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PROJECT-BASED LEARNING IN ENGINEERING: DESIGN OF A MECHATRONIC SYSTEM TO MITIGATE RAINWATER INGRESS THROUGH RESIDENTIAL WINDOWS

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Abstract. *This paper presents the development of a mechatronic system designed to autonomously prevent rainwater ingress through residential sliding windows. The project was conducted within the context of a project-based engineering course at the University of São Paulo and reflects a comprehensive design methodology grounded in real-world needs. The process encompassed market research, user surveys, problem formulation, requirement specification, and the systematic generation and evaluation of design alternatives. A total of 34 concepts were developed and assessed based on functional, operational, structural, and economic criteria. The final design integrates a humidity-triggered actuation mechanism, hybrid power supply, and a modular structure compatible with standard window dimensions. The study demonstrates how project-based learning can foster critical engineering skills, including interdisciplinary thinking, system-level integration, and decision-making under constraints. Furthermore, the paper highlights the pedagogical value of confronting students with open-ended design challenges that emulate authentic engineering practice. The resulting solution offers a cost-effective and technically feasible response to a common domestic problem, while exemplifying the educational potential of structured project-based methodologies in mechanical engineering curricula.*

Keywords*: Project-Based Learning, Engineering Design, Mechatronics, Rainwater Protection, Smart Home Systems*

Resumo. *Este artigo apresenta o desenvolvimento de um sistema mecatrônico projetado para impedir autonomamente a intrusão de água da chuva por janelas de correr residenciais. O projeto foi realizado no contexto da disciplina de Metodologia do Projeto da Escola Politécnica da Universidade de São Paulo, com foco em uma abordagem de aprendizagem baseada em projetos aplicada a uma necessidade real. O processo metodológico incluiu pesquisa de mercado, levantamento de usuários, formulação do problema, especificação de requisitos e geração e avaliação sistemática de alternativas de projeto. Ao todo, 34 conceitos foram propostos e avaliados com base em critérios funcionais, operacionais, estruturais e econômicos. A solução final integra um mecanismo de acionamento por sensor de umidade, alimentação híbrida e estrutura modular compatível com as dimensões padrão de janelas residenciais. O trabalho evidencia como a aprendizagem baseada em projetos pode desenvolver competências essenciais da engenharia, como pensamento interdisciplinar, integração de sistemas e tomada de decisão sob restrições. Ademais, destaca-se o valor pedagógico de submeter os alunos a desafios de projeto abertos, que simulam a prática profissional da engenharia.*

Palavras chave: *Aprendizagem Baseada em Projetos, Projeto de Engenharia, Mecatrônica, Proteção contra Chuva, Automação Residencial*

1. INTRODUCTION

The infiltration of rainwater through inadequately sealed residential windows poses significant challenges, including structural degradation, mold proliferation, and compromised indoor air quality (ALFANO *et al.*, 2023; BOOKER *et al.*, 2025; PANERU *et al.*, 2025). Addressing this issue necessitates the development of automated systems capable of detecting and preventing water ingress (KAMEL *et al.*, 2024; YANG *et al.*, 2019). Mechatronic solutions, which synergistically integrate mechanical components with electronic control systems, offer a promising avenue for enhancing the resilience of residential infrastructures against environmental adversities (YOU *et al.*, 2025; HABIB, 2007).

In the field of engineering education, Project-Based Learning (PBL) has emerged as a pedagogical approach that immerses students in the complexities of real-world problem-solving (O'CONNOR *et al.*, 2024). By engaging in projects that mirror professional engineering challenges, students cultivate critical competencies such as interdisciplinary collaboration, system integration, and innovative design thinking (COPOT *et al.*, 2016). The incorporation of PBL in mechatronics curricula has been shown to enhance students' ability to apply theoretical knowledge to practical applications, thereby bridging the gap between academia and industry demands (POUNDS, 2015).

This paper delineates the development of an automated window sealing system conceived within a PBL framework in an undergraduate engineering course (MARTIN; BOMBAERTS, 2024). The project encompassed comprehensive stages, including market analysis, user needs assessment, rigorous design methodology, and iterative prototyping (CAMBURN *et al.*, 2017). Such an approach not only facilitated the creation of a viable mechatronic solution but also provided students with experiential learning opportunities that reflect the multifaceted nature of contemporary engineering practice (PRABHU *et al.*, 2024).

