

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

# HALOgen: on the foundations for NLP interactions in electrical engineering education

João Pedro Cardoso Ferreira

MASTER'S THESIS REPORT



Mestrado em Multimédia, Especialização em Tecnologias Interativas e Jogos Digitais

Supervisor: Mário Alves

Co-supervisor: André Rocha

Co-supervisor: António Coelho

July 31, 2025



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# Abstract

This dissertation addresses the persistent challenges faced by electrical engineering students in learning the fundamentals of electrical circuit analysis, a core subject regarded as demanding both theoretically and practically. To promote a more effective, autonomous, and engaging learning experience, this work builds on the *U=RI*solve Academy educational platform — developed at the *Instituto Superior de Engenharia do Porto* — by restructuring its codebase to improve scalability and enable the future integration of additional learning modules with greater ease. One of the modules to be integrated is based on artificial intelligence, for which a dataset was created, bringing together materials used by first-year students in the Electrical and Computer Engineering programme at *Instituto Superior de Engenharia do Porto*, in the Fundamentals of Eletrotechnical Engineering and Circuit Theory courses. The trained model, named *HALO* assistant, was then integrated into the platform. This natural language processing is based on a model with a reduced number of parameters. Its performance was tested on content related to the nodal voltage method and the mesh current method through a blind evaluation alongside baseline models and the latest model released by OpenAI. The study involved more than 150 students and 18 domain experts, and the ongoing analysis is contributing to a scientific article in preparation with preliminary findings indicating that the trained models provide responses of comparable quality — and in certain aspects superior — to the significantly larger model that requires substantially greater computational resources.

**Keywords:** Autonomous Learning; Electrical Engineering; Artificial Intelligence.



# Resumo

Esta dissertação aborda os desafios persistentes enfrentados pelos estudantes de engenharia electrotécnica na aprendizagem dos fundamentos da análise de circuitos eléctricos, uma disciplina nuclear considerada exigente tanto a nível teórico como prático. Para promover uma experiência de aprendizagem mais eficaz, autónoma e envolvente, este trabalho desenvolve-se a partir da plataforma educativa *U=RSolve Academy* — desenvolvida no *Instituto Superior de Engenharia do Porto* — através da reestruturação da sua base de código, de modo a melhorar a escalabilidade e permitir, no futuro, a integração de módulos de aprendizagem adicionais com maior facilidade. Um dos módulos a integrar é baseado em inteligência artificial, para o qual foi criado um conjunto de dados, reunindo materiais utilizados por estudantes do primeiro ano da Licenciatura em Engenharia Electrotécnica e de Computadores do *Instituto Superior de Engenharia do Porto*, nas unidades curriculares de Fundamentos de Engenharia Electrotécnica e Teoria de Circuitos. O modelo treinado, denominado assistente *HALO*, foi então integrado na plataforma. Este processamento de linguagem natural baseia-se num modelo com um número reduzido de parâmetros, que teve o seu desempenho testado em conteúdos relacionados com o método das tensões dos nós e o método das correntes nas malhas, através de uma avaliação cega, em comparação com modelos de referência e o mais recente modelo lançado pela OpenAI. O estudo envolveu mais de 150 estudantes e 18 especialistas na área, com a análise em curso a contribuir para um artigo científico em preparação, cujas conclusões preliminares indicam que os modelos treinados fornecem respostas de qualidade comparável — e, em certos aspectos, superior — às do modelo significativamente maior, que exige recursos computacionais substancialmente superiores.

**Palavras-chave:** Aprendizagem Autónoma; Engenharia Electrotécnica; Inteligência Artificial.



# Acknowledgements

I would like to begin by expressing my sincere and profound gratitude to Professor André Rocha, who accompanied me throughout this dissertation on a regular basis. His guidance not only helped me resolve minor issues as they arose but also allowed me to better understand how to carry out work in an academic environment. During the course of this dissertation, his support enabled me, for example, to start co-supervising three undergraduate final-year projects, which in turn greatly enriched both the completion of this dissertation and my academic development.

I am especially grateful to Professor Mário Alves for continuing to believe in me over these past two years and for supporting me in carrying out this dissertation. Even in the most difficult moments, it was Professor Mário Alves who gave me the support that kept me from giving up and helped me maintain a vision for the future. I am also thankful for his support in writing my first scientific paper, the development of which is intrinsically linked to this dissertation and which, in turn, allowed me to approach the writing of this report with greater calm, seriousness, and professionalism.

To my co-supervisor, Professor António Coelho, I extend my thanks for his involvement, for sharing valuable ideas related to gamification and for all the advice he has provided, advice that has already proven helpful and will surely continue to do so in the future.

I would also like to thank Professor Paulo Oliveira for his support in the design and analysis of the evaluation study, which contributed both to this dissertation and to the two scientific papers currently in preparation.

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João Ferreira



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# Abbreviations

- AI** Artificial Intelligence. 3–7, 11–13, 15, 17, 23, 33, 44–47, 69
- API** Application Programming Interface. 4, 5, 7, 30, 46
- BCM** Branch Current Method. 2, 22
- DEE** Departamento de Engenharia Eletrotécnica. 5, 42
- ECE** Electrical and Computers Engineering. 2, 5–7, 9, 24–26, 41, 42, 69
- FEELE** Fundamentos de Engenharia Eletrotecnia. 7, 9, 42, 61, 67, 70
- GenAI** Generative Artificial Intelligence. 3–5, 11–13, 15, 17–19, 45
- GPT** Generative Pre-trained Transformer. 12
- HTTP** Hypertext Transfer Protocol. 32
- IDE** Integrated Development Environment. 33
- ISEP** Instituto Superior de Engenharia do Porto. 1, 9, 11, 24, 42, 45
- LCM** Loop Current Method. 2, 22, 45, 51, 52
- LLaMA** Large Language Model Meta AI. 45
- LLM** Large Language Model. 49–51
- MVC** Model, View, Controller. 28, 29, 32
- NLP** Natural Language Processing. 3–5, 23, 41
- NVM** Node Voltage Method. 2, 22, 43, 45, 51, 52
- PL** Practical-Laboratory. 9
- QUCS** Quite Universal Circuit Simulator. 1, 9, 22

**RAG** Retrieval-Augmented Generation. [27](#), [41](#), [44](#), [46](#), [49](#), [50](#), [58](#), [69](#)

**STT** Speech-To-Text. [7](#), [47](#)

**T** Theoretical. [9](#)

**TCIRC** Teoria dos Circuitos. [7](#), [9](#), [42](#), [57](#), [61](#), [67](#), [70](#)

**TTS** Text-To-Speech. [7](#), [47](#)

**UI** User Interface. [63](#)

**UX** User Experience. [63](#)

# Chapter 1

## Introduction

### 1.1 Research Context and Motivation

Electrical engineering lies at the heart of numerous technological advancements that define the modern world. Among its several domains, electrical circuit analysis stands out as a fundamental pillar, underlying both theoretical developments and practical innovations. Mastering this subject is essential for the formation of competent professionals capable of addressing increasingly complex engineering challenges.

Despite its importance, students frequently encounter significant difficulties in acquiring the core principles of circuit analysis. These difficulties arise from various factors, including the abstract nature of the mathematical reasoning involved and the limited emphasis placed on foundational logical skills in earlier stages of education. Furthermore, the lack of interactive, user-friendly learning environments exacerbates these challenges, preventing students from developing the analytical skills required in a rapidly evolving, technology-driven world.

Over the years, to address these persistent difficulties in learning the fundamentals of electrical circuit analysis, a research team led by the two Instituto Superior de Engenharia do Porto (ISEP) supervisors of this dissertation have conducted several projects and initiatives aimed at developing innovative educational strategies and tools. Such as:

- Realistic oscilloscope simulators aimed at reducing the learning curve associated with laboratory equipment [Sal05] [Per15] [FRAO25].
- Deterministic algorithms for solving electrical circuits according to different methods of analysis [SRAP21a] [Pin22].
- Add-ons for the open-source and widely used Quite Universal Circuit Simulator (QUCS), augmenting the functionality of the official version with education-orientated instruments and graphical outputs [Mar] [Sil17].

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- Foundational research that, although not directly applied by students, has facilitated communication across projects or served as a basis for future developments.

These research lines have been developed in the context of the *U=RIolve Academy* framework, an ongoing academic initiative aimed at the design of innovative educational tools in electrical engineering. Coordinated by Professor Mário Alves (lead supervisor of this dissertation) and Professor André Rocha (technical coordinator and co-supervisor of this dissertation), this framework supports research and development work at various academic levels, namely undergraduate final-year projects, master's dissertations, and doctoral research.

The framework originated back in 2018 with the creation of the *U=RIolve* application, developed by Lino Sousa as part of his undergraduate project in Electrical and Computers Engineering (ECE) [SRAP21b]. Initially conceived as a web-based algorithmic solver employing the Node Voltage Method (NVM), this application laid the foundation for subsequent advancements. Over time, additional analytical methods—including the Branch Current Method (BCM), Loop Current Method (LCM) [Pin22], and the Superposition Theorem—were integrated, extending the platform's educational utility. The *U=RIolve* application is currently accessible at <https://urisode.pt/app/>.

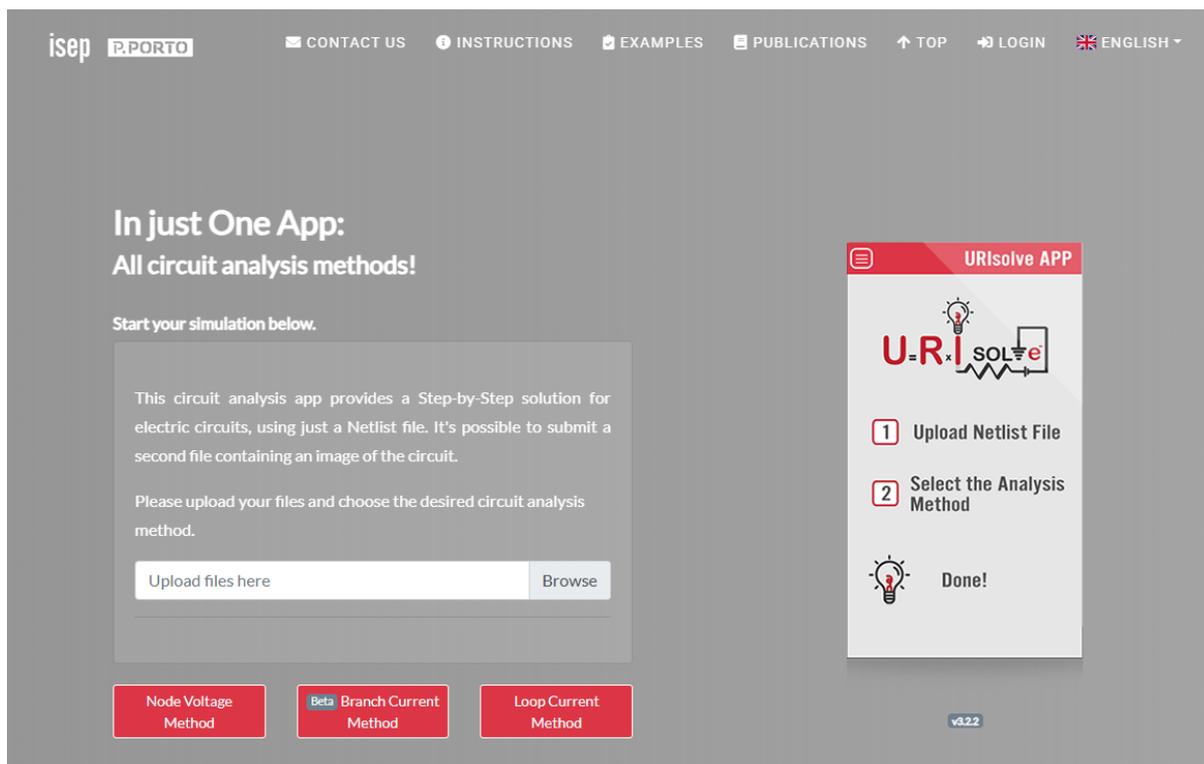


Figure 1.1: *U=RIolve* main page.

Building on this foundation, the framework evolved in 2023 with the development of *U=RIolve Academy*, authored by Ana Castedo as a final-year ECE project [Cas23]. This new project aimed to aggregate previous innovations into a single portal that integrates various tools and introduces a new

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concept for studying electrical circuit analysis through the use of multiple-choice and short-answer questions. Figure 1.2 illustrates the interface of the "practice mode", which implements this concept.

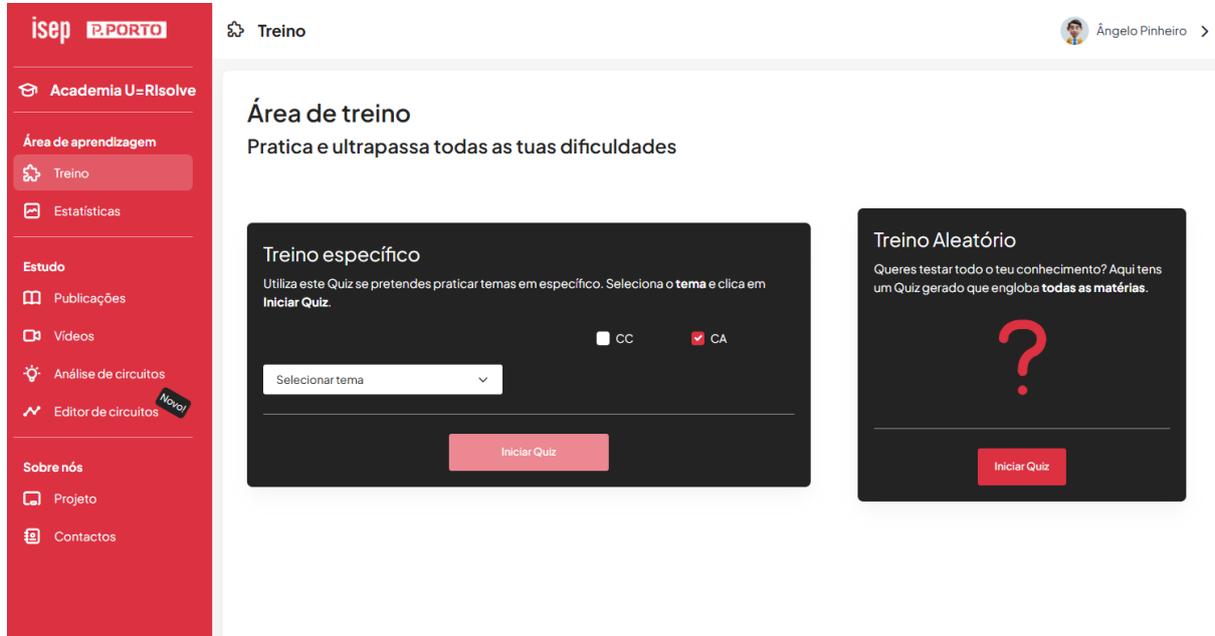


Figure 1.2: *U=RSolve Academy* practice mode page.

While these initiatives have yielded valuable contributions, they share common limitations that restrict their broader pedagogical impact due to their nature of application. In particular, their reliance on deterministic, static content constrains their ability to provide personalised feedback, adapt to individual learning trajectories, or scale efficiently to accommodate evolving curricular demands.

A persistent gap thus remains in the development of educational platforms capable of delivering dynamic, adaptive, and interactive learning experiences in the field of circuit analysis. Addressing this gap is crucial for preparing graduates who are not only proficient in technical knowledge but also equipped to engage with complex, real-world problems.

Recent advances in Artificial Intelligence (AI), particularly in Generative Artificial Intelligence (GenAI) and Natural Language Processing (NLP), present promising opportunities to address these gaps. Such technologies enable:

- The creation of adaptive learning environments capable of generating dynamic content
- The possibility of providing personalised feedback in real time.

However, their integration into educational tools also introduces new challenges, including the need to ensure content accuracy and pedagogical soundness in automatically generated materials.

It is in this context that the present dissertation is situated. This work aims to contribute to the evolution of the *U=RSolve Academy* framework by (i) exploring the integration of AI-driven mechanisms, such as *HALO*—developed under the guidance of the framework’s technical coordinator—and (ii) preparing the *U=RSolve Academy* codebase to support this integration and future developments.

It is within this context that the need arises for educational tools that not only consolidate previous developments but also leverage emerging technologies to overcome existing pedagogical limitations. The evolution of frameworks such as *U=RSolve Academy* reflects an ongoing effort to address these challenges through the integration of innovative approaches that promote more dynamic, adaptive, and interactive learning environments. This dissertation is positioned within this broader endeavour, motivated by the potential of AI and related technologies to enhance the teaching and learning of electrical circuit analysis.

### 1.2 Objectives

To address the challenges identified in the previous section, this dissertation is structured around two primary objectives. The first is the restructuring of the *U=RSolve Academy* codebase to enhance scalability and long-term maintainability, thereby facilitating future development and integration of new features. The second objective, which is aligned with the research direction of Professor André Rocha, technical coordinator of the *U=RSolve Academy* framework, focused on exploring the integration of GenAI and NLP technologies into educational tools.

Specifically, this second objective aims to contribute to the design, development, and initial validation of a proof-of-concept AI-driven assistant capable of supporting personalised learning experiences within the domain of the fundamentals of electrical circuit analysis. This effort forms part of the broader *HALO* framework, developed under Professor André Rocha's doctoral research.

