol and colleagues [3], several basins face water shortages due to pollution, intensified by agricultural expansion, industrialization, and rampant urbanization. According to the World Health Organization (WHO) in 2021, globally,

269 billion m<sup>3</sup> of sewage are generated per year and only 53% are correctly treated [2]. Thus, 47% of the effluents do not undergo adequate treatment when released into the environment.

This contamination impacts public health, agriculture, ecosystems, and socioeconomic aspects [1].

Environmental sanitation is essential for public health, water resource preservation, and ecosystem balance. However, traditional water and wastewater management methods, based on conventional processes, are proving insufficient in the face of population growth, rapid urbanization, and climate change [6]. In this scenario, integrating Industry 4.0 with environmental sanitation emerges as an alternative to making the sector more efficient, resilient, and sustainable.

Industry 4.0, with technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, blockchain, and advanced manufacturing, is redefining management practices, including sewage treatment and monitoring. An example of this application is the use of IoT-based effluent monitoring systems and sensors, where real-time

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data tracking provides significant improvements in the management and performance of treatment plants, reducing losses and making the process safer and more efficient.

The implementation of sensors and predictive modeling based on data analysis enable a more precise and adaptive approach to water quality control and treatment plant operations, enabling rapid action to mitigate environmental damage and reduce operating costs.

Thus, this paper considers that the Fourth Industrial Revolution, associated with sanitation, is likely to transform the sector through new technologies, contributing to achieving SDG 6 by expanding access to safe water, reducing water pollution, and increasing the effectiveness of treatment systems [2]. In this context, an analysis was carried out on how Industry 4.0 can optimize sewage network monitoring and effluent treatment. To this end, we conducted a systematic literature review, gathering approximately ten studies that exemplify real-world applications of Fourth Industrial Revolution technologies in the sector, mapping the sensors and digital platforms used.

## Materials and Methods

This study is characterized as qualitative research, with a descriptive approach, with the main objective of analyzing and synthesizing advances in the application of Industry 4.0 technologies in environmental sanitation.

This research began with the adoption of the scientific String search strategy for articles to be analyzed. The String search strategy was used in the Scopus database, combining keywords to identify recent and relevant articles on Industry 4.0 in sanitation. Table 1 presents the keyword combinations used, and the number of articles found.

The search was limited to open publications published in the last five years (2019-2024) to ensure the most recent research incorporating Industry 4.0 technologies and studies into environmental sanitation and presenting empirical

**Table 1.** Combination of keywords for article selection.

Keyword Combinations	Number of Articles
Sewer AND system AND control	3
Remote sensing in wastewater systems	5
Predictive analytics in wastewater networks	3
IoT sensors in sewer systems	4
Smart AND sewer AND systems AND iot	2
Sewer AND systems AND IoT	6
"Smart sewer systems"	2
"Smart manufacturing" AND "Wastewater treatment"	1
"Efficiency improvement" AND "Sewer systems"	1
"Smart manufacturing" AND "Wastewater treatment"	1
"Sensor network" AND "Wastewater treatment"	2
"IOT" AND "Wastewater treatment"	7

results and technical analyses or models applicable to the environmental sanitation sector. The articles found were subsequently organized into a database for subsequent analysis.

In the initial selection phase, approximately seventy articles were identified based on relevant keywords, encompassing the application of Industry 4.0 both in water treatment and in wastewater treatment plants. Following a thorough review and the refinement of the central themes, thirty-seven articles were retained, specifically addressing the implementation of emerging technologies in wastewater treatment. Ultimately, after comprehensive analysis and research on the

subject, ten articles were highlighted for their strong alignment with the objectives of this study, as they presented real-world applications, pilot projects, simulations, or practical models involving the use of Fourth Industrial Revolution technologies for the treatment, analysis, management, and monitoring of sewage networks.

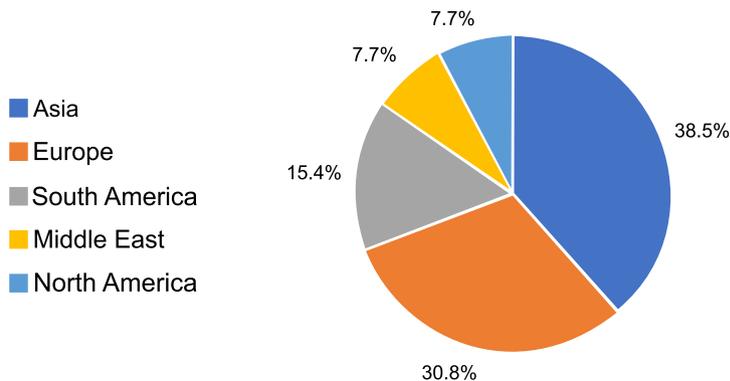
**Results and Discussion**

Based on the research carried out, it was observed that most applications and studies are developed in Asia and Europe, with countries such as China, India and Germany standing out, which lead initiatives aimed at modernizing sanitation based on innovative technological solutions (Figure 1) [1,4].

