WIP: MEXLEfirst- a Vision for an Inclusive and Impactful Education for the Introduction to Electrical Engineering

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***Abstract*— Engineering education must adapt to evolving societal and technological demands, addressing challenges like high dropout rates, limited student engagement, and the need for inclusive, hands-on learning environments.**

MEXLEfirst reimagines the introduction to electrical engineering through a multimodal, scalable, and accessible learning platform. Central to the approach is the Lab-in-a-Box system: a modular hardware kit paired with an integrated Web App that supports both structured and self-guided learning. Unlike existing modular learning systems, MEXLEfirst integrates real-time nodal analysis with image recognition to provide immediate and adaptive feedback on student circuits.

This paper outlines MEXLEfirst's hardware architecture, software integration, and pedagogical framework, emphasizing its innovative approach to scalable, accessible, and impactful education in electrical engineering.

Keywords— Engineering education, modular hardware, learning analytics, hands-on learning, circuit simulation, adaptive learning, data-driven feedback, inclusive education, electrical engineering, server-based evaluation

I. Introduction

Engineering education has continuously evolved to meet the demands of changing eras, particularly in electrical engineering [1,2]. In recent decades, technological advancements and economic shifts have accelerated this transformation [3]. However, many traditional education systems still rely on outdated methods, leaving students underprepared for modern workforce requirements.

In the field of electrical engineering, these challenges are particularly pronounced. High dropout rates, disengaged students, and limited access to modern resources highlight significant barriers to success. Electrical engineering concepts are often taught in abstract terms, with insufficient hands-on learning opportunities, making it difficult for students to connect theoretical knowledge to practical applications. These challenges are further exacerbated by a lack of inclusivity in many programs, limiting the diversity of future engineers and their ability to address complex, real-world problems from multiple perspectives.

To address these issues, the MEXLEfirst platform introduces a modular and adaptive learning system that integrates hands-on experimentation with real-time feedback and digital automation. MEXLEfirst is designed to be scalable and cost-effective, making electrical engineering education more accessible across diverse learning environments, including universities, vocational training programs, and remote learners.

MEXLEfirst addresses major challenges in higher education, including digital transformation, sustainability, and inclusivity. Integrating AI-driven feedback and structured assessment aim to enhance student engagement and improve learning efficiency.

MEXLEfirst's modularity enables a circular usage model. Students can borrow, return, and refurbish hardware components, ensuring repeated use. An institutional lending model could be established to ensure responsible usage while maintaining affordability for students. This approach not only makes laboratory-based learning more cost-effective but also minimizes electronic waste, addressing environmental concerns often associated with disposable educational kits.

Additionally, as an open-source, scalable system, MEXLEfirst extends hands-on learning opportunities beyond traditional university labs, enabling more flexible, scalable, and resource-efficient engineering education. This ensures that institutions with limited lab infrastructure, vocational training programs, and remote learners can benefit from practical experimentation without the constraints of physical lab access.

This paper outlines the comprehensive approach of MEXLEfirst, starting with an exploration of the challenges in engineering education and prior initiatives to address them (section II). It then sets the stage for introducing the conceptual foundation of MEXLEfirst and its system architecture (sections III and IV). Further, we outline the pedagogical approach, discuss the evaluation of the suggested platform and show the roadmap of the project (sections V to VII). Finally, the current state and future outlook of the project are discussed, followed by the conclusions.

II. Related Work

A. Challenges in Engineering Education

Engineering education is at a crossroads, facing numerous challenges driven by external factors that require transformative solutions to prepare future engineers effectively.

Engineering colleges and universities are experiencing funding reductions and increasing costs, necessitating creative solutions to maintain high-quality education and research outputs [3]. Inadequate funding and insufficient equipment are especially in developing countries often major obstacles for engineering education [4].

Many engineering programs struggle with high dropout rates [5-7]. Focusing on Germany, the attrition rate in the field of electrical engineering has risen steadily over the past decades, from approximately 35% in 1995, to 50% in 2010 to an alarming 60% by 2020 [8]. The key reasons for these dropouts were also revealed [9]: a lack of perceived meaningfulness, the absence of voluntary self-assessment opportunities, outdated teaching methods, insufficient enjoyment, and overly theoretical, impractical curricula.

For students from marginalized groups, such as persons excluded because of their ethnicity or race (PEERs), studies have consistently shown the experience of significant inequality, particularly in engineering courses [10]. These structural inequities can hinder the development of a strong engineering identity and result in lower course performance, especially in the early semesters.

Research indicates that the increasingly diverse academic backgrounds among first-year engineering students lead to varying levels of prior knowledge, particularly in electrical engineering concepts [11,12]. This diversity can result in misconceptions and flawed conceptual models of fundamental electrical principles, such as current, voltage, and circuit connections.

B. Hands-On Learning and Inclusive Pedagogy

Education in engineering must go beyond knowledge transfer to actively engage the cognitive, psychomotor, and affective domains [13]. In engineering education, balancing these domains is essential for preparing students to meet the demands of an evolving professional world. This taxonomy was later extended into the "Head, Hands, and Heart" model, which integrates cognitive understanding (Head), practical skill-building (Hands), and emotional connection (Heart) [14]. This framework underscores the importance of aligning theoretical knowledge with actionable skills and fostering a sense of purpose among learners. When applied in engineering education, it supports student-centered learning and bridges the gap between theory and practice.

