

DESIGN AND VALIDATION OF A PORTABLE COFFEE-MAKING DEVICE FOR URBAN DRIVERS: A PROJECT-BASED ENGINEERING EDUCATION CASE STUDY

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Abstract. *This paper presents the design and validation of a portable coffee-making device tailored to the needs of urban drivers, developed as part of an undergraduate project-based engineering course. The project originated from a real-world problem identified by students: the lack of practical, affordable, and high-quality solutions for consuming freshly brewed coffee during urban commutes. A comprehensive design methodology was employed, encompassing market research, user surveys, thermal and energy analyses, as well as CAD modeling and prototyping. Multiple alternatives were evaluated through a multicriteria decision-making framework using the Analytic Hierarchy Process (AHP). The final concept integrates a stainless-steel body, a straw-type lid, and a 12V vehicle-powered heating system. The prototype underwent simulations and calculations addressing thermal retention, heating performance, structural stability, and material compatibility. Results indicate that the solution meets key performance and usability criteria, including preparation time, user safety, and manufacturing cost. This study demonstrates the pedagogical effectiveness of using project-based learning to develop not only technical competencies but also critical thinking and innovation in engineering education.*

Keywords: *Project-Based Learning, Thermal Design, Coffee Brewer, Engineering Education, Product Development*

Resumo. *Este artigo apresenta o projeto e a validação de um dispositivo portátil para preparo de café, desenvolvido para atender às necessidades de motoristas urbanos, no contexto de uma disciplina de engenharia baseada em projetos. A iniciativa surgiu da identificação de um problema real pelos alunos: a ausência de soluções práticas, acessíveis e de qualidade para o consumo de café fresco durante os deslocamentos urbanos. Foi empregada uma metodologia de projeto abrangente, incluindo pesquisa de mercado, levantamento com usuários, análises térmicas e energéticas, modelagem CAD e prototipagem. Diversas alternativas foram avaliadas por meio de uma matriz de decisão multicritério baseada no método Analytic Hierarchy Process (AHP). A solução final integra corpo de aço inoxidável, tampa tipo fenda e sistema de aquecimento alimentado por fonte veicular de 12 V. O protótipo foi submetido a simulações e cálculos que abordam retenção térmica, desempenho de aquecimento, estabilidade estrutural e compatibilidade de materiais. Os resultados indicam que a solução atende aos critérios essenciais de desempenho, usabilidade e custo de fabricação. O estudo reforça a eficácia pedagógica do ensino por projeto no desenvolvimento de competências técnicas, pensamento crítico e inovação na formação em engenharia.*

Palavras chave: *Ensino por projeto, Projeto térmico, Cafeteira portátil, Educação em Engenharia, Desenvolvimento de Produto*

1. INTRODUCTION

Coffee consumption is deeply embedded in the cultural and social fabric of São Paulo, Brazil, with over 25 million cups sold daily across the metropolitan region (DE RESENDE, 2008). For many, particularly urban drivers, coffee serves not only as a source of energy but also as a comforting ritual within the constraints of a fast-paced lifestyle (GOSALVITR *et al.*, 2024). However, the city's intense traffic conditions, extended working hours, and lack of time for morning routines pose a significant challenge to accessing high-quality coffee during daily commutes (SILVA *et al.*, 2024).

Conventional alternatives, such as preparing coffee at home and carrying it in thermal containers or purchasing it at cafés, present drawbacks (SANCHEZ & CHAMBERS, 2015). The former compromises freshness and temperature retention, while the latter can result in substantial cumulative costs over time. Furthermore, most portable coffee-making solutions available on the market lack integrated water-heating functionality, failing to address the full scope of the user's need (TAVARES; MOURAD, 2020).

Within this context, a group of undergraduate mechanical engineering students at the University of São Paulo (USP) engaged in the development of a practical and innovative solution as part of a Project-Based Learning (PBL) initiative in the course "PME3320 – Engineering Design Methodology I" (LARSEN, 2025). The aim was to design a compact, self-contained, and vehicle-compatible device capable of heating water, brewing ground coffee, and maintaining the beverage at optimal temperature, all while being cost-effective, user-friendly, and manufacturable.

This paper presents the comprehensive development process of the proposed device, from problem definition and market analysis to the evaluation of design alternatives, thermodynamic modeling, structural considerations, and prototyping. The case exemplifies how project-based engineering education can foster creativity, technical competence, and system-level thinking by tackling real-world problems through structured design methodologies (REICH & VERMEYEN, 2025).