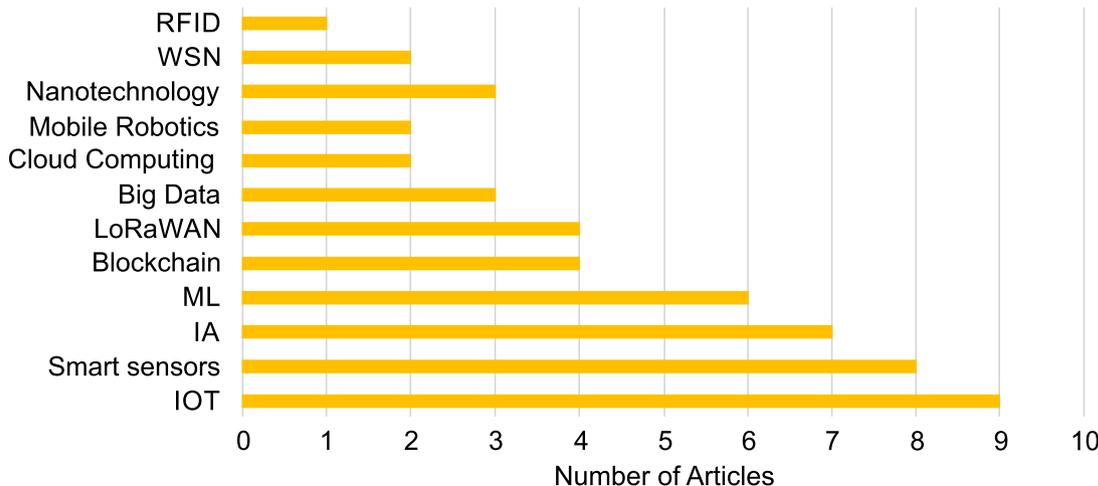
Technological advances presented in the studies include the Internet of Things (IoT) for data collection and transmission, the use of multiparametric sensors (level, pH, turbidity, dissolved oxygen), and the application of Artificial Intelligence (AI) alongside Machine Learning (ML) for predictive analysis and automated decision-making [3,5]. Figure 2 shows the technologies presented and the number of articles that provide this information.

Sensors play a fundamental role in the sewage monitoring systems analyzed, as they are essential components of the Internet of Things (IoT), capable of collecting data and detecting system problems, in addition to capturing information. Some models are being tested to detect manholes and pipe blockages, and to operate with lower energy consumption [4,6].

**Figure 1.** Geographical distribution of studies on sanitation and Industry 4.0.



**Figure 2.** Frequency of Industry 4.0 technologies in articles.



IoT transforms real-time data monitoring and efficient wastewater management by connecting sensors, controllers, and cloud platforms [1]. Wireless communication technologies are essential, enabling the transmission of sensor data to servers or cloud platforms. LoRaWAN is also used in this process, standing out for its long range and low power consumption, ideal for remote areas and challenging environments [6].

Some specific sewage treatments, such as membrane bioreactors (MBRs), which offer high efficiency, permeate quality, and compaction, in addition to occupying a reduced area, have been integrated with the IoT, enabling dynamic monitoring and stable and efficient operation [2]. Another treatment used is nanocomposite membranes (NFM), which have greater porosity to water and solute rejection compared to TFC membranes, and whose manufacturing can be optimized with Artificial Intelligence and Industry 4.0 [8].

Case studies with the APAH, HADA, and SPUDD systems demonstrate the effectiveness of emerging technologies in environmental sanitation, as they use sensors, AI, and low-energy networks to monitor sewage systems in real time and perform automated interventions in critical situations. Chavhan and colleagues [1] point to improvements in the performance of treatment plants, with reduced losses, increased safety, better use of natural resources, and process stabilization. Drenoyanis and colleagues [5] highlighted that radar sensors integrated with LoRaWAN networks for monitoring pumping stations generated operational and economic gains, in addition to reducing maintenance costs by replacing manual inspections with remote monitoring, increasing safety by avoiding interventions in unhealthy environments.

Another example is the implementation, in Malang (Indonesia), of an effluent monitoring system in a WWTP, using sensors to measure pH, temperature, turbidity and dissolved oxygen, allowing data storage and real-time operation [1]. Utepov and colleagues [7] presented a system to

detect opening of manholes, critical liquid levels and siltation, with successful integration to prevent flooding, sewage accumulation, lid thefts and obstructions.

Table 2 shows a relationship between the applied technologies and their contributions to sanitation for each author of the articles selected for this systematic review, as well as the objectives of the studies. Through this table, it is possible to identify the most studied applications by the authors and what can be optimized and added in relation to environmental sanitation. An example of this is the Internet of Things, where nine out of ten studies present applications using this technology for the improvement, automation of processes, and early detection of problems that may occur in sewage networks.

These cases reinforce the viability of smarter and more sustainable sewage management models, improving early detection of problems such as blockages, leaks, and contamination. Anticipating these failures prevents environmental damage by preventing waste from reaching water bodies, preserving water quality [4] and supporting SDG 6, which promotes the efficient management and proper treatment of wastewater [2].

## Conclusion

Based on the analysis of the selected articles, it was possible to conclude that technologies associated with Industry 4.0, such as the Internet of Things (IoT), smart sensors, and Artificial Intelligence (AI), have great potential to transform the environmental sanitation sector. The main contribution of these technologies lies in the possibility of continuous, automated, and efficient monitoring of sewage networks. In this context, IoT allows real-time monitoring of the network operation, faster failure identification, and proactive action. AI and Machine Learning (ML)-based systems enable the analysis of large volumes of data, failure prediction, and the optimization of operational processes, contributing to cost reduction and increased environmental safety.

**Table 2.** Data obtained from the literature review regarding Industry 4.0 and ICT technologies applied to environmental sanitation.