A systematic review on experiential learning in engineering education [15] highlights the transformative potential, noting its role in enhancing student engagement, fostering interdisciplinary skills, and promoting practical understanding through authentic and simulated activities. For example, project-based tasks where students simulate real-world engineering scenarios have been shown to enhance both engagement and interdisciplinary collaboration.

Modern trends in engineering education have further promoted student-centered learning, with the integration of theory and practice, digital and online learning, and the definition of professional competencies

[16]. These trends aim to align educational objectives with the evolving needs of the professional world, particularly in disciplines like electrical engineering.

In a vision for “the future of electrical and computer engineering education” [2] Berry et al. anticipated over two decades ago that future educational practices would focus on:

- *Motivating Independent Learning*: Encouraging students to take ownership of their learning journey and promote long-term retention of knowledge.
- *Deeper Understanding through Experiential Learning*: Developing a more profound grasp of fundamental principles by enabling students to observe and experience these principles in action.
- *Anytime, Anywhere Access*: Providing flexibility for students to learn at their own pace and convenience through on-demand educational platforms.
- *Scalable and Personalized Education*: Designing systems capable of educating large numbers of students while maintaining the feel of small class sizes or even one-on-one instruction.

Theory-to-practice approaches offer promising solutions to address the challenges of inequality. For example, applying design thinking in project-based courses allows students to design prototypes that address real-world challenges, fostering both creativity and collaboration. However, implementing design thinking in electrical engineering courses presents challenges. These include resistance from students accustomed to traditional, linear methods, difficulties in aligning design thinking projects with highly technical course objectives, and insufficient integration into the broader curriculum, which may result in inconsistent learning experiences [17].

Existing platforms fail to fully support first-year engineering students due to their lack of real-time, data-driven feedback, minimal focus on hands-on practice, and insufficient customization for individual learning paths supporting students with varied backgrounds. MEXLEfirst fills this void by offering a transformative learning environment.

C. Relevant Existing Educational Projects and Initiatives

Attempts are being made to overcome the challenges in electrical engineering education through laboratory-enhanced courses.

Remote lab platforms in electrical engineering, such as the emerging VISIR [18] provide students with anytime-anywhere-access to laboratory experiences without requiring costly equipment or the students. These systems aim to replicate the feel of working with real equipment and they can help to support marginalized communities [19]. However, remote labs often face notable limitations in terms of flexibility, performance, and maintenance, which can hinder their effectiveness [20]. Because of these constraints, they often struggle to achieve higher-level learning objectives, such as fostering advanced "design skills" essential for engineering practice [21,22].

At-home systems, such as those used in system and control laboratories [23,24], showcase promising alternatives to remote labs, fostering haptic experiments. The hands-on learning experience promotes a better understanding of the underlying concepts. However, the used solution in the mentioned example showed difficulties in the needed software installation for the students and a high assembly time of the developed boards.

Multiple other implementations showed the strength of such portable at-home systems [25-34]: These systems offer reduced costs, foster autonomy, and significantly boost student motivation. They effectively bridge the gap between theory and practice, allowing for deeper engagement with experimentation and design processes, which in turn cultivates confidence in tackling and completing projects.

The referenced flexible solutions use either prototype breadboards combined with application-specific circuit boards [25-33] or individual modules, which have to be connected by jumper cables [34]. Both lead to tangled cables ("cable spaghetti") for complex setups. Prototype breadboards also suffer from loosening the breadboard contacts, increasing the difficulty of debugging the circuits.

One of the difficulties noted was assisting first-year students in diagnosing and correcting issues when their experiments did not perform as intended [32]. While fostering deeper understanding and critical thinking, this often led to frustration.

Each of the discussed educational projects has its limitations (see Table 1). This highlights the critical need for a solution that overcomes these limitations, e.g. tangled wiring, insufficient feedback, or purely virtual interaction with the hardware. To address these issues, an effective platform must offer seamless system integration, real-time feedback, and automated evaluation mechanisms, along with haptic, modular hardware that is durable, affordable and user-friendly.

TABLE I. FEATURES OF DIFFERENT LEARNING APPROACHES

Feature	Learning approach			
	University Labs	***Remote Labs***	***Home-based Systems***	***MELXE first***
Haptic Interaction	Full haptics	No haptics	Full haptics	Full haptics
Instant Feedback	Instructor feedback	Automated feedback	No direct feedback	Automated feedback
Accessibility	Restricted to lab hours & location	anytime, anywhere by WiFi	Accessible anytime	anytime, anywhere by WiFi
Scalability	Low (Limited by lab space & scheduling)	High (limited by centralized hardware)	High (Limited by hardware)	High (Limited by hardware)
Cost Efficiency	High lab costs	Medium costs, centralized hardware	Very low costs (home kids)	Low costs (Lab-in-a-box)

III. Conceptual Framework

The primary vision of MEXLEfirst is to establish a comprehensive, hands-on learning environment that bridges the gap between theoretical knowledge and practical application in electrical engineering education. Building on the foundational work of previous projects, MEXLEfirst will support students by providing accessible, scalable, and engaging learning experiences and by offering a learning environment tailored to individual learning paths.

To help first-year students to explore and deepen their understanding of fundamental electrical engineering concepts through hands-on practice, two innovative components are under development: an intuitive hardware (Lab-in-a-Box) and a user-centered learning assistant (Web App with Wiki).