2. METHODOLOGY

The present study was developed within the scope of PME3320, an undergraduate course offered at the University of São Paulo (USP) to Mechanical Engineering students in the fourth semester. The course focuses on the application of structured design methodologies to solve real-world problems through the development of functional product concepts (ASIMOW, 1962). Students work in teams to identify user needs, conduct technical and market analyses, define design specifications, generate and evaluate design alternatives, and develop a functional prototype supported by analytical and simulation-based validation (DIETER and SCHMIDT, 2013). The course emphasizes critical thinking, interdisciplinary integration, and practical problem-solving in early-stage product development (LESKO, 2011).

2.1. Problem identification and user need analysis

The genesis of the project lies in a pressing and context-specific urban issue: the inability of São Paulo drivers to access high-quality, freshly brewed coffee during their daily commutes (GRIGG, 2002). With over 25 million cups consumed daily in the metropolitan area, coffee is not merely a beverage, it is a culturally embedded ritual that intersects productivity, personal well-being, and social identity (REHM *et al.*, 2020).

A preliminary qualitative assessment revealed that the routines of São Paulo residents are marked by prolonged working hours, sleep deprivation, and excessive time lost in transit (PINGEL, 2022). According to public datasets, average commute times surpass two hours per day, significantly eroding the time available for morning preparation activities, including coffee brewing (CHIQUELLO *et al.*, 2022). This temporal constraint, combined with the high cost of out-of-home coffee consumption, frames a multifaceted problem involving practicality, cost-efficiency, and beverage quality (BATALI *et al.*, 2020).

To deepen the understanding of the target users, an empirical study was conducted through a structured questionnaire administered via an online platform. The sample (n=143) comprised primarily urban commuters who rely on private vehicles. The data revealed that the majority of respondents consume between two and four cups of coffee per day, with a significant proportion purchasing at least one cup outside the home. Furthermore, over 75% of participants expressed interest in a portable solution that would enable them to brew coffee during their commutes, provided that the price remained under R\$ 220. These findings substantiate the existence of a well-defined user need: a compact, reliable, and user-friendly device capable of brewing coffee within the vehicular environment, without compromising on beverage quality or safety. The solution would not only reduce daily expenses but also enhance convenience and autonomy for the user, key factors in urban product design.

2.2. Market research and technical benchmarking

A thorough examination of existing market solutions was conducted to contextualize the design opportunity and benchmark technical requirements. The research revealed a proliferation of portable coffee-making devices aimed at

commuters and outdoor users, yet most fall short of delivering a fully integrated brewing experience. Notably, the majority of commercially available models lack an autonomous water-heating system, instead relying on pre-heated water, a limitation that significantly impairs user convenience and product independence.

To establish a comparative framework, a selection of ten representative products was analyzed based on criteria such as power source, compatibility with coffee formats (e.g., ground coffee, capsules), thermal insulation capabilities, ease of use, and retail price. The price range of these devices spanned from R\$ 150 to over R\$ 1000, with more advanced models offering minimal improvements in functionality relative to cost, as presented in Tab. 1.

Table 1. Comparative analysis of commercially available portable coffee makers

Product	Power source	Heating capability	Coffee format	Price
Nano Espresso	Battery	No	Capsules	~ R\$ 718.76
iCafilas USB	Battery	No	Capsules	~ R\$ 374.94
Aeropress Go	Manual	No	Ground	~ R\$ 499.90
Uny Home USB	Battery	Yes (limited)	Ground	~ R\$ 222.95
Cadence Dream	AC Power	Yes	Ground	~ R\$ 159.90
Makita DCM501Z	Battery	Yes	Capsules	~ R\$ 1099.00

Most models require pre-heated water, which limits autonomy and real-time usability for vehicle-based applications. Despite partial compliance with user expectations, such as portability and quick brewing, no existing solution combined heating, filtration, and thermal storage within a compact, vehicle-compatible design. This benchmarking exercise not only highlighted the technological gap in the current market but also informed the delineation of essential performance parameters and cost constraints for the proposed device.

2.3. Specification definition

Based on the identified user needs and market limitations, a set of functional, dimensional, operational, and economic specifications was defined to guide the development of the proposed solution. These specifications emerged from a synthesis of quantitative data obtained through user surveys and technical requirements derived from benchmarking analysis.