<b>Authors (Year)</b>	<b>Applied ICTs</b>	<b>Contributions to Sanitation</b>
Alprol and colleagues (2024)	IoT, AI, ML, sensors and cloud computing	Real-time monitoring, process optimization and automation, quality prediction and modeling, early problem detection, increased efficiency and cost reduction.
Alzahrani and colleagues (2023)	IoT, wireless sensor network, blockchain, anomaly detection algorithms, GPS- based remote sensing and simulation analysis.	Improved management, extraction of refinements and pollutants, real- time monitoring, anomaly detection and cost reduction
Chavhan and colleagues (2025)	IOT, ML, Multiparametric Sensors, Cloud Platform and Android Mobile App	Real-time monitoring of treatment processes, contamination prevention, automatic valve control, real-time alerts and post- treatment water quality improvements.
Drenoyanis and colleagues (2019)	IoT, radar sensors, Low Power Wide Area Networks (LPWAN), microcontrollers, mobile applications and cloud platforms.	Early detection of network problems, prevention and reduction of sewage overflow, improvement of operational efficiency and cost reduction
Makowska and colleagues (2024)	Structural and existing equipment modernization.	Increased capacity of WWTPs and the introduction of modern, more efficient treatment equipment
Saadatinavaz and colleagues (2024)	Specific treatment technologies and collection and transportation systems.	Modular DWTS designs for water reuse, quantitative CAPEX/OPEX assessments for sewer networks, and facilitates decision-making to achieve a comprehensive sanitation network.
Solano and colleagues (2022)	IOT, wireless sensor and actuator network, multi-parameter sensors, distributed real- time anomaly detection and localization (HADA) algorithm, source determination algorithms, simulation software and tracking robot.	Real-time monitoring, location of illegal industrial discharges and monitoring within main sewer lines.
Utepov and colleagues (2023a)	Sensors, multifunctional device, wireless interfaces (WI-FI, LoRAWAN) and microcontrollers	Efficient management of sewage systems, real-time monitoring, automatic detection of manhole openings and critical liquid and siltation levels, cost optimization and alerts for overflow, clogging and vandalism.
Utepov and colleagues (2023b)	IOT, sensors, wireless technologies (LoRaWAN - SX1278, WiFi --ESP8266, GSM/GPRS -SIM800L), data collection station, wireless sensor device and algorithm for sewage problem detection integrated with GIS.	Real-time, low- cost monitoring, early detection, rapid response, automated corrective actions, alerts and notifications, and improved operational efficiency and cost reduction.
Uwamungu and colleagues (2022)	Cyber-physical models, IoT, AI, Big Data analytics, ML, Deep Learning, Artificial Neural Networks (ANNs), Nanocomposites	Innovative treatment technologies, effective pollutant removal processes, AI/ML- powered performance optimization and prediction, cost reduction, and operational efficiency.

Thus, the present study brings several analyses regarding the implementation of Industry 4.0 for environmental sanitation and its benefits. However, there is still a need for the creation and adaptation of standards and public policies that promote the standardization of monitoring systems, ensuring the security, expansion, and integration of the proposed solutions

In addition, it is possible to carry out a monitoring prototype in Brazil in regions that still do not have access to effluent collection and treatment and thus develop a network and sewage treatment plants together with new technologies so that it is possible to analyze the implementation stages and the benefits of the technologies in the process and ensure safety, efficiency, and improvement of the population's quality of life.

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## Green Hydrogen (H<sub>2</sub>V) Logistics in Brazil: Comparison of Modals and Environmental Impacts

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Cargo transport in Brazil is composed of road, rail, waterway, pipeline and air modes. The road modal stands out, representing about 64.8% of the total cargo transported in the country, according to data from the National Transport Confederation (CNT) in 2023. The rail modal configures 14.9%, while other modes, such as waterway, correspond to smaller portions, with cabotage and waterways, adding up to 12%. In the transport of dangerous products, the choice of the most appropriate modal must consider not only technical and safety aspects but also costs and environmental impacts. Green hydrogen (which is characterized as a dangerous product) has been consolidated as an essential element in the global energy transition. Ensuring its economic viability in Brazil requires optimization in transportation methods. Although the road modal is predominant in the transport chain of dangerous products, the other modes, such as rail, pipeline and waterway, can contribute significantly to the chain, reflecting even more relevance due to their greater efficiency, safety and contribution to the reduction of environmental impacts. To enable the use of the various modes available, it is essential to invest in infrastructure, such as the expansion of road and rail networks, retrofit or construction of new pipelines, as well as the modernization of ports and waterways. These investments are essential to improve efficiency, increase safety and enhance the contribution of these modes in reducing environmental impacts, offering more sustainable alternatives in a context of a low-carbon economy. This article proposes a detailed comparison of the modes for transporting green hydrogen. The advantages, limitations and environmental impact of each modal were analyzed. Qualitative research was used as a methodology, based on bibliographic research and observations. The article aims to contribute to the analysis of the most appropriate mode of transport for the transport of green hydrogen, in terms of sustainability and efficiency, comparing the operating scenarios (involving costs, infrastructure, among others), in order to identify viable solutions that meet the economic, environmental and technological demands for the global energy transition.

**Keywords:** Modes of Transport. Green Hydrogen. Renewable Energies. Decarbonization. Sustainability.

Brazil, one of the largest producers of renewable energy in the world, stands out on the global stage for its capacity to produce green hydrogen, a clean and sustainable alternative for the energy transition. Green hydrogen is produced from renewable sources, such as solar and wind energy, and its use is seen as a crucial solution for the decarbonization of sectors such as transportation, industry, and energy [1]. However, one of the biggest challenges that Brazil faces is the safe and efficient transportation of this product, especially due to its nature as a dangerous product [2].

The logistics of green hydrogen depends on the choice of the most appropriate mode of transport, considering factors such as safety, cost, efficiency and, above all, environmental impacts. The efficiency of the green hydrogen logistics chain is essential not only to ensure the economic viability of the product, but also to ensure that it actually contributes to the reduction of carbon emissions in Brazil [3].

### Theoretical Framework

#### The Overview of Transport Modes in Brazil

Logistics in Brazil is predominantly centered on the road modal. According to the National Transport Confederation [4], the road modal represents 64.8% of all cargo transported in the country. This high participation is a result of the flexibility and extensive network of highways,

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which allows access to almost all Brazilian municipalities [4].

However, the road model, despite its high participation, presents challenges in terms of cost and environmental impact. Road transport is more expensive compared to other modes, such as rail and waterway, and contributes significantly to greenhouse gas emissions [5].

In addition to road, other modes also play important roles. Rail transport, for example, has proven to be efficient for high-volume cargo and long distances [6]. The waterway modal, which includes cabotage and waterways, also offers advantages in terms of cost and energy efficiency for heavy and bulky loads [7]. Pipeline transport, in turn, has proven to be safe and efficient for the transport of liquids and gases, such as hydrogen, but still faces structural challenges in Brazil [8].