The ensuing sections provide an in-depth exposition of the design process, from conceptualization to implementation, underscoring the pedagogical efficacy of PBL in fostering engineering acumen (GARCÍA-LLAMAS *et al.*, 2025). The findings contribute to the discourse on educational strategies that effectively prepare engineering students for the demands of a rapidly evolving technological landscape (NEAL *et al.*, 2011).

2. METHODOLOGY

The project described in this paper was developed within the scope of the undergraduate course PME3320 –Design Methodology I, offered at the Polytechnic School of the University of São Paulo. This course introduces students to a structured, engineering-oriented approach to product development, grounded in classic and contemporary methodologies such as the model proposed respectively by Asimow (1962) and Dieter & Schmidt (2013), and the systematic design process outlined by Lesko (2011).

Operating under a PBL paradigm, PME3320 aims to immerse students in authentic engineering practice by guiding them through the initial stages of product design, from problem identification to concept selection (MICHEL & FÖRSTER, 2025). The pedagogical goal is to foster critical thinking, creativity, teamwork, and decision-making under constraints, while ensuring that students become familiar with the rigor and discipline inherent in professional engineering design workflows (REHMAN *et al.*, 2024).

2.1. Course context and educational approach

The project began with the identification of a practical, high-impact need within the domain of residential automation: preventing the ingress of rainwater through sliding windows that are accidentally left open (FENG *et al.*, 2022). The students investigated this issue through a primary survey conducted via Google Forms, which targeted Brazilian users across multiple social strata. The survey collected 71 responses and focused on three aspects: (1) number of sliding windows per household, (2) perceived financial losses due to rainwater ingress, and (3) the willingness to pay for an automated closing system.

Survey analysis revealed that rainwater infiltration leads to both material damage and sanitary risks, particularly due to the growth of mold and structural degradation (VAN LINDEN; BOSSCHE, 2022; GWENZI *et al.*, 2015). The majority of respondents reported financial damages exceeding R$ 100, and approximately 90% indicated a willingness to invest in a solution within the price range of R$ 150 to R$ 300.

2.2. Problem identification and needs assessment

To evaluate existing solutions, a comprehensive benchmarking of seven commercially available automated window systems was performed (WEVER *et al.*, 2007). Technical specifications such as actuation type, power consumption, noise level, dimensions, materials, and the presence of rain sensors were cataloged. Most products relied on remote manual control and lacked automated response to precipitation, revealing a technological gap in the market.

Moreover, the import tariffs and shipping costs associated with these devices, primarily sourced from China, were found to significantly increase the final consumer price in Brazil, further justifying the development of a cost-effective domestic solution (SOUSA *et al.*, 2021).

2.3. Technical requirements and design constraints

Based on user feedback and benchmarking data, the team defined a set of technical requirements grouped into three categories:

a) Functional Requirements: automated detection and closure within 30 seconds, maximum operating noise of 45 dB, actuation force between 36 N and 450 N.
b) Operational Requirements: compatibility with 127 V and 220 V electrical grids; battery operation at 24 V; maximum power consumption of 38 W.
c) Constructive Requirements: maximum device dimensions of 600 mm × 127 mm × 127 mm; total mass below 2 kg.

Additionally, market-driven constraints were considered: the maximum acceptable retail price was set at R$ 350, based on the weighted average derived from survey responses and competitor pricing.

2.4. Concept generation and evaluation

The team employed a morphological matrix method to generate a broad set of conceptual alternatives (BIANCHI & AMARAL, 2021; CHEN *et al.*, 2005). A total of 34 distinct concepts were proposed, combining variations of actuation mechanisms (pneumatic pistons, stepper motors), control systems (IoT, humidity sensors, remote control), power sources (AC, battery, hybrid), and structural materials (metal, injected plastic, 3D-printed polymers). Each alternative was evaluated through a multi-criteria decision matrix, assessing physical feasibility, economic viability (component cost, manufacturing cost), technical compliance (with the previous requirements) and innovative potential (GUL; GUNERI, 2016).