Given the intended vehicular application, the device was constrained to a cylindrical geometry compatible with standard automotive cup holders. Maximum dimensions were set at 250 mm in height and 80 mm in diameter, with a total system mass not exceeding 1.5 kg, including liquid contents and internal components. The minimum liquid capacity was fixed at 200 mL, allowing for the preparation of a standard serving of coffee.

From a usability standpoint, the brewing process was required to be completed within 15 minutes, with minimal user interaction, ideally limited to a one- or two-step activation procedure. The device had to be self-contained, intuitive, and safe to operate in a vehicular environment, without compromising thermal performance or structural integrity.

Thermal insulation was a critical design consideration: the external surface temperature was not to exceed a safe handling threshold, while internal temperature retention had to maintain beverage quality for at least 30 minutes post-brewing. Finally, the maximum acceptable manufacturing cost was set at R\$ 220, as determined by willingness-to-pay data obtained from the user survey.

2.4. Generation and evaluation of design alternatives

The conceptual design phase involved a systematic exploration of the solution space through morphological decomposition and multicriteria decision-making. The goal was to identify viable configurations that met the defined technical specifications while ensuring manufacturability, cost-efficiency, and user satisfaction.

To construct the design space, the overall system was decomposed into four fundamental subsystems: external casing, lid mechanism, energy source, and material selection. Each subsystem was assigned a discrete set of feasible options based on technical literature, market offerings, and user expectations.

A morphological matrix was developed, resulting in a total of 64 possible configurations (ÖLVANDER *et al.*, 2009). These combinations arose from the Cartesian product of four alternatives for the body geometry, two types of lids (click and slit), two types of power sources (battery and vehicle-powered via 12 V socket), and two materials (stainless steel and plastic with thermal insulation). This initial solution space was then reduced using feasibility filters, excluding options that violated dimensional constraints, cost ceilings, or thermal requirements. A shortlist of four viable alternatives was retained for further evaluation (Fig. 1).

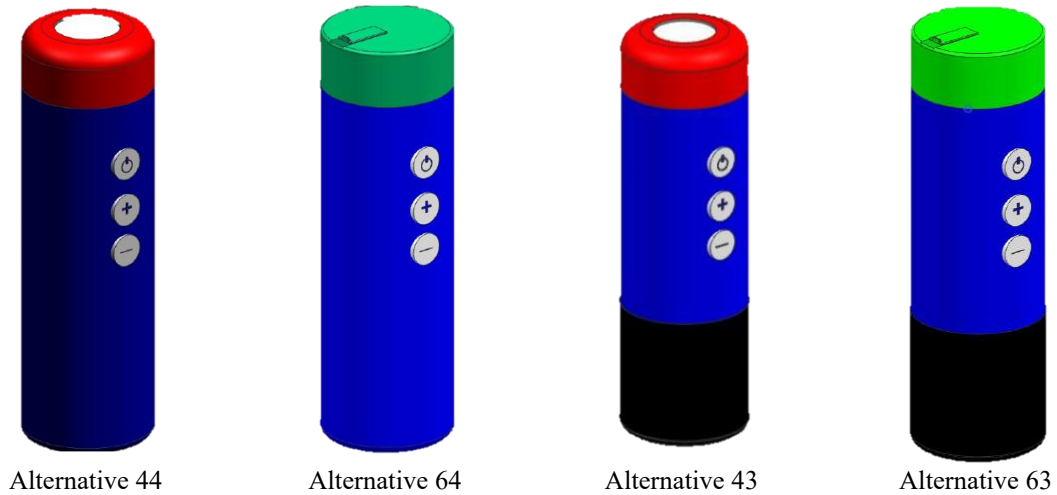


Figure 1. Four viable alternatives

Each alternative offers distinct trade-offs among cost, performance, and usability. The details are shown in Tab. 2.

Table 2. Shortlisted design alternatives after technical and financial feasibility screening

Solution	Lid type	Material	Power source	Estimated cost
Alternative 44	Click	Stainless steel	12 V socket	~ R\$ 48.78
Alternative 64	Slit	Stainless steel	12 V socket	~ R\$ 48.78
Alternative 43	Click	Stainless steel	Battery	~ R\$ 144.09
Alternative 63	Slit	Stainless steel	Battery	~ R\$ 144.09

To objectively select the most appropriate alternative, a multicriteria decision-making process was employed using the Analytic Hierarchy Process (AHP) (SOLAIMANIAN, 2025). Seven evaluation criteria were established: cost, ease of use, energy efficiency, weight, capacity, sustainability, and ease of maintenance. Pairwise comparisons were conducted to derive the relative importance of each criterion. The weights are: Cost (0.365), Ease of use (0.158), Energy efficiency (0.159), Mass (0.064), Capacity (0.064), Sustainability (0.031) and Maintenance (0.158).