The air modal is recognized for its speed and global reach, being ideal for high value-added, time-sensitive cargo or destined for remote locations. Representing 35% of the value of world trade, despite carrying less than 1% of the total cargo volume, it is essential to meet modern demands of markets that demand efficiency and safety. It is especially strategic in the transport of perishable products, preserving their quality, and dangerous products, where strict protocols are required. The air transport of dangerous products goods is strictly controlled by international bodies, such as IATA, which sets safety standards through the Dangerous Goods Regulations (DGR) [9].

Despite the high costs, it stands out as an efficient solution for specific loads.

### Green Hydrogen and Logistical Challenges Green

Green hydrogen is a light and highly volatile molecule, which requires special care in its storage and transportation. As a dangerous product, its transport must comply with strict safety standards to avoid leaks or explosions. To ensure the safety and efficiency of transport, it is necessary to choose the most appropriate mode of transport [2,10].

Hydrogen storage presents several key challenges:

**Energy Density:** Hydrogen has a low energy density, which means it needs to be compressed or liquefied in order to be stored efficiently. This requires specialized equipment and consumes a lot of energy.

**Extreme Conditions:** To store liquid hydrogen, it is necessary to keep it at extremely low temperatures (about  $-253^{\circ}\text{C}$ ). For gaseous storage, it needs to be compressed to high pressures (usually between 350 and 700 bar). Both methods are technically complex and expensive.

**Safety:** Hydrogen is highly flammable and can form explosive mixtures with air, requiring stringent safety measures during storage and transportation.

**Infrastructure:** The current infrastructure for hydrogen storage and transportation is still limited and requires significant investments to scale, including the construction of specialized storage tanks and the adaptation of distribution networks.

These challenges need to be overcome if hydrogen is to become a viable and widely used alternative in the transition to a low-carbon economy. However, it can be transported by different modes, which will depend on the available infrastructure and logistical needs. However, each of these modes has advantages and limitations that need to be carefully analyzed.

### Road

Road transport, despite being the most used in Brazil, has disadvantages in terms of  $\text{CO}_2$  emissions and high costs. In the transport of green hydrogen, specialized tanker trucks would be needed, which further raises costs [3]. In addition, Brazilian roads are not always suitable for transporting dangerous cargo, which poses an additional risk [11].

## Rail

The rail modal offers advantages in terms of cost per ton transported, especially for long distances. Rail transport is also more energy-efficient when compared to road transport, resulting in lower CO<sub>2</sub> emissions [6]. However, the railway infrastructure in Brazil is still insufficient, which limits the use of this modal for the transport of hydrogen on a large scale.

## Waterway

Waterway transport, including cabotage and waterways, offers excellent value for money, especially for heavy and bulky loads. Brazil has an extensive network of waterways and ports that could be better used for the transport of green hydrogen, especially in the North and Southeast regions [7]. However, existing waterways need to be modernized and expanded to ensure transportation safety and efficiency.

## Pipeline

The pipeline modal is particularly suitable for the transport of liquid and gaseous products, such as hydrogen. However, Brazil still lacks an efficient pipeline network for the transport of this type of cargo [8]. Construction or retrofit of existing pipelines would be necessary to enable the safe and large-scale transportation of green hydrogen.

The current infrastructure presents significant challenges to enable the safe and efficient transportation of this fuel, due to technical limitations, such as the fragility of the metallic materials of the pipelines and the high permeability of hydrogen [8,12].

One of the main issues is hydrogen embrittlement, which occurs due to hydrogen's ability to penetrate the microstructure of steel used in pipelines. This phenomenon reduces the mechanical strength and durability of the material, increasing the risk of cracks and catastrophic failures over time.

In addition, hydrogen has a higher leakage capacity due to its extremely small molecule, which can lead to significant losses and pose safety risks, such as explosions, if proper adaptations are not implemented.

Another challenge is the need to operate under higher pressures to transport hydrogen in a gaseous state, which requires structural reinforcement in the pipelines. The gaskets, valves and other components would also need to be updated to meet the technical specifications of this new use.

## Aerial

Although air transport is the fastest, it is the most expensive and is usually used only for high value-added cargo. In the case of hydrogen, air transport is not a viable option due to high costs and low cargo volume [1].

In the specific case of hydrogen, air transport is not feasible due to two main factors: the high operating cost and the low volumetric density of hydrogen. Hydrogen, when transported in its liquid or compressed form, has a considerable volume in relation to its mass, which requires aircraft with a large load capacity for transport to be minimally efficient. However, due to the limitation of space and the high cost of operating aircraft, the volume of cargo transported of hydrogen would be small compared to the cost, making the operation economically unfeasible [1]. In addition, the lack of adequate infrastructure for the storage and safe handling of hydrogen at airports also contributes to the unfeasibility of this modal for this type of cargo.

## The Energy Transition and Infrastructure Challenges

Brazil's energy transition requires the implementation of a modern and integrated infrastructure that supports the growth of the green hydrogen market. The expansion of road and rail networks, the construction of new pipelines, and the modernization of ports and waterways are essential to ensure logistical efficiency and minimize environmental impacts [3].

Significant investments are needed to overcome the current structural limitations and create a logistics network that meets the needs of the green hydrogen market. Modernizing ports, for example, could facilitate the export of green hydrogen to other countries, while building dedicated hydrogen pipelines would reduce costs and improve transport safety.

## Materials and Methods

An exploratory study was conducted to evaluate transportation modes, adopting qualitative methods to characterize the different transportation modes and their current status regarding various factors important for H2V transportation. The study encompassed several stages developed between August 2024 and June 2025, with an exploratory–descriptive used to support the study with a review of the existing literature on the transport of green hydrogen. This involved analyzing academic articles, books, technical reports, and other relevant publications. The objective was to identify theories, models, and previously collected data on the subject, which helped to build a solid basis for understanding the subject [13]. A qualitative approach was also used, together with the bibliographic research, which guided us in the analysis of case studies and observations of global trends in hydrogen logistics [3]. The research sought to compare transport modes in terms of efficiency, safety, costs, and environmental impacts [14].