From the 34 initial conceptual alternatives generated through the morphological matrix, a first technical feasibility screening was conducted (ATEFI; GALLAGHER, 1991). This assessment considered fundamental aspects such as functional compatibility, operating principal soundness, and basic compliance with the defined physical and operational constraints (NAKAZAWA, 2023). As a result, 13 alternatives were deemed technically viable and selected for further evaluation. These are listed below with the respective associated manufacturing costs presented in the brackets:

- Alternative 12: Stepper motor, battery-powered, metallic structure [R$ 215.38]
- Alternative 13: Stepper motor, battery-powered, metallic structure with pulley system [R$ 315.22]
- Alternative 14: Retractable film-based sealing [R$ 250.18]
- Alternative 15: Tensioned cable mechanism [R$ 225.82]
- Alternative 16: Surveillance camera, battery, and linear actuator [R$ 311.09]
- Alternative 17: Electric motor, friction wheel, hybrid power supply, with geolocation, and injection-molded plastic structure [R$ 368.71]
- Alternative 19: Electric motor, friction wheel, battery-powered, IoT-enabled, with 3D-printed plastic structure [R$ 293.97]
- Alternative 20: Electric motor, friction wheel, hybrid power supply, RFID activation, with metallic structure [R$ 466.19]
- Alternative 21: Electric motor, friction wheel, hybrid power supply, with geolocation, and using a metallic structure [R$ 370.86]
- Alternative 22: Electric motor, friction wheel, battery-powered, humidity sensor, and using a metallic structure [R$ 240.26]
- Alternative 23: Electric motor, friction wheel, hybrid power supply, humidity sensor, with a rigid plastic structure [R$ 338.76]
- Alternative 24: Electric motor, friction wheel, hybrid power supply, remote activation, with metallic structure [R$ 349.56]
- Alternative 29: RFID-based passive triggering mechanism [R$ 299.55]

These 13 technically viable concepts were subsequently subjected to a second filtering process focused on economic feasibility. Based on the analysis of existing commercial solutions and user survey responses regarding willingness to pay, the team established a target retail price of R$ 350. To ensure profitability, a net profit margin of 20% was defined as appropriate for small-scale production and commercialization (BANERJI, 1978).

Accordingly, the group determined that the maximum allowable production cost per unit should not exceed R$ 275. This value ensures a net profit of R$ 75.00 per unit, aligning with both market expectations and sustainable financial planning (LARIONOVA *et al.*, 2024). The estimated material and manufacturing costs for each alternative, including the bill of materials (BOM), actuation components, control systems, and structural elements, were compared against this R$ 275 ceiling.

Any concept whose projected cost structure exceeded this threshold was eliminated from further consideration, regardless of its technical merits. This economic screening ensured that only solutions capable of achieving both functional performance and cost-effectiveness would proceed to the final stages of analysis and development.

Following the economic filtering, Alternatives 12, 14, 15, and 22 were retained for analysis, having met both technical and financial feasibility criteria.

Alternative 12 is presented in Fig, 1. The system includes a water sensor, guide rails, and a battery-powered stepper motor integrated with a control unit.

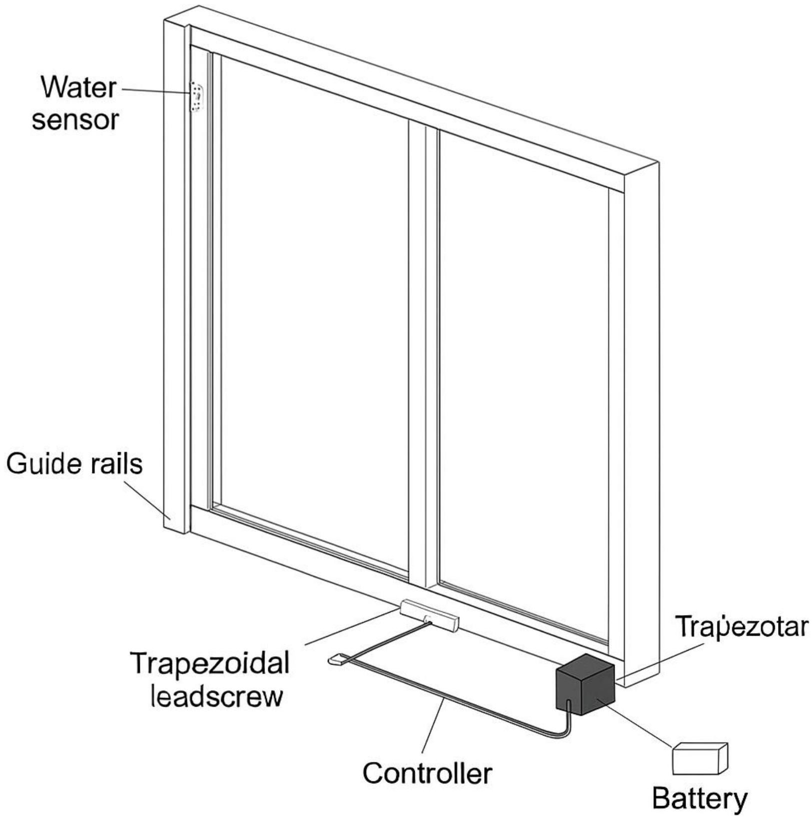

Figure 1. Technical schematic of the linear actuation system using a trapezoidal leadscrew

Alternative 14 is presented in Fig, 2. Upon detecting rain, a Wi-Fi-enabled controller activates a stepper motor that deploys a transparent film to protect the window area.