Accordingly, this dissertation pursues the following concrete tasks:

- Design and implement a robust codebase structure for the *U=RSolve Academy* platform, enabling future extensions and integration of advanced features, in line with all the previous *U=RSolve* projects and also ongoing projects.
- Contribute to the development of an NLP-based educational assistant by creating a baseline dataset and supporting the evaluation of the model's performance in the context of the *HALO* framework.
- Connect, via Application Programming Interface (API), the *HALO* model to the *U=RSolve Academy* platform to create an initial integration pathway for GenAI-driven functionalities.

The expected outcomes of this work include a robust and extensible software foundation that supports ongoing innovation within the *U=RSolve Academy* framework, as well as a well-structured dataset capable of serving as a basis for training and refining AI-driven educational tools.

### 1.3 Research Approach

The research strategy adopted in this dissertation is structured to align with the dual focus on software engineering and educational technology innovation, as outlined in the objectives. The work is organised into four interrelated phases, designed to incrementally build towards the envisioned integration of AI-driven educational support.

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1. **Software architecture analysis and restructuring.** The initial phase involved a systematic review and reorganisation of the existing *U=RSolve Academy* codebase. This process began with a detailed study of the original architecture, followed by the proposal of a new structure and the evaluation of suitable technologies to support this restructuring. The codebase was then adapted to the new design, preserving as much as possible of the work developed by previous contributors, in line with established software engineering principles;
2. **Dataset development.** The second phase focused on the design and compilation of a baseline dataset on the fundamentals of electrical circuit analysis, intended for the training and evaluation of NLP models within the *HALO* framework. This dataset was carefully curated from official teaching materials produced by the Departamento de Engenharia Eletrotécnica (DEE);
3. **API-based integration of AI components.** Building on the outcomes of the preceding phases, the third phase established an API-driven communication layer between the *U=RSolve Academy* platform and the *HALO* framework. This approach enabled the initial exploration of GenAI capabilities without embedding AI components directly into the core platform;
4. **Fine-tuned model evaluation.** The final phase involved the evaluation of the AI-driven assistant, trained using the developed dataset, with respect to accuracy, response quality, and other relevant dimensions. This evaluation was carried out through a blind test involving more than 150 first-year students from the ECE and 18 selected experts in fundamental circuit analysis, including both professors and advanced students, and compared the fine-tuned model performance with that of commercially available models.

Throughout all phases, the work focused on incremental development, exploratory testing, and continuous alignment with pedagogical goals. An overview of the project timeline and key milestones is provided in the Gantt chart in Figure [1.3](#).

## Introduction

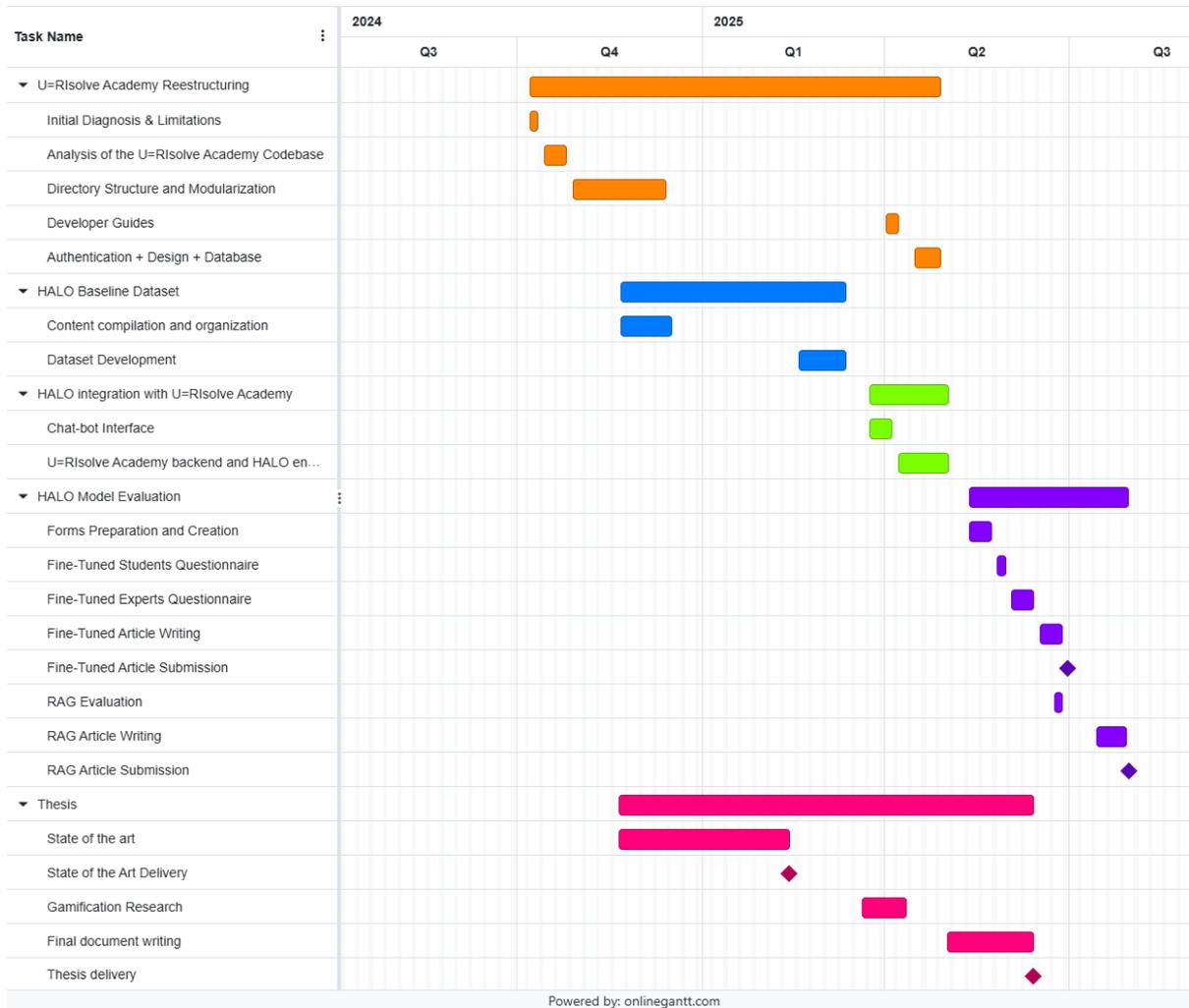


Figure 1.3: Gantt chart

## 1.4 Contributions

This dissertation provides four main contributions to the advancement of educational tools in electrical circuit analysis, each aligned with the objectives outlined previously.

- Restructured codebase for the *U=RIssolve Academy* platform:** A robust and scalable platform architecture, accompanied by guidelines for future developers, designed to support current functionalities and facilitate future extensions and integrations. These may include AI-driven components, gamification elements, or additional electrical circuit analysis tools (e.g., those currently under development by three final-year ECE students under the co-supervision of the author). Further details on the structure, guidelines, and these associated projects are provided in Chapter 3.
- Baseline dataset for the fundamentals of electrical circuits:** A curated dataset covering 11 chapters and 75 distinct topics related to the fundamentals of electrical circuits, as taught in the

first-year Teoria dos Circuitos (TCIRC) and Fundamentos de Engenharia Eletrotecnia (FEELE) courses of the ECE programme. The dataset was designed to ensure uniform coverage of the syllabus and provides a solid foundation for training and refining AI models aimed at enhancing student learning. Further details are presented in Chapter 4 while the full dataset can be seen in the repository [https://github.com/urisolve/halogen/blob/main/dataset\\_fundamentos\\_circuitos.md](https://github.com/urisolve/halogen/blob/main/dataset_fundamentos_circuitos.md).

- **Integration of *HALO* into the *U=RI*solve Academy platform:** The establishment of an API-based communication layer bridging the *U=RI*solve Academy platform and the *HALO* framework. This integration is implemented as a chatbot within the platform, enabling multimodal interaction through Speech-To-Text (STT) and Text-To-Speech (TTS) functionalities, without embedding the AI components directly into the core platform.
- **Fine-tuned model evaluation:** The design and execution of survey questionnaires and the corresponding data collection used to evaluate a fine-tuned model trained on the developed dataset through a blind comparison against the base models and a commercially available model. The evaluation involved over 150 first-year ECE students and 18 domain experts. Both the methodology and the initial analysis are presented in Chapter 5. Finally, a comprehensive study will form part of a scientific article currently in preparation, authored by Professor André Rocha and the author of this dissertation (as second author), with contributions from Professor Mário Alves and Professor Paulo Oliveira. Submission is planned following the completion of this dissertation.

Additionally, this dissertation prepared the groundwork for three future research directions that are outlined in Chapter 6, which aim to further expand and refine the integration of future educational technologies in the field of electrical engineering education.

## 1.5 Dissertation Organization

The remainder of this document is structured as follows:

- Chapter 2 presents a comprehensive review of the state of the art, examining current challenges in electrical engineering education and exploring the roles of GenAI and gamification in this context.
- Chapters 3, 4, and 5 detail the main contributions of this research according to the methodological plan.
- Chapter 6 outlines two potential directions for future work.
- Chapter 7 summarises the conclusions drawn from this dissertation.

## Introduction

## Chapter 2

# State Of The Art

This chapter provides an overview of the current state of knowledge and research related to the dissertation. It is divided into two large sections: literature review and related.

### 2.1 Literature Review

#### 2.1.1 Electrical Engineering Challenges and Innovations

The first year of the bachelor's degree in ECE at ISEP comprises two core modules: FEELE and TCIRC. Each consists of traditional lectures (Theoretical (T) classes) in an auditorium style with 60 students expected per class and practical hands-on laboratory sessions (Practical-Laboratory (PL) classes) with 10 to 15 students in a laboratory, distributed across nine workbenches.

To facilitate practical experience, a set of 8-9 pre-laboratory guides is supplied, allowing the students to prepare for experiments asynchronously before engaging in the lab sessions. For these asynchronous preparations, the students have to answer a list of multiple-choice, short-answer and file submission-type exercises. For the latter, the students are advised to make use of popular simulation tools such as QUCS [Mar] [Sil17] and PSpice [Sys] for circuit editing and the web-based oscilloscope simulator (developed by the first three authors of this dissertation) [JPCFO24] [FAR23] [FRAO25] to understand the fundamentals of the oscilloscope and signal generator (TCIRC Lab Script 2) in order to simulate the lab experiment beforehand. In addition to these preparations for the experiments, there are two practical laboratory works for each module to evaluate students' ability to apply the practical knowledge in a controlled environment under a certain time limit.

With a high number of annual enrolments, ISEP plays a significant role in training electrical engineers, contributing to the field's development and the broader engineering community.

As technological advancements continue to reshape education, the adaptation of new methodologies, such as distance learning and digital tools, has become increasingly relevant. Distance learning

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is an educational paradigm wherein students and instructors do not imply to be physically present in the same location, relying on digital technologies for communication and knowledge dissemination. This approach can be executed using pre-recorded lectures, live transmissions, discussion forums, interactive resources, and learning management systems [AA14].

Distance learning can be classified into two main formats [ZL24]:

- Synchronous learning: Activities occur in real-time, requiring simultaneous connection between students and instructors. This is possible via video conferencing, resembling the traditional classroom settings.
- Asynchronous learning: Content is available for students to access at their convenience, without the need for real-time interaction. This might include recorded lectures, reading materials, and assessments that students can complete independently.

The integration of distance learning in engineering education aims to enhance accessibility, offering increased flexibility for students and mitigating geographical limitations. This concept has been particularly beneficial for professionals seeking continuous education, students in remote locations, and individuals balancing studies with work and personal commitments [L+17] [AA14].

The mandatory shift to distance learning during the COVID-19 pandemic highlighted both the strengths and limitations of this approach, particularly in engineering disciplines that heavily rely on laboratory-based instruction. This unexpected shift prompted institutions worldwide to reassess their educational methodologies and adopt innovative strategies to replicate practical experiences remotely. Several universities implemented virtual and remote laboratory solutions, enabling students to continue conducting experiments despite restrictions on physical presence [WDK+21] [EH20] [SZM21] [IAMK22].

These adaptations underscored the necessity for flexible and scalable solutions in technical education. While digital platforms facilitated continued learning, the absence of hands-on experiences posed challenges in skill acquisition, necessitating further innovations in remote engineering education.

While distance learning provided a necessary solution during the pandemic, its effectiveness in replacing traditional, in-person education remains a topic of debate [KBSP24]. Studies suggest that, when supported by robust digital technologies, distance learning can match or even exceed traditional methods in certain areas, such as accessibility and scalability [PSS+20]. However, barriers remain, including reduced physical interaction, limited opportunities for collaborative problem-solving, and technological constraints.

### 2.1.2 Modern Educational Methodologies

In response to evolving educational needs, modern teaching approaches have moved beyond traditional lecture-based instruction to emphasise student-centred learning. These methods prioritise active engagement, personalised guidance, and the development of problem-solving skills, aligning with the demands

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of engineering education. Research highlights that fostering autonomy and critical thinking in students leads to improved knowledge retention and skill acquisition [CDMC22] [PKL21].

Coaching is one approach within student-centred learning that emphasises individualised support and active participation. Unlike conventional instruction, which primarily focuses on content delivery, coaching encourages students to take ownership of their learning journey, fostering deeper comprehension and self-motivation [AMIM19].

Student-centred learning presents several key advantages over traditional methods [GR22] [FEM<sup>+</sup>14]:

- **Personalised Learning Pathways:** Tailoring instruction to individual student needs enhances comprehension and long-term retention of concepts.
- **Development of Critical Thinking Skills:** Encouraging inquiry-based learning and problem-solving fosters analytical reasoning, a crucial skill in STEM disciplines.
- **Increased Student Engagement and Motivation:** Interactive learning environments promote active participation, which has been linked to higher academic achievement.
- **Encouragement of Self-Regulated Learning:** Promoting autonomy in students prepares them for continuous learning beyond formal education.

By integrating these principles into educational frameworks, institutions can create more effective and engaging learning experiences, equipping students with the necessary skills to navigate complex professional challenges. However, despite its benefits, implementing student-centred learning faces some challenges [KNea23] [OW20]:

- **Dependence on Instructor Expertise:** This approach requires educators to act as facilitators rather than traditional lecturers, demanding not only subject-matter expertise but also strong mentoring and adaptive teaching skills. Variability in instructors' experience with such methods may lead to inconsistencies in student outcomes.
- **Scalability in Large Classrooms:** The need for personalised feedback and mentorship makes it difficult to implement student-centred teaching effectively in large student groups without sufficient institutional support.

The success of this method depends on both educators' ability to transition to facilitative roles and students' willingness to take responsibility for their own learning. Institutional support, adequate training, and structured implementation strategies are essential to address these challenges effectively.

Certain courses at ISEP have already incorporated elements of student-orientated learning, particularly through guided exercises and interactive problem-solving environments. Examples include the *U=RI*solve Academy described with more detail in Section 3.1, which utilises structured, step-by-step methodologies to support student engagement and comprehension. These initiatives demonstrate how adaptive teaching strategies can be integrated into engineering education, enhancing both theoretical understanding and practical application.

The principles of student-orientated learning align closely with the capabilities of GenAI, which can offer personalised guidance, adaptive feedback, and interactive problem-solving experiences. AI-driven

educational tools have the potential to act as facilitators, dynamically adjusting to individual student needs and providing tailored support throughout the learning process [CCL20].

By leveraging AI to implement student-centred methodologies at scale, institutions could enhance both traditional and remote education. While AI cannot fully replicate human intuition and mentorship, its ability to provide structured feedback and adaptive learning experiences makes it a promising tool for supporting more engaging and effective educational practices.

### 2.1.3 Usage of GenAI in Education

The emergence of GenAI tools, such as ChatGPT, has initiated a significant transformation in education. These technologies are reshaping the ways students interact with learning materials while simultaneously influencing educators' approaches to content delivery [SH23] [MVVPSN+23]. As AI systems become increasingly sophisticated, their integration into educational frameworks presents new opportunities and challenges for both students and instructors [MMD24].

Generative AI refers to AI models designed to generate content autonomously based on patterns and knowledge extracted from vast datasets. Unlike traditional AI systems that operate on predefined rules, GenAI utilises machine learning techniques, particularly deep learning, to produce human-like text, images, and even code [Wan19]. These systems, such as Generative Pre-trained Transformer (GPT)-4 [(2023)] and similar models, can process queries, generate explanations, and simulate conversations, making them highly adaptable for educational purposes.

Generative AI encompasses a diverse range of applications designed to enhance the learning experience across various educational contexts. Key capabilities include:

- **Personalised Tutoring and Feedback:** GenAI systems can simulate one-on-one tutoring by providing detailed explanations, answering questions, and offering tailored feedback to students. By dynamically adapting to individual learning needs, these tools enhance motivation and improve the quality of student revisions, fostering deeper engagement and comprehension [MJS+24].
- **Content Generation and Summarisation:** Tools like ChatGPT can assist educators by generating teaching materials, creating quizzes, and summarising complex topics, saving time and ensuring consistency in instructional design [MMD24] [AB23].
- **24/7 Support and Accessibility:** Many GenAI tools are available for free or at low cost, allowing students to access learning assistance at any time. While some limitations exist, such as occasional disconnection from the servers, these tools significantly increase access to educational resources [MVVPSN+23].