## Results and Discussion

The choice of the most suitable modal for transporting green hydrogen depends on several factors, including costs, safety, available infrastructure, and environmental impacts. Table 1 summarizes the main characteristics of each modal.

### Environmental Impacts and Sustainability

The transition to more sustainable modes of transport is essential for reducing greenhouse

**Table 1.** Main characteristics of each modal.

Modal	Advantages	Limitations
Road	Flexibility, capillarity (*)	High cost, high CO <sub>2</sub> emission
Rail	Lower cost per ton, energy efficiency	Insufficient infrastructure
Waterway	Cost-effective in large volumes, efficient for export	Insufficient infrastructure, need for modernization
Pipeline	Safety, efficiency for liquids and gases	Limited infrastructure, high upfront costs
Aerial	Speed, ideal for high-value loads	High cost, low volume, operational safety

(\*) A physical phenomenon that occurs when a liquid rises or falls in a very thin tube (capillary) due to the interaction between the molecules of the liquid and the surfaces of the material that forms the tube.

gas (GHG) emissions, one of the main causes of climate change. The adoption of clean and efficient alternatives contributes directly to the decarbonization of the planet. According to Carvalho (2020) [5], this change has a direct impact on the reduction of emissions in the transport sector, which is one of the largest global emitters.

The use of efficient and clean infrastructure helps to reduce dependence on fossil fuels and mitigate CO<sub>2</sub> emissions.

Modernizing the logistics infrastructure is key to promoting a more sustainable transportation system. This not only reduces GHG emissions but also facilitates the integration of cleaner technologies, such as electric vehicles and biofuels, which have a lower environmental impact compared to traditional fuels [1]. As Santos (2019) [15] emphasizes, Brazil must ensure that its logistics infrastructures evolve to meet global standards and contribute to a low-carbon economy.

Brazil, by assuming global climate commitments, has the responsibility to implement public policies that encourage the use of these modes and the modernization of logistics infrastructure. This will contribute not only to the reduction of CO<sub>2</sub> emissions, but also to the creation of a more resilient transport system, capable of facing the challenges of climate change and meeting the demand for sustainability in transport [5].

However, the transition faces challenges, such as the high costs of investing in modernization and the adoption of new technologies. The resistance of traditional sectors, such as road transport and the use of fossil fuels, is also an obstacle, in addition to the need for training professionals and the implementation of effective public policies to promote decarbonization [16]. Finally, rail, waterway, and pipeline modes, when compared to road, show a significant reduction in CO<sub>2</sub> emissions, which reinforces the importance of modernizing infrastructure to achieve Brazil's global climate commitments [5].

## Conclusion

In the face of the logistical challenges involved in the transport of green hydrogen, it is evident that Brazil faces the need to adapt its infrastructure to ensure efficiency, safety, and sustainability in the transport of this essential product for the global energy transition. Although the road modal is predominant in the country, the rail, waterway and pipeline modes have significant advantages in terms of energy efficiency, cost reduction and lower environmental impact. The transition to a low-carbon economy therefore depends on substantial investments in the modernization and expansion of existing logistics infrastructure, especially in relation to road and rail networks, ports and pipelines.

Green hydrogen, due to its volatile nature and dangerous product, requires strict care in its transport, which makes the choice of the most appropriate modal a crucial factor to ensure its

economic viability and safety in the process. The analysis of the different modes, considering their advantages and limitations, points to the need for integrated and strategic planning, which prioritizes sustainability and the reduction of greenhouse gas emissions.

Therefore, the study reinforces the importance of a holistic approach, which includes the modernization of logistics infrastructure and the improvement of green hydrogen transport capacity in Brazil. Such actions will not only contribute to the consolidation of the country as a leader in the production and export of clean energy but will also be fundamental for achieving global climate goals and building a more sustainable and resilient economy.

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## 3D Models Allow the Recovery of Information from Video Transects: A Case Study in Coral Reefs

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Image data acquisition is crucial for understanding long-term ecological processes. The video transect technique, developed in 1996 in Australia, has the main advantage of continuously visual recording the reef, allowing for the recovery of information that was previously unrecognized as relevant. With technological advances, the recovery of this information has reached a new level. Using photogrammetric techniques, it is possible to three-dimensionally reconstruct the filmed surface of reefs, enabling the collection of fundamental data on the structural complexity and population structure of corals and other benthic species. Structural complexity is the number of irregularities and indentations in the reef, indicating the amount of shelter it provides to marine fauna. Population structure describes the age distribution of species and is positively correlated with structural complexity. In this paper, we present the application of a 3D photogrammetry method to measure structural complexity in coral reefs using video transect images. The video transects used are 20 meters long by 48 centimeters wide, with an average duration of two to three minutes. To construct the models, 350 deinterlaced images were extracted from each video, ensuring a high overlap rate. The models were generated using Metashape 2.0.0 (Agisoft). The images were automatically aligned, followed by the generation of a mesh of overlapping points, which was then textured. A mosaic model was then produced. Spatial scale was calibrated using ten one-centimeter markings arranged along a 20-meter measuring tape. Structural complexity was estimated by the ratio between the number of points and vertices and the reconstructed area of the transect. To ensure comparability between models, it is essential to standardize the parameters used during processing to avoid bias. Changes in camera lens, resolution, and image quality can also affect the results. Despite these limitations, the technique offers a valuable opportunity to revisit the past of ecosystems recorded on video, allowing retrospective analyses with a high level of detail.

**Keywords:** Photogrammetry 3D. Structural Complexity. Marine Ecology. Todos os Santos Bay.

Image data acquisition is essential for understanding long-term ecological processes. The video transect technique, developed in 1995 in Australia, has the main advantage of continuously visual recording the reef, allowing for the recovery of information that was previously unrecognized as relevant. With technological advances, the recovery of this information has reached a new level (Carleton and Done, 1995) [1].