Each alternative was scored against the criteria using a 3-level ordinal scale (1.0, 1.5, 2.0), and the weighted scores were aggregated to yield a final ranking. The results are: Alt. 64 (1.5), Alt. 44 (1.2), Alt. 63 (1.1) and Alt. 43 (0.9).

The analysis identified Alternative 64, a stainless-steel container with a slit-type lid and 12 V vehicle power source, as the optimal solution. It offered a favorable balance between cost, usability, and thermal performance, while remaining within all physical and economic constraints.

2.5. Prototyping and experimental validation

Following the selection of the optimal design configuration, the team proceeded with the detailed modeling and validation of the system, comprising virtual simulations and physical prototyping. The purpose of this phase was to assess the functional performance of the proposed solution under realistic usage conditions, ensuring that thermal behavior, structural integrity, and material compatibility conformed to the established specifications.

A complete three-dimensional CAD model of the selected alternative was developed using Autodesk Inventor®, detailing the external geometry, internal fluid volume, insulation layers, and electrical connections (CIMINO *et al.*, 2023). The design-maintained compatibility with automotive cup holders and included a lid optimized for ease of cleaning and safe pouring. A technical drawing with precise dimensions and manufacturing annotations was produced to guide prototype assembly (Fig. 2).

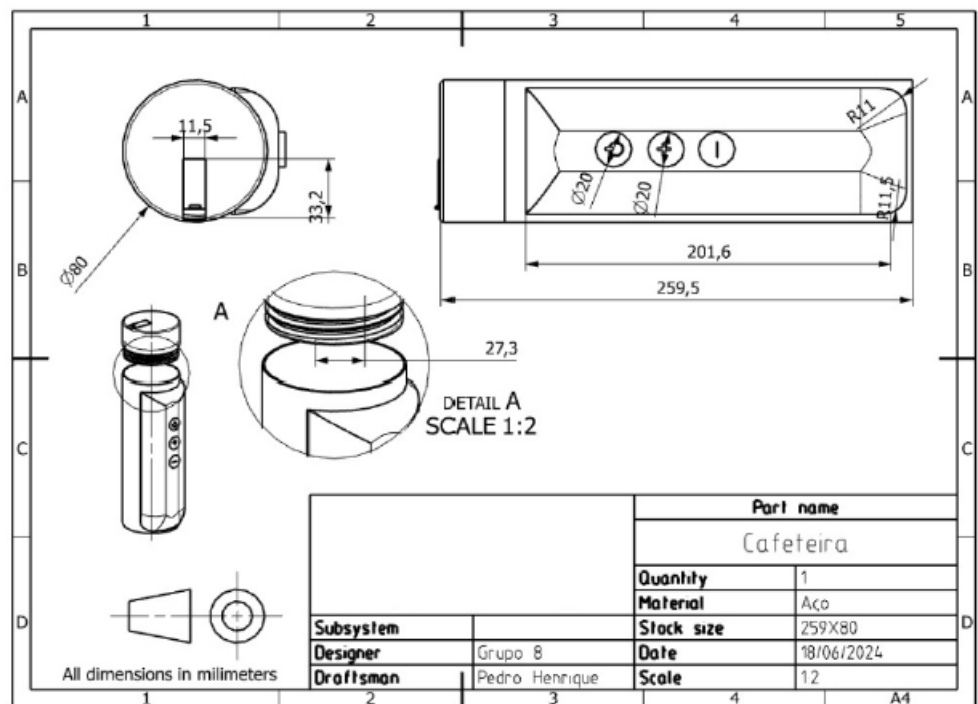


Figure 2. Technical drawings of Alternative 64

The internal structure included a resistive heating element, thermally insulated walls with aerogel lining, and a power interface compatible with a 12 V vehicle outlet.

