Unlocking Digital Electronics: A Hybrid Educational Escape Room Approach to Vocational Learning

Carla Barbosa[1], José Brito[2,3], Sara Cruz[2,4,5]

[1]Instituto Politécnico do Cávado e Ave, Barcelos, Portugal
[2]2Ai – School of Technology, Instituto Politécnico do Cávado e Ave, Barcelos, Portugal
[3]LASI – Associate Laboratory of Intelligent Systems, Guimarães, Portugal
[4]CIEd - Research Centre on Education, University of Minho, Braga, Portugal
[5]inED - Center for Research & Innovation in Education, Polytechnic University of Porto Porto, Portugal

Abstract

Vocational Electronics education increasingly requires pedagogical approaches capable of connecting conceptual understanding, practical reasoning, and learner engagement. However, teaching practices in this field often remain centred on transmissive models that insufficiently reflect students' digital cultures, collaborative ways of learning, and the applied nature of vocational education. This study examines the pedagogical potential of a hybrid Educational Escape Room designed to support the learning of number systems, logic gates, and digital circuits among tenth-grade vocational students. Grounded in game-based and active learning principles, the intervention combined digital tasks, physical clues, collaborative challenges, and a culturally situated narrative inspired by Guimarães Castle and the historical figure of Mumadona Dias. The study adopted a mixed-methods design, integrating quantitative evidence on academic performance and usability with qualitative data on students' perceptions, motivation, collaboration, and learning experience. The design was informed by prior research on educational escape rooms as structured game-based learning environments and by evidence suggesting that escape-room activities can enhance motivation and learning in computing and technical domains. Results indicate gains in academic performance and high perceived usability, alongside strong student reports of engagement, collaborative participation, and consolidation of core concepts in digital electronics. Qualitative findings suggest that the hybrid format, narrative framing, time-bound challenges, and puzzle progression helped students attribute meaning to abstract technical content while developing transversal skills such as communication, teamwork, and problem-solving. The study contributes to current debates on innovation in vocational education by showing how hybrid Educational Escape Rooms can support more active, situated, and collaborative forms of electronics learning when carefully aligned with curricular objectives, usability principles, and opportunities for conceptual consolidation.

Keywords: *Educational Escape Rooms; Hybrid Learning Environments; Gamification; Vocational Electronics Education; Game-Based Learning.*

1. Introduction

Vocational education occupies an increasingly strategic position within contemporary educational systems, particularly in technologically intensive fields such as Electronics. As digital infrastructures, automation systems, and embedded technologies continue to evolve, so too must the pedagogical approaches through which foundational concepts—including number systems, Boolean logic, and digital circuits—are taught. Yet instruction in many vocational classrooms remains predominantly expository, privileging transmission over participation and procedural replication over conceptual understanding.

Within Portuguese vocational education, these challenges are intensified by the distinctive profile of learners, who often respond more productively to practical, contextualised, and action-oriented pedagogies. The resulting tension between traditional pedagogical models and digitally mediated learning cultures calls for structured, theoretically grounded innovation rather than ad hoc technological adoption.

Despite growing interest in Educational Escape Rooms, existing research has predominantly focused on general education contexts, with limited attention to vocational STEM domains. Furthermore, few studies have systematically examined hybrid configurations combining physical and digital components, particularly in relation to conceptual learning rather than engagement alone.

Educational Escape Rooms (EERs) have emerged as a promising response to this challenge. By integrating game-based learning, collaborative problem-solving, narrative immersion, and technological mediation, EERs have the potential to transform abstract technical content into situated and meaningful learning experiences. A hybrid EER extends this format by combining digital and physical elements within a coherent learning design, such that online interaction, material artefacts, and embodied action work together in support of intended educational outcomes.