Using photogrammetric techniques, it is possible to three-dimensionally reconstruct the filmed surface of reefs, enabling fundamental data on the structural complexity and population

structure of corals and other benthic species to be obtained (Levy et al., 2022; Young et al., 2017) [2,3]. Structural complexity is the number of irregularities and indentations in the reef, indicating the amount of shelter it provides to marine fauna (Graham and Nash, 2012; Willis et al., 2005) [4,5]. Population structure describes the age distribution of species and is positively correlated with structural complexity.

In this work, we present the application of a 3D photogrammetry method to measure structural complexity in coral reefs through video transect images.

### Materials and Methods

The video transects used are 20 meters long by 48 centimeters wide, with an average duration of two to three minutes. To construct the models, 280 to 350 deinterlaced images are extracted from

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each video, ensuring a high overlap rate. The models were generated using Metashape 2.0.0 (Agisoft) on an Intel i7-8550u CPU @ 1.8GHz with 16 GB of RAM and a 2 GB GeForce MX150 GPU.

The images were automatically aligned with high accuracy. The mesh was generated using depth map source data, with an arbitrary surface type, high quality, and a high number of faces. Texturing was performed using an occlusion map, 3D model source data, and an orthogonal mapping model. The tiled model was built from depth map source data, with high quality and a high face count per megapixel.

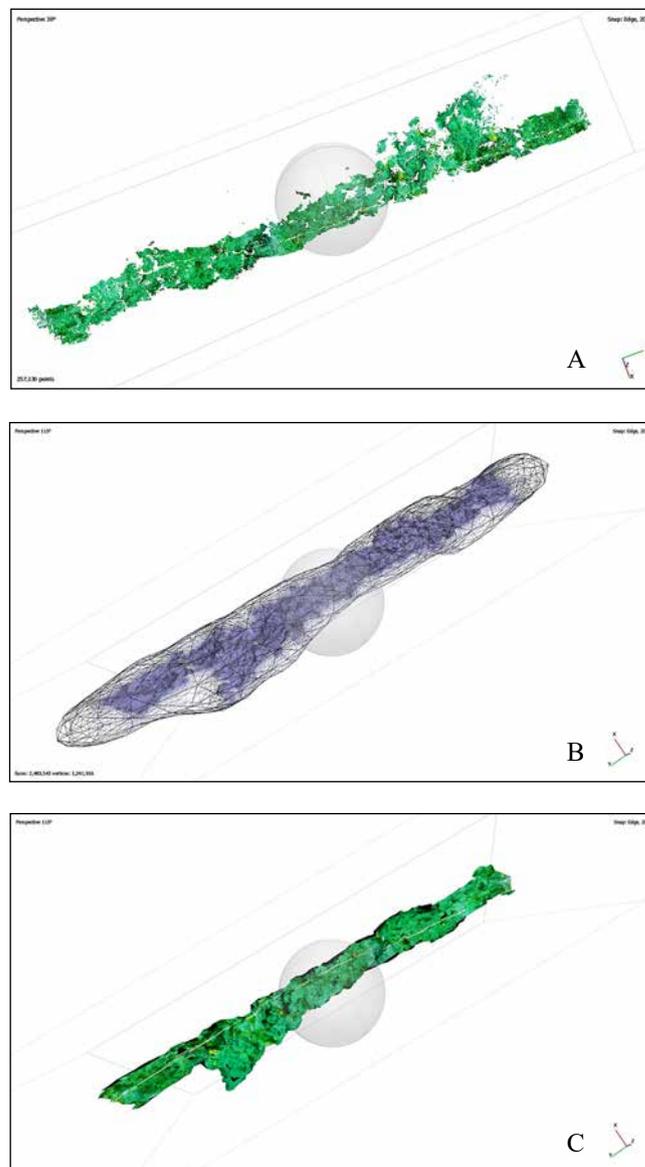
The spatial scale was calibrated using ten one-centimeter markings placed along a 20-meter measuring tape. Structural complexity was estimated as the ratio between the number of points and vertices and the reconstructed area of the transect. To ensure comparability between models, it is essential to standardize the parameters used during processing to avoid bias. Variations in camera lens, resolution, and image quality can also affect the results.

## Results

In the example of transect 2 of Cardinal Reef from April 2022, 295 images were used, of which 143 were aligned, generating 157,130 intersection points and 2,483,543 easy points. In the following images, we observe the intersection and easy points used to construct the 3D images of the reef transects (Figure 1A); the 3D images of the transect itself, with the roughness and complexity of the reef transect in Figure 1B; and the texture 3D models in Figure 1C.