Unlike VISIR, which enables real-time remote experiments but lacks individualized student progression tracking, MEXLEfirst integrates adaptive learning pathways, to provide targeted, real-time feedback while maintaining hands-on interaction. Unlike other traditional hands-on lab environments, which provide structured in-person support but lack scalability, and home lab kits, which offer flexibility but no real-time structured feedback, MEXLEfirst provides a hybrid approach that integrates hands-on practice with automated assessment and adaptive learning pathways.

MEXLEfirst builds upon the existing MEXLE system, a Multimodal Experimental and Learning Environment, refining its approach by incorporating new pedagogical and technological advancements. It prioritizes Flexibility, Interactivity, Responsiveness, Situational adaptability, and Transformative learning experiences. The following key elements distinguish MEXLEfirst from its predecessor and other engineering education tools:

- *Flexible Learning Paths*: A Web App delivers modular learning units and learning nuggets for the Lab-in-a-Box, allowing students to adapt learning to their needs. A narrative-driven approach featuring a young engineer motivates learners through relatable scenarios.
- *Interactive Student Engagement*: A student advisory group provides continuous feedback, ensuring the platform reflects evolving student needs and perspectives, promoting active learning and engagement.
- *Responsive and Situative Knowledge Transfer*: The Web App integrates voltage and image-based circuit analysis to offer feedback and simulations, aligning theoretical concepts with real-life applications through practical exercises.
- *Transformative Learning*: The platform enables experiential learning by integrating theoretical knowledge with practical applications through guided experiments, interactive tasks, and real-world problem-solving scenarios.

Key goals include fostering technical competence through interactive, project-based learning. The MEXLE Lab-in-a-Box system empowers students to construct and evaluate circuits independently while receiving real-time feedback from a central server. This approach enhances active learning, stimulates critical thinking, and encourages self-directed exploration.

Additionally, MEXLEfirst promotes inclusivity and equal access to education by leveraging open-source technologies and platform-independent tools. Its modular design ensures flexibility, adaptability, and continuous system expansion. Through collaboration with educational institutions, industry partners, and student advisory groups, MEXLEfirst aims to address evolving educational and technological needs.

The project collaborates closely with industry, schools, and other educational stakeholders through an advisory board that guides its development. These collaborations ensure that the curriculum addresses current industry demands for technological literacy and problem-solving skills.

Furthermore, with the Ludwigsburg University of Education on the advisory board and planned support from an education-focused student, MEXLEfirst ensures professional pedagogical input. Their expertise in educational psychology and instructional design ensures that the platform supports diverse learners, aligns with cognitive development principles, and integrates best practices in self-directed and problem-based learning.

The project plans to engage regional schools and vocational institutions to create a bridge between secondary education and university-level engineering, promoting continuity in STEM learning.

IV. SYSTEM ARCHITECTURE AND DESIGN

MEXLEfirst offers an innovative and sustainable concept that reimagines early engineering education through hands-on, practical learning pathways. The following explores how MEXLEfirst addresses these interconnected challenges, advancing engineering education to be more adaptable, impactful, and aligned with industry and societal expectations (Fig. 1).

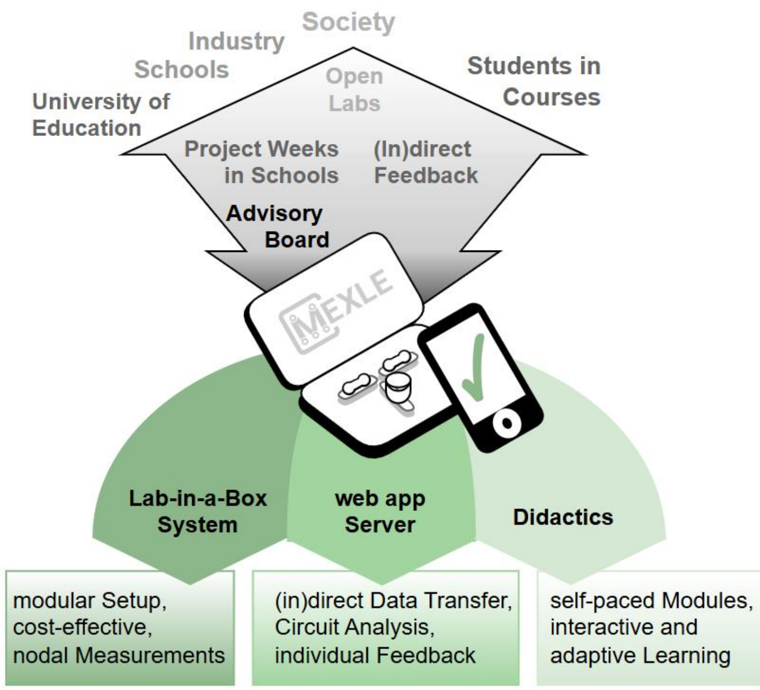

Fig. 1. Structure of the project behind MEXLEfirst. The interaction with the industry, schools, and society is channeled by the advisory board, project weeks, and open labs. The students give and receive feedback via the system. The technical implementation of MEXLEfirst is threefold.