This study addresses these gaps through the design, development, implementation, and evaluation of a hybrid EER for tenth-grade students enrolled in vocational Electronics, focused on number systems, logic gates, and digital circuits, and embedded within a historical-cultural narrative inspired by the Castle of Guimarães and the figure of Mumadona Dias. In doing so, it advances both empirical and design-based knowledge on the pedagogical use of hybrid Educational Escape Rooms in vocational STEM education. The study was guided by four research questions: (RQ1) How can core Digital Electronics concepts be epistemically and pedagogically structured within a hybrid EER? (RQ2) What design issues emerge during expert review? (RQ3) To what extent does the resource demonstrate usability and pedagogical viability for classroom integration? (RQ4) How do students experience the hybrid EER in terms of engagement, collaboration, and perceived conceptual understanding?

2. Literature Review

2.1 Vocational Electronics as a Pedagogical Design Challenge

Vocational education is frequently defined by an imperative to connect theoretical knowledge with situated practice, developing both technical and transversal competences for employability [1]. However, classroom practices often remain predominantly transmissive, with limited scope for learner participation and meaning-making [3]. These conditions can be especially detrimental in abstract technical domains such as number systems, Boolean logic, and digital circuits, where conceptual learning requires sustained engagement and iterative reasoning.

The study is informed by three complementary perspectives. First, game-based learning (GBL) provides the basis for examining how challenge, feedback, progression, and narrative can be aligned with curricular goals. Secondly, self-determination theory offers a lens for understanding how the intervention may support autonomy, competence, and relatedness [15]. Thirdly, sociocultural perspectives on learning foreground the collaborative and dialogic character of problem-solving. However, there remains a lack of pedagogical models that effectively translate these theoretical principles into structured learning designs within vocational Electronics.

2.2 Educational Escape Rooms as Hybrid Epistemic Environments

EERs can be interpreted as a designed sequence of interdependent problems requiring learners to mobilise concepts, test hypotheses, and coordinate actions under constraints. In STEM education, EERs are frequently reported to increase involvement and active participation by embedding curricular tasks within time-bound collaborative missions [12]. The conceptual value of EERs depends on whether puzzles are epistemically aligned with disciplinary structures rather than merely entertaining.

Contemporary EERs have evolved from logic-only puzzle rooms to more immersive and technologically mediated experiences, including hybrid and virtual formats. Platforms such as Genially are often highlighted for rapid development of narrative pathways and multimedia interactivity [19], while physical components afford embodied interaction that anchors abstract reasoning in observable phenomena.

Despite these potentialities, EER design involves risks including cognitive overload, time-pressure effects, and inequitable participation [7]. Effective EER design must therefore balance challenge with cognitive accessibility, ensuring that all learners can engage meaningfully and equitably. Nevertheless, much of the literature treats EERs primarily as engagement-enhancing tools, with limited attention to their epistemic design and alignment with disciplinary knowledge structures.

This study addresses these gaps through the design: (i) limited research in vocational STEM contexts; (ii) insufficient focus on hybrid physical-digital escape room designs; and (iii) a lack of empirical evidence linking EERs to conceptual understanding rather than engagement alone. To address these gaps, the present study adopts a design-based and mixed-methods approach.

3. Method

3.1 Design and Procedure

This study employed a development-oriented research design [18] to design, refine, and evaluate a hybrid EER for vocational Electronics. The study adopts a design-based research (DBR) orientation, combined with a quasi-experimental comparison to examine both design validity and learning outcomes. The development cycle comprised: (i) prototype conception aligned with curricular outcomes; (ii) expert review and iterative refinement; (iii) usability evaluation; (iv) implementation in an authentic classroom setting; and (v) impact analysis.
The intervention followed a standardised sequence comprising briefing, mission completion, and structured debriefing. Students worked in small teams of three to four for approximately 90 minutes. The teacher assumed the role of facilitator, providing support only when necessary. A mixed-methods case-study approach with a quasi-experimental non-equivalent groups design was adopted, comparing a pilot class exposed to the EER with a control class receiving conventional instruction.