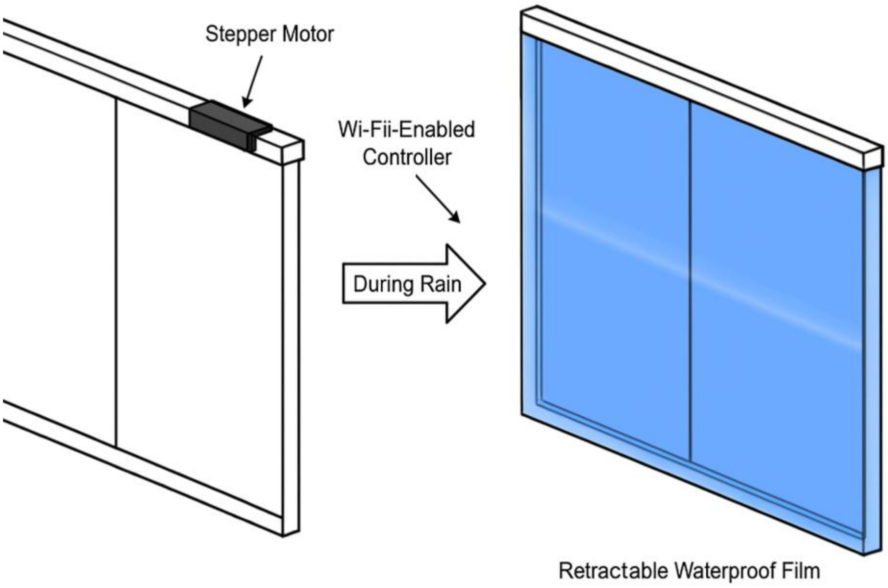

Figure 2. Diagram of the retractable waterproof film sealing concept

Alternative 15 is presented in Fig, 3. The system employs a stepper motor to pull the cable and close the sliding window when rain is detected by the water sensor