MEXLEfirst leverages a compact “Lab-in-a-Box” - an affordable, modular hardware kit that enables students to engage in interactive, self-paced learning from any location, whether at home or in the classroom. The open-source, low-cost hardware-software platform empowers students to build knowledge outside traditional lab environments through practical experimentation. The circuit board is complemented by a multi-platform server solution that incorporates AI-driven learning pathways, allowing for personalized educational experiences via any mobile device.

A key feature of the underlying project structure of MEXLEfirst is its inclusive design, incorporating feedback from a dedicated student advisory group to ensure the system aligns with student perspectives and diverse learning preferences. This participative approach fosters a student-centered learning environment and promotes sustainable engagement by directly involving learners in the development of educational content and methodologies.

A. Lab-in-a-Box Concept

The MEXLE Lab-in-a-Box system serves as a multimodal experimental and learning platform designed to facilitate hands-on education in electrical engineering. Rooted in the pedagogical principles outlined in the previous projects, its primary goal is to offer an engaging, self-directed learning environment by combining modular hardware with a supportive digital ecosystem. Students can build, test, and analyze circuits using a user-friendly interface. This system bridges the gap between theory and practice, providing a structured yet flexible hands-on learning experience.

MEXLEfirst builds upon the existing hardware concept of the MEXLE system [36-39]. The existing MEXLE Lab-in-a-Box system centers around a modular and scalable system optimized for practical learning in electrical engineering. At its core is the carrier board as a base for modules, which provides an orthogonal matrix of electrical nodes arranged in a grid. Fig. 2 shows a populated MEXLE Lab-in-a-Box with two circuits as an example.

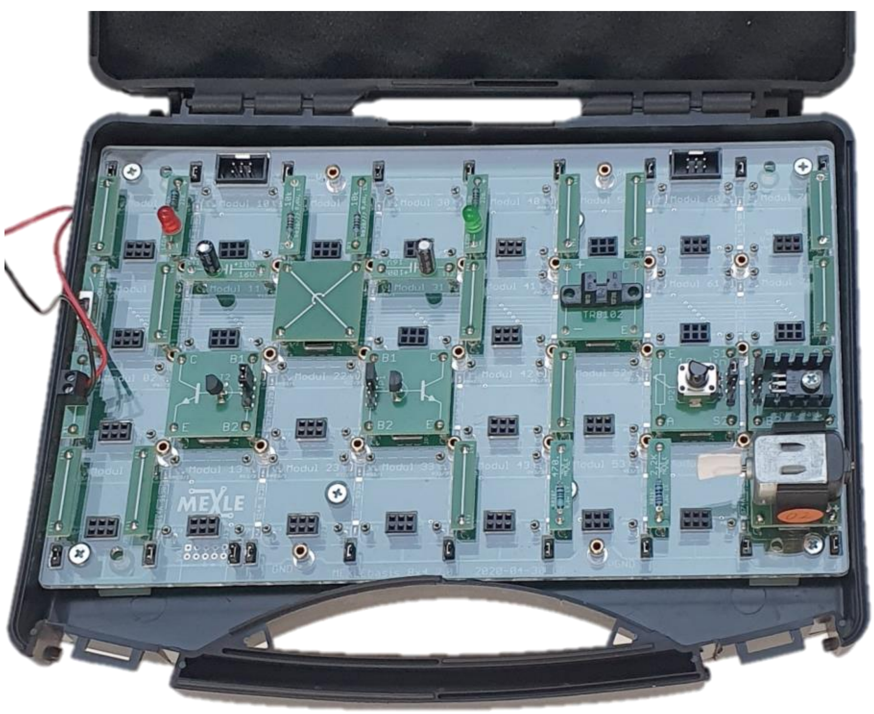

Fig. 2. Existing MEXLE carrier board of the lab-in-a-box for the lecture electronics. The circuit on the left shows an astable multivibrator with red and green diodes (on the top). The circuit on the right is a motor driver, which acts on the onput from an opto-interrupter. The motor and the power transistor are on the lower right.

This enables the circuit module's precise and repeatable placement, forming the foundation for practical circuit-building exercises. Each slot within the matrix allows the insertion of one 1x1-inch module or two 0.25x1-inch modules, making the learning process highly customizable. This design supports a wide range of modules:

- *0.25x1-inch modules*: bypass connectors, switches, LEDs, and passive components like resistors, capacitors, and inductors.
- *1x1-inch modules*: active modules such as transistors, operational amplifiers, power supplies, micro-controllers, sensors, and signal processing units.

B. Hardware and Software Design

For the project MEXLEfirst, only simple modules with passive components, sources, transistors, and operational amplifiers are used as it focuses on the introduction of electrical engineering and electronics.

The carrier board, as depicted in the drawing, currently relies on a supplementary laser-cut acrylic glass cover to ensure a flat surface for module connections. Additionally, the use of through-hole connectors (THD) results in a soldering effort of about 2 hours per unit.

To optimize production, the MEXLEfirst carrier board is redesigned for industrial assembly, minimizing post-production effort and enhancing scalability

Another key advancement is the implementation of an advanced data acquisition and transfer system that enables server-based circuit analysis (Fig. 3). The data transfer process from the carrier board to the central server occurs through two primary mechanisms: direct and indirect data transfer.