Thermal performance was evaluated through both simulation and analytical methods (WIJAYA *et al.*, 2025). Using ANSYS®, transient thermal simulations were conducted under three ambient conditions: 25°C (standard), 3.2°C (extreme cold), and 38.4°C (extreme heat). The results confirmed that the thermal insulation system minimized heat loss, maintaining the beverage temperature within acceptable limits for over 30 minutes in all cases (Fig. 3).

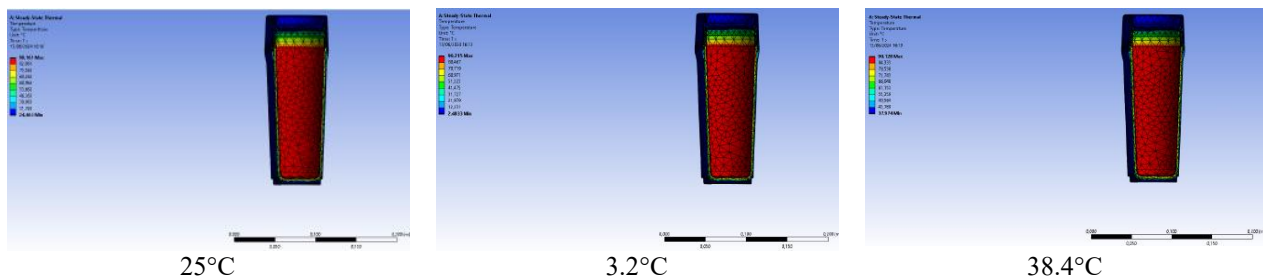


Figure 3. Thermal simulation results under different ambient temperatures

In parallel, a simplified analytical model based on radial heat conduction in cylindrical coordinates was developed to validate the simulation data (PUVIANI *et al.*, 2025). The predicted cooling curves under different ambient temperatures closely matched simulation results, reinforcing the consistency of the model (Fig. 4).

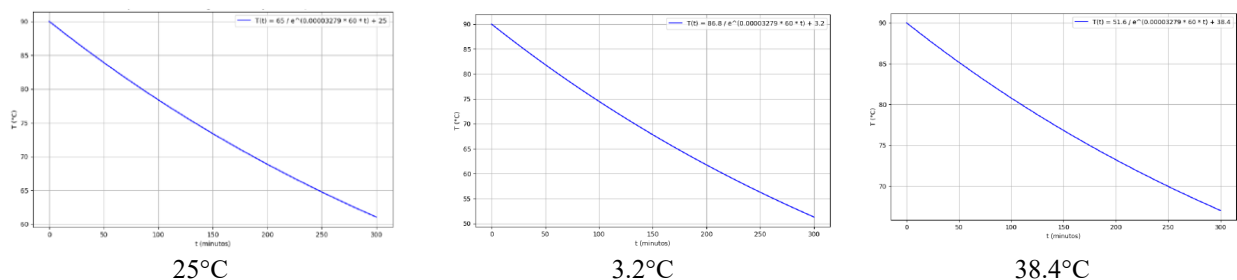


Figure 4. Analytical heat loss curves

The heating system was analyzed using the classical energy balance equation, presented in Eq. (1), assuming ideal heat transfer, where “t” is temperature, “m” is mass, “c” is specific heat capacity of the substance, “ΔT” is temperature variation and “P” is power.

$$t = \frac{m \cdot c \cdot \Delta T}{P} \quad (1)$$

Three parametric studies were performed using the following conditions:

- Power variation (120–240 W): decreasing heating time as power increased (Fig. 5a);
- Volume variation (100–500 mL): linear increase in heating time with volume (Fig. 5b);
- Initial temperature variation (3.2°C–38.4°C): colder water required significantly longer heating time (Fig. 5c).

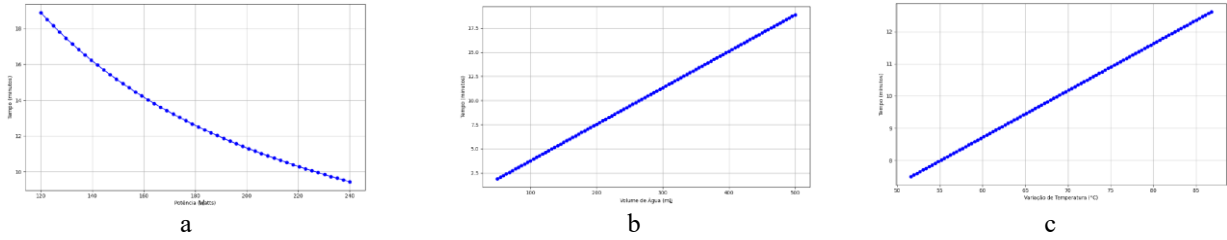


Figure 5. Heating time vs. power, volume, and initial temperature

These studies demonstrated that brewing 200 mL of coffee at 120 W would require approximately 10–12 minutes, within the target performance specification.

