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Innovative Research on Construction Models and Operational Management of Electrical and Electronic Laboratories

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Abstract: Electrical and electronic laboratories are crucial for developing engineering talent, yet they face challenges such as outdated hardware, rigid management, and faculty shortages. This paper proposes an integrated reform model featuring virtual-physical equipment upgrades, open and intelligent management platforms, a dual-qualified teaching team, and a full-process safety assurance system. It offers a practical framework for modernizing such laboratories and supporting the cultivation of high-quality innovative engineering professionals.

Keywords: Electrical and electronic laboratory; Construction model; Management model; Talent development; Safety management

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1. Introduction

Electrical and electronic engineering is a foundational technology that underpins the development of strategic emerging industries such as modern information technology, intelligent manufacturing, new energy, and aerospace. The proficiency of relevant professionals in the knowledge system of electrical and electronic engineering directly determines the quality of their training. In higher engineering education, theoretical instruction and practical training are as indispensable as the two wheels of a cart or the two wings of a bird. Electrical and electronic laboratories serve as the primary battleground for practical teaching. They function as both a "testing ground" for theoretical knowledge and a "training camp" for fundamental skills, while also acting as an "incubator" for cultivating engineering thinking, stimulating innovation capabilities, and shaping a scientific spirit.

As the wave of higher engineering education reform, epitomized by the "New Engineering" initiative, deepens, and as industry demands increasingly higher levels of engineering practice capabilities and innovative qualities from graduates, the traditional concepts and management models of electrical and electronic laboratories face unprecedented challenges. Historically, these laboratories primarily focused on verification experiments, featuring single-function equipment, rigid management approaches, and insufficient resource accessibility. Such laboratory structures struggle to meet the new demands for cultivating students' abilities to solve complex engineering problems and integrate across disciplines. Consequently, systematically reconstructing the laboratory's hardware environment, innovatively optimizing its operational management mechanisms, building a high-caliber experimental teaching team, and establishing a robust safety defense system to comprehensively enhance the laboratory's overall effectiveness have become a critical and urgent issue in university teaching reform [1,2].

Against this backdrop, this paper aims to transcend the limitations of conventional thinking. It seeks to comprehensively examine and explore the construction and management of electrical and electronic laboratories from a more holistic, systematic, and forward-looking perspective. By analyzing the current state, diagnosing issues, and proposing solutions, it seeks to explore a new path for laboratory construction and management that not only meets current teaching needs but also adapts to future technological developments. This approach combines scientific rigor, efficiency, and safety, providing a solid platform to cultivate high-caliber electrical and electronic professionals capable of addressing future challenges.

2. The core role and value reinvention of electrical and electronic laboratories in talent development

Against the backdrop of engineering education accreditation, the cultivation of students' engineering practice and innovation capabilities has been elevated to unprecedented importance. The role of electrical and electronic laboratories extends far beyond merely supporting theoretical instruction as they are undergoing a profound reevaluation of their core functions.

2.1. From theoretical validation to knowledge-building accelerator

Traditional laboratory instruction primarily aims to verify theoretical formulas and theorems, such as validating Kirchhoff's Voltage Law (KVL) and Current Law (KCL) through actual circuit connections. However, modern educational philosophy places greater emphasis on active knowledge construction. A well-designed laboratory environment should guide students in transitioning from "verifiers" to "explorers." For instance, after completing fundamental circuit characteristic tests, students can engage in extended tasks such as "analyzing the impact of parameter variations on system performance" or "investigating errors introduced by non-ideal components." When students observe phenomena in experiments that deviate slightly from theoretical predictions, they should be guided to analyze the source of these deviations, whether it stems from instrument accuracy, connection wire resistance, or environmental interference. This process itself represents a deeper level of understanding, critical evaluation, and internalization of theoretical knowledge, achieving a leap in knowledge construction from merely knowing "what" to comprehending "why" [3].

2.2. From skill training to engineering capability development arena

Proficiency in using instruments such as oscilloscopes, signal generators, and multimeters, along with the ability to correctly solder and assemble circuits, constitutes the fundamental skills in the field of electrical and electronic engineering. However, modern engineering capabilities extend far beyond these basics, encompassing comprehensive competencies such as system design, project management, teamwork, and communication skills. Laboratories should serve as integrated training grounds for cultivating these competencies. By adopting the

Project-Based Learning (PBL) model, students work in teams to experience the complete engineering process: project initiation, solution design, simulation optimization, procurement and material preparation, hardware implementation, debugging and testing, report writing, and final presentation. For instance, a project like "Microcontroller-Based Intelligent Temperature and Humidity Monitoring System" not only hones students' circuit design, programming, and debugging skills but also subtly cultivates essential soft competencies: project planning, cost control, team division of labor and collaboration, and technical documentation writing. These represent the core competencies indispensable for future engineers [4].