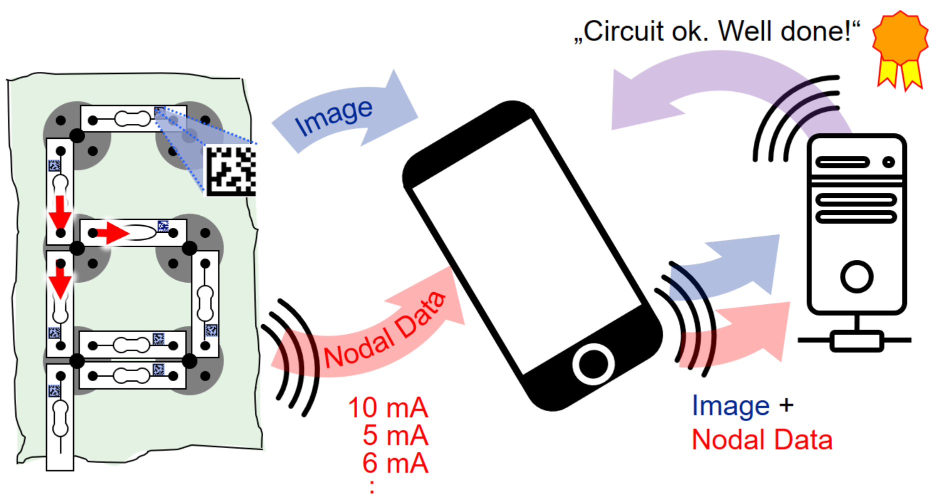

Fig. 3. Data transfer of the MEXLEfirst platform: The data acquisition starts on the carrier board (left) on each node (grey full circle). Exemplarily three red currents are shown. These values are sampled and passed through to the server via the mobile phone.Additionally, recorded images are also transmitted to the server. The server analyzes the data and sends a feedback.

For the indirect data transfer, students capture images of the assembled circuits by their mobile devices. Each module and the carrier itself feature unique barcodes, enabling the server's computer vision algorithms to identify components and their placements (blue in Fig. 3). This data is uploaded to the server via a Web App, which supports both Android and iOS platforms. This supports accessibility across various devices and operating systems without additional software dependencies. The choice of unique identifiers, such as 2D barcodes like Micro-QR, Aztec, or Data Matrix codes, requires careful evaluation based on factors like readability, durability, and compatibility with the server's image recognition algorithms.

Direct data transfer involves real-time measurement of electrical potentials and currents at each circuit node (red in Fig. 3). Analog signals are sampled using Analog-to-Digital Converters (ADCs) integrated into the carrier board. Sampled data is securely transmitted to the server through the Web App, eliminating the need for additional software installation on mobile devices.

Given the need to digitize approximately 180 voltage and current measurements, a cost-effective ADC solution is crucial for scalability. Microcontrollers such as STM8S003F3 are utilized, offering a cost of about 6 cents per ADC channel. Additional measures, such as protective circuitry, are implemented to safeguard the input channels from damage.

C. *Server Integration and Learning Analytics*

Server integration and learning analytics are fundamental to the MEXLEfirst educational platform, enabling efficient data handling and personalized learning experiences. The system processes data locally on an institutional server, eliminating dependency on cloud-based solutions while ensuring streamlined functionality.

The Web App, hosted on a local institutional server, serves as the primary interface between students and the learning system. It enables students to upload circuit designs, access feedback, and interact with other educational resources. The server handles data processing and storage, ensuring that the system remains responsive and reliable. The engine evaluates student-submitted circuit designs using simulation tools such as SPICE. By analyzing the designs and comparing them to predefined benchmarks, the system identifies errors and areas for improvement, ensuring a robust feedback loop.

A well-designed GUI enhances the user experience by providing clear, actionable feedback. For instance, the Web App may display messages such as "Voltage discrepancy detected at Node 3. Suggested action: Adjust resistance to achieve the target output." This interactive feedback fosters iterative learning and helps students build troubleshooting skills.

Gamification features, such as achievement rewards, progress tracking, and introducing competition through interactive challenges will be integrated. Additionally, seamless integration with Learning Management Systems can be ensured by SCORM (Sharable Content Object Reference Model) compatibility, enabling robust tracking of learning outcomes, standardized reporting, and alignment with institutional educational frameworks.

MEXLEfirst emphasizes a user-friendly Web App and robust server infrastructure to create an engaging and scalable educational system, aligning theoretical concepts with practical applications.

D. *Security, Privacy, and Data Protection Considerations*

Implementing strong security and privacy measures is critical for the implementation of MEXLEfirst. The system is designed to meet stringent data protection requirements while providing students with a reliable platform for learning and experimentation.

Student data is anonymized and stored in compliance with relevant regulations, such as GDPR. For example, identifiers linked to submitted circuits are decoupled from personal data, ensuring that privacy is preserved throughout the analysis process. This design minimizes risks associated with data breaches or unauthorized access.

All data transferred between the Web App and the institutional server is encrypted using modern protocols, such as Transport Layer Security (TLS). This ensures that student submissions, including circuit designs and measurements, remain secure during transit. Additionally, APIs integrated into the system are designed with secure access controls to prevent unauthorized data uploads or retrievals.

The MEXLEfirst platform incorporates fault-tolerant design principles to ensure uninterrupted operation. This includes robust error-handling mechanisms on the server. For example, in the event of a server failure, data is automatically recovered from secondary storage, allowing students to continue their work without disruption.