3.2 Participants and Context

The study was conducted at a secondary school within regular vocational education provision. Two 10th-grade vocational classes participated: a pilot group from the Professional Course in Information Systems (n = 14) and a control group from the Professional Course in Electronics, Automation and Computers (n = 9), yielding a total of N = 23 participants aged 14–17 years. All participants were male, reflecting the demographic composition typical of the participating vocational programmes. The all-male composition of the sample reflects programme demographics and is acknowledged as a limitation regarding generalisability.

3.3 Instruments

Data were collected using a set of complementary instruments. A motivation questionnaire adapted from the Science Motivation Questionnaire II (SMQII) [10] assessed baseline motivational dispositions. Pre-test and post-test knowledge assessments enabled estimation of short-term learning gains. System usability was assessed through the System Usability Scale (SUS) [6]. A structured observation protocol recorded indicators of engagement, collaboration, and problem-solving. A feedback questionnaire and focus-group protocol captured students' perceptions of the experience. All instruments demonstrated acceptable internal consistency.

4. EER Design and Development

4.1 Conception and Narrative

The EER "The Lost Code" was designed as a hybrid pedagogical resource, integrating a digital component developed on the Genially platform and a physical component—a 3D-printed box housing an electronic circuit based on an Arduino Uno board. The design was guided by principles of active learning, gamification, and user-centred design [11].
The framing narrative draws on the historical figure of Mumadona Dias, the countess who founded the Castle of Guimarães in the 10th century. Students are challenged to decipher a secret code hidden within the castle's stones. This historical-cultural dimension provides a contextualised and meaningful framework, linking Digital Electronics content with Portuguese cultural heritage within a STEAM logic.

4.2 Mission Organisation and Game Progression

The EER is organised into five virtual rooms inspired by symbolic spaces associated with the Castle of Guimarães. Progression follows a conditional sequential logic: access to each room depends on the correct resolution of previous challenges, ensuring a gradual increase in difficulty and phased consolidation of knowledge. Table 1 summarises the mission structure, and Fig. 1 illustrates the reading of the letter attributed to Mumadona Dias, which introduces the narrative mission and contextualises students within the historical setting.

Table 1. Mission organisation of the EER "The Lost Code"

Room	Curricular Content	Challenge Type	Outcome
Entry Tower	Number systems: binary, decimal, hexadecimal	Multiple-choice conversion	Fragment 1
Library	Logic gates: truth tables and symbolic representations	Association matching	Fragment 2
Museum	Logic circuits: Boolean expressions and circuit diagrams	Circuit analysis	Fragment 3
Royal Workshop	Physical logic gate identification	Hands-on: switches, LEDs, truth table	Fragment 4
Keep Tower	Integration of all content	Sequential code entry via digital padlock	Mission complete

Fig. 1. Letter introducing the mission of the hybrid EER “The Lost Code”, AI-generated and adapted by the author using ChatGPT.

4.3 Digital and Physical Components

The digital component was developed on the Genially platform, enabling integration of multimedia elements, interactive challenges with conditional progression logic, and a digital padlock system. The visual design evoked the medieval atmosphere of the Castle of Guimarães. Accessibility features included user-controlled audio settings, minimum reading time constraints, multimodal cues combining visual elements and textual information, and consistent layout structures to minimise extraneous cognitive load.

The physical component consists of a 3D-printed box, modelled in Autodesk Fusion 360 and printed with PLA filament. Inside, an Arduino Uno-based circuit includes two input switches and three output LEDs, allowing students to manipulate input states, observe output behaviour, and empirically construct the circuit’s truth table. The “hidden” logic gate can be changed by the teacher through simple code modification, reinforcing resource versatility and reusability. Figure 2 illustrates both the digital interface and the physical component of the hybrid EER.

This component fulfilled a clear epistemic function: enabling students to establish explicit connections between symbolic representations and observable system behaviour, supporting hypothesis testing, inference, and iterative reasoning.