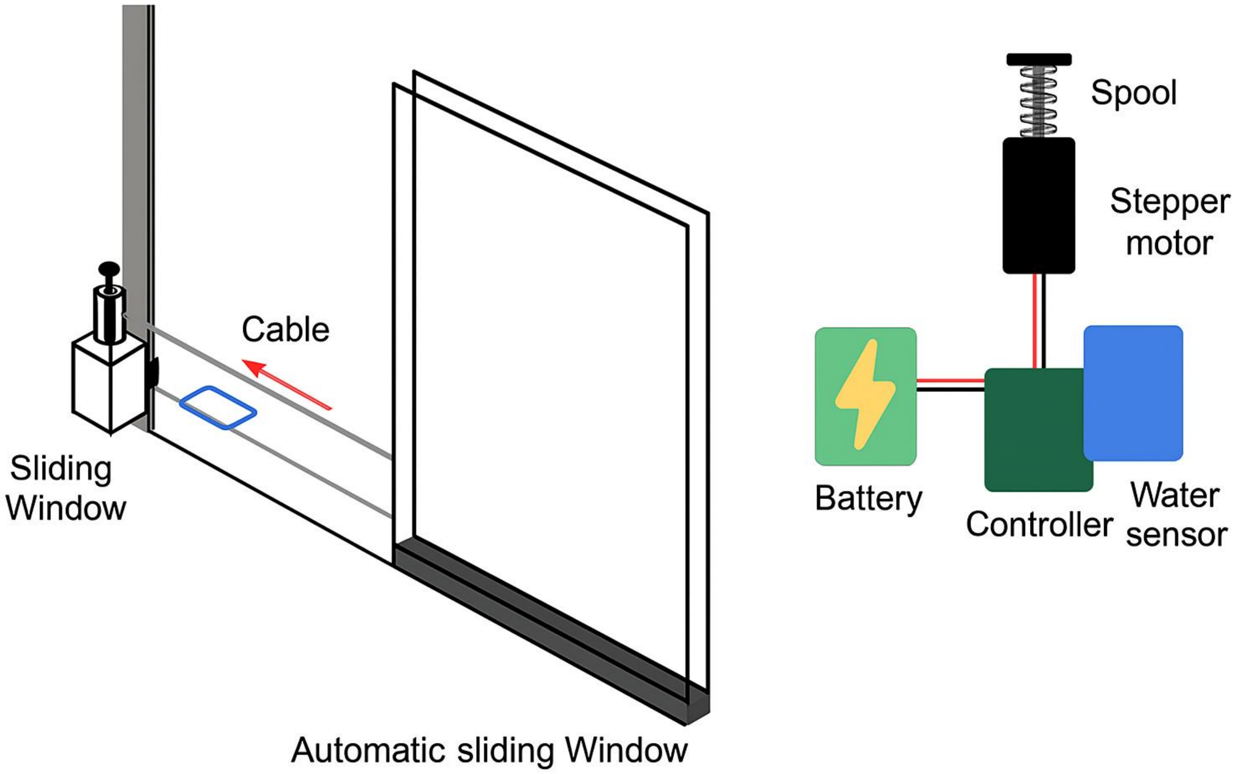

Figure 3. Schematic representation of the automatic window sealing system using a tensioned cable mechanism

Alternative 22 is presented in Fig, 4. The system is powered by a battery and triggered by a humidity sensor.

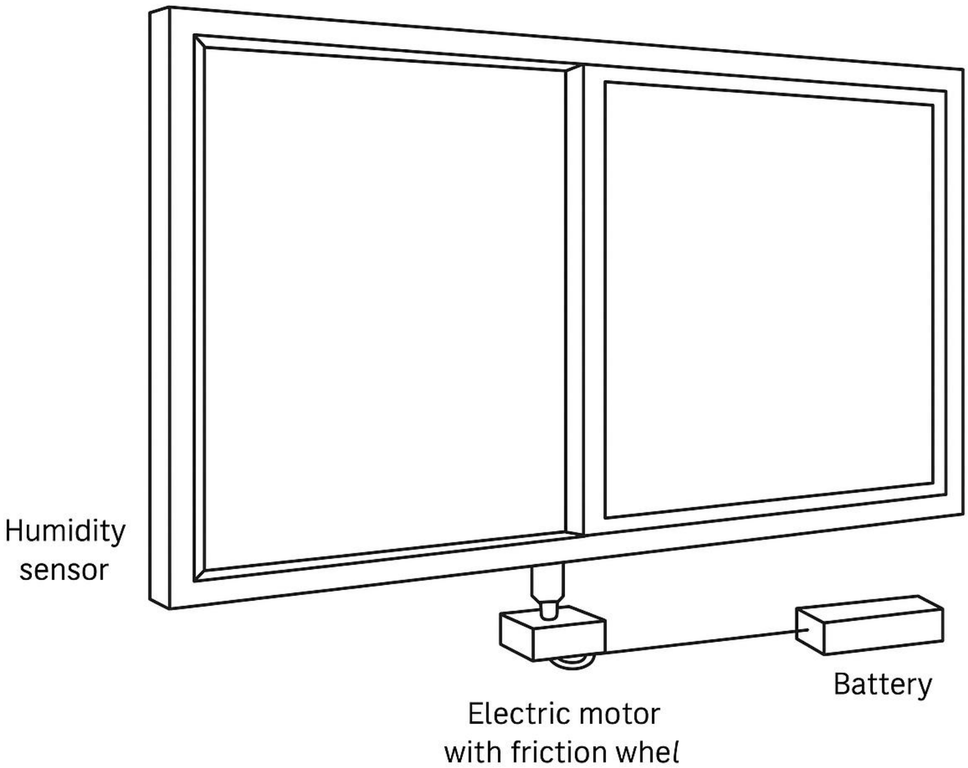

Figure 4. Functional layout of the automated closure mechanism based on a friction wheel and electric motor

2.5. Financial feasibility and final selection

The final evaluation stage focused on the financial feasibility of the four alternatives that had passed both the technical and economic filters. This stage aimed to assess the initial investment required to bring each product to market, considering two categories:

1. Machinery and production line costs, which include equipment needed for manufacturing components and assembly.
2. Research and development (R&D) costs, related to prototyping, validation, and any required technological development.