V. Pedagogical Approach

The MEXLEfirst platform integrates new pedagogical strategies to ensure that students engage meaningfully with both theoretical concepts and practical applications. Its approach is rooted in fostering independent learning, active participation, and adaptive support tailored to diverse student needs.

To enhance emotional engagement, MEXLEfirst employs a narrative-driven learning pathway. Students accompany a virtual character, a rookie engineer, tasked with solving authentic industrial challenges. Each learning module introduces a scenario, such as troubleshooting a faulty circuit or optimizing a production design. By aligning tasks with this narrative, students see how their skills directly apply to professional settings, enhancing both motivation and relevance.

A. *Self-Paced Learning Modules*

MEXLEfirst offers self-paced learning nuggets that enable students to progress through the curriculum at their own speed. These learning nuggets prioritize conceptual understanding over rote memorization, promoting long-term knowledge retention. For example, students are guided through circuit-building exercises that start with fundamental concepts and gradually introduce complexity, ensuring mastery at each step.

Each learning nugget incorporates interactive quizzes and reflection tasks, allowing students to evaluate their progress and revisit difficult concepts. For instance, a learning nugget on an unloaded and loaded voltage divider might include a practical exercise where students construct a simple circuit, measure voltages and currents, and validate their results through the Web App.

The built-in milestones and rewards, such as badges, certificates, or leaderboard rankings, encourage consistent student engagement and celebrate achievements. These features not only maintain an emotional connection to the learning journey but also act as crucial checkpoints, ensuring students remain on track while progressing through content at their own individual pace.

B. *Interactive Learning Environment*

The Web App serves as the hub for student interactions with the platform. Through this tool, students can upload circuit designs, receive real-time feedback, and explore additional learning resources. For instance, a student submitting a circuit design might receive feedback like, "Node 3 voltage is inconsistent. Consider adjusting the resistance value."

Complementing the Web App is a collaborative Wiki that provides a repository of tutorials, troubleshooting guides, and peer-generated learning content. This resource encourages students to share insights and learn from each other's experiences, fostering a sense of community and collaboration.

Usability testing with diverse student groups will ensure the interface remains intuitive and accessible, preventing cognitive overload and improving engagement.

C. *Adaptive Learning and AI-Driven Pathways*

MEXLEfirst employs adaptive learning technologies to personalize the educational experience. By analyzing individual performance data, the system dynamically adapts task difficulty and recommends additional resources. For example, if a student struggles with resistor networks, the platform will suggest additional practice exercises and video tutorials on circuit simplification.

The adaptive engine also provides instructors with data-driven insights, allowing them to identify common student challenges and adjust teaching strategies accordingly. This ensures that both individual and group learning outcomes are optimized.

D. *Participatory Development*

An essential component of MEXLEfirst is the active involvement of a student advisory group in shaping the platform's development and functionality. This group plays a crucial role in ensuring that the platform remains user-centered by providing regular feedback on system usability, content relevance, and overall design. Their input helps to refine features, prioritize improvements, and adapt the platform to meet the diverse needs of its users.

To measure the effectiveness of these pedagogical strategies, a structured evaluation framework has been developed, assessing student engagement, knowledge retention, and learning efficiency.

VI. Evaluation of MEXLEfirst

As MEXLEfirst is still in its early implementation phase, empirical results are not yet available. However, a rigorous multi-phase evaluation process is planned to assess its effectiveness in engineering education. The evaluation framework combines small-scale controlled experiments with real-world deployment in an electrical engineering course, as suggested in [40]. The methodology includes:

- *Pre- and Post-Testing*: To measure knowledge acquisition and conceptual understanding of circuit design and analysis.
- *Engagement Tracking*: Analyzing time spent on exercises, error correction patterns, and participation in hands-on tasks.
- *Self-Assessment and Peer Feedback*: Students assess their own progress and motivation. They provide structured feedback on usability, time invested and learning effectiveness.
- *Instructor Observations*: Engineering educators provide qualitative insights into student motivation, troubleshooting efficiency, and adaptability to the system.

Pilot studies will be conducted at Heilbronn University and partner institutions to validate the effectiveness of MEXLEfirst. The studies at Heilbronn University will involve approximately 30 first-year students enrolled in "Electrical Engineering I/II" and “Electrical Engineering Lab”.

To benchmark its impact, MEXLEfirst will be compared to traditional university lab environments, which provide structured guidance but lack the flexibility of anytime, anywhere learning. The study will span one academic semester for each of the phases 1-3 (see VII. Project Roadmap), tracking performance through pre- and post-tests, engagement metrics, and instructor observations. Data analysis will employ statistical comparisons and correlation analyses to measure the impact of MEXLEfirst on student learning outcomes.

The evaluation provides a foundation for assessing the overall success of MEXLEfirst. As explained in the following, the data acquisition strategy is based on direct and indirect feedback.

A. Direct Feedback

Direct feedback will be gathered through qualitative methods, such as interviews and focus groups. Students and educators will provide insights into their experiences with MEXLEfirst, discussing its usability, relevance, and overall impact on the learning process. These sessions aim to identify strengths and areas for improvement while capturing subjective impressions that quantitative metrics might miss.

For instance, interviews with students will explore how the platform affects their confidence in applying electrical engineering concepts, while focus groups will delve into collaborative learning experiences and the perceived value of interactive features. Educator feedback will provide a complementary perspective, highlighting how the platform supports or challenges traditional teaching practices.