Fig. 2. Hybrid EER "The Lost Code": (left) Library room, AI-generated and adapted by the author using ChatGPT; (right) physical component.

5. Resource Validation

5.1 Expert Review and Iterative Refinement

The expert review process involved four specialists with over 18 years of experience: two from Computing and two from Electrical Engineering. Each specialist independently interacted with the EER following a structured expert walkthrough protocol organised around seven heuristic dimensions adapted from Nielsen [13]. Table 2 summarises the main findings and corresponding redesign decisions.

Table 2. Expert review findings and redesign decisions

Spec.	Finding	Redesign Decision	Severity
S1	No clear indication of mission progress	Added visual progress indicators (padlocks + markers)	Major
S2	Background music could disrupt concentration	Implementation of user audio control	Minor
S3	Entry Tower too demanding as entry point	Adjustment of difficulty level	Major
S4	Museum task was overly complex and risked disengagement before students had processed the instructions	Adjusted difficulty and instruction timing	Major

5.2 Usability Evaluation

Following iterative refinement, the EER's usability was evaluated using the SUS [6], administered to eight students from other year groups. Results revealed a mean SUS score of 86.18 (SD = 3.90), with individual scores ranging from 80.00 to 92.50. This mean score places the system within the Excellent category (Grade A), exceeding both the 80.3-point threshold identified by Bangor et al. [2] and the 68-point benchmark for acceptable usability. Item-level analysis showed particularly positive ratings for ease of use (M = 5.00), user confidence (M = 4.63), and systemic integration (M = 4.63).
As the SUS was administered to students from other year groups, the results provide evidence of perceived usability but should not be interpreted as direct evidence of learning effectiveness among the intervention participants.

6. Results and Discussion

6.1 Learning Outcomes

No statistically significant difference was found between groups in baseline motivation, $t(21) = -0.095$, $p = .925$, confirming initial equivalence. Regarding academic performance, the pilot class improved from a mean of 56.36 (pre-test) to 63.38 (post-test), whereas the control group showed only a modest increase of less than two points. Although between-group differences did not reach statistical significance—attributable to the small sample size—the descriptive gain pattern is consistent with a possible positive contribution of the hybrid EER to short-term learning gains. Although statistical

significance was not achieved, the observed trend suggests a possible practical effect, warranting further investigation with larger samples.

6.2 Motivation, Engagement, And Collaboration

Across data sources, a consistent pattern emerged: students described the activity as more dynamic and involving than conventional instruction, and observation records indicated active participation, sustained attention, and persistence. The escape-room structure required coordinated participation, negotiation of meaning, and shared decision-making, supporting what sociocultural perspectives describe as learning through participation [16]. From the perspective of self-determination theory, the intervention can be interpreted as supporting autonomy (through problem-solving), competence (through progressive challenge and feedback), and relatedness (through collaborative interaction) [15]. These findings align with self-determination theory, suggesting that the design supported intrinsic motivation through structured challenge and social interaction.

6.3 Perceived Contribution of Hybridity and Narrative

One of the most distinctive findings concerns students' perceptions of the hybrid and narrative dimensions. Participants highlighted the value of combining digital progression with physical manipulation, suggesting that the interaction between the Genially-based environment and the electronic box contributed to making abstract Electronics concepts more intelligible and meaningful. Rather than functioning as a superficial motivational layer, the narrative acted as a structuring device that linked tasks, supported progression, and contextualised abstract content, extending existing work on culturally situated storytelling in technical learning contexts [17].
The physical component functioned as an epistemic tool enabling learners to connect symbolic representations with observable system behaviour—supporting hypothesis testing, inference, and iterative reasoning central to conceptual understanding in Electronics [14].
This finding is particularly relevant, as it suggests that hybridity is not merely a technological enhancement but a pedagogically meaningful design feature.

