

Digital Strategies for Training Electricians using 3D models, AR and VR

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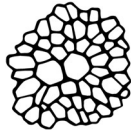
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Abstract. This paper presents the development of an innovative training framework for electricians working in power distribution networks, combining immersive and non-immersive digital technologies with conventional instructional tools. Grounded in robust pedagogical theories, including constructivism, constructionism, and Freirean dialogic pedagogy, the project aimed to transform traditional technical training into an educational experience that fosters critical engagement and learner autonomy. The central hypothesis was the creation of a 3D Interactive Virtual Network (IVN) embedded in a fictional urban-rural environment, from which all instructional materials would be derived, including VR/AR simulations, 2D animations, and interactive presentations. In its first phase, the project involved pilot courses with 15–20 participants of diverse backgrounds, ranging from novices to experienced electricians and recently hired engineers, over several months of prototyping and refinement. Preliminary results highlight the production of the IVN and related instructional materials, indicating the potential for scalable and pedagogically grounded training solutions.

Keywords: Instructional Design, Digital Pedagogy, Virtual Reality, Technical Training, Electrical Distribution Networks

1 Introduction

The maintenance of electricity distribution networks entails significant risks for operators, particularly when they lack full knowledge of the technical and structural aspects of the networks and their components. The training of electricians represents a major challenge for instructors, as trainees are not



allowed to perform hands-on activities on live lines due to the high risk of accidents. Nor can they operate expensive and sophisticated protective devices, such as reclosers and voltage regulators, during training sessions, given the potential for irreparable damage.

CEMIG, which operates the largest electricity distribution network in Minas Gerais, has established a corporate university equipped with full-scale 1:1 mock-ups of distribution networks and various real equipment, allowing for the simulation of real work scenarios in a safe environment. While this approach has yielded satisfactory results, it presents a number of limitations. Among the most significant are: the need for direct and continuous supervision by the instructor to prevent accidents, which requires an inefficiently low trainee-to-instructor ratio; the mock-ups are installed outdoors, making training sessions susceptible to interruptions or cancellations due to weather conditions; and training activities are restricted to the company training campus (Univercemig), requiring trainees to spend extended periods away from their workplaces and families.

To address these challenges, CEMIG decided to explore the use of digital simulations, both immersive and non-immersive, given that digital technologies enable the development of highly accurate models that can be freely manipulated by trainees. This approach could eliminate both the risk of accidents and interruptions caused by weather, while also fostering greater autonomy in the learning process. It thus represents both a methodological and technological innovation in training.

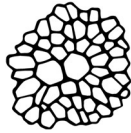
To move this initiative forward, the company established a partnership with NEXT, which has extensive experience in developing 3D virtual models of buildings and urban environments - a skillset that could be extended to other fields of application. For our lab, the development of innovative educational materials using new digital technologies offered an opportunity to enhance its expertise in interactive 3D modeling and in the use of the software and hardware infrastructure that supports immersive VR and AR applications. The knowledge gained from this experience would certainly have a positive impact on architectural and urban education, particularly in courses related to building systems, urban infrastructure, and facilities maintenance.

2 Methodology

2.1 Theoretical and Conceptual Framework

The introduction of new technologies into teaching and learning processes yields better results when supported by robust pedagogical theories; otherwise, there is a risk of wasting time and financial resources (Serdyukov, 2017).

It is understood that meta-responsive approaches should begin within educational processes, which are often fragmented into isolated content



blocks—dissociating not only theory and practice, but also disconnecting knowledge, methods, and techniques. This issue has been emphasized since the early 20th century by John Dewey, and later by Vygotsky, Piaget, and other key figures of modern pedagogy in the United States and Europe, whose focus was primarily on the education of children and adolescents.

Dewey's (1938) theory of reflective practice, later expanded by Schön (1984), emphasizes that learning occurs through the interaction between subject and object of knowledge, integrating theory and practice by doing and reflecting. In a complementary way, Piaget's constructivism (1970) conceives knowledge as socially built, requiring learners to take an active role in identifying problems, seeking information, experimenting with solutions, and comparing outcomes. Although originally focused on child development, his concepts are broadly applicable to knowledge formation.