B. Indirect Feedback

Indirect feedback will be gathered by analyzing student interactions on the Web App. Metrics such as task completion rates, time spent on activities, and error frequencies will provide insights into how students interact with the platform and progress through the learning modules. Additionally, pre- and post-tests will measure improvements in knowledge, offering objective evidence of learning outcomes.

Task completion rates will indicate the platform's accessibility and the effectiveness of its instructional design, while error trends will highlight whether students are successfully applying feedback to improve performance. Combined with engagement statistics, such as participation rates and frequency of use, this data will offer a comprehensive view of how well MEXLEfirst facilitates learning.

VII. Project Roadmap

The implementation of MEXLEfirst follows a structured roadmap, divided into four key phases, ensuring the systematic development and deployment of the platform (Fig. 4). Each phase builds upon the previous one, enabling iterative improvements and the integration of feedback from students, educators, and external advisors.

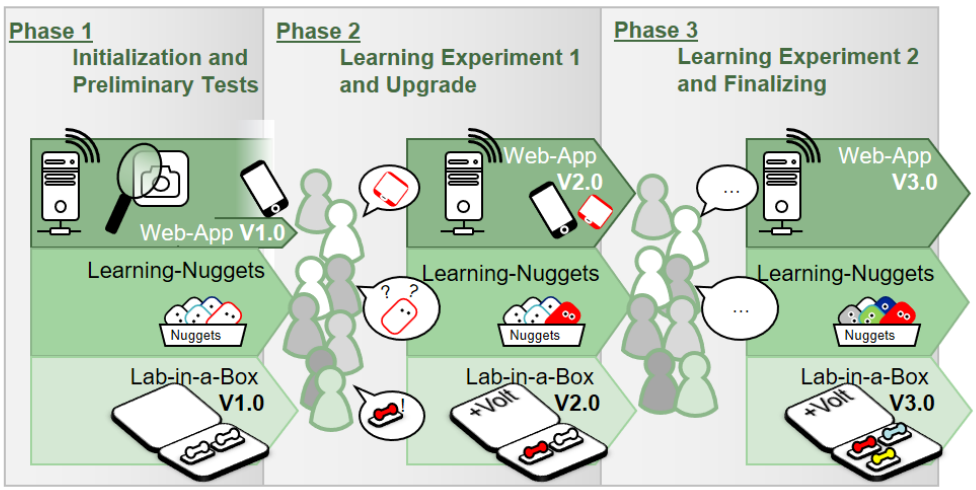

Fig. 4. The project roadmap shows four phases, where only the first three phases focus on improving the MEXLEfirst technical implementation. Phases 2 and 3 begin with learning experiments as testing methodologies.

Phase 1 focuses on establishing the foundational elements of the MEXLEfirst platform. This includes forming a student advisory group to represent the diverse needs of learners and incorporating their input into the design process. A prototype of the Lab-in-a-Box system, adapted from existing hardware, is developed alongside the initial version of the Web App. During this phase, learning nuggets are drafted to align with the current electrical engineering curriculum, and the first version of the Web App (V1.0) is prepared for integration. Early usability testing ensures that the system aligns with the educational and practical needs of its users. These initial outputs are then prepared for testing in controlled environments during the next phase.

Phase 2 involves deploying the system in a pilot program with first-semester engineering students. This phase serves as a testing ground for the Lab-in-a-Box system, the learning nuggets, and the Web App. A/B testing methodologies are planned as part of this phase to assess the platform's influence on student motivation, understanding, and engagement. Feedback collected from students and educators is used to identify areas for improvement. Based on these insights, updates are made to the hardware and software, resulting in enhanced functionality. This phase concludes with the development of Lab-in-a-Box V2.0 and Web App V2.0, incorporating lessons learned from the pilot program.

Phase 3 builds upon the outcomes of the pilot testing by implementing an expanded version of the platform for a larger group of students. Advanced learning nuggets and storytelling elements are introduced to deepen engagement. The Lab-in-a-Box system is upgraded to V3.0, featuring improved usability, robustness, and integration capabilities. At this stage, the Web App also reaches its final iteration (V3.0), integrating simulation tools such as SPICE and providing enhanced learning analytics. The platform's adaptability and scalability are tested to ensure readiness for broader deployment. Collaboration with external stakeholders, including industry and academic institutions, further strengthens the system's relevance and practicality.

Phase 4 focuses on deploying MEXLEfirst at scale, both within the institution and in collaboration with regional schools and vocational training centers. This phase includes training educators to effectively use the platform and mentoring programs where advanced students support beginners.

VIII. Discussion

Engineering education must not only adapt to technological advancements but also address broader institutional challenges such as equitable access, digital transformation, and sustainable learning solutions. These objectives must be kept in mind when designing a solution for lab-based learning.

A. *Analysis of Learning Approaches*

Existing solutions for practical learning in electrical engineering can generally be categorized into three approaches: traditional university labs, remote labs, and home-based systems. Each of these methods presents advantages and limitations (see Table 1):

- *Traditional university labs:* These provide hands-on interaction and instructor feedback but lack flexibility in terms of time and accessibility.
- *Remote labs (such as VISIR):* They offer anytime, anywhere access and instantaneous feedback, yet they lack the haptic interaction with real components.
- *Home-based systems:* These allow students to work directly with hardware, fostering tactile learning, but they often lack structured feedback and require additional support for troubleshooting.