Despite its potential to enhance personalisation and scalability in education, the integration of GenAI also introduces challenges that must be carefully addressed. As educational institutions explore these tools, it is crucial to assess their broader implications to ensure they support, rather than compromise, learning objectives. Some key considerations include:

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- **Ethical and Privacy Concerns:** The use of AI in education raises questions about data privacy, algorithmic bias, and the ethical implications of relying on automated systems for personalised learning [AB23].
- **Dependence and Skill Development:** Over-reliance on GenAI may hinder the development of critical thinking and problem-solving skills if students excessively depend on AI-generated responses without engaging with the material [WYC<sup>+</sup>24].
- **Accuracy in response:** Since GenAI models generate text based on probabilistic predictions, occasional inaccuracies are inevitable. This can lead to misunderstandings, especially for users who may not be aware of the tool's limitations, potentially resulting in the absorption of incorrect information [NDH<sup>+</sup>23] [LS24].

GenAI is not a one-size-fits-all solution but rather a complementary tool that, when integrated thoughtfully, can help address specific educational challenges. Since traditional teaching methods and hands-on experimentation remain fundamental, as they provide essential practical skills and deeper conceptual understanding. The role of GenAI should be seen as a support mechanism rather than a standalone replacement, enhancing learning experiences rather than substituting core educational practices [AB23].

To maximise its benefits, engagement strategies must be developed to encourage students to use these tools effectively. Approaches such as interactive learning frameworks and gamification can play a crucial role in fostering student motivation and active participation, ensuring that AI-driven resources are leveraged in a meaningful and pedagogically sound manner.

### 2.1.4 Role of Gamification in Education

Gamification is a concept that integrates game design elements into non-game contexts to enhance user engagement and motivation. This approach has gained traction across various fields, including education, healthcare, and business, as it leverages the intrinsic motivations associated with gaming to promote desired behaviours and outcomes. Sebastian Deterding, a key figure in the field, defined gamification as the use of game design elements in non-game contexts, emphasising its potential to transform user experiences and interactions [DDKN11].

The roots of gamification can be traced back to sociological discussions on play and games, notably in the works of Roger Caillois, who highlighted the complex nature of games and their role in human behaviour [BAO<sup>+</sup>23]. Deterding and his colleagues further developed this concept, providing a framework that outlines how gamification can be effectively implemented to foster engagement and motivation [DDKN11]. Their research indicates that gamification can disrupt traditional learning environments, encouraging active participation and making the learning process more enjoyable [DR20].

Building on these insights, its practical implementation relies on the strategic use of game mechanics and design principles to enhance user engagement and motivation. These mechanics—such as points,

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badges, leaderboards, challenges, and rewards—are strategically designed to foster a sense of achievement, progression, and competition. Their effectiveness depends on how they are implemented and the specific context in which they are applied. Table 2.1 summarises key gamification mechanics, their definitions, and an example of their application in the education scope based on the research by the authors [ZSHC20] [DDKN11] [CSMLRF<sup>+</sup>23].

<b>Game Mechanic</b>	<b>Definition</b>	<b>Example of Application</b>
<b>Points</b>	Numerical values awarded for completing tasks or achieving goals.	Students earn points for completing quizzes or assignments in an online learning platform.
<b>Badges</b>	Visual symbols of achievement that represent milestones reached by users.	Learners receive badges for mastering specific skills or completing course modules.
<b>Leaderboards</b>	Rankings that display users' performance relative to others, fostering competition.	A leaderboard that showcases the ten best highest-scoring students when comparing the number of correctly answered questions (in a quiz).
<b>Challenges</b>	Specific tasks or objectives users must complete, often within a time limit.	Students engage in timed coding challenges to reinforce problem-solving skills.
<b>Rewards</b>	Incentives provided for achieving certain goals, which can be tangible or intangible.	Learners unlock rewards, either in game or at the final grade upon reaching a certain level of engagement.
<b>Feedback</b>	Information provided to users about their performance to help them track progress.	Immediate feedback on quiz answers helps students identify areas for improvement.
<b>Progress Tracking</b>	Visual representation of user progress through bars, graphs, or milestones.	A progress bar indicates course completion percentage, motivating learners to stay on track.

Table 2.1: Key Gamification Mechanics and Their Applications

Furthermore, game mechanics strike a delicate balance between challenge and reward. They adapt difficulty levels as users progress, ensuring tasks are neither too easy nor too difficult, which fosters a continuous sense of achievement, encouraging sustained engagement and effort. This structure is rooted in various psychological theories, including Flow Theory, which posits that individuals experience optimal enjoyment when the challenge of a task aligns with their skill level [RFL19].

The application of gamification in education offers a promising solution to some of the most persistent issues in traditional learning systems. Education often struggles with maintaining student motivation, particularly when learners perceive the material as irrelevant or disconnected from their interests.

Gamification presents an opportunity to reframe the learning experience, making it more interactive, engaging, and aligned with students' needs [SNO21].

However, it is crucial to adapt these elements thoughtfully. Unlike games, the ultimate goal of education is not engagement for its own sake but fostering deep understanding and long-term skill development. Gamification should therefore be seen as a tool to enhance learning, not as a replacement for traditional pedagogical strategies [DDKN11] [KSvK21].

A particularly promising avenue is the integration of gamification with GenAI and coaching methodologies. AI-driven systems can personalise gamified learning experiences by dynamically adjusting challenges and content based on student progress. When combined with student-centred learning principles, these tools can provide tailored guidance while sustaining high levels of engagement through gamified elements. While this approach does not replace traditional learning, it remains a valuable tool worth investing in [Oua24].

## 2.2 Related Work

Building on the discussions presented in Sections 2.1.3 and 2.1.4, GenAI models have already been submitted to tests. This section aims to compare and draw conclusions about various educational tools that incorporate gamification concepts, are enhanced by GenAI, or combine both approaches. The tools to be analysed include ChatGPT, Wolfram Alpha, Duolingo, Brilliant, and Khan Academy. The insights gathered from these reviews are then consolidated in a comparative table to summarise these tools as e-learning platforms.

### 2.2.1 ChatGPT as an Educational Assistant

In the context of electrical engineering education, ChatGPT has emerged as a promising educational assistant [CSMLRF<sup>+</sup>23]. Developed by OpenAI and built upon the Transformer architecture [VSP<sup>+</sup>17], ChatGPT offers the potential to provide instant explanations and personalised support for a wide range of problems [BB24]. However, when applied to technical subjects that demand precise, multi-step problem solving—such as those encountered in circuit theory and laboratory-based courses—the tool reveals certain limitations [NDH<sup>+</sup>23].

For routine or less complex tasks, ChatGPT can effectively simulate one-on-one tutoring, offering detailed explanations and adaptive feedback. This capability can enhance practical sessions, where students benefit from immediate assistance in an uncontrolled environment [CSMLRF<sup>+</sup>23].

Conversely, when facing complex exercises that require multiple sequential steps, ChatGPT's performance can be inconsistent. Because ChatGPT lacks symbolic reasoning and operates on token probability, it may misapply formulas or fail to maintain logical consistency across multi-step circuit problems [LS24]. This over-reliance risks undermining the development of critical analytical and problem-solving skills, which are vital in engineering disciplines. Moreover, in more controlled assessment environments, the benefits observed in practical sessions are less evident, suggesting that ChatGPT may not

adequately replicate the nuanced guidance provided by human instructors; its ease of providing direct solutions might discourage the active learning processes essential for mastering complex technical content [ZH24].

While ChatGPT represents a valuable supplementary tool for electrical engineering education, its use must be balanced with traditional, hands-on methods. Studies say educators are encouraged to adopt it as an aid—one that supports, rather than replaces, the rigorous analytical and practical training central to engineering. This balanced integration is crucial to ensure that students continue to develop the essential skills needed for success in complex technical fields.

### 2.2.2 Wolfram Alpha

Wolfram Alpha, available at <https://www.wolframalpha.com/> is a computational knowledge engine developed by Wolfram Research that leverages symbolic computation, numerical analysis, and a vast, curated database to deliver precise answers to user queries. Unlike generative language models, Wolfram Alpha interprets natural language input and employs established algorithms to compute results, offering high accuracy for complex calculations or questions [Wol23]. This makes it a trusted resource across numerous academic disciplines [Abr21].

In the mathematical realm, Wolfram Alpha proves particularly useful for solving complex equations or graphically showing functions. When shifting to the electrical engineering realm, there is not much to be done. It can solve systems of equations derived from Kirchhoff's laws, compute equivalent resistances in intricate networks, and analyse both steady-state and transient behaviours of circuits. Moreover, the engine can generate detailed visualisations—such as circuit diagrams, Bode plots, and time-response graphs—that are essential for comprehending the dynamic performance of electrical systems; however, it cannot deal with the most complex methods of analysis, read written circuits or plot a circuit diagram.

Wolfram Alpha's rigorous computational capabilities and curated data make it an effective educational tool. Its specialised applications, especially in the mathematical realm, not only enhance quantitative analysis but also serve to integrate theoretical concepts with practical problem-solving, thereby enriching the overall learning experience. However, the same cannot be said for the electrical engineering material.

### 2.2.3 Duolingo

Duolingo is one of the most well-known examples of a gamified educational platform, designed initially for language learning but now widely recognised for its user engagement mechanics and adaptive learning models. Launched in 2011, Duolingo's success is largely attributed to its ability to make learning feel like a game—blending structured content with reward systems, progress tracking, and behavioural nudges that keep users consistently engaged [STK<sup>+</sup>23].

The platform leverages microlearning techniques by breaking lessons into small, manageable units that can be completed in minutes. Each session incorporates listening, reading, writing, and speaking

tasks, reinforced by immediate feedback and corrections. The design encourages repetition and retention, key aspects of skill acquisition supported by spaced repetition algorithms, such as:

- Language Score, daily streaks, total XP, and gems (virtual currency);
- Leagues and competitive elements that foster social comparison and consistent engagement;
- Achievement and monthly badges to also give users a sense of progression and accomplishment.

Despite its achievements, Duolingo’s domain-specific limitations must be acknowledged. Its model is highly effective for language acquisition but may not transfer directly to STEM disciplines such as electrical engineering, where concepts are more abstract and learning often requires symbolic manipulation, problem-solving heuristics, and lab-based application. Nevertheless, its engagement architecture and micro-assessment loops serve as a strong reference point for building motivating educational interfaces—even in more technical fields.

Duolingo proves that behavioural design and gamification, when paired with adaptive learning technology, can significantly increase learner retention and motivation.

### 2.2.4 Khan Academy

Khan Academy is a nonprofit educational platform that has become a global benchmark for delivering free, high-quality, and personalised instruction across a variety of subjects, including mathematics, science, computer programming, and economics. Originally launched by Salman Khan as a series of YouTube tutorials, the platform has evolved into a data-driven learning ecosystem that combines instructional videos, interactive exercises, and intelligent feedback mechanisms. Its pedagogical model is rooted in mastery-based learning, allowing students to progress at their own pace while revisiting concepts until proficiency is achieved. Adaptive algorithms support this model by presenting increasingly complex problems, offering scaffolded feedback and real-time hints, and visualising learning progress through personalised dashboards.

More recently, Khan Academy has integrated GenAI through its collaboration with OpenAI, leading to the development of *Khanmigo*, an AI-powered tutor capable of engaging students in Socratic-style dialogues, guiding them through problem-solving steps, and assisting teachers with lesson planning and feedback. Although still in the pilot stage, Khanmigo illustrates how GenAI can augment educational platforms without displacing their foundational pedagogical principles.

Nevertheless, the effectiveness of Khan Academy remains strongly domain-dependent. The platform excels in areas that benefit from stepwise reasoning and visual explanation, such as algebra, calculus, and physics, but proves less effective in hands-on technical domains like circuit simulation or laboratory experimentation. It lacks features such as symbolic computation, as offered by tools like Wolfram Alpha, or the linguistic adaptability of models like ChatGPT. Consequently, Khan Academy functions more as a conceptual reinforcement and skill-building platform than a substitute for real-world experimentation. Still, it serves as a valuable case study in AI-enhanced learning, demonstrating how a solid pedagogical

foundation can be meaningfully augmented with AI and gamification to increase motivation, personalisation, and engagement. Moreover, it highlights best practices in balancing structured content delivery with intelligent automation—an essential principle for the design of scalable and effective e-learning systems in engineering and other STEM disciplines.

### 2.2.5 Comparative Summary and Educational Implications

After discussing the individual characteristics of each tool, Table 2.2 provides a comparative summary of their key strengths, limitations, general educational focus, and specific usefulness within the context of electrical engineering education. This consolidation aims to give readers a clear, high-level overview of how each platform contributes to modern digital learning and what aspects could be adapted or improved for more technical and engineering-orientated use cases.

Table 2.2: Comparative Overview of GenAI-Enhanced and Gamified Educational Platforms

Tool	Strengths	Limitations	Educational Focus	Usefulness in Electrical Engineering Education
<b>ChatGPT</b>	Natural language interaction; personalized feedback; flexible explanations	Inconsistent with complex multi-step problems; may encourage shortcut learning	General, including STEM	Useful for tutoring-style support; limited for formal circuit analysis or lab simulations
<b>Wolfram Alpha</b>	Accurate symbolic/numeric computation; visual output; step-by-step solutions	Not interactive; no adaptive guidance; lacks engagement elements	Math and STEM computation	Very useful for solving and visualizing circuit problems; not engaging for long-term learning
<b>Duolingo</b>	Strong gamification (XP, streaks, rewards); microlearning; highly engaging design	Domain-limited to languages; no technical computation or STEM content	Language learning	Not useful for content, but highly useful as a gamification model
<b>Khan Academy</b>	Structured curriculum; adaptive feedback; some gamification features (badges, streaks); Khanmigo AI assistant	Lacks depth in complex technical subjects; limited hands-on application	K–12 and early undergraduate STEM	Useful for foundational topics; not suited for advanced or interactive circuit analysis

From this comparison, two clear trends emerge. First, platforms that incorporate *GenAI and natural language interaction*, such as ChatGPT and Khan Academy’s Khanmigo, offer valuable real-time support and flexibility, particularly in guiding users through personalised learning paths.

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Second, tools with *strong gamification elements*, such as Duolingo and Khan Academy, demonstrate higher potential for sustaining learner motivation and engagement over time. By integrating reward systems, progression tracking, and challenge loops, they transform educational effort into an intrinsically motivating experience. In this context, gamification doesn't just incentivise task completion—it **re-frames learning as a side effect of play**, which may be especially impactful for early-stage engineering students grappling with complex and abstract concepts.

These observations support the hypothesis that a hybrid system—one that blends **GenAI personalised support** and **gamified structures for sustained engagement**—could be particularly effective in teaching foundational concepts in electrical circuit analysis. This insight directly informs the design goals of the proof-of-concept platform presented in the following chapters.

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## Chapter 3

# U=RI solve Academy Software Architecture

This chapter begins by presenting an overview of the foundational work that preceded this dissertation, with a particular focus on the *U=RI solve Academy* framework. It then provides the necessary contextual background and delineates the principal objectives that informed the development of this study. Finally, it introduces the first major contribution of this dissertation: the restructuring of the *U=RI solve Academy* codebase to improve scalability, support future enhancements, and facilitate subsequent research initiatives.

### 3.1 *U=RI solve Academy* framework

The *U=RI solve Academy* framework constitutes a unified platform that integrates the various contributions developed under the *U=RI solve* initiative. Its overarching goal is to serve, in the future, as a comprehensive portal designed to support electrical engineering students in studying and practising electrical circuit analysis through interactive and pedagogically informed tools.

#### 3.1.1 Framework Origins and Development

The development of this platform began in 2018 with the creation of the *U=RI solve* application. At that time, it was implemented as a website featuring a deterministic algorithm for analysing electrical circuits using the nodal voltage method. This initial tool laid the foundation for the broader framework envisioned in the present dissertation, originally conceived by Professor Mário Alves (supervisor of this dissertation and lead coordinator of the framework) and Professor André Rocha (co-supervisor of this dissertation and technical coordinator of the framework) [SRAP21b] [SRAP21a].

To access the original application, users may visit <https://urisolve.pt/app> and submit an electrical circuit either in `.sch` (schematic) format—typically generated by circuit editors such as QUCS [Mar] or PSpice [Sys]—or in netlist format [Sol25], which contains a textual description of the circuit. After submission, users select their preferred method of analysis, currently including the NVM, BCM and LCM. The application then executes the corresponding algorithm and generates a detailed, step-by-step explanation of the solution process.

In addition to this circuit analysis tool, the *U=RIolve Academy* platform includes and is intended to include several other features, such as a circuit editor (currently under development by Ângelo Pinheiro), a realistic oscilloscope simulator [FRAO25], a generic oscilloscope simulator (currently in progress by Óscar Pinheiro), and the named "*Practice Mode*", originally conceived by Ana Castedo [Cas23], which presents students with quizzes on topics related to circuit analysis methods.