2.3. From imitative learning to innovation-sparking catalyst

Innovation stems from free exploration and persistent trial and error. Traditional "recipe-style" experiment manuals largely constrain students' thinking. Establishing open innovation labs equipped with abundant components, open-source hardware (e.g., Arduino, Raspberry Pi), programmable logic devices (e.g., FPGA), and essential testing facilities encourages students to pursue self-selected topics and engage in free exploration [5]. Moreover, an "Innovation Fund" program that can support students' unconventional ideas should be established, and competitions like electronic design contests or the Challenge Cup should be organized to foster learning and innovation through competition [6]. When students repeatedly test different solutions and overcome technical hurdles to solve real-world problems, their critical thinking, divergent thinking, and innovative problem-solving abilities are most effectively stimulated and honed.

2.4. From individual learning to collaborative community for teamwork and professional growth

Modern engineering projects are almost invariably the result of teamwork. The open environment of the laboratory naturally provides students with a space for collaborative exchange. Within project teams, members must jointly discuss technical solutions, allocate tasks reasonably, cross-check code and circuits, and collectively overcome debugging challenges. This process not only enhances technical expertise but also cultivates team spirit, accountability, and communication skills. Simultaneously, the laboratory's rigorous 5S management (Sorting, Straightening, Sweeping, Sanitizing, Sustaining), strict safety protocols, and instrument usage standards subtly instill a meticulous, disciplined scientific approach and strong professional ethics. This lays a solid foundation for students' seamless transition from "student" to "professional" [7].

3. Analysis of deep-seated issues in the construction and management of electrical and electronic laboratories

Although the importance of laboratories has become widely recognized, their construction and management still face numerous deep-seated contradictions that require urgent resolution in many universities, particularly regional institutions and newly established colleges.

3.1. The aging and unbalanced hardware infrastructure cannot support cutting-edge teaching

Current laboratory equipment faces numerous issues as follows:

(1) Equipment upgrades lag behind technological advancements. Many labs still rely on traditional box-style workbenches with fixed core functions and unchanged experimental procedures for years. Advanced

equipment widely adopted in industry, such as virtual instruments, programmable system-on-chip devices, industrial robots, and IoT modules, remains scarce in academic settings. This gap between "what is taught in schools" and "what is used in enterprises" forces graduates into lengthy retraining cycles;

(2) Equipment configurations suffer from structural imbalance. On one hand, low-end equipment for basic experiments is redundantly over-configured with low utilization rates. On the other hand, high-end and specialized equipment essential for cutting-edge research and comprehensive, innovative experiments is severely lacking. This contradiction of "too much of some and too little of others" limits the depth and breadth of experimental teaching content;

(3) A widespread tendency to "prioritize hardware over software" prevails. Equipment procurement often focuses solely on hardware specifications while neglecting complementary software, simulation platforms, teaching resource libraries, and post-purchase upgrade services. Consequently, advanced hardware devices fail to achieve their full potential due to the absence of suitable "souls" to complement them [8,9].

3.2. The closed and inefficient management model stifles the enthusiasm of both faculty and students

Laboratory management faces multiple challenges. The "teacher-centered" closed-door approach strictly limits operating hours to scheduled classes only. Experiment content, procedures, and methods are predetermined by instructors, leaving students to execute tasks passively. While this "nanny-style" management facilitates control, it severely stifles students' initiative for independent learning and exploration. Simultaneously, low levels of laboratory informatization result in high management costs. Many labs still rely on paper logbooks for equipment borrowing and consumable collection, while experiment reservations require multi-level relay through class representatives or student committee members. This traps administrators in tedious administrative tasks, preventing effective analysis and optimization of equipment status, usage data, and experimental outcomes. Furthermore, the evaluation system is simplistic and lacks incentive-driven mechanisms. Student assessments often focus solely on whether lab reports are neatly formatted or data aligns with expectations, overlooking critical aspects like critical thinking, experimentation, collaboration, and innovative contributions during the process. Similarly, evaluations for lab instructors and administrators fail to adequately reflect the complexity and creativity inherent in their roles, ultimately undermining team stability and work enthusiasm [10].