7. Discussion

The findings of this study are interpreted in relation to the four research questions that guided the investigation.
Regarding RQ1, the five-room conditional progression demonstrated that Digital Electronics content can be systematically embedded within a hybrid EER, connecting number systems, truth tables, Boolean expressions, and circuit behaviour within a coherent pedagogical sequence. The alignment between the narrative arc and the curricular scope ensured that each room contributed a conceptual building block, supporting the kind of structured challenge-feedback loop identified as central to effective game-based learning [11, 12].
Regarding RQ2, the expert review process surfaced critical design issues — particularly related to difficulty calibration and progress visibility — that would likely have compromised engagement and learning if left unaddressed. The iterative refinement cycle adopted here reinforces the value of structured expert evaluation as a design validity mechanism prior to classroom implementation [8].
Regarding RQ3, the SUS mean score of 86.18 confirms that the hybrid EER reached a level of usability consistent with excellent classification, supporting its viability for classroom integration [2]. This finding is significant because usability functions as a necessary precondition for meaningful engagement: a resource that students cannot navigate fluently is unlikely to support the epistemic goals it was designed to serve.
Regarding RQ4, student reports of motivation, collaboration, and conceptual consolidation are consistent with evidence from comparable EER interventions in STEM and technical education [4, 14, 16]. The hybrid format appears to have added pedagogical value beyond digital-only designs by grounding abstract symbolic reasoning in observable physical phenomena. From a self-determination theory perspective [15], the intervention supported autonomy through open-ended problem-solving, competence through progressive challenge and immediate feedback, and relatedness through sustained collaborative interaction — conditions associated with intrinsic motivation and deeper engagement.
Taken together, these findings suggest that hybrid Educational Escape Rooms can function as epistemically structured learning environments rather than merely motivational tools, extending the

conclusions of recent systematic reviews [12, 19] to the specific context of vocational Electronics education. These findings should be interpreted in light of several limitations. The small sample size and the non-equivalent groups design limit the statistical power of between-group comparisons and restrict the generalisability of the results. Additionally, the all-male composition of the sample, which reflects the demographic profile of the participating vocational programmes, limits the extent to which findings can be extrapolated to more diverse learner populations.

8. Limitations

This study has several limitations. First, the sample was small, comprising 23 students distributed across two non-equivalent vocational classes. Secondly, all participants were male, reflecting the demographic composition of the programmes but limiting the transferability of the findings to more diverse learner populations. Thirdly, the absence of random assignment prevents causal interpretation of the observed learning gains. Fourthly, the pilot and control groups belonged to different vocational courses, which may have introduced differences in prior knowledge, curriculum exposure, or learner profile. Fifthly, the study examined short-term learning outcomes only; no delayed post-test was administered to assess retention. Finally, although the hybrid design appeared pedagogically promising, further research is needed to examine transfer to unfamiliar digital electronics problems and to evaluate scalability across teachers, schools, and cohorts.

9. Conclusion

This paper described the design, development, validation, and classroom implementation of the hybrid EER “The Lost Code”, conceived as a pedagogical resource for teaching Digital Electronics in vocational education. By combining a structured historical-cultural narrative, interactive digital challenges in Genially, and a physical Arduino-based electronic circuit, the intervention established a hybrid learning environment aligned with principles of active learning and game-based learning.

The validation process confirmed the technical robustness and pedagogical coherence of the resource (SUS mean: 86.18). The classroom implementation provided empirical evidence suggesting improvements in academic performance in the pilot group and, more importantly, qualitative evidence of increased motivation, active engagement, collaborative problem-solving, and meaningful interaction with abstract technical content.

This study advances the field by demonstrating that hybrid Educational Escape Rooms can function not only as engagement-enhancing strategies but as epistemically structured learning environments capable of supporting conceptual understanding in vocational STEM education. By integrating narrative, physical interaction, and digital progression, the proposed design model offers a scalable and pedagogically grounded approach for technology-enhanced learning. Future research should seek to replicate this study with larger and more heterogeneous samples, and to examine longer-term effects on knowledge retention and transfer.

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