While these components represent important milestones, the existing platform (still under development) exhibits limitations that have motivated the enhancements proposed in this dissertation. These limitations raise concerns regarding scalability and the labour-intensive nature of producing educational materials, issues that this work seeks to address. The key challenges identified are as follows:

- **Lack of personalised feedback:** The electrical circuit analysis functionality provides users with a static, step-by-step resolution of the submitted circuit problem. While informative, this output is entirely deterministic and does not allow users to request additional explanations, alternative perspectives, or clarification on specific steps. This absence of interactivity may hinder deeper understanding, particularly when students encounter conceptual difficulties.
- **Manual and time-consuming question generation:** In the "*Practice Mode*", each individual quiz item must be carefully designed, authored, and pedagogically validated by educators. This process demands substantial time and effort, making it both labour-intensive and difficult to scale. As a result, expanding or diversifying the question bank to accommodate evolving curricula or varied student needs becomes increasingly impractical.
- **Limited engagement and learner motivation:** Although static question banks serve as useful tools for reinforcing knowledge, they often fall short in promoting sustained engagement. The lack of adaptive content, real-time feedback or other already introduced gamified learning elements (Section 2.1.4) may reduce student motivation and the overall effectiveness of the learning experience.
- **Generic and static help system:** The existing help features consist of predefined, manually written hints that remain the same regardless of user context or progress. This static approach does not adapt to individual learning trajectories and offers limited pedagogical support in addressing misconceptions or errors dynamically.

These limitations mostly stem from the deterministic nature of the existing tools. While this approach ensures consistency and pedagogical control, it restricts adaptability and personalisation.

The integration of NLP models offers the potential to overcome these constraints by enabling dynamic content generation and adaptive feedback. However, this transition introduces new pedagogical and technical challenges:

- **Content fidelity:** AI-generated questions may contain inaccuracies or misrepresent concepts. Inexperienced users may fail to identify such issues, thereby absorbing inaccurate content.
- **Precision of feedback:** AI-generated explanations and hints may sometimes be vague and misleading, inadvertently reinforcing misunderstandings and increasing cognitive load.

These challenges are inherent to probabilistic systems; however, they can be minimised through strategies such as expert curation, continuous validation and iterative refinement. Nevertheless, such trade-offs are expected when shifting from deterministic to AI-driven content generation. While the latter offers greater flexibility and scalability, it inherently lacks the control characteristic of static systems.

### 3.1.2 Research Positioning

The *U=RIolve Academy* framework has continued to expand through multiple parallel projects, each addressing specific challenges, some of which are unrelated to the previously identified constraints. Figure 3.1 provides an overview of selected recent projects that have been developed or are currently under development within the *U=RIolve Academy* framework.

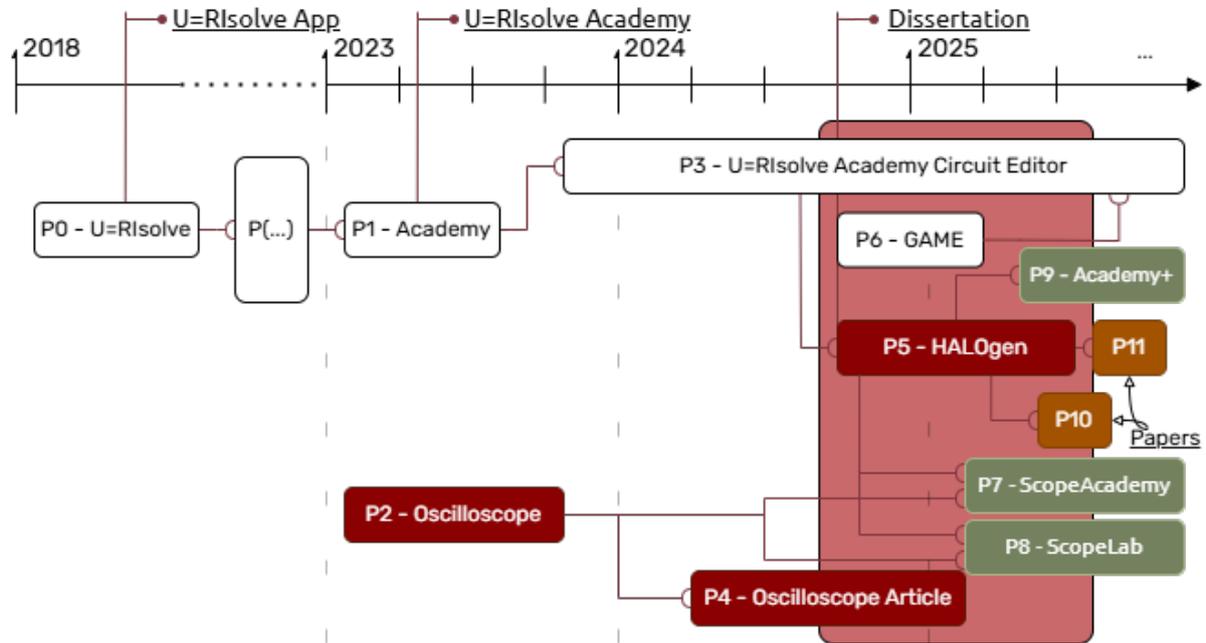


Figure 3.1: Timeline of selected projects under the *U=RIolve Academy* framework.

**Red:** Projects led by the author of this dissertation.

**Orange:** Scientific publications co-authored by the author of this dissertation.

**Green:** LEEC students' projects co-supervised by the author of this dissertation.

## U=RIolve Academy Software Architecture

These and other projects reflect the collaborative contributions of students at various academic levels, including final-year undergraduate projects in the LEEC programme at ISEP, master's dissertations, and doctoral research. Collectively, these efforts pursue a common goal: to evolve the *U=RIolve Academy* framework into a comprehensive portal designed to support electrical engineering students in studying and practising electrical circuit analysis.

**P0, P(...) and P1 - Prior developments (2018 - 2023)** Projects P0 (*U=RIolve* Application) and P1 (*U=RIolve Academy*) represent the core developments mentioned in the preceding section. Projects denoted as P(...) encompass additional initiatives that contributed to the current version of the framework. These include the implementation of alternative methods of analysis within the original *U=RIolve* tool, as described earlier, as well as various other supporting projects.

**P2 – Oscilloscope Interface (02/2023 – 09/2023)** This project involved the development of a web-based oscilloscope simulator designed to mimic the functionality of real laboratory equipment used in the Circuits and Signals lab at ISEP. The application supports two modes of operation: *simulation mode*, allowing users to interact with simulated signals generated via a built-in waveform generator or uploaded in .csv format, and *acquisition and control mode*, enabling remote manipulation and data acquisition from an actual oscilloscope in the lab. This was the first project inside the *U=RIolve Academy* framework led by the author of this thesis and was developed as part of the final ECE project. The application is publicly accessible at <http://osciloscopio.dee.isep.ipp.pt> [FAR23][FRAO25].

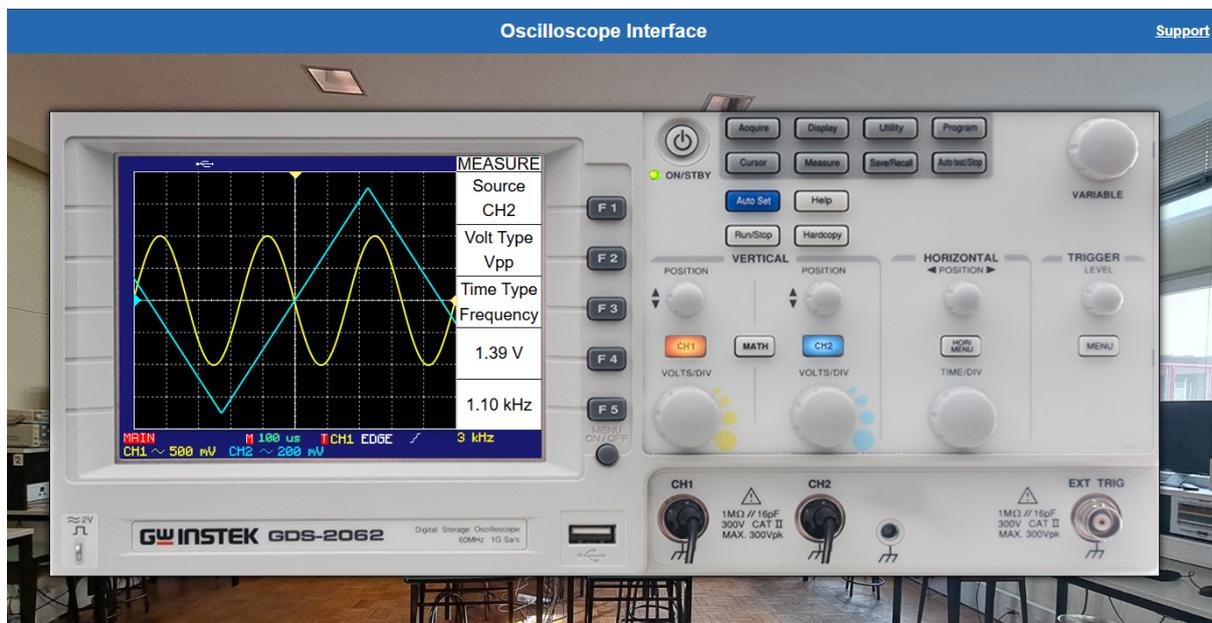


Figure 3.2: Oscilloscope Interface displaying two signals generated by the built-in signal generator.

**P3 – Circuit Editor (10/2023 - Ongoing)** This project, developed by Ângelo Pinheiro as part of his master’s dissertation in the master’s in ECE, builds upon the *U=RIsove Academy* platform. It involves the design and implementation of a built-in circuit editor that allows users to draw and customise electrical circuits directly within the *Academy* interface, enhancing interactivity and flexibility in circuit creation.

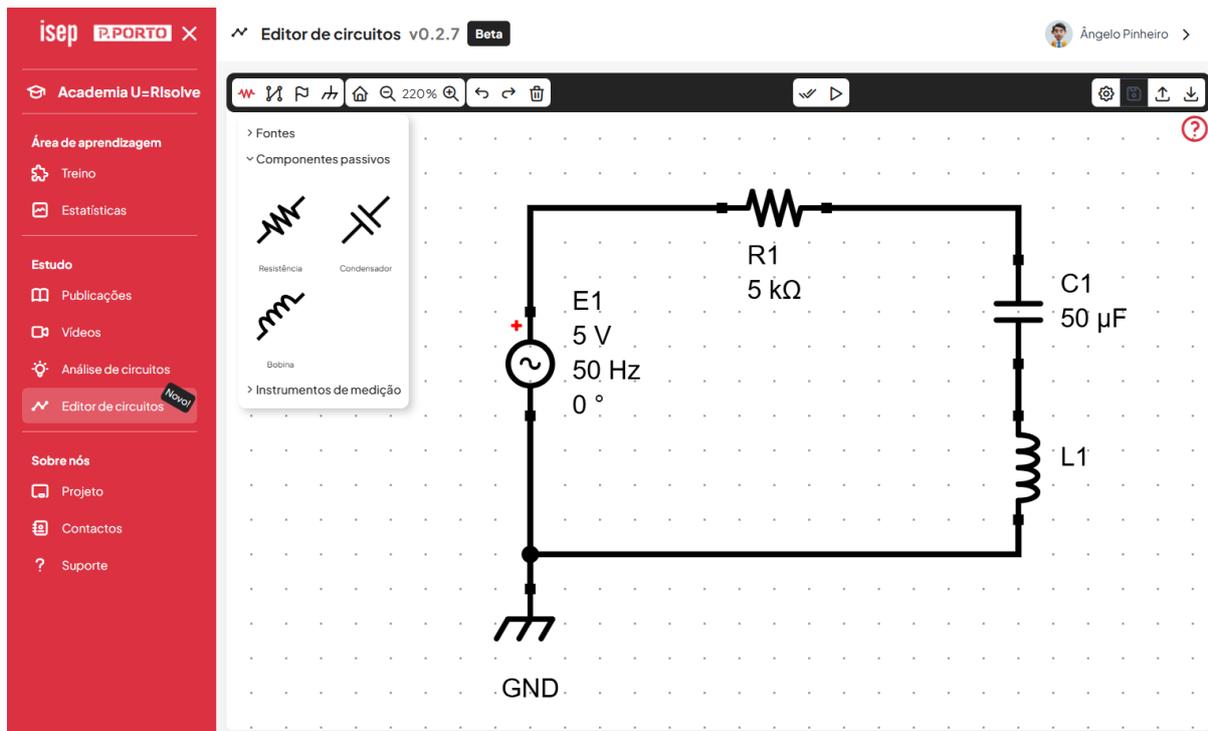


Figure 3.3: RLC circuit created using the built-in Circuit Editor.

**P4 – Oscilloscope Interface Article (03/2024 – 02/2025)** To assess the pedagogical value of the Oscilloscope Interface (P2), over 250 first-year ECE students used the application during lab preparation and a formal assessment requiring simulation-based tasks. Preceding these activities, a survey collected over 200 responses regarding the usability and perceived effectiveness of the tool. The outcomes of this empirical study are presented in an article accepted for publication in MDPI (February 2025), where the author of this dissertation is the first author [FRAO25].

**P5 – HALOgen (10/2024 – 07/2025)** Represents graphically this dissertation, highlighting its contribution in five projects within the broader framework and overall placement inside the framework.

**P6 – GAME (09/2024 – 02/2025)** Developed by Rodrigo Ferrero for his ECE final project, this initiative produced an algorithm capable of automatically generating electrical circuits based on user-defined

parameters (e.g., number of nodes, components, and branches). The resulting circuits can be exported in .json format, making them directly compatible with the Circuit Editor (P3) [FR25].

**P7 – ScopeAcademy (02/2025 – Ongoing)** Building on both the Oscilloscope Interface (P2) and the restructured codebase developed in this dissertation, this project aims to design a generic oscilloscope component for integration within the Circuit Editor (P3). In contrast to the realism of P2, ScopeAcademy offers a more pedagogically flexible interface. The project is led by Óscar Pinheiro as part of his final ECE project and is co-supervised by the author.

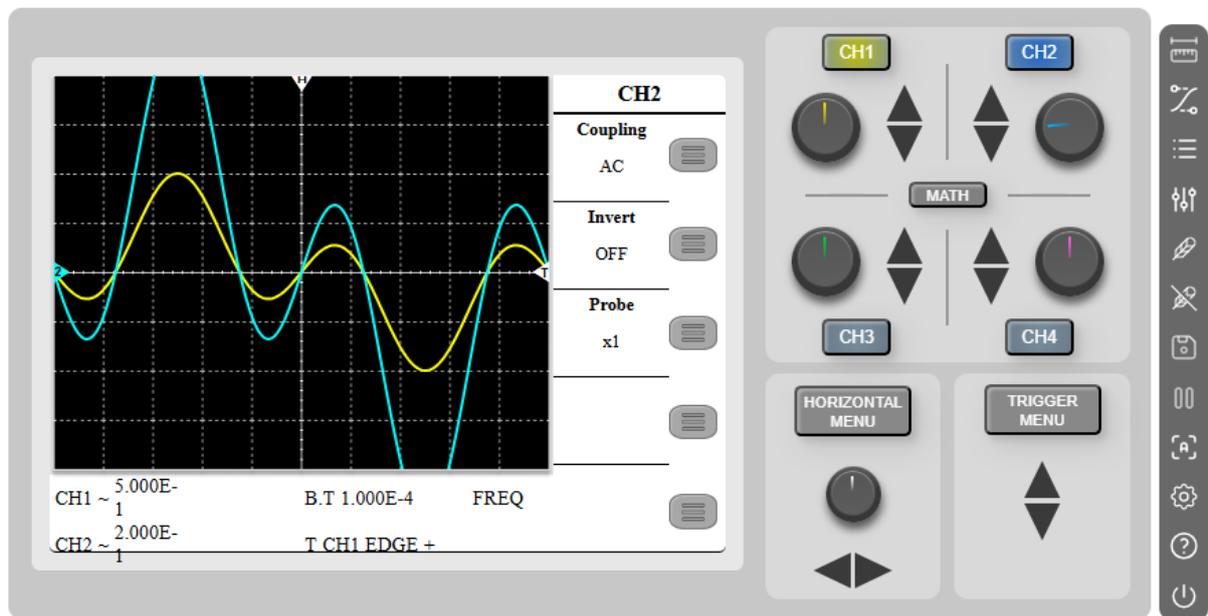


Figure 3.4: ScopeAcademy Oscilloscope simulating two signal inputs.

**P8 – ScopeLab (02/2025 – Ongoing)** Also derived from the Oscilloscope Interface (P2), this project focuses on codebase refactoring to align the application with the new *U=RIolve Academy* architecture. Additionally, it addresses the completion of pending simulation functionalities and the formalisation of the *acquisition and control mode*. The project is led by Simon Cruz as part of his final ECE project and is co-supervised by the author.

**P9 – U=RIolve Academy+ (05/2025 – Ongoing)** This project implements backend logic for part of the gamification features outlined in Section 6.1. While the full implementation (as detailed in the future research direction) is beyond the current timeline (which concludes in September 2025), this project goal is to establish the necessary backend infrastructure. The project is led by Pedro Cruz as part of his final ECE project and is co-supervised by the author.

**P10 – Fine-Tuned Evaluation (05/2025 – 06/2025)** An article currently under preparation and scheduled for submission in the first weeks of July 2025. The work provides a deeper analysis of the results discussed in Section 5.3, offering further insights into the fine-tuning strategies applied within the HALO framework (described in Section 4.1). The article is authored by the *U=RIolve Academy* technical coordinator, with the author as the paper’s second author, in collaboration with Professors Mário Alves and Paulo Oliveira.

**P11 – RAG Evaluation (06/2025 – 07/2025)** This ongoing research article follows a similar structure to P10 but focuses on evaluating Retrieval-Augmented Generation (RAG) strategies. The study is expected to be published after the submission of this dissertation. As with P10, the work is led by the technical coordinator, with the author of this dissertation as second author, in collaboration with Professors Mário Alves and Paulo Oliveira.