In South America, Paulo Freire (1970) emphasized that adult education must engage with learners' lived experiences to foster meaningful knowledge construction. Building on Dewey, Vygotsky, and Piaget, he developed a pedagogy grounded in experience and sustained through dialogue between educators and learners.

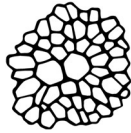
Papert (2018), a former student of Piaget, reinterpreted constructivism in the digital age through constructionism. He argued that interaction with computers adds new dimensions to knowledge construction, making learning more dynamic and iterative rather than strictly sequential.

Popper's epistemology (1972) complements these perspectives by asserting that theory precedes practice, which then tests and refines knowledge through trial and error. He explained this through three interrelated worlds: the physical world (World 1), subjective experiences (World 2), and objective knowledge embodied in texts, models, or digital memory (World 3). Knowledge emerges when the subject critically interacts with World 3, mediated by World 2. Although distinct from constructivist approaches, this framework reinforces reflection and critical testing as central to technical training.

In our view, Popper's epistemology completes the theoretical-conceptual framework required to pedagogically underpin the training process for electricians.

In general, companies tend to view training as solely aimed at optimizing performance in specific operations. Under this perspective, training becomes a form of mere conditioning, which contributes little to the personal development of trainees. The challenge for educators is to transform training into genuinely educational activities, as professional conditioning alone does not significantly contribute to societal advancement. To address this challenge, the following guiding principles were established:

- Enable trainees to understand the theories, methods, and techniques underlying their activities;
- Promote dialogical situations in which individual experiences can emerge and contribute critically to problematizing maintenance operations;



- Develop motivational instructional materials that allow both trainees and instructors to broaden their skills and competencies beyond their immediate specialties.

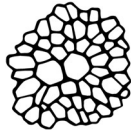
In this context, the shift from conditioning to true capacity-building involves three categories of actors: trainees, company instructors, and external consultants. These actors engage at three distinct stages: (1) construction of the theoretical/conceptual framework (instructors and consultants); (2) development of instructional materials and planning of activities (instructors and consultants); (3) implementation of the training process (instructors and trainees).

Motivational instructional materials should possess the following characteristics:

- Be easy to use for instructors and easy to understand for trainees;
- Incorporate the knowledge and experience of instructors, engaging them in the development of the instructional material;
- Embrace a progressively disruptive innovation process, expanding Christensen and Overdorf's (2000) concept of disruptive innovation to the educational field. In this sense, the introduction of new technologies should not radically alter training structures or fully replace existing instructional modalities. Instead, as instructors become more familiar with these technologies, their use can be gradually expanded;
- Courses should be developed using non-specialist software tools, considering the digital literacy levels of instructors, as there is strong evidence of a direct relationship between teachers' digital competence and the effectiveness of digital technology integration in teaching (Instefjord & Munthe, 2017, p. 37).

Based on these theoretical foundations and innovation strategies, it was decided that the instructional materials would be developed around three combined axes, as illustrated in the diagram in Figure 1. The development process followed a structured workflow: company sketches based on technical standards were translated into 3D models in SketchUp Pro and refined in Blender. Instructional animations were prototyped in Keynote, while finalized models were published on Sketchfab for mobile access and validation by instructors.

The "local/remote" axis refers to the distinction between activities that take place in person and those that can be carried out remotely via the web. The "individual/collective" axis distinguishes between activities that the trainee must perform individually, due to the nature of real-world work scenarios, and those that should be carried out collectively or with the involvement of other actors (even if the actual execution remains individual). The "degrees of immersion" axis pertains to the type of interactive interface employed:



- **Level 1 (non-immersive):** supported by tablets, smartphones, desktops, laptops, and 2D instructional materials (texts, images, videos, animations);
- **Level 2 (semi-immersive):** supported by augmented reality (AR) using head-mounted displays such as the HoloLens 2;
- **Level 3 (fully immersive):** supported by virtual reality (VR) using head-mounted displays such as the Meta Quest 2, supported by PCs equipped with R14 Ryzen processor, 128GB RAM, and RTX 3090Ti GPUs.