The physical stability of the device under vehicular motion was evaluated by analyzing its critical tilt angle. The equilibrium was kept up to tilt angles exceeding 40°, ensuring safe placement during typical driving conditions (Fig. 6).

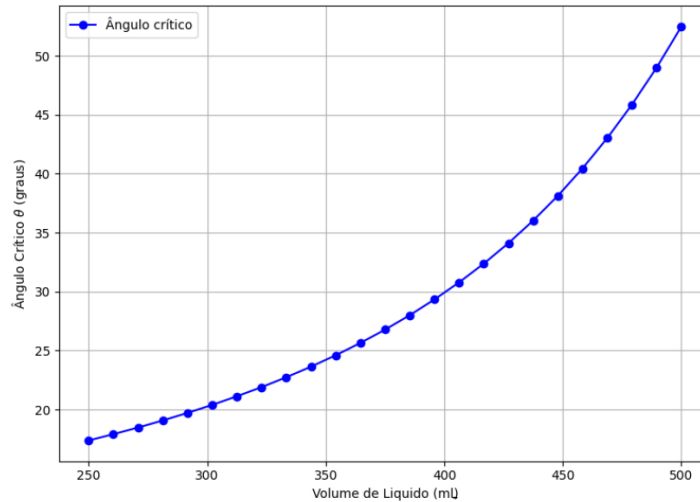


Figure 6. Stability analysis (critical tilt angle)

Additionally, material compatibility under thermal expansion was assessed using standard linear expansion equations for the stainless steel and plastic components. The analysis confirmed that dimensional variations across the expected temperature range would not compromise the seal integrity or usability (Fig. 7).

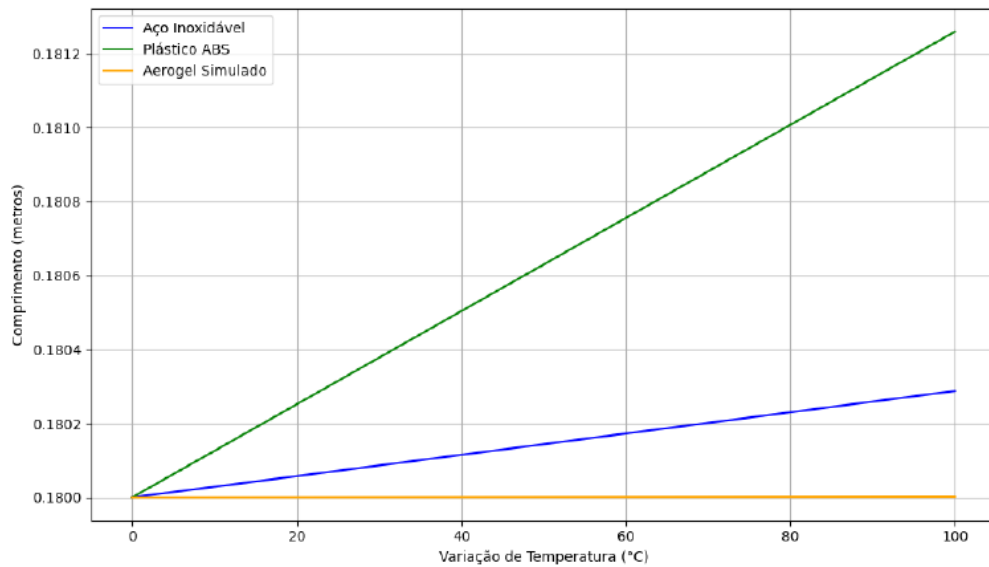


Figure 7. Thermal expansion behavior

A functional prototype was assembled using off-the-shelf components and custom-fabricated elements, closely replicating the selected concept. The assembled device included all key subsystems: container, lid, heating element, insulation layers, and power interface. The total cost of the prototype, including materials and fabrication, was approximately R\$ 77.68 (well below the target ceiling of R\$ 220).