As demonstrated by the interconnected components described above, the *U=RIolve Academy* ecosystem comprises an increasingly complex set of interdependent modules. This complexity underscores the importance of a codebase that is reliable, scalable, and maintainable. Consequently, the main objective of this dissertation was to restructure the existing *U=RIolve Academy* codebase to meet these requirements. Building on this foundational goal, the principal technical contribution of this work identifies the limitations of the prior architecture and proposes a solution that facilitates the seamless integration of future projects.

## 3.2 Analysis of the former Software Architecture

### 3.2.1 Initial Diagnosis and Limitations

To address the limitations outlined above, the initial phase of this dissertation focused on a comprehensive diagnostic evaluation of the *U=RIolve Academy* codebase.

As previously mentioned, the codebase had been developed in parallel by multiple researchers across distinct branches. Consequently, the application gradually evolved into a fragmented and inconsistent structure, lacking a unified architectural vision. While this did not pose major challenges during isolated development phases, the growing scale and complexity of the framework began to expose issues. In particular, inconsistencies in structural organisation and naming conventions complicated the merging of branches and compromised further development, scalability, and maintainability.

Recognising these challenges, this dissertation established a structured plan to guide the re-architecture of the codebase. The plan was defined with the following key objectives:

- Conduct a thorough review of the existing codebase to identify architectural deficiencies and sources of technical debt.
- Define a new structural paradigm that would enhance modularity, clarity, and extensibility.
- Select and standardise the appropriate technological tools to support the restructured architecture.

- Systematically refactor the codebase in alignment with the identified goals while minimising disruption to existing functionalities.

### 3.2.2 Former Codebase Details

The codebase selected for evaluation and subsequent restructuring was the ongoing implementation of the Circuit Editor by Ângelo Pinheiro, developed as part of his master's dissertation. This version of the *U=RIolve Academy* platform already served as a central aggregation of several prior contributions and was therefore considered an ideal foundation for the architectural review.

The initial inspection revealed clear evidence of the codebase's fragmented origins and the expected issues associated with such a collaborative and incremental development process. Nevertheless, the project exhibited several promising characteristics. These included partial adherence to the Model, View, Controller (MVC) paradigm, the presence of inline documentation, and a relatively clear separation between front-end and back-end logic.

To identify the required intervention points, the codebase was categorised into three distinct classes of files during the review:

1. Files requiring no modification.
2. Files that require relocation or renaming to solve namespace issues, allowing the merge of some files into the same directory, consequently improving clarity.
3. Files demanding internal refactoring to improve modularity, eliminate duplication, or enhance separation of concerns.

The project was organised around two principal directories: `src/` and `public/`. The `src/` directory contained all server-side logic, whereas `public/` hosted the static front-end assets.

The complete directory structure is presented below:

```
1 public/
2 |-- code/
3 |-- css/
4 |-- images/
5 |-- js/
6 |-- libs/
7 |-- scss/
8 \-- vendor/
9 src/
10 |-- config/
11 |-- controllers/
12 |-- middleware/
13 |-- models/
14 |-- pages/
15 |   |-- partials/
```

```
16 |   \-- views/  
17 |   \-- index.js
```

**Back-end, Server-side structure (`src/`)** The inspection of the server-side components revealed some minor inconsistencies that required attention:

- **Routing and controllers:** Routes were distributed inconsistently between `index.js` and the `src/config/` folder. Furthermore, many routes bypassed controllers entirely, limiting the modularity and clarity of request handling.
- **Views and partials:** Despite the generally functional code, there was organisational ambiguity due to the presence of both templates and partial views in the `partials` folder.
- **Middleware:** Repeated logic across routes suggested the need for centralised middleware components to promote code reuse and reduce redundancy.

**Front-end, Client-side structure (`public/`)** The static assets generally followed more standardised practices; however, certain areas were identified for improvement:

- The `public/js/` folder exhibited various files, each with their topic-specific organisation; however, there were different files in `public/code/`, `public/libs/` and `public/vendor/` that could blend together in the `public/js/` folder, minimising the need for various folders (and files).
- The `public/scss/` folder, while functional, contained redundant variable definitions and inconsistent structural patterns.

To address the latter issues, a comprehensive inspection was undertaken to identify and eliminate redundancy, unify variable declarations, and improve file modularity. This ensured a scalable styling system more in line with industry best practices.

### 3.2.3 Codebase Structure Update Proposal

The overarching objective was not to rebuild the entire codebase from scratch but rather to identify and systematically resolve architectural weaknesses while preserving the valuable contributions made by previous developers. The refactoring effort led to the adoption of a more modular and standardised architecture, still inspired by the MVC paradigm but enhanced with:

- Clearly defined routing layers.
- Middleware support for common logic.
- Reusable and well-scoped view components.
- Improved directory hierarchies and naming conventions.

## U=RIolve Academy Software Architecture

These architectural improvements laid the groundwork for the integration of advanced features and intelligent components, aligning the platform with the long-term vision of *U=RIolve Academy* as a comprehensive, scalable, and maintainable e-learning platform.

To address the architectural issues previously identified, a new modular directory structure was designed and implemented. This structure emphasises the principles of separation of concerns, scalability, and collaborative development, thereby facilitating long-term maintainability.

All server-side logic and configuration were consolidated under a unified `app/` directory, as illustrated below:

```
1 app/
2 |-- config/
3 |-- controllers/
4 |   |-- api/
5 |   |-- auth/
6 |   \-- pages/
7 |-- locales/
8 |   |-- en/
9 |   \-- pt/
10 |-- middleware/
11 |-- models/
12 |-- public/
13 |   |-- css/
14 |   |-- img/
15 |   |-- js/
16 |   |-- scss/
17 |   \-- vendor/
18 |-- routes/
19 |-- utils/
20 |-- views/
21 |   |-- layouts/
22 |   |-- partials/
23 |   \-- pages/
24 \-- app.js
```

Each folder serves a clearly defined function within the application's architecture:

- **controllers/**: Encapsulates business logic, organised into:
  - `api/` – RESTful JSON endpoints.
  - `auth/` – Authentication-related logic.
  - `pages/` – Rendering logic for server-side views.
- **routes/**: Contains all routing declarations, now structured by domain (API, views, authentication) for enhanced traceability.

- **middleware/**: Centralises cross-cutting concerns such as session validation, authentication, and localisation.
- **views/**: Houses Handlebars templates, divided into:
  - `layouts/` – Base templates shared across multiple views.
  - `partials/` – Reusable UI components.
  - `pages/` – Page-specific content templates.
- **public/**: Contains static front-end assets, now reorganised for clarity and modularity.
- **models/**: Manages database interactions, facilitating MySQL integration.
- **locales/**: Supports internationalisation via `i18next`, containing language-specific JSON files.
- **utils/**: Contains utility functions reused across controllers and middleware layers.

This architecture promotes parallel development by clearly separating functional domains, facilitates testing, and better reflects the semantics of real-world application modules.

### 3.3 Technological Tools Selection

To develop the proposed e-learning platform and meet the functional and pedagogical requirements defined in the previous section, a set of technological tools and frameworks was selected. This section presents the selected technologies, structured according to their role in the system architecture. Additionally, the rationale behind each selection is discussed, emphasising aspects such as community support, developer familiarity, integration feasibility, and suitability to the educational context.

#### 3.3.1 Selection Criteria

Although this work does not aim to conduct an exhaustive benchmarking of all possible tools, the selection of the technological stack followed a pragmatic and context-driven methodology. The following criteria guided the choices made:

- The technology is capable of fulfilling the main functional requirements defined for the platform.
- The technology was already in use within a prior version of U=RIolve and, in the absence of critical limitations, was retained.
- The technology was already mastered by the main researcher, which contributed to development efficiency and reduced the learning curve.
- The technology is supported by a large community and has accessible documentation and educational resources.

This approach ensured a balance between innovation and productivity, allowing for rapid prototyping without sacrificing maintainability or scalability.

### 3.3.2 Back-end Technologies

The back end of the platform was developed using a modular and lightweight architecture focused on scalability and clarity of design. The technologies adopted for back-end development include:

- **Node.js** – Chosen for server-side execution due to its event-driven, non-blocking I/O model and extensive ecosystem, which is particularly well-suited to real-time applications.
- **Express.js** – A minimalist web framework for Node.js that simplifies routing, middleware integration, and the creation of RESTful APIs.
- **MVC Architecture** – The system follows the MVC design pattern to separate data management, business logic, and user interface concerns.
- **JavaScript (Back-end)** – JavaScript was used consistently across back-end and front-end to streamline development and ensure language coherence throughout the codebase.
- **MariaDB** – A relational database selected for persistent storage of structured data, including user information, quiz results, and progress tracking.
- **Axios** – A promise-based Hypertext Transfer Protocol (HTTP) client used for internal communication between different services and for calling external APIs.
- **bcrypt** – Employed to securely hash user passwords and sensitive credentials.
- **dotenv** – Used to manage environment variables and protect confidential information, such as the database credentials.
- **i18next** – A robust internationalisation framework that supports dynamic content translation to enable multilingual support within the platform.

### 3.3.3 Front-end Technologies

The frontend of the application was designed to be lightweight and easily adaptable to various devices and user preferences. The selected tools provide structure, reusability, and enhanced user experience:

- **SASS** – A preprocessor that improves maintainability and consistency in style definitions through variables, nesting, and modular organisation.
- **JavaScript (Front-end)** – Enables dynamic user interaction, DOM manipulation, and integration with backend APIs.
- **Handlebars** – A logic-less templating engine used to generate HTML views dynamically based on data served by the backend.
- **Marked and MathJax** – Utilised to render Markdown content and mathematical notation, respectively, used to correctly format the responses provided by the *HALO* Assistant.

### 3.3.4 Deployment and Dev Tools

Although some were not strictly required for the core application to function, several tools were incorporated to enhance reliability, reproducibility, version control, and task organisation. These tools support good software engineering practices and collaborative workflows:

- **GitHub and GitHub Desktop** – Used for version control and source code hosting, enabling collaborative development and history tracking.
- **Docker** – Adopted to containerise the application, ensuring consistent deployment across different environments and simplifying dependency management.
- **Trello** – Used for coordinating tasks and managing collaboration between the researchers.
- **Notion** – Utilised primarily by the main researcher to organise specific development milestones and document ongoing issues. While Notion was preferred for its flexibility, future iterations may migrate to GitHub Issues for better integration.
- **Visual Studio Code (VSCode)** – The Integrated Development Environment (IDE) used for writing, testing, and debugging the codebase.
- **GitHub Copilot Pro (Student License)** – Served as an AI-powered coding assistant to enhance productivity by providing displaying code suggestions during development.

### Final Remarks

The chosen technological stack reflects a balance between innovation, practicality, and educational purpose. While future iterations of the platform may benefit from incorporating new tools or refactoring existing components, the current setup provided a stable foundation for the design, implementation, and evaluation of the proposed e-learning environment.

## 3.4 Brief Overview of the Updated Codebase Structure

### 3.4.1 Views Directory Structure

The views layer utilises the Handlebars template engine to extend native HTML functionality and support dynamic, server-rendered pages. Among its primary benefits are:

- Seamless integration of partial templates.
- Use of server-passed variables for dynamic content rendering.
- Compatibility with internationalisation via `i18next`.

The following listing presents the main layout template, which serves as the structural foundation for all rendered pages:

## U=RIolve Academy Software Architecture

```
1 <!-- File that will be used as a template for every other webpage -->
2 <!DOCTYPE html>
3 <html lang="pt">
4 <head>
5   <meta charset="UTF-8">
6   <meta name="viewport" content="width=device-width, initial-scale=1">
7   <title>U=RIolve Academy</title>
8   <link rel="icon" type="image/png" href="/img/favicon.png">
9   <link rel="stylesheet" href="css/styles.css" type="text/css">
10  {{!--* Vendors to be used in the Frontend --}}
11  <script src="/vendor/handlebars.min.js"></script>
12  <script src="/vendor/marked.min.js"></script>
13  <style>
14    body { visibility: hidden; } /* Hide the body until the page is fully loaded */
15  </style>
16 </head>
17 <body>
18
19   {{> header}}
20
21   {{> content}}
22
23   {{> footer}}
24
25   <script src="/js/pages/main.js"></script>
26 </body>
27 </html>
```

In this layout, the syntax `{{> header}}`, `{{> content}}`, and `{{> footer}}` indicates the use of partials, which are compiled and inserted dynamically at runtime. These promote modularity by isolating reusable interface components.

An example of a partial is the header template shown below:

```
1 <header>
2   {{> sidebar}}
3   <div class="header-bar">
4     <div class="header-title">
5       <span> {{ t headerTitle }} </span>
6     </div>
7     {{#if user}}
8       <div class="header-profile">
9         
10      </div>
11     {{else}}
12     <div class="header-auth">
```

## U=RIolve Academy Software Architecture

```
13     <a class="auth-login" href="/login">{{ t 'login' }}</a>
14     <a class="auth-register" href="/register">{{ t 'register' }}</a>
15   </div>
16   {{/if}}
17 </div>
18 {{> profile}}
19 {{> settings}}
20 <script type="module" src="/js/pages/profile.js"></script>
21 </header>
```

This template illustrates two additional Handlebars capabilities:

- **Internationalisation:** The tag `{{t 'headerTitle'}}` utilises the `i18next` translation engine to dynamically render the appropriate label according to the active language.
- **Conditional Rendering:** The logic block `{{#if user}}` conditionally displays content based on the user's authentication status.

Beyond the layout and partials, the remaining views are stored in the `pages/` directory. These templates define route-specific content rendered within a central container of the application interface.

### 3.4.2 Public Folder and Asset Management

The `public/` directory is reserved for all static frontend assets. Among its subdirectories, the most structurally significant are `js/` and `scss/`, which respectively manage JavaScript functionality and styling logic.

```
1 public/
2 |-- css/
3 |-- img/
4 |-- js/
5 |   |-- api/
6 |   |-- logic/
7 |   |-- pages/
8 |   |-- ui/
9 |   \-- utils/
10 |-- scss/
11 |   |-- abstracts/
12 |   |-- base/
13 |   |-- pages/
14 |   \-- partials/
15 |-- vendor/
16 \-- DEVELOPER_FRONTEND_JS.md
```

**js/ directory** The subdivision of the `js/` directory was motivated by the increasing complexity and size of JavaScript files, with some surpassing 2000 lines. Despite being readable and well-documented, such large files presented significant challenges in terms of scalability, debugging, and future maintenance.

To mitigate these issues, the JavaScript codebase was modularised according to functional domains. The naming convention `<pageName>_<folderName>.js` was adopted to ensure clarity and facilitate navigation. For instance, scripts under `js/pages/` correspond to views located in `views/pages/`, while supportive logic can be distributed across `logic/`, `ui/`, or `api/` as needed.

Figure 3.5 illustrates the logical flow and organisation strategy of the `js/` directory.

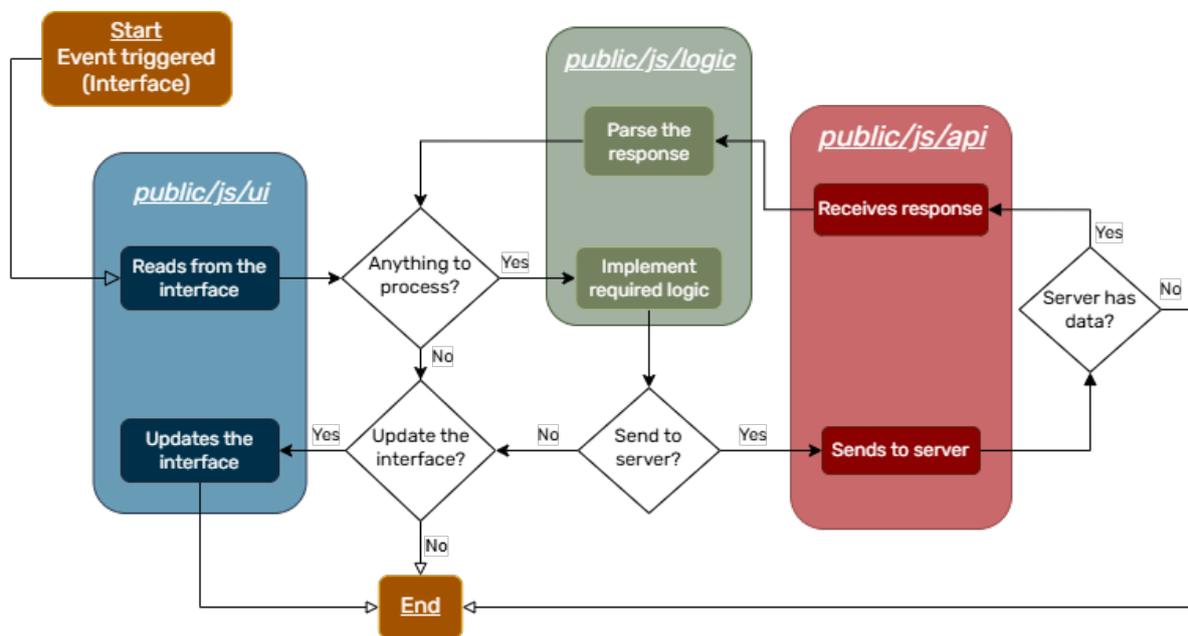


Figure 3.5: Organisational flowchart of the public JavaScript directory.