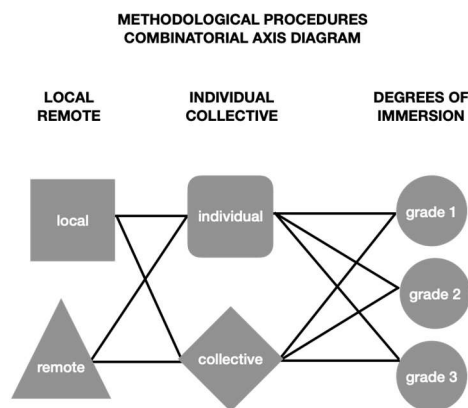


Figure 1- Diagram of combinatorial axes. Source: authors.

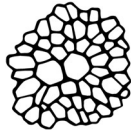
Based on this framework, it was possible to determine where, when, and which technologies (both interfaces and hardware) should be deployed by instructors and trainees in accordance with the pedagogical objectives of each training activity. In addition to its pedagogical alignment, this structure is inherently flexible and allows for the future implementation of new functions and interfaces, thereby enhancing the system's potential for expansion and scalability.

This separation into degrees of immersion was established for schematic clarity and to facilitate understanding of the proposed framework. It is important to emphasize that such classification is heuristic and should not be interpreted as a strict ontological hierarchy (cf. Rolla et al., 2022).

2.2 Formulating Solutions

2.2.1 Review of Relevant Literature

Once the problem had been characterized and the theoretical and conceptual framework established to support the development of solutions, an exploratory



literature review was conducted. This review was guided by previously defined keywords and aimed to identify cases of professional training—preferably for electricians—that made use of digital technologies.

The literature from the past five years consistently demonstrates that immersive technologies measurably enhance professional learning. A meta-analysis conducted by the World Bank (Angel-Urdinola, Castillo-Castro, & Hoyos, 2021) reported statistically significant gains in efficiency and skill transfer when compared to traditional training methods. Similar findings are noted in the reviews by Jongbloed et al. (2021) and Han et al. (2022). The impact appears to be even more pronounced in safety-related scenarios. Meta-analyses by Man, Wen, & So, and by Scorgie et al., show that virtual reality (VR) improves performance in construction safety training and enhances hazard recognition across multiple industries. Guo et al. (2020) document reduced task times and fewer errors in industrial maintenance training, especially when realistic 4D models are used.

However, the evidence also suggests that effectiveness does not stem from technology alone, but rather from its alignment with learning theories. Orozco & Giraldo-García (2024) emphasize that principles of andragogy and constructivism are essential for fostering autonomy among adult learners. From a critical perspective, Novoa Muñoz & Alsinglawi (2023) explore how Freirean pedagogy can be incorporated to empower learners as co-creators of VR content.

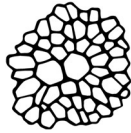
Practical challenges nonetheless remain. Joglekar (2024) highlights the complexity involved in content creation and the widespread lack of digital competency among instructors. Guo et al. (2020) also identify low interoperability across platforms as a significant technical bottleneck.

Across the reviewed literature, the simulation of real-world situations through interactive virtual models, whether immersive or non-immersive, emerges as both a technically viable and pedagogically effective solution, provided it is appropriately contextualized. This aligns with the authors' own understanding, grounded in their teaching experience with similar cases and in other disciplinary domains.

2.2.2 Hypothesis of Solution

The proposed solution was to anchor training activities in the simulation of an Interactive Virtual Network (IVN), a 3D mock-up of an urban-rural area encompassing key training scenarios. Designed to reflect the diversity of Brazilian cities, the IVN includes informal settlements, affluent neighborhoods, and commercial zones, fostering critical discussions on socio-economic issues in line with Freire's transformative pedagogy. It also serves as the basis for all instructional materials (Figure 2).

Instructional material developed in this manner would possess the necessary attributes to support the engagement of both instructors and trainees



in the training activities, fostering a dialogical relationship in which personal experiences, combined with existing theoretical frameworks, could contribute to problematizing real-world situations.