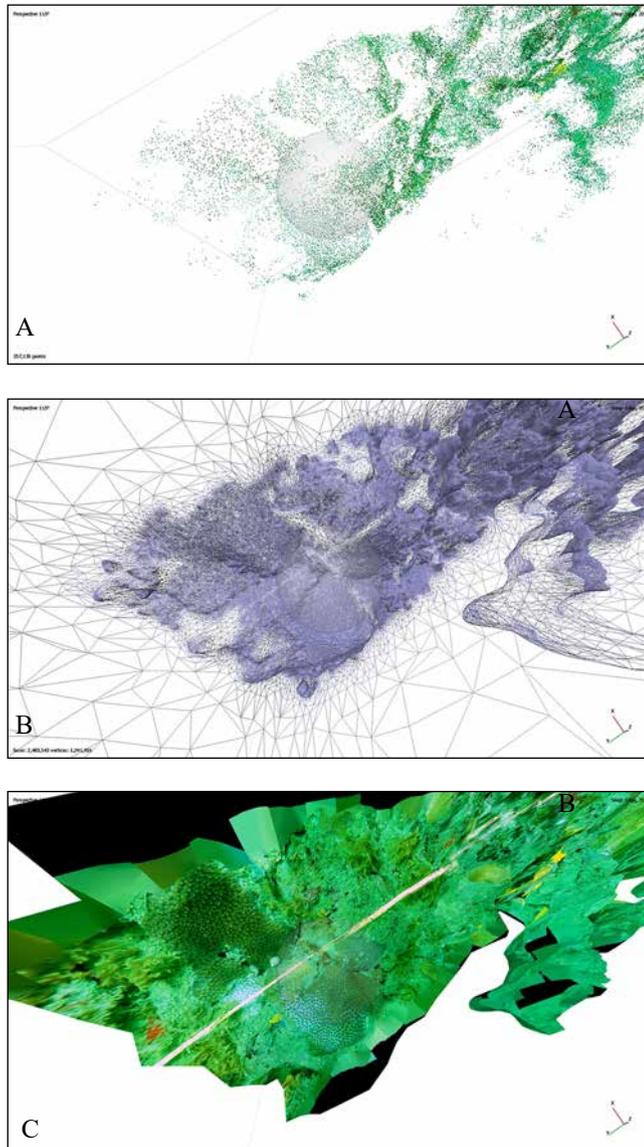
In Figure 2, we observed the intersection points (Figure 2A) and easy points (Figure 2B) used to construct 3D images of the corals (Figure 2C) with the images of the coral species. Here, two species can be identified: *Montastraea cavernosa* and *Siderastrea* spp. by photogrammetry used in the Pedra Cardinal reef transect (close-up showing coral species).

**Figure 1.** Reconstructed images, as intersection points (A), 3D models with phases (B) and textured 3D models (C).



The use of this technology can help us gain increasingly accurate insights into the seabed. Fixed monitoring areas can help us better understand changes in reef quality over time, including the roughness and complexity that maintain reefs and are extremely important for maintaining marine diversity and, consequently, for food production and tourism. Ways to measure these characteristics still need to be developed in future studies and research.

**Figure 2.** Detail of first one meter of reconstructed images, as intersection points (A), 3D models with phases (B) and textured 3D models (C).



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## From Manual Analysis to Predictive Automation: A Case Study in Financial Forecasting

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This paper presents the design and implementation of a business intelligence solution developed to automate, optimize, and scale financial forecasting processes in a multi-organization environment. The initiative was applied within the FIEB system, encompassing entities such as SENAI, SESI, IEL, and CIEB. The proposed solution integrates a data lake hosted in Microsoft Azure, a complete statistical and machine learning modeling pipeline, and an interactive dashboard built in Power BI to support data-driven decision-making and strategic financial planning. Initially, historical financial records were processed through a robust cloud-based ETL pipeline developed with Azure Data Factory. This pipeline performed automated cleaning, standardization, type correction, and monthly aggregation of accounting transactions. To define appropriate modeling strategies for each time series, we applied statistical analyses including signal-to-noise ratio (SNR) calculations and outlier smoothing techniques such as winsorizing and moving averages. Based on these insights, ARIMA and SARIMA models were trained to predict future values for each accounting item across the institutions. A custom API was developed to deliver prediction results and evaluation metrics to the Power BI dashboard, which updates automatically every month. The dashboard aggregates the accounting items by economic nature and displays six-month rolling forecasts, enabling financial managers to make proactive and informed decisions. As a result, the solution reduced manual workload, increased forecast accuracy, incorporated seasonal variations, and cut execution time by 90%. This project exemplifies how cloud computing, automation, and statistical modeling can modernize financial workflows and improve decision-making quality in complex organizational ecosystems. **Keywords:** Cash Flow Predictions. Items Account. Automated Process. Data-Driven Decision Making. Machine Learning Models (ML Models). Microsoft Azure.

Data-driven decision-making (DDDM) constitutes a methodological approach in corporate finance whereby strategic and operational decisions are derived from systematic data analysis, as opposed to intuition or subjective reasoning [1]. This approach is very important to identify opportunities for improvement and critical points in business. Companies realized that data is a strategic asset with potential drive innovation and can optimize resource allocation. Business Intelligence changed the management process, bringing value to the company, adding reliability as the information is produced constantly and automatically through an integrated system [2].

However, DDDM requires not only an appropriate technological infrastructure, but also an organizational culture that recognizes data as a strategic asset. In this study, we discuss the development of the infrastructure required to implement DDDM at FIEB in the context of corporate finance management, and we present the findings of this innovative approach within the company.

### Materials and Methods

The original data source of the company contains historical financial data from five organizations, such as FIEB, SENAI, IEL, SESI and CIEB. The data contains transactions related to accounting items such as personnel expenses, consumable materials, transportation and travel, other payments, service revenues, direct collections, etc.

First, we built a data lake on Azure Cloud with four layers to store raw and preprocessed data, following best practices of data governance.

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Second, we developed a pipeline for extracting, transforming, and loading data using Azure Data Factory (ADF). During the transformation process, we cleaned the data and applied business rules to ensure process reliability, data quality, and to reflect the operational reality of the company. A monthly incremental data extraction from the same source was configured using the same Azure service.

In addition, we developed a machine learning pipeline to train one predictive model for each account item in each organization. In total, forty-eight models were created. This pipeline was also responsible for training, evaluating, and saving the machine learning models in the Azure repository.