**scss/ Directory** The `scss/` directory follows a modular structure inspired by the "7-1 pattern" from the Sass Guidelines [Gir15], with slight adaptations to better align with project-specific requirements.

- `abstracts/`: Defines global variables, mixins, and utility functions not directly compiled into CSS.
- `base/`: Contains base styles and general body rules.
- `pages/`: Holds styles that are specific to individual pages.
- `partials/`: (formerly `layout/`) Stores styles associated with reusable UI components found in partial templates.

This modular approach enhances maintainability and promotes a clear separation of concerns, which would be difficult to achieve using plain CSS alone.



### 3.4.3 Controllers and Routing Structure

The back-end architecture was significantly restructured to promote modularity, clarity, and scalability. Controllers were grouped into three primary categories, each with clearly defined responsibilities:

- `api/` – responsible for managing external API communications.
- `auth/` – responsible for handling authentication and user credential logic;
- `pages/` – responsible for rendering front-end views;

This separation ensures a clear division of concerns, which simplifies both development and maintenance.

A standard controller in `pages/` renders templates using predefined layout options and contextual data, as illustrated below:

```

1  const homeController = (req, res) => {
2      res.renderPage('home', {
3          layout: 'main',
4          headerTitle: 'U=RI solve Academy'
5      });
6  };
7
8  module.exports = homeController;

```

Routing is handled via a straightforward mechanism that connects each endpoint to its corresponding controller. Middleware functions are employed to abstract and manage shared logic, such as authentication checks or contextual data injection. An example of an authentication middleware is shown below:

```

1  const requireAuth = (req, res, next) => {
2      /* Skip authentication check for static assets (public files) */
3      /* TODO See what CDN is */
4      const isStaticAsset = req.path.startsWith('/css') ||
5                          req.path.startsWith('/img') ||
6                          req.path.startsWith('/js') ||
7                          req.path.startsWith('/scss') ||
8                          req.path.startsWith('/vendor') ||
9                          req.path.startsWith('/favicon.ico');
10
11     if (isStaticAsset) {
12         return next();
13     }
14
15     /* If the user is authenticated, continue */
16     if (req.session && req.session.userId) {
17         return next();
18     }

```

## U=RIolve Academy Software Architecture

19  
20  
21  
22  
23  
24  
25

```
    /** If not authenticated redirects to a custom warning page (which indicates that the user needs t  
    req.session.redirectTo = req.originalUrl;  
    return res.redirect('/auth-warning');  
  }  
  
module.exports = requireAuth;
```

Middleware is then easily integrated within the route definitions:

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16

```
const requireAuthentication = require('../middleware/authMiddleware');  
  
const homeController = require('../controllers/pages/homeController');  
router.get('/', homeController);  
  
const aboutController = require('../controllers/pages/aboutController');  
router.get('/aboutus', aboutController);  
  
const practiceController = require('../controllers/pages/practice');  
router.get('/practice', practiceController);  
  
const analysisController = require('../controllers/pages/analysis');  
router.get('/analysis', requireAuthentication, analysisController);  
  
const chatController = require('../controllers/pages/chatController');  
router.get('/chat', requireAuthentication, chatController);
```

This approach ensures a scalable and modular back-end routing system, where new features can be integrated with minimal disruption to existing logic.

### 3.4.4 Developer Guidelines for Future Code Contributions

To guide future developers on understanding and following the designed restructure, special attention was given to documenting and systematising the structure of the codebase. One of the key initiatives in this direction is the development of a series of Markdown-based developer guides, intended to explain how and where to implement features within the project's architecture.

The first completed guide focuses on the `public/js/` folder and provides detailed instructions for integrating front-end logic. Additional guides are currently planned to cover the following areas:

- **Controllers and Routes** – back-end logic and integration;
- **CSS and SASS** – styling conventions and architecture;
- **Views** – templating and HTML structure;
- **Database and JSON Models** – data modelling and persistence logic.

Each guide will adhere to a common structure to ensure clarity and usability:

- Overview of the folder’s purpose and scope;
- Directory layout and explanation of file responsibilities;
- Flowcharts and sequence diagrams to illustrate code interactions;
- Practical implementation and debugging tips.

Although a similar rationale has already been introduced in the discussion of the JavaScript folder (Section 3.4.2), these guides are meant to serve as active, in-code documentation. Written in Markdown and included directly within the repository, they remain accessible during development and are updated alongside the codebase.

In conclusion, the restructuring of the *U=RIolve Academy* platform establishes a robust foundation for future growth. By adopting a scalable architectural approach, the platform is now well-equipped to support the integration of future modules. Section 4.4 will further illustrate how this restructured architecture has facilitated the implementation of new features. In fact, the three associated projects—*ScopeLab*, *ScopeAcademy*, and *U=RIolve Academy+* are already employing this updated codebase in their ongoing development efforts. Although final deployment is expected in September, preliminary feedback from researchers has been positive, particularly regarding the system’s improved organisation and maintainability.

## Chapter 4

# HALO Software Architecture and Baseline Dataset

The second and third contributions of this dissertation are aligned with the *HALO* framework; they involved the construction and organisation of a dataset that contains pedagogical information on the fundamentals of electrical circuit analysis and the integration of the model fine-tuned and trained with the dataset into the *U=RI solve Academy* application.

### 4.1 The *HALO* framework

The *HALO*, a hybrid and interactive Human-Artificial approach for electrical engineering Learning-Oriented tools is an AI-based framework that aims to provide models or tools to enhance interactivity in electrical engineering educational applications currently under development by the technical coordinator of the *U=RI solve Academy* framework as part of his ongoing doctoral programme in ECE at FEUP.

The *HALO* system is centred around a NLP-based educational assistant. The core research question is: *Can smaller, domain-specific large language models outperform general-purpose commercial alternatives in terms of response quality and adequacy for electrical engineering education applications?*

To explore this question, the technical coordinator structured his research across four complementary publications, each addressing a critical component of the *HALO* framework:

1. Fine-tuning on human-curated pedagogical documents.
2. Improved performance using RAG and referencing techniques.
3. AI agents for fully automated learning assistant.
4. AI Assistant for Microcontroller Programming ( $\mu$ CP) Education.

This dissertation contributes directly to the first two publications and indirectly supports the remaining ones.

For the first publication, focused on fine-tuning models with educational data, the main activities can be summarised as follows:

1. Collect and organise data for a human-curated dataset.
2. Create a high-quality dataset composed of question–answer (QA) pairs.
3. Fine-tune a language model using the QA dataset.
4. Evaluate the fine-tuned model performance.

Among these tasks, the first (data collection and organisation) and fourth (evaluation) represent part of the technical contributions of this dissertation, while the remaining were executed under the leadership of the technical coordinator.

## 4.2 Dataset Construction Methodology

The primary objective of the *HALO* dataset is to encapsulate the essential theoretical and pedagogical knowledge covered in foundational electrical engineering courses, specifically those related to electrical circuit analysis. These include, but are not limited to:

- Circuit theory fundamentals;
- Electrical components and their behavior;
- Analytical methods such as loop and nodal analysis;
- Theorems such as Thévenin, Norton, and Superposition.

These topics are aligned with the syllabi of the TCIRC and FEELE units taught in the 1st year of the ECE at ISEP, and the dataset is constructed from materials available on the institution’s Moodle platform.

This material included:

- 4 class presentation slides from FEELE and 6 class presentation slides from TCIRC;
- 8 practical laboratory guides (which usually include a theory contextualization of certain topics) from FEELE and 3 from TCIRC;
- Conceptual sentences fetched from 4 FEELE Kahoots and 9 TCIRC Kahoots, each Kahoot has a set of 10/20 pairs of question and answers, which sometimes can form either good affirmation sentences or negation sentences (depending on the topic);
- Multiple scientific papers written by specialists (members of *U=RI*solve and DEE professors).

### 4.2.1 Content Compilation and Organization

Once fetching all the relevant available information at the Moodle of both courses, the next step was compiling everything into one document.

For this approach, rather than learning and then creating the content from scratch, which could lead to some degree of errors, the dataset was composed of carefully curated and transcribed content from the official academic documents. While some changes were made to the formatting, the overall content was not modified. Also, since the original academic documents were in Portuguese, that language was kept while organising the dataset document.

Then, to better organise all the content between the two courses, a structure was created which divided all the 75 existing different topics between a relative chapter and turned out to be divided into **11 chapters**. A schematic overview of the chapter distribution can be represented in the hierarchical tree diagram below.

Each chapter includes the following elements (if needed):

- A comprehensive summary of the topic, synthesized from the multiple sources available to ensure accuracy and depth of understanding;
- Clarifications on specific concepts, where necessary, provided through concise statements aimed at affirming or refuting common misconceptions;
- A structured set of metadata associated with each topic, as detailed in the following section.

### 4.2.2 Standartization

To ensure the long-term usability, traceability, and academic integrity of the dataset, each chapter is supplemented with a set of metadata entries stored in a structured format, such as JSON. These entries are essential for content validation, version control, and future integration into advanced retrieval systems.

The metadata is composed of the following elements:

- **Source:** Specifies the origin of the content, including detailed references such as slide or page numbers, ensuring transparency and verifiability;
- **Validation:** Indicates who validated each chapter, adding an additional layer of reliability and academic rigor;
- **Version:** Follows a simple two-level versioning system. The major version is incremented when substantial changes are made, such as the addition of new sources, while the minor version reflects minor edits, such as error corrections.
- **Last update:** Records the date of the most recent modification. This is particularly useful for maintaining consistency between the dataset and the models trained on it, allowing for straight-forward version tracking and alignment.

Below is an example of the metadata associated with the chapter NVM in its original version (with the elements translated to English):

## HALO Software Architecture and Baseline Dataset

Metadata

Source:

- Ana Viana, Mário Alves e Francisco Pereira; (outubro de 2023); Slides  
→ FEELE Capítulo 3 (25- 33);
- Departamento de Engenharia Eletrotécnica; (novembro de 2021); Guião  
→ FEELE 8 (3 - 4);
- Lino Sousa, André Rocha, Mário Alves e Francisco Pereira; (março de  
→ 2021); Revisiting the nodal voltage method for both human  
→ comprehension and software implementation: Towards a  
→ teaching/self-learning simulation tool (1647 - 1648).

Validation: João Ferreira

Version: 1.1

Last update: 13/03/2025

This metadata structure enables the dataset to evolve over time while preserving academic standards and integrity. Furthermore, it lays the groundwork for future integration with RAG systems, where each query can be dynamically supported by source-specific content fetched in real time.

### 4.2.3 Advantages Over General-Purpose Datasets

Compared to broad, publicly available datasets (e.g., those used by OpenAI or Meta), the *HALO* was developed to offer a number of distinct advantages:

- **Pedagogical Alignment:** Content is directly mapped to the curriculum, increasing relevance and trustworthiness.
- **Terminological Accuracy:** Uses correct technical vocabulary as taught in class.
- **Structure for Retrieval:** Clearly segmented chapters and metadata allow for easy integration into document retrieval systems.
- **Customisation Potential:** Allows for future expansion with pedagogical specialised inputs.

Additionally, since the dataset is open for continuous improvement, it can eventually embed additional layers of pedagogical intelligence, such as learning objectives, Bloom's taxonomy levels (into the dataset itself), or prerequisite concept graphs. More details on this future work is specified in Section 6.2

Also, another key consideration in the design of the dataset is its compatibility with RAG pipelines. Rather than relying solely on memorised content, the AI assistant can dynamically retrieve chapters, explanations, or examples from the dataset based on a query's context. This has the following benefits:

- Reduces hallucination risks by grounding answers in verified documents.
- Allows real-time content updates without retraining the base model.
- Enables citation of sources and contextual explanation.

Its alignment with the academic context of ISEP ensures its relevance to real students, while its modularity prepares it for continual growth and technological integration. The dataset will play a critical role in enabling the AI assistant to provide personalised, trustworthy, and context-aware support to learners in the field of electrical engineering.

### 4.3 Overview of the Fine-Tuned Model Training

As a preliminary step toward validating the pedagogical and technical viability of the dataset and overall framework, a proof-of-concept training was conducted using a GenAI model based on the Large Language Model Meta AI (LLaMA) architecture, including variants with different parameter scales.

The objective of this training was to specialise the model in answering questions and solving problems related to two specific topics from the dataset: the NVM and the LCM. These topics were selected due to their foundational importance in introductory electrical circuit analysis and their frequent appearance in early undergraduate coursework.

To generate the training data, a large language model was prompted with structured content derived from the dataset itself. This process resulted in a collection of instruction–response pairs, following a methodology inspired by the Alpaca-style datasets. These pairs represent simplified pedagogical interactions, where the model is guided to produce answers aligned with institutionally curated material.

A limited manual validation process was applied to a subset of the generated data to ensure the factual accuracy and pedagogical alignment of the pairs. Non-conforming entries were reviewed and either corrected or discarded. Although the validation covered only a portion of the dataset, it provided a preliminary quality control layer prior to training.

Multiple model variants were trained, each designed to align with a specific cognitive domain of **Bloom’s Taxonomy**:

- **Conceptual:** Reinforces foundational concepts, ensuring learners acquire a clear understanding of terminology and definitions.
- **Procedural:** Guides learners through structured steps involved in problem-solving techniques.
- **Application:** Encourages the practical use of theoretical knowledge in solving contextualised problems.
- **Evaluation:** Identifies and addresses common student misconceptions and frequent errors.
- **Advanced:** Presents higher-order questions that integrate multiple concepts and require analytical reasoning.
- **Full:** Includes a mix of all the previous cognitive domains.

Although the training was constrained to a narrow subset of the full dataset and conducted under limited resources, the experiment yielded promising initial insights. Notably, it demonstrated the feasibility of aligning domain-specific datasets with fine-tuned models to enhance instructional coherence. Section 5.3 also reflects on the evaluation conducted by both students and professors.

It is important to note that further technical detail, such as the hardware setup, fine-tuning parameters, training strategy, and evaluation metrics, is beyond the scope of this dissertation and is being prepared for inclusion in a separate scientific publication currently under development.

Overall, this phase represents a foundational proof of concept, validating the potential of domain-specific, instruction-aligned fine-tuning as an effective approach in educational AI development.

### 4.4 API-Driven Integration of *HALO* and *U=RI*solve Academy

Building upon the refactored architecture of the *U=RI*solve Academy application, described in Section 3.4, this phase of the project involves the integration of the *HALO* assistant trained on the domain-specific dataset outlined in Chapter 4.

This integration enables the system to support interactive, personalised, and intelligent educational assistance for students learning electrical circuit analysis.

#### 4.4.1 System Overview and Integration Architecture

Thanks to the back-end/front-end separation and route organisation established during the initial refactoring, the integration of *HALO* required minimal disruption to the existing codebase. The AI assistant is hosted externally on a dedicated inference server, and communication with the platform is achieved via RESTful API calls.

The complete interaction pipeline follows a three-step process:

1. The user submits a query through the *U=RI*solve Academy front-end interface.
2. The back-end receives the request and routes it to the external *HALO* API server.
3. The *HALO* System processes the query using the fine-tuned or RAG model and returns a response, which is parsed and rendered back to the frontend.

To ensure a smooth user experience, the front-end handles content formatting, markdown rendering, and language detection while maintaining performance and responsiveness.

#### 4.4.2 *U=RI*solve Academy Chatbot

From the user's perspective, the integration manifests as an interactive chat interface embedded within the existing website layout. This chat component supports natural language queries in both English and Portuguese, leveraging automatic language detection.

While the current version supports only text input and response, future updates may enable multi-modal capabilities, such as:

- TTS responses for accessibility
- STT input for voice queries
- Dynamic display of images and electrical circuits (due to the project *GAME*)

### 4.4.3 Communication Flow and API Interaction

The current integration is highly scalable due to the decoupled architecture. Since *HALO* runs on a separate server, multiple front-end clients can query the model without overloading the main educational platform. This opens the door for future integrations with other courses or tools beyond *U=RSolve Academy*.

Additionally, the routing system explained in Section 3.4.3 allows the chatbot to be conditionally embedded in specific pages or extended for specialised use cases (e.g., lab simulations, real-time feedback systems).

The integration of the *HALO* assistant into the *U=RSolve Academy* marks the initial step towards student-centred AI-driven learning support. By combining a purpose-built AI model with a modular web platform, the system now offers intelligent, multilingual, and extensible educational assistance.

## HALO Software Architecture and Baseline Dataset

## Chapter 5

# Comparative Performance Evaluation of the different NLP models

This section corresponds to the final contribution of this dissertation and also the last point of the 2 first scientific papers described in Subsection 4.1. Initially the team worked on conceiving the communication between *HALO* and *U=RI*solve Academy which even if not of necessity for the evaluation of the model, served to validate the first contribution and also to launch the set of directions presented in the chapter.

### 5.1 Methodology

This section outlines the methodology employed to evaluate the *HALO* model's performance, as trained according to the specifications in Section 4.3. The objective of this evaluation is to assess the quality, pedagogical relevance, and overall effectiveness of the model's responses in comparison to the baseline models and commercially available Large Language Models (LLMs).

To this end, two distinct studies were designed:

- **Fine-Tuned Model Evaluation**
- **Retrieval-Augmented Generation (RAG) Evaluation**

The fine-tuned model evaluation has already been conducted, and a preliminary analysis is presented later in the chapter, while a more comprehensive discussion is planned for the first related publication. In contrast, the RAG evaluation is still planned to be carried out, which will then have detailed analysis in the second publication.