Each of the remaining alternatives was analyzed according to these criteria.

Alternative 12: Stepper motor, battery-powered, metallic structure

a) Machinery and Production Line: The main investment involves equipment for cutting and bending metallic sheets and the manufacturing of a trapezoidal leadscrew. Considering a production volume of 36,600 units per year (145 units per day), the team calculated that 60 metal sheets per shift would be needed to account for production and rework. To meet this demand, a manual sheet metal bending and cutting machine with a maximum width of 1067 mm would be required, at a cost of R$ 15,700.00. Additionally, a CNC lathe would be necessary for the leadscrew manufacturing, with a cost of R$ 14,849.10.
b) R&D Costs: The product operates entirely offline and does not require development of apps or digital interfaces. Therefore, R&D is limited to embedded firmware programming for the controller and stepper motor driver. No significant additional investment was required.
c) Total estimated initial investment: R$ 30,549.70.

Alternative 14: Retractable waterproof film

a) Machinery and Production Line: This solution requires two primary machines: (1) a plastic film extrusion machine to produce the retractable membrane, with an estimated cost of R$ 110,935.60, and (2) a metal sheet cutting and bending machine for the aluminum casing, adding R$ 15,700.00.
b) R&D Costs: Although no software development is required, the team anticipated the need to test and select appropriate film materials with sufficient tear resistance and impermeability. However, this exploratory phase was not considered to involve significant capital expenditure.
c) Total estimated initial investment: R$ 126,635.60.

Alternative 15: Tensioned cable mechanism

a) Machinery and Production Line: This design requires metal cutting and bending machinery, identical to that described above, with an initial investment of R$ 15,700.00.
b) R&D Costs: Development efforts were limited to mechanical durability tests of cables under continuous tension. As no digital or software development was necessary, no additional R&D investment was allocated.
c) Total estimated initial investment: R$ 15,700.00.

Alternative 22: Electric motor with friction wheel, battery-powered, humidity sensor, metallic structure

a) Machinery and Production Line: As with other metallic-frame designs, this alternative requires sheet metal forming equipment, with an investment of R$ 15,700.00.
b) R&D Costs: Functional testing was required to evaluate the efficiency of the humidity sensor and the structural reliability of the metallic frame. As no digital systems or user interfaces were developed, R&D costs were considered negligible.
c) Total estimated initial investment: R$ 15,700.00.

Finally, the remaining alternatives were ranked according to the total investment required for market implementation. The following list presents the solutions in ascending order of initial financial commitment. The ranking of design alternatives based on financial feasibility, considering initial investment required for production setup and development is presented in Tab. 1.

Table 1. Quantitative design targets

Ranking	Alternative	Initial investment
1st	15	R$ 15,700.00
2nd	22	R$ 15,700.00
3rd	12	R$ 30,549.70
4th	14	R$ 126,635.60

After evaluation, a solution was selected that integrated the following features: stepper motor-driven linear actuation mechanism, powered by a hybrid energy source (battery and AC charging), controlled via humidity sensor, triggering automatic closure and structured using metallic components for robustness and manufacturability.

This configuration was deemed the most effective in balancing cost, performance, and manufacturability, while fully addressing the identified user need.

2.6. Educational outcomes

Throughout the project, students demonstrated progressive mastery of key engineering competencies, including:

a) Application of quantitative methods for decision-making under uncertainty;
b) Integration of mechanical and electronic systems in a cohesive design;
c) Consideration of market and economic factors in product planning.

The project not only fulfilled academic objectives but also produced a concept with clear potential for prototyping and commercialization in future stages.

3. RESULTS

The survey conducted by the student team yielded insights that directly informed the product design. Results indicated that most households possess between four and six sliding windows, with a significant portion of respondents having experienced financial damages caused by rainwater intrusion. Notably, over 15% of participants reported losses exceeding R$ 1000 due to water-related deterioration of floors, furniture, or electronic devices.

In terms of price sensitivity, a dual-peak distribution was observed. One segment expressed willingness to pay between R$ 150 and R$ 200 per unit, while another accepted prices above R$ 400. From these data, a weighted average acceptable price of R$ 275 was determined, guiding the pricing strategy. Combining this with competitive benchmarking, the team set a target retail price of R$ 350, balancing market viability and profitability.