Preliminary tests confirmed the system's usability, safety, and thermal retention capabilities, validating the technical feasibility of the concept (Fig. 8).

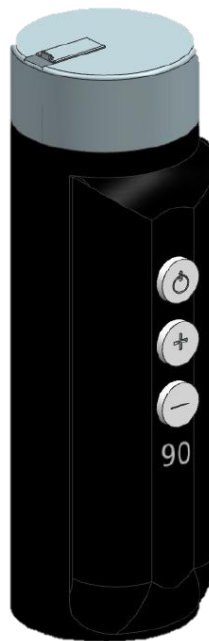


Figure 8. Assembled prototype model

3. RESULTS

The results obtained throughout the development and validation of the coffee-making device confirmed the feasibility and robustness of the proposed design. The integrated approach, spanning from user-centered need identification to functional prototyping, enabled a holistic understanding of both technical and practical aspects of the solution.

3.1 Functional performance

The final prototype successfully met all core performance specifications. Thermal simulations and analytical calculations demonstrated that the device could retain the coffee temperature within a 5% loss margin during the first 30 minutes post-brewing under standard ambient conditions (25°C). Even under extreme external temperatures (3.2°C and 38.4°C), the beverage remained within acceptable sensory thresholds, with temperature drops occurring in predictable, linear patterns.

Heating performance was also consistent with expectations. The system was capable of bringing 200 mL of water from ambient temperature (25°C) to 90°C in approximately 10 to 12 minutes when powered at 120 W, safely within the 15-minute target window. These results validate the selection of the heating element and the adequacy of the 12 V vehicle power source.

3.2 Stability and usability

Stability analysis showed that the device maintained equilibrium on inclined surfaces up to 40°, exceeding typical in-vehicle tilt angles, even during acceleration or abrupt maneuvering. Furthermore, the selected lid design (slit-type) provided both ease of use and spill resistance, aligning with ergonomic expectations identified in the user survey.

In terms of usability, the prototype required only two simple steps: water input and activation via a single button, making it suitable for use while stationary or during extended stops. All operations could be performed safely and intuitively, without exposing the user to hot surfaces or open heating elements.

3.3 Cost and manufacturability

The final prototype was constructed at a total cost of R\$ 77.68, approximately 35% of the predetermined cost ceiling (R\$ 220). This suggests a strong potential for cost-effective production at scale, particularly with further optimization in material selection, part integration, and supplier negotiation.

The bill of materials consisted largely of readily available components, and no advanced manufacturing processes were required for assembly. This characteristic enhances the product's viability for low-volume production scenarios, such as local fabrication initiatives or crowdfunding-based launches.

3.4 Educational impact

Beyond the technical achievements, the project exemplifies the pedagogical efficacy of PBL in engineering education. Students were required to synthesize knowledge across thermodynamics, materials science, electronics, cost analysis, and CAD modeling. They also engaged in collaborative decision-making, iterative problem-solving, and empirical validation, skills that closely mirror those required in professional design environments.

The project's real-world context, tangible constraints, and multidisciplinary nature fostered high levels of engagement, autonomy, and critical thinking, reinforcing the course's core educational objectives.

4. CONCLUSIONS

This study presented the complete development cycle of a portable coffee-making device tailored to the needs of urban vehicle users, as part of a project-based engineering design course at the University of São Paulo. From initial problem identification through market analysis, specification definition, conceptual design, and experimental validation, the project adhered to a structured and multidisciplinary methodology aimed at solving a real-world challenge.

The final solution successfully integrated heating, brewing, and thermal retention functionalities into a compact, low-cost system powered by a 12 V vehicle outlet. Analytical models and thermal simulations demonstrated strong performance in heat retention and energy efficiency, while stability and usability analyses confirmed the product's safety and ergonomic viability. The prototype was manufactured using commercially available components at a cost well below the established ceiling, reinforcing its feasibility from both technical and economic perspectives.

Beyond the engineering outcome, the project reinforced the effectiveness of PBL in cultivating essential skills for future professionals, including critical thinking, interdisciplinary collaboration, and design decision-making under constraints. The ability to deliver a tangible, validated prototype in response to a real consumer need exemplifies the pedagogical value of integrating theory with practice in undergraduate engineering education.

Future work may include further testing in dynamic automotive environments, integration of automated brewing systems, and exploration of sustainable materials and packaging for commercial scalability.

5. ACKNOWLEDGEMENTS

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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.