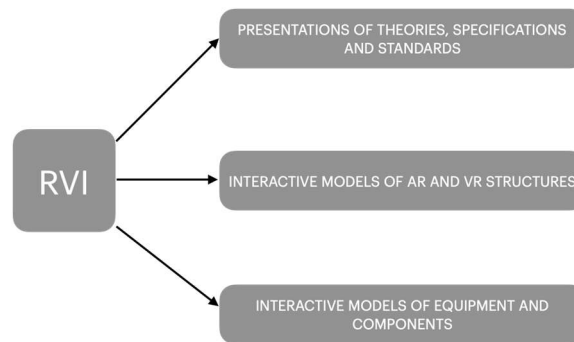


Figure 2 - Diagram of instructional materials. Source: authors

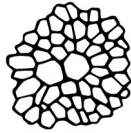
2.3 Development of Instructional Materials

All materials were developed through the integration of theoretical foundations, technological innovations in VR and AR, and conventional digital instructional resources such as image-based presentations, texts, audio, and video. Each product was preceded by a prototype, which underwent critical evaluation by the company—including technicians, instructors, and managers who had not been involved in its development. Following any adjustments suggested during the review, the finalized version would be produced.

2.3.1 The Interactive Virtual Network (IVN)

The IVN was designed to support a general understanding of electricity distribution networks, including their components and operational logic. It consists of an interactive 3D model of a fictional distribution network, representing streets, buildings, a substation, a railway line, and an adjacent rural area. The urban and architectural modeling was primarily developed in SketchUp Pro (v.2025), with some elements imported from Blender (v.4.3).

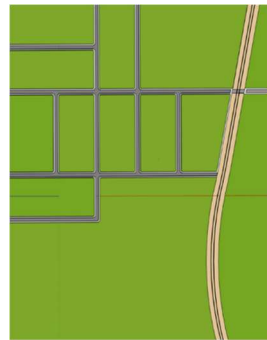
Initially, company instructors created a sketch of the IVN, indicating the layout of streets, the positioning and type of utility poles, and the specification of each structure, in accordance with the relevant standards: ND-2.1 (Basic Installations of Urban Overhead Distribution Networks), ND-2.2 (Basic Installations of Rural Overhead Distribution Networks), ND-2.7 (Basic Installations of Isolated Overhead Distribution Networks), and ND-2.9 (Basic Installations of Compact Overhead Distribution Networks). The architects on



the team interpreted the sketch through an urbanistic lens and modeled an urban settlement adjacent to a rural area, placing the utility poles in accordance with the architectural typologies of the surrounding buildings (Figure 3).



Instructors' sketch



Urbanistic Interpretation of the sketch

Figure 3: IVN – Dimensional and Urban Translation of the Initial Sketch. Source: authors.

Although the IVN is a relatively simple virtual mock-up developed in SketchUp, its programming to enable appropriate navigation and user interactivity is not—this functionality is implemented via Sketchfab, through predetermined camera positioning. Figure 4 presents visualizations of the IVN, including buildings, utility structures, and cabling.

2.3.2 Structural Models

One of the core training activities involved assembling a complete structure, including the utility pole and its components. To support this, each element was modeled at full scale and animations were created in Keynote using images exported from SketchUp (Figure 5), allowing instructors to demonstrate procedures and trainees to replicate them.



Figure 4: IVN Visualization. Source: authors

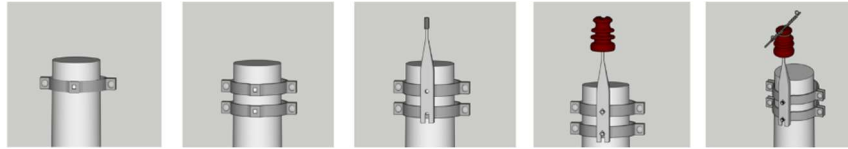
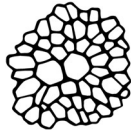


Figure 5: Step-by-step assembly – animation. Source: authors

This strategy ensured accuracy and consistency across training sessions, while also allowing the materials to be reused in both face-to-face and remote learning contexts. The modular approach facilitates future updates, since new components or variations can be incorporated without remaking the entire model.

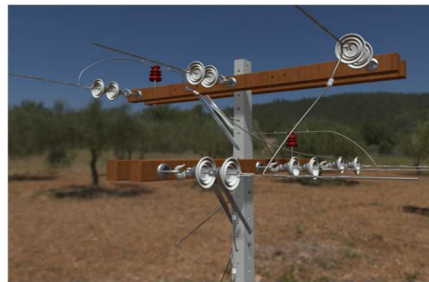


Figure 6: Navigable model of structure N3-N3 (NBI 170 kV). Source: authors

In addition to generating animations for conventional presentations, the models can also be explored in virtual reality (Figure 6) via Sketchfab. This makes them accessible on smartphones or tablets, allowing trainees to navigate the models to clarify doubts or review procedures.