3.1. Technical benchmarking and gap identification

The analysis of seven existing automated window systems revealed that most devices lacked integrated rain detection and required manual actuation via remote controls or smartphone apps. Only one product incorporated a rain sensor, and even that offered limited automation. Moreover, high import taxes and shipping fees rendered foreign-made products prohibitively expensive for the Brazilian market, with final prices reaching up to R$ 1284 per unit. These findings reinforced the need for a nationally-developed, low-cost solution equipped with autonomous functionality.

3.2. Technical specification definition

Based on the collected data a set of quantitative design targets was established. These criteria framed the design space within which all alternatives would be evaluated. The targeted design parameters are presented in Tab. 2.

Table 2. Quantitative design targets

Specification	Target value	Specification	Target value
Actuation time	≤ 30 s	Maximum power consumption	38 W
Average actuation speed	20 mm/s	Maximum device dimensions	600 × 127 × 127 [mm]
Noise level	≤ 45 dB	Maximum mass	2 kg
Actuation force	36–450 N	Target retail price	R$ 347
Power supply	127 V / 220 V (AC), 24 V (battery)	Estimated annual production	36600 units

3.3. Conceptual design and selection

A total of 34 conceptual alternatives were systematically generated by combining various actuation mechanisms (pneumatic, electromechanical), control strategies (humidity sensor, IoT, remote control, geolocation), power configurations (battery, AC, hybrid), and structural materials (metal, plastic injection, 3D printing). Each alternative was subjected to a multi-criteria assessment involving four dimensions: Physical Feasibility (based on compatibility with defined constraints), Functional and Operational Compliance (Including speed, power, and noise limits), Cost Structure (components, manufacturing, and final pricing) and Market Potential (assessed qualitatively through alignment with user expectations).

From this analysis, four alternatives were shortlisted. Ultimately, the selected design featured:

- A stepper motor-driven linear motion mechanism
- Hybrid power system, combining rechargeable batteries and AC charging
- Humidity sensor activation for autonomous response to rain
- Structural frame made of aluminum profiles, offering strength and low mass

3.4. Cost breakdown and feasibility

A detailed Bill of Materials (BOM) was prepared for the selected concept, incorporating real quotes from local and international suppliers. Total cost per unit (excluding labor and logistics) was estimated at R$ 174.55. After factoring a 40% markup and fixed costs allocation, the product remained competitive within the target retail price of R$ 350, yielding economic feasibility for small- and medium-scale production.

Additionally, an annual production volume of 36,600 units was projected, based on market penetration rates and user acceptance data. This production scenario supports break-even feasibility within one year for a startup venture operating with moderate overhead.

3.5. Educational impact

The structured project methodology empowered students to apply theoretical concepts in mechanics, electronics, cost modeling, and product development to a real-world problem. Furthermore, they engaged in: data-driven decision making, cost-performance tradeoff analysis, CAD-based conceptual illustration, technical writing and presentation skills. These experiences reflect the educational impact of integrating open-ended design problems into undergraduate curricula, reinforcing competencies critical for future professional practice.

4. CONCLUSIONS

This study presented the design and preliminary validation of an automated mechatronic system aimed at preventing rainwater ingress through residential sliding windows. Developed within the context of an undergraduate engineering course at the University of São Paulo, the project embodied a project-based learning approach grounded in rigorous design methodology and real-world applicability.

The students successfully identified a relevant and underexplored problem in the domain of residential automation, substantiating its importance through user surveys and market benchmarking. A comprehensive design process followed, encompassing the formulation of technical requirements, generation of 34 conceptual alternatives, and a multi-criteria evaluation that led to the selection of a robust, cost-effective, and manufacturable solution.

The selected design, a humidity-activated, stepper motor-driven system with a hybrid power supply, met all functional and operational targets, including actuation time, noise level, and physical constraints. Cost analysis confirmed the solution's economic viability, with a projected unit cost substantially lower than existing imported alternatives.

Beyond its technical contributions, the project exemplified the pedagogical strength of project-based learning in engineering education. It enabled students to integrate knowledge across mechanics, electronics, systems thinking, and market analysis, while also developing soft skills such as teamwork, documentation, and structured communication.

Future work may involve the prototyping and experimental validation of the proposed solution, followed by reliability testing and integration with smart home platforms. Moreover, this project may serve as a replicable educational model for other engineering programs seeking to bridge the gap between theory and practical innovation.

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7. RESPONSIBILITY FOR THE INFORMATION

The authors bear full responsibility for the accuracy and integrity of the information presented in this work.