### 5.1.1 Evaluation Design

The evaluation methodology was initially proposed by Professor André Rocha and consists of two questionnaire types targeting two distinct participant groups (fine-tuned mode and RAG):

- **Type 1: experts** – this group is formed by invited teachers or electrical circuit analysis experts to evaluate random samples of questions and responses using grading criteria.
- **Type 2: students** – a group of students/learners invited to participate. Their opinion might be useful for assessing the model responses regarding aspects such as clarity, understandability, and educational value (as these users will be users of these applications).

Each questionnaire presents a set of prompts alongside anonymised responses generated by different models: the *HALO* model, its base model, and a widely used commercial LLM. Responses were blinded to prevent bias.

Then, the objective was to ensure that both experts and students evaluated the model's responses based on five distinct metrics.

#### Expert Evaluation Metrics:

- **Correctness:** Is the response accurate?
- **Coherence:** Is the response logically structured?
- **Relevance:** Does the response fully address the questions?
- **Conciseness:** Is the response as brief as possible, while remaining comprehensive?
- **Depth:** Does the response comply with the principles of electrical circuits?

#### Students Evaluation Metrics:

- **Clarity:** Is the response clear (unambiguous)?
- **Understandability:** Does the response explain the concept in an easy way?
- **Educational Value:** Does the response help to build a critical mass of the topic?
- **Engagement:** Is the response presented in a way that sparks curiosity for further exploration of the topic?
- **Relevance:** Does the response fully address the question?

### 5.1.2 Implementation Strategy

From the outset, several meetings were conducted within the team, which included Professor Mário Alves, André Rocha and also Paulo Oliveira, who is the team's specialist for the statistics, to determine the optimal approach for the evaluation. The following key implementation decisions were recorded:

- The questionnaire would be presented in Portuguese, the native language of the students, to avoid potential linguistic barriers;

## Comparative Performance Evaluation of the different NLP models

- Evaluation dimensions were adapted to elicit more relevant and differentiated feedback from both experts and students;
- A total of 10 prompts were selected, six pertaining to the NVM and four to the LCM;
- Each prompt was submitted to five models: one commercially recognized LLM, two fine-tuned *HALO* variants (8B and 1B parameter configurations), and the two corresponding base models;
- Google Forms to serve as the platform for designing and hosting the questionnaires and Google Sheets for data collection and questionnaire organisation
- To prevent participant fatigue, the questionnaires were divided into smaller, unique subsets to ensure a manageable workload and encourage completion.

Further insights on specific aspects of the implementation are provided in the following subsections.

### 5.1.3 Prompts and Responses

The selected ten prompts were as follows:

- Prompt 1 (NVM) - What is the nodal voltage method, and what is its main purpose in circuit analysis?
- Prompt 2 (NVM) - In an electrical circuit that contains multiple supernodes, which supernode should I choose as a reference to ground?
- Prompt 3 (NVM) - What are the required steps to solve a circuit using nodal voltage method?
- Prompt 4 (NVM) - What are the required steps to solve a circuit using nodal voltage method when is possible to form supernodes?
- Prompt 5 (NVM) - In an electrical circuit containing isolated voltage sources, if I assign the ground reference to a node that is not connected to any terminal of those sources, how many equations will be required to analyze the circuit?
- Prompt 6 (NVM) - How can Kirchhoff's Current Law be adapted when applied to a super-node instead of a regular node?
- Prompt 7 (LCM) - When should I choose Mesh Current Method instead of Nodal Voltage Method?
- Prompt 8 (LCM) - Why is the assumed direction of mesh current sometimes different from the actual current direction?
- Prompt 9 (LCM) - Can you explain me the steps to solve a circuit using the mesh current method?
- Prompt 10 (LCM) - How can I determine the number of equations needed when applying the mesh current method?

Each prompt was submitted to the following five models:

- **gpt-4.5-preview-2025-02-27** - A state-of-the-art model developed by OpenAI. While the exact number of parameters is undisclosed, it is estimated to exceed 5 trillion;

## Comparative Performance Evaluation of the different NLP models

- **Llama-3.1-8B** - An 8 billion parameter model developed by Meta, which served as the base model for *HALO* training;
- **Llama-3.2-1B** - An 1 billion parameter model developed by Meta, which served as the base model for *HALO* training;
- **halo-<topic>-full-8B** - The *HALO* fine-tuned model from the base (Llama-3.1-8B) specific to the topic of the prompt (NVM or LCM);
- **halo-<topic>-full-1B** - A *HALO* variant fine-tuned from the base (Llama-3.2-1b), also topic-specific.

All prompts were query in English, and each model's responses were stored in Markdown format. An example of one such Markdown response is shown below.

### ### Step 1: Determine the number of nodes in the circuit.

The number of nodes (including the ground reference) in an electrical  
→ circuit determines how many KCL equations are needed. The basic  
→ approach is to count each node minus one (for the reference), and  
→ then add one for each isolated voltage source.

### ### Step 2: Count the number of isolated voltage sources.

In this problem, we know that there are isolated voltage sources. Each  
→ one adds a constraint because its voltage can be set in advance  
→ without needing to calculate it using Ohm's Law or other means.

### ### Step 3: Apply the Nodal Voltage Method formula.

To find the total number of equations needed for analysis, subtract two  
→ from the sum of the total number of nodes (including ground) and the  
→ number of isolated voltage sources. This is because one node acts as  
→ a reference (ground), reducing the count by 1.

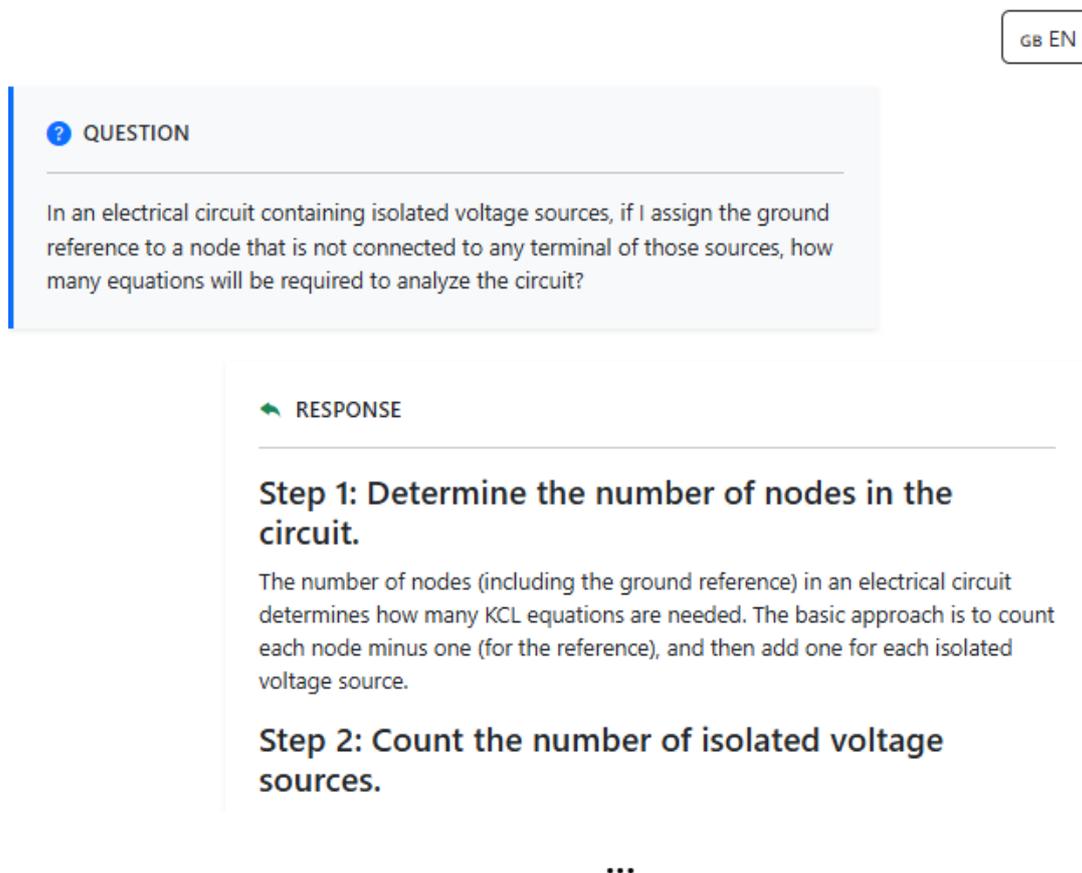
### ### Step 4: Calculate the final number of required equations.

Total nodes including ground = Number of actual nodes + 1 (for  
→ reference) Number of isolated sources = Number of sources  
Total equations needed = Total nodes including ground - 1 - Number of  
→ isolated sources

## Comparative Performance Evaluation of the different NLP models

The final answer is:  $\boxed{N - 1 - S}$

To ensure consistent formatting and enhance readability, the Markdown files were rendered into HTML. This approach not only promoted visual uniformity across responses but also enabled evaluators to examine the outputs as they would appear in their generated form. Figure 5.1 illustrates the rendered version of a response, shown alongside its corresponding prompt and a language-switching button (described below).



The screenshot shows a web interface for a questionnaire. At the top right, there is a language toggle button labeled "GB EN". Below it, a light blue box contains a question icon and the text "QUESTION". The question text is: "In an electrical circuit containing isolated voltage sources, if I assign the ground reference to a node that is not connected to any terminal of those sources, how many equations will be required to analyze the circuit?". Below the question, a light green box contains a response icon and the text "RESPONSE". The response is structured into two steps: "Step 1: Determine the number of nodes in the circuit." followed by a paragraph explaining that the number of nodes (including the ground reference) determines the number of KCL equations needed, and the basic approach is to count each node minus one (for the reference), and then add one for each isolated voltage source. "Step 2: Count the number of isolated voltage sources." is listed below. Three dots "..." are centered below the response box.

Figure 5.1: *HALO* questionnaire HTML page with one of the responses given by the model.

Since the evaluation was to be conducted in Portuguese, all Markdown responses were translated using a high-performing language model, followed by human validation to ensure accuracy. The HTML-rendered outputs were subsequently converted into static images and embedded within the questionnaire. Evaluators were able to switch between the original and Portuguese versions using a toggle button presented beforehand. Figure 5.2 illustrates how these responses were presented to participants.

**Pergunta:** Num circuito elétrico com fontes de tensão isoladas, se atribuir a referência de massa a um nó que não está ligado a nenhum terminal dessas fontes, quantas equações serão necessárias para analisar o circuito?

**Resposta 2 de 2:**

RESPOSTA

### Passo 1: Determinar o número de nós no circuito

O número de nós (incluindo o nó de referência ou massa) num circuito elétrico determina quantas equações da Lei das Correntes de Kirchhoff (LCK) são necessárias. A abordagem básica consiste em contar cada nó e subtrair um (para o nó de referência), e depois somar um por cada fonte de tensão isolada.

### Passo 2: Contar o número de fontes de tensão isoladas

Neste problema, sabemos que existem fontes de tensão isoladas. Cada uma delas adiciona uma restrição, pois a sua tensão pode ser imposta diretamente, sem necessidade de a calcular com a Lei de Ohm ou outros métodos.

### Passo 3: Aplicar a fórmula do Método das Tensões Nodais

Para encontrar o número total de equações necessárias para a análise, subtrai-se dois à soma do número total de nós (incluindo a massa) e do número de fontes de tensão isoladas. Isto deve-se ao facto de um dos nós funcionar como referência, reduzindo a contagem em 1.

### Passo 4: Calcular o número final de equações necessárias

- Total de nós incluindo a massa = número de nós reais + 1 (referência)
- Número de fontes de tensão isoladas = número de fontes
- Equações necessárias = Total de nós incluindo a massa - 1 - Número de fontes de tensão isoladas

A resposta final é:  $N - 1 - S$

Figure 5.2: HALO Questionnaire question display in the form.

In this study, a questionnaire item refers to a single prompt–response pair. Any future reference to a "question" in the context of this evaluation denotes this pair.

## 5.2 Refinements and Data Collection

### 5.2.1 Students' Questionnaire

Several modifications were implemented in the students questionnaire since its initial conception.

First, the evaluation dimensions were revised. The original dimensions were found to be potentially unclear for students, and alternative metrics were considered more effective in capturing their feedback. The final set of dimensions is listed below:

- Clarity: I think the answer is correct.
- Understandability: The answer is clear and easy to understand.
- Educational Value: I learned something from this answer.
- Precision: The answer corresponds to what was asked.
- Style: I like the style of the response.

Another key consideration in the study design was the overall length of the questionnaire. To ensure high-quality data collection without causing participant fatigue, the total completion time was limited to approximately 10 minutes.

The initial design included 10 prompts, each paired with five model responses, resulting in 50 questions. However, the team decided that some of the prompts might be too complex or ambiguous for students to reliably interpret, potentially compromising the quality of the evaluation. Additionally, preliminary timing estimates indicated that students could complete at most six questions within the allocated time, assuming an average of 1:15 to 1:30 minutes per question.

To address both the cognitive load and time constraint, the number of prompts was reduced from 10 to 6. This adjustment allowed each questionnaire to include six questions, aligning with participants' expected capacity while maintaining a manageable evaluation workload. The selected prompts for inclusion in the students questionnaire are as follows:

- Prompt 1 (NVM) - What is the nodal voltage method, and what is its main purpose in circuit analysis?
- Prompt 4 (NVM) - What are the required steps to solve a circuit using nodal voltage method when is possible to form supernodes?
- Prompt 7 (LCM) - When should I choose Mesh Current Method instead of Nodal Voltage Method?
- Prompt 8 (LCM) - Why is the assumed direction of mesh current sometimes different from the actual current direction?
- Prompt 9 (LCM) - Can you explain me the steps to solve a circuit using the mesh current method?
- Prompt 10 (LCM) - How can I determine the number of equations needed when applying the mesh current method?

## Comparative Performance Evaluation of the different NLP models

Reducing the total number of questions from 50 to 30 also allowed the creation of five distinct questionnaire versions, each containing six items. This ensures that each individual question can receive approximately 30 independent responses, which is an adequate sample size for subsequent statistical analysis.

The distribution of questions across the five questionnaires was semi-random but guided by the following constraints:

- Estimated completion time across all questionnaires should be approximately equal, achieved by balancing question length and complexity;
- Each questionnaire included three to four distinct prompts, with one to three model responses per prompt (for a total of six questions);
- Model representation across questionnaires was balanced to prevent bias toward any specific model.

After finalising the design, all questionnaires were prepared for distribution.

### 5.2.2 Experts' Questionnaire

For the expert questionnaire, all ten original prompts were retained. However, modifications were made to the evaluation dimensions to better align with expert-level analysis. Some questions were refined for clarity, and certain dimensions were redefined to ensure alignment with domain-specific evaluation criteria.

The final expert evaluation dimensions are listed below:

- Correctness: The answer is correct.
- Structure: The response is logically well-structured.
- Completeness: The answer is complete.
- Precision: The answer corresponds exactly to what was asked.
- Conciseness: The answer is short and concise.

Each questionnaire was designed to take approximately 20 minutes to complete. Although experts may be more patient, this time limit was set to maintain engagement without imposing excessive effort. Consequently, each expert was assigned a questionnaire containing 10 questions, distributed across 5 unique forms.

It was anticipated that approximately 20 responses would be collected, yielding around 4 evaluations per question. While this number is lower than statistically ideal, it was considered sufficient to provide valuable qualitative insights.

Additionally, to distinguish between educators and other invited participants, a new question was included asking the experts whether they were currently teaching electrical circuit analysis to students.

### 5.2.3 Questionnaire Distribution and Data Collection

Given the existence of five distinct forms for both students and experts, a centralised and user-friendly distribution method was required. To streamline this process, two dedicated landing pages were created, one for students (shared via the TCIRC course Moodle) and one for experts (shared via email to the invited). Both pages featured identical design and introductory information about the evaluation process. Figure 5.3 illustrates the layout of these landing pages.



Figure 5.3: HALO Evaluation distribution page layout.

Each page included a button that, when clicked, randomly assigned the participant to one of the five corresponding questionnaires. This mechanism ensured equal distribution of responses across all forms while maintaining anonymity.

To ensure ethical standards and data integrity, the following measures were implemented:

- No personally identifiable information was collected from participants.
- Only the timestamp of each submission and the corresponding evaluation data were recorded.

## Comparative Performance Evaluation of the different NLP models

- The sole exception applied to the expert questionnaire, which included one optional demographic question to determine whether the respondent was an active professor in electrical circuit analysis.

To consolidate data management, for each study (students and experts), all Google Forms were linked to a single Google Spreadsheet, with each form populating a separate worksheet. This structure enabled automated updates upon submission and streamlined monitoring of participation metrics. A master summary table was also generated to aggregate frequency data and facilitate real-time tracking and quality control.

All procedures described above were replicated for the RAG-based model questionnaire. The only difference was the content of the responses being evaluated.

### 5.3 Preliminary Evaluation of Fine-Tuned Models

This section presents a summary of preliminary findings from the evaluation of the fine-tuned models. The purpose was to determine whether significant differences exist in the quality of responses produced by each model. A comprehensive statistical analysis will be included in the forthcoming scientific publication.

#### 5.3.1 Student-Based Evaluation

Out of the six prompts designed for the students assessment, three were selected for the preliminary evaluation. The distribution of evaluated responses by prompt and model is presented in Table 5.1.