MEXLEfirst bridges these gaps by integrating the haptic experience of physical circuit building with automated, real-time assessment through a server-based evaluation system. This hybrid approach fosters deeper learning, enhances accessibility, and provides a scalable and flexible learning environment that can support students with diverse academic backgrounds.

B. *Challenges*

While MEXLEfirst presents a promising solution, several challenges must be addressed to ensure its effectiveness. First, scalability remains a critical factor. The modular hardware and open-source nature of MEXLEfirst support widespread adoption, but considerations such as manufacturing costs and technical support must be further explored.

Additionally, the integration of adaptive learning mechanisms presents both opportunities and complexities. By leveraging AI-driven learning pathways and real-time feedback, MEXLEfirst can offer students a personalized learning experience, adapting to their progress and difficulties. However, designing adaptive algorithms that effectively support all learning styles while maintaining pedagogical rigor requires further investigation.

Ensuring smooth user interaction and data transfer on Android and iOS systems presents additional technical challenges. Seamless integration between real-time data acquisition, computer vision-based circuit recognition, and server-side processing must be optimized for a consistent user experience.

C. *First Feedback of External Advisory Board*

To validate the conceptual framework and gather expert insights, MEXLEfirst was presented to an external advisory board composed of industry professionals, engineering educators, and academic stakeholders. This external evaluation provided valuable feedback on system feasibility, implementation challenges, and alignment with industry needs.

The board highlighted the need for a flexible and affordable open-source solution. Current solutions in the industrial training facilities are limited to on-site education due to their costly components and large size.

Additionally, following this presentation, MEXLEfirst was invited to be showcased at the "New Learning Tech Lab" of a company-based education fair, demonstrating industry interest and potential for broader application.

D. *Future Evaluation*

While this paper primarily presents the conceptual foundation of MEXLEfirst, future work will focus on empirical validation. The initial deployment of MEXLEfirst will be conducted at Heilbronn University, where first-year electrical engineering students will use the system in foundational courses.

The evaluation will be structured in multiple phases, starting with small-scale trials in controlled environments, followed by broader student engagement in first-semester courses. Learning analytics, user surveys, and direct performance assessments will form the core of this validation process. The first empirical results from small-scale trials are expected in the next academic semester (Winter 2025/26), with a second-phase expansion in Summer 2026.

By embedding MEXLEfirst into first-year curricula, the system will address the common challenge of early-stage disengagement, which is a significant contributor to dropout rates in electrical engineering programs. The student advisory board will continue to provide feedback, ensuring that iterative improvements align with student experiences and expectations.

English-taught mechatronics courses at Heilbronn University provide an ideal testbed to investigate inclusivity and to assess the platform’s effectiveness across different student demographics. Additionally, collaborations with pre-university programs will explore its adaptability beyond traditional university settings.

Beyond its technical and pedagogical benefits, MEXLEfirst aligns with the broader objectives of higher education reform by addressing systemic challenges such as accessibility for underrepresented students, cost-effective scaling for large institutions, and sustainability in lab-based education. By reducing hardware costs and minimizing e-waste through modular reusability, MEXLEfirst provides a scalable and sustainable alternative to traditional lab environments.

IX. Conclusion

The MEXLEfirst project represents a forward-thinking approach to addressing critical challenges in engineering education. It integrates modular hardware, an intuitive Web App, and innovative teaching strategies. This approach bridges the gap between theoretical knowledge and practical application. Through its emphasis on inclusivity, accessibility, and adaptability, MEXLEfirst aspires to redefine how foundational concepts in electrical engineering are taught and learned.

The integrated approach of MEXLEfirst offers holistic solutions to interconnected educational challenges, fostering inclusivity, reducing dropout rates, and enhancing student motivation. It is particularly well-suited for low-resource settings and can be replicated in developing countries, providing a pathway to quality engineering education that meets global standards. Ultimately, MEXLEfirst represents a versatile and impactful solution for quality in early engineering education worldwide, preparing students to meet the critical challenges of tomorrow while aligning with societal and industry needs.

As a work in progress, MEXLEfirst lays the groundwork for a transformative educational platform. Although quantitative and qualitative data are not yet available, the conceptual framework and system architecture demonstrate a strong potential for fostering student engagement, improving learning outcomes, and enhancing inclusivity. Key contributions of the project include the development of a scalable Lab-in-a-Box system, the implementation of adaptive learning pathways, and the integration of real-time feedback mechanisms to support active and self-directed learning.

Future work will focus on refining the platform through iterative development, testing, and evaluation. Pilot studies, including A/B testing, will be essential in assessing the impact of MEXLEfirst on key metrics such as learning outcomes, engagement levels, and error reduction. The feedback gathered from students, educators, and stakeholders will guide the ongoing development of both the hardware and software components, ensuring that the platform aligns with diverse educational needs.

MEXLEfirst is well-positioned to contribute to the broader discourse on engineering education reform. By leveraging open-source principles and participatory design, the project aspires to create a model that is both replicable and adaptable, particularly in resource-constrained environments. While initially focused on electrical engineering, its versatile approach makes it equally suitable for lectures in electronics, embedded systems, control theory, and other STEM disciplines. This broad applicability ensures that MEXLEfirst addresses a wider range of educational challenges, providing a promising foundation for empowering students to succeed in a rapidly evolving technological landscape.

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