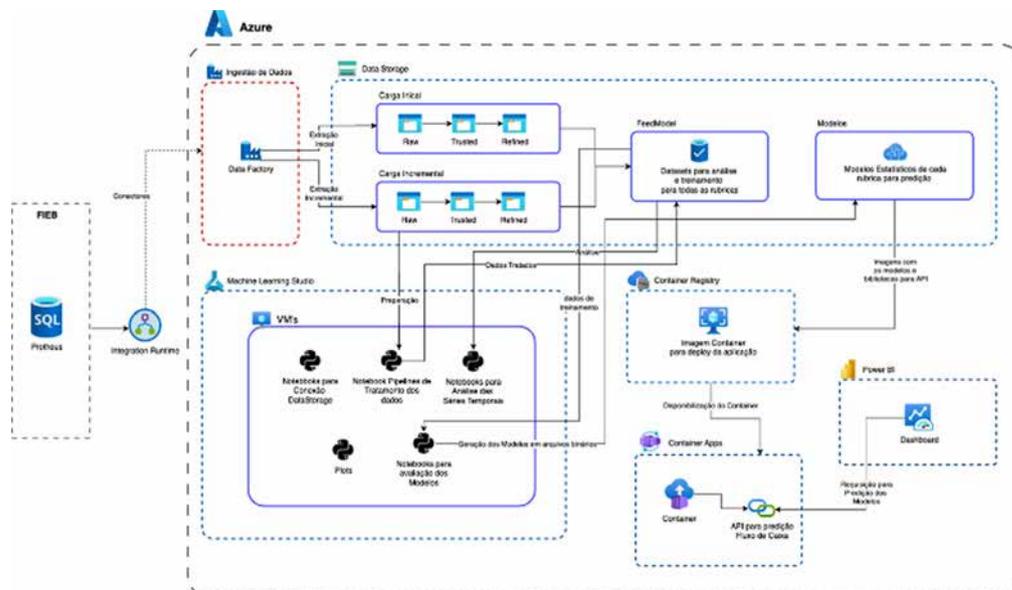
Moreover, we developed a custom API from scratch, which plays a central role in enabling

data integration and automation within the business intelligence pipeline. It was developed to feed the end-user dashboard with not only the predictions results, but also the historical data and the evaluation metrics. Both ML model training pipeline and the API were coded in Python and deployed using Azure Container. Finally, we created a Power BI dashboard to support DDDM for managers. We automated the entire process, from data extraction to dashboard updates, to meet the business requirement of delivering monthly updated forecasting of cash-flow for six months ahead. Table 1 summarizes and compares the characteristics of BI solution with procedures before the solution. Figure 1 presents the architecture of the BI solution.

**Table 1.** Comparison between methods.

Method	Traditional	Creative Innovation
Procedures	Manual	Automated
Staff Involved	One or more	None
Forecasting Method	Simple average	Machine learning
Seasonal Events Inclusion	Not	Yes
Time Consumption	Several days	Few hours

**Figure 1.** Architecture of the BI solution.



### Preprocessing Data

We initially cleaned the raw data, deleted duplicated records, removed useless columns, and corrected their data types. Secondly, we aggregated the records and summed the transactions' values by month. The results were stored in the following data lake layers. All the process was done using a data pipeline with ADF.

### Statistical Analysis

We performed statistical analysis to understand each data collection and to find patterns and outliers. We calculated the signal-to-noise ratio (SNR) for each accounting classification using the following formula:

$$SNR = \frac{VAR(Signal)}{VAR(Noise)}$$

In the formula above, VAR means a variance, signal means the sum of values of seasonality and trend for each time series, and noise means the unpredictable component of time series obtained after the decomposition of time series [3,4]. This type of analysis allowed us to identify which rubric would be modeled using either the whole data or only the trend component. The ratio of amplitude of the signal to error is called the signal-to-noise ratio (SNR); the larger the SNR, the easier it is to detect the signal.  $SNR > 1$  means signal well defined, and we can model the time series using whole information, and  $SNR < 1$  means more noise than signal; we need to extract the trend to perform the model.

We also identified and smoothed the outliers using several statistical techniques such as moving average, median, and winsorizing.

### Machine Learning Training Pipeline

Due to the amount of data for each accounting item, which was between sixty and eighty, we decided to use statistical methods such as ARIMA and SARIMA to develop each model. During the exploratory and prior predictive analysis, we

created a file that contains each characteristic of time series, which is used to guide the training, such as if we would use the trend or all components, ARIMA or SARIMA, expenses or revenue, etc. The pipeline follows the instructions given by the file guide. At the end of the pipeline, each model is saved in a repository on Azure.

ARIMA is the acronym for AutoRegressive Integrated Moving Average. This type of model is widely used to analyze and predict short time series. There are three main components in ARIMA model: AR (AutoRegressive – p), which captures the linear dependency between the current value and past values; I (Integrated – d), which indicates the number of times the data must be differentiate to achieve stationarity; and MA (Moving Average – q), which represents the linear dependency between the current value and past error values. SARIMA is an extension of the ARIMA model that incorporates seasonal components, meaning that certain patterns occur in regular cycles [5].

### Integration

We created an API from scratch to feed Power BI dashboard with the results of predictions. Besides, API also carries the historical data and metrics of evaluation of models, such as root mean square error, mean square error, mean absolute percentage error. This API downloads the models into the application to avoid delays during requests. It was designed to update automatically the models once a month after their updating, and a security redundance layer was added to ensure high availability and fault tolerance.

### Power BI Dashboard

We developed a dashboard designed to meet business needs by applying data visualization best practices, supporting data-driven decision-making, and ensuring alignment with user requirements and organizational objectives. We grouped and aggregated the accounting items by economic nature to calculate the cash flow and predicted the

cash flow for six months ahead. So, the decision maker can anticipate and make decisions to manage better resources company, aiming to improve profitability and minimize risks.

## Results and Discussion

After implementing the solution, we improved the quality of the predictions, by increasing accuracy and incorporating seasonal components for some accounting items, since the methodology used initially was the simple average of the last months. In addition, the solution reduced the time of analysis due to all steps being automated reducing not only the execution time to achieve the results but also operational costs reduction. The execution time was reduced by approximately 90%. Finally, the forecasting horizon expanded from ten days to six months.

## Conclusion

The solution built has proven to be useful and highly important for the decision-making process, as it reduced both execution time and costs. All automated steps ensure that task are executed consistently and accurately, saving days due through faster execution, reducing man-hours for repetitive tasks, providing easy scalability

to handle large volumes of data or operations, and allowing professionals to focus on analysis, innovation, and decision-making rather than operational activities.

## Acknowledgement

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