2.4 Interactive Presentations

To support the theoretical content, interactive presentations were developed using Keynote (v.14). This software was chosen for its formatting capabilities and its ability to export files to PowerPoint (used by the company) as well as to HTML, allowing both instructors and trainees to access the content via any web browser. The presentations can be navigated in a manner similar to a website homepage (Figure 7), which facilitates their later use by trainees for content review or even as support in their professional activities.

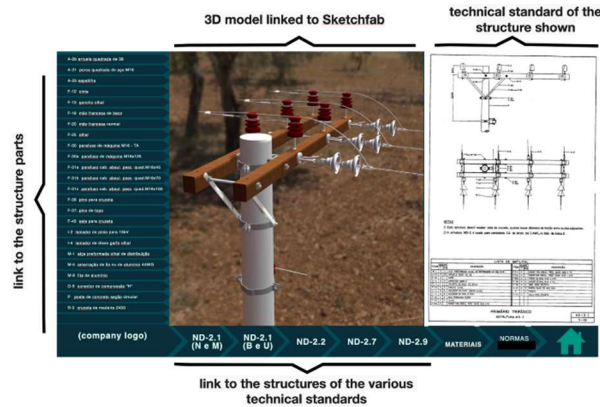
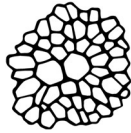


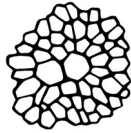
Figure 7: Navigation structure of the interactive presentations. Source: authors

The pilot courses involved groups of 15–20 participants with diverse profiles, ranging from individuals with no prior experience to residential electricians and newly hired maintenance workers. The group also included recently contracted electrical engineers and more experienced permanent staff, creating a heterogeneous learning environment that reflects real training conditions.

3 Results

The outcomes of this work unfold in two distinct and sequential phases. The first phase—presented in this article—consists of the development of a training proposal for technical personnel through the integration of both innovative and traditional digital technologies. The second phase, which involves implementing the proposal in real training contexts to evaluate its pedagogical effectiveness, is currently underway and will be the subject of a future publication once the evaluation process is complete. The next phase will validate the proposal in real training contexts. Evaluation will combine learning metrics (task completion time, error rates, knowledge retention), usability questionnaires (e.g., SUS), and indicators of instructional effectiveness, including learner engagement and instructor adoption. Together, these measures will provide a comprehensive assessment of pedagogical impact and technological feasibility.

This stage of the project produced all necessary instructional content for integrating digital technologies into electrician training, grounded in a solid pedagogical framework and innovations in VR and AR. Instructor involvement in design and validation fostered strong engagement, increased familiarity with immersive tools, and boosted confidence in applying them to enhance teaching practices and develop new VR/AR content.



4 Discussion

The use of new digital technologies in AR and VR—mastered by the university faculty—in combination with 2D presentations—well understood by the company’s instructors—was the key motivating factor for the integration of researchers and instructors in the development of an innovative instructional resource. This strategy enabled both parties to contribute their knowledge and experience to the process, which will undoubtedly support the company’s transition toward the use of digital technologies in training.

Although the project signals a new era for Univercemig, there is still a long road ahead, particularly with respect to content development for the consolidation of distance education and the integration of AR into more complex activities, such as equipment parameterization and remote operation for monitoring the performance of electricity distribution networks.

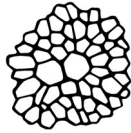
This phase of the project proved especially enriching for the university faculty, as it offered the opportunity to observe, in practice, that educational applications of digital technologies cannot be dissociated from a solid pedagogical foundation—otherwise, they risk becoming nothing more than promotional tools.

These outcomes are consistent with studies showing the effectiveness of VR/AR in training and safety (Angel-Urdinola et al., 2021; Guo et al., 2020; Man et al., 2024; Scorgie et al., 2024). They also confirm, at least partially, our hypothesis that the Interactive Virtual Network can serve as the pedagogical core of a scalable training framework, while highlighting the need for further validation in practice.

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