Table 5.1: Distribution of responses by prompt and model

<b>Model</b>	<b>P7</b>	<b>P8</b>	<b>P10</b>	<b>Total</b>
<i>gpt-4.5-preview-2025-02-27</i>	34	31	30	95
<i>Llama-3.2-1B</i>	31	30	30	91
<i>Llama-3.1-8B</i>	31	30	30	91
<i>halo-lcm-full-8B</i>	31	30	30	91
<i>halo-lcm-full-1B</i>	34	30	30	94

The evaluation employed the following statistical methods:

- Cross-tabulations were used to visualize Likert-scale ratings across models and dimensions.
- Pearson’s Chi-square test was applied to examine the independence between the model and response distribution, with statistical significance set at  $p < 0.05$ .
- Standardised adjusted residuals greater than  $|1.96|$  were interpreted as statistically significant at the 95% confidence level.
- The Kruskal–Wallis test, followed by Bonferroni-adjusted pairwise comparisons, was used to assess differences in ordinal ratings across models.

## Comparative Performance Evaluation of the different NLP models

The analysis revealed consistent performance trends:

- **Llama-3.2-1B** received the most unfavourable ratings across all dimensions, often falling into the lower categories of the Likert scale. Chi-square and Kruskal–Wallis results confirmed statistically significant underperformance.
- **GPT-4.5-preview-2025-02-27** consistently achieved the highest ratings in Dimensions D1, D2, D4, and D5, though its performance was statistically comparable to both *halo-lcm-full-1B* and *halo-lcm-full-8B*.
- **Llama-3.1-8B** demonstrated intermediate performance, surpassing *Llama-3.2-1B* but underperforming relative to the *halo-lcm* and *GPT-4.5* models.
- In Dimension D5 (style-related evaluation), *Llama-3.1-8B* was significantly outperformed by *halo-lcm-full-8B*.
- In Dimension D3 (“I learned something from this answer”), while global statistical tests showed significance, pairwise comparisons did not reveal clear differences. This may be attributed to students’ prior familiarity with the content.

To provide a clearer comparative overview, Table 5.2 displays the average Likert-scale rating (1–5) received by each model across the five evaluation dimensions.

Table 5.2: Average Likert-scale ratings (1–5) by model and evaluation dimension

Model	D1	D2	D3	D4	D5	Avg
<i>gpt-4.5-preview-2025-02-27</i>	4.2	4.1	3.8	4.3	4.0	4.08
<i>Llama-3.2-1B</i>	2.5	2.6	2.7	2.4	2.6	2.56
<i>Llama-3.1-8B</i>	3.2	3.1	3.0	3.3	3.1	3.14
<i>halo-lcm-full-8B</i>	4.0	3.9	3.7	4.0	4.2	3.96
<i>halo-lcm-full-1B</i>	3.9	4.0	3.6	4.1	4.0	3.92

As shown in Table 5.2, the *GPT-4.5* and *halo-lcm* models consistently performed well across all dimensions. Conversely, the *Llama-3.2-1B* model displayed significant weaknesses, particularly in Dimensions D1 (completeness) and D4 (clarity), where its ratings were markedly lower.

Further insights on this analysis are currently under development and will be presented in the first publication paper alongside the expert evaluation, which is still in the preliminary evaluation stages.

## Comparative Performance Evaluation of the different NLP models

## Chapter 6

# Ongoing and Future Research Directions

This chapter outlines two main avenues that originated from this dissertation, each corresponding to a core module or pedagogical feature. These directions highlight both technical enhancements and pedagogical objectives, setting the foundation for future interdisciplinary research and deployment in educational contexts.

### 6.1 *U=RI*solve Academy Gamification

One of the most promising directions for future work is the integration of gamification elements within the *U=RI*solve Academy platform. This section outlines the rationale, core mechanics, and implementation principles for these gamified features, ensuring alignment with pedagogical objectives. The design is informed by established frameworks such as Werbach and Hunter's 6Ds model [WH12], which supports structured integration of game thinking into educational contexts. For this particular avenue, the contribution from Professor António Coelho was essential for defining both the elements and also the methodology.

#### 6.1.1 Rationale and Objectives

As previously mentioned, this platform is supposed to be used by first-year students enrolled in FEELE and TCIRC during the first and second semesters, respectively. The main goals are then to complement the traditional study methods without replacing them and not to demand that the student invest time beyond that recommended by the ECTS of each class.

In line with the initial 2023 implementation of the *U=RI*solve Academy, the objective remains to provide a large, well-organised set of questions across various topics, fostering both engagement and learning through practice. To achieve this, the following principles will guide the design:

- The gamified elements should not distract the students from the main goal of learning the content.
- The expected time to invest in the application should not surpass 50% of the recommended independent study time for these modules.

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- The platform organisation should resemble the course organisation to ensure seamless integration with classroom learning.
- The platform should record and analyse the students progress to provide guidance and possibly indirectly recommend the students' next step

The subsections that follow propose key gamified features—drawing on frameworks such as Octalysis [kC]—and, where relevant, provide the necessary technical context for their implementation.

### 6.1.2 Core Mechanics and Pedagogical Alignment

The foundation of the platform remains a comprehensive question bank consisting of multiple-choice and short-answer questions spanning all relevant module topics. These questions should fulfil the following requirements:

- The questions should be categorised based on the topic they are included in.
- Questions should be presented within "tests" or sets, rather than individually, ensuring a better experience and more practice instead of navigation, which is important when reasoning the students' study schedules and optimised time management when using the platform.
- Correct answers should contribute towards immediate or cumulative rewards, reinforcing engagement.
- Answering a question correctly should contribute towards immediate or cumulative rewards.
- Students should be able to evaluate their own performance on each topic, thereby implying the platform to track their performance and providing analytics that highlight the strengths and areas to still focus on of the student.

These core mechanics involve some key elements of recognised gamification frameworks to fulfil the designed main objectives. However, additional features are proposed to address aspects such as ownership and accomplishment:

**Mastery track** To guide the users, a set of questions and explanations would follow a dedicated storyline, identified as "mastery tracks", corresponding to the different topics covered weekly in classes. Thus, another system to also provide students further motivation to repeat and engage with the platform is the addition of quests directly related to each week's topic, which consequently would recommend simple tasks such as completing the recommended week's topic or, to better engage with some exercises, additional exercises to allow the student to better engage with the application.

**Points System** To promote a feeling of ownership and accomplishment, the students will be rewarded with points as they complete questions, tests and quests. These points then will accumulate in a virtual wallet, providing tangible feedback on progress and further enabling students to unlock cosmetics or other rewards.

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**Achievements and badges** Achievements and badges will provide alternative motivational pathways, recognising milestones that reflect students' overall progress and expertise. These visual markers will be optional for display, respecting students' preferences for privacy or public recognition.

To provide the users an alternative goal besides the expected weekly motivation given with the mastery tracks and quests, students could contribute to overall achievements that therefore could reflect on their progression in the platform, which ideally would correlate with the students' expertise on the topics. These achievements could have a visual implementation in the form of badges, which would be optional for display, respecting students' preferences for privacy or public recognition.

### 6.1.3 Implementation Principles and Evaluation

The successful integration of gamification elements within the *U=RI*solve Academy platform requires a robust technical foundation that ensures scalability, maintainability, and a seamless user experience. In this context, several critical components have been identified as priorities for implementation.

**User authentication and profile** First, a secure and reliable authentication system must be developed to manage user accounts and safeguard personal data. This will enable the persistent tracking of student progress, support the delivery of personalised content, and maintain the integrity of the gamification features. To complement this, the introduction of profile avatars will allow users to customise their identity within the platform, fostering a stronger sense of engagement and ownership. From a technical perspective, the avatar system will need to integrate with the authentication module, ensuring that user preferences are consistently applied across sessions.

**Statistics** Another core requirement is the implementation of comprehensive profile statistics. The system will record and analyse tracking metrics such as accuracy in answering the questions, progression through the mastery tracks and completion rates of quests and tests. These statistics shall be made accessible via a user dashboard, providing students with clear, actionable insights into their strengths and areas for improvement. On the technical side, this necessitates the design of a data model capable of efficiently storing, querying, and visualising performance data, with an emphasis on extensibility to accommodate future metrics.

**User experience** To enhance the overall user experience, the inclusion of audio elements and polished User Interface (UI)/User Experience (UX) design will be essential. Subtle audio cues—for example, feedback sounds for correct or incorrect answers—can provide immediate reinforcement without becoming intrusive. Technically, this will require careful integration with the front-end framework to ensure low-latency playback and compatibility across devices. Similarly, the user interface should be designed for clarity and responsiveness, enabling intuitive navigation through gamified elements while preserving accessibility standards. The UI architecture must support modular enhancements, allowing future additions (e.g., new gamification components) to be incorporated with minimal disruption.

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These technical implementations will adhere to the same tooling and development methodologies outlined in Section 3.4, ensuring consistency across the platform. All components will be designed with extensibility in mind, facilitating future development and integration of additional gamified features as the platform evolves. Below is represented the expected taxonomy to be implemented in the user's database:

```
{
  "user_profile": {
    "user_id": "string",
    "name": "string",
    "email": "email",
    "role": "string",
    "registration_date": "date"
  },

  "studying_activity": {
    "user_experience": "number",
    "started_questions": "number",
    "answered_questions": "number",
    "correct_questions": "number",
    "time_spent_on_platform": "number",
    "last_active_date": "date",
    "topics_progress": {
      "topic_1": {
        "answered": "number",
        "correct": "number",
        "topic_mastery": "percentage"
      },
      "topic_2": {
        "answered": "number",
        "correct": "number",
        "topic_mastery": "percentage"
      }
    }
  },

  "bookmarked_content": ["question_id"],
  "answered_questions": [
    {
      "question_id": "string",
      "answered_correctly": "boolean",

```

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```
        "timestamp": "datetime"
    }
]
},

"gamification": {
    "achievements_earned": ["string"],
    "leaderboards": {
        "experience_leaderboard": "number",
        "correct_questions_leaderboard": "number"
    }
},

"system_usage": {
    "device_used": "string",
    "browser_info": "string",
    "preferred_language": "string",
    "last_login_country": "string"
}
}
```

Given the great potential and broad scope of the gamification aspect on this platform, it will be highly valuable to gain insights into the implementation and development of these concepts.

## 6.2 Expert-Curated Improvements

The second avenue for future research focuses on enhancements that go beyond technical implementation and instead require significant domain expertise. This work entails a rigorous process of content validation in collaboration with subject-matter experts, particularly in the fields of electrical and electronic engineering education.

### 6.2.1 HALO Enhancements

A central component of this research direction concerns improvements to the *HALO* system, which includes both the *HALO* dataset, originally developed with extensibility in mind, and the continued development of the *HALO* framework, which is in charge of Professor André Rocha according to its PhD plan.

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**HALO Dataset** As discussed in Section 5.3, the *HALO* Dataset demonstrates potential for further refinement. Enhancing the pedagogical quality of the dataset is expected to improve even more the performance of the underlying models and thus enrich the overall user experience.

These refinements involve incorporating expert-level pedagogical insights—specifically, explanatory elements and problem-solving strategies that are commonly conveyed in classroom settings but often omitted from textbooks or slides. By integrating multiple expert perspectives, the dataset can be expanded to offer diverse solution pathways for the same problem, supporting a broader range of learner preferences.

The following steps should be carefully considered, given the reliance on expert contribution:

- Due to time constraints faced by subject-matter experts, an efficient and structured collaboration strategy must be devised to optimize their input;
- All modifications to the dataset must adhere to the metadata and structural requirements outlined in Section 4.2.2;
- The construction of the Alpaca-style dataset for fine-tuning should involve more rigorous human validation. Rather than validating a small subset (e.g., 20 out of 200 entries), a larger portion should be manually reviewed—e.g., 150 out of 300 entries—to ensure pedagogical quality and consistency.

Given the extensive time commitment required from experts, it is essential to distribute the workload over several weeks and adopt a phased, collaborative approach to dataset expansion.

**HALO framework** Further development is also anticipated in the context of Professor André Rocha’s doctoral research, particularly regarding the implementation of key functionalities introduced in Section 4.1. These improvements aim to elevate *HALO*’s performance beyond the current baseline.

One of the core components under development is the Taskmaster module, which will be responsible for classifying incoming prompts and routing them to the appropriate specialised agent(s) for resolution. This will also involve the integration of additional tools, including support for multimodal communication, to extend the system’s versatility and applicability.

Upon completion of these enhancements, a new round of evaluations—comparable to the methodology described in Section 5.3—will be necessary. In particular, expert-based evaluations will be critical to verify the pedagogical validity and technical improvements introduced in the updated framework.

### 6.2.2 Topic Organization and creation

Another essential direction for future research involves the systematic organisation and development of course content. This includes structuring topics across different mastery levels, designing weekly assignments that reflect on the content covered in the theoretical coursework and follow a logical progression, and curating educational materials—such as summaries, guided exercises, and exam preparation documents—to be made available for the students using some elements presented in the previous research

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direction. Additionally, most parts of these features are meant to be utilised within the gamified version of *U=RI* *Solve Academy* as it builds upon the foundational structure proposed there and further elaborates on how the content can be effectively implemented and made accessible.

**Content Organization** A standardised framework must be established to categorise the curriculum effectively. This framework should follow a structure similar to that used in the dataset and be guided by the following principles:

- The content for FEELE and TCIRC must be treated independently;
- Topics should be divided into chapters, with each chapter subdivided into clearly defined subtopics of roughly equal scope;
- Chapter and subchapter titles must be descriptive and intuitive, allowing students to quickly identify the subject matter;
- Each subtopic should begin with a concise summary to orient the student and highlight the key learning points.

Additionally, a catalogue of exercise types must be established. This list should include formats such as true/false, multiple choice, and short answer. For more complex problems traditionally requiring extended responses, simplified or adapted formats should be devised to enable automated evaluation by the system.

**Weekly assignments** Weekly assignments serve to guide students through a structured, time-bound learning path that parallels the content covered in theoretical classes. Each weekly assignment should be composed of three distinct tasks. While the specific phrasing of each task can be determined later, the thematic alignment with the content structure is essential.

An example task might be: “*Correctly answer 15 questions related to Ohm’s Law.*”

The primary objective is to ensure that each weekly assignment aligns closely with the designated topics, thereby reinforcing timely and relevant learning.

**Student’s guidance material** One of the objectives presented in the previous future research was the addition of points that would work as a virtual currency. Therefore, to make use of those points, a virtual shop shall offer academic resources that complement the gamified elements of the platform. These include solved exercise collections, chapter summaries, and exam guidelines. This way students would feel incentivised to work towards the year to gather the most extra material possible to be ready for the exam (this material should only be extra and should not require a big effort to get). The preparation of these materials involves:

- Curating and organizing content by topic;
- Segmenting materials into individual files, each focused on a single concept or chapter to avoid cognitive overload;

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- Ensuring pedagogical clarity and student-friendly language, particularly in summaries, which may build upon existing *HALO* dataset explanations.

Materials should be designed to facilitate targeted studying and to promote self-guided learning without overwhelming the student.

### **6.2.3 Methodology**

As previously noted, this research direction is less focused on technical development and more orientated towards content design and instructional planning. Consequently, it is crucial to define a clear work plan from the outset, tailored to the time available and the researcher's level of expertise in the subject matter.

Adherence to the organisational guidelines outlined above is essential for ensuring consistency, clarity, and usability across all educational materials. The success of this research depends on a methodical and well-structured approach that prioritises both pedagogical effectiveness and ease of access for the learner.

## Chapter 7

# Conclusions

This dissertation addressed the persistent pedagogical challenges faced by students in mastering the fundamentals of electrical circuit analysis — a topic recognised for its theoretical complexity and practical demands. In response to these challenges, this work focused on advancing the *U=RI*solve Academy educational platform by restructuring its codebase to improve scalability for future contributions and therefore exploring the integration of AI technologies to enhance the platform’s educational impact.

The restructuring of the codebase resulted in a robust and extensible architecture that not only preserves the efforts of previous contributors but also establishes a solid foundation for future developments. This new structure was validated by the author during the integration of the *HALO* assistant chatbot and is currently in use by three other students working on projects within the *U=RI*solve Academy framework.

The key contribution of this dissertation was the creation of the baseline curated dataset covering the fundamentals in electrical circuit analysis as taught in the first year of the ECE programme. Preliminary evaluations produced positive results, supporting both its development and the future research directions outlined in Section 6.2.

Future directions include the publication of the article reporting on the fine-tuned model’s evaluation, the creation of a new evaluation based on RAG models as discussed in Section 4.1, and the continuation of studies on additional pedagogical innovations. In particular, future work will explore enhanced expert collaboration to further improve the dataset and the integration of gamification elements to increase engagement and learning outcomes. This work is already under preliminary testing within the project *U=RI*solve Academy+, co-supervised by the author.

In connection with these future directions, the following hypotheses are proposed for investigation in subsequent iterations of the platform:

1. The *HALO* assistant’s personalised feedback will be able to fulfil students’ requests with responses comparable in quality to those provided by human experts.

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2. Students will dedicate more time to studying the FEELE and TCIRC course materials when interacting with a gamified version of the *U=RSolve Academy* platform, motivated by rewards, challenges, and progress tracking mechanisms.
3. A positive correlation will emerge between student engagement metrics (e.g., experience points) and their final academic performance in the respective courses.

Overall, this dissertation contributes to the ongoing effort to create dynamic, interactive, and personalised learning experiences in electrical engineering education under the *U=RSolve Academy* framework.

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