3.3. The insufficient quantity and capability of the teaching staff constrain the improvement of educational standards

University laboratory teaching staff face multiple challenges. In terms of team structure, there exists a "generation gap" issue. High-level laboratory instructors require both solid theoretical foundations and extensive engineering practice experience. However, universities often prioritize academic publications and research projects during talent recruitment, making it difficult to attract "dual-qualified" professionals with industry backgrounds. Among existing faculty, younger instructors lack experience, while older ones may have outdated knowledge structures, creating a generational disconnect. Career advancement pathways remain narrow. Within many university evaluation systems, faculty in experimental teaching series face disadvantages in promotion and resource allocation compared to theoretical course instructors and research-focused faculty. This discourages talented individuals from pursuing experimental teaching roles, resulting in poor team stability and high turnover. Furthermore, the training system is inadequate, with insufficient systematic and cutting-edge training for laboratory technicians. This hinders their ability to keep pace with new technologies and master new equipment, thereby affecting the updating of experimental teaching content and the improvement of teaching effectiveness [11,12].

3.4. The weak safety management awareness system poses significant latent risks

Laboratory safety management harbors significant hidden dangers that cannot be overlooked. There is a severe lack of safety culture and weak safety awareness. Faculty and students commonly hold the mistaken notion of "prioritizing operations over safety," believing that low-voltage electrical and electronic experiments pose minimal risk. They lack sufficient understanding of potential hazards such as electric shock, short circuits, fires, device explosions (e.g., reverse connection of electrolytic capacitors), and high-frequency radiation. This leads to safety education and training remaining superficial and failing to take root. Conversely, there are significant shortcomings in policy enforcement and regulatory blind spots. Although formal laboratory safety codes exist, factors like tight class schedules and insufficient oversight personnel often lead to compromised implementation. This is particularly evident in student-led open labs and innovation projects, where unsafe behaviors lack effective real-time monitoring and early warning mechanisms. Furthermore, inadequate investment in safety facilities and poor maintenance are prominent issues. Laboratories commonly lack essential safety signage, emergency lighting, and first-aid equipment. Critical safety installations like residual current devices (RCDs) and fire extinguishers are not subject to mandatory periodic inspections, making their effectiveness difficult to guarantee. Should an accident occur, the consequences could be severe [13].

4. Systematic improvement measures and implementation pathways for the construction and management of electrical and electronic laboratories

To address the aforementioned issues, systematic reform measures must be implemented, advancing in a coordinated manner across four dimensions (hardware, management, personnel, and safety) to achieve the comprehensive transformation and upgrading of laboratories.

4.1. Establish a modern hardware platform system that integrates virtual and physical elements and advances in a tiered, progressive manner

To comprehensively enhance laboratory construction standards, coordinated advancement across three levels is required as outlined:

(1) At the foundational level, emphasis should be placed on updating and optimizing traditional laboratory equipment. Core, frequently used fundamental equipment should undergo systematic upgrades to ensure precision and reliability. Concurrently, older equipment with functional viability should have its lifespan extended through third-party technical services and regular calibration. Additionally, modular retrofits can be implemented for certain traditional lab benches, converting fixed experimental circuits into freely pluggable modules. This approach increases experimental flexibility, facilitates student-designed circuitry, and reduces long-term maintenance costs;

(2) In the enhancement layer, vigorously develop a "virtual-physical integration" experimental model. On one hand, introduce high-performance virtual instruments by procuring PC-based virtual instrument systems and building integrated hardware-software experimental platforms with relevant software. This allows students to perform circuit simulation and program design on computers before conducting real-time data

acquisition and system control via hardware platforms, achieving seamless integration between simulation and reality. In addition, establish a cloud-based circuit simulation laboratory. Utilize specialized software to build an online simulation platform, enabling students to design circuits and perform simulation analyses anytime, anywhere via personal computers. This effectively alleviates the spatial and temporal constraints of physical laboratories, making it particularly suitable for experiment preparation, complex system analysis, and experimental instruction during special periods;

(3) At the innovation level, an open, comprehensive innovation platform must be established. This includes setting up open innovation labs with dedicated spaces equipped with diverse tools like 3D printers and laser engravers, operating on a 24*7 reservation basis to support student course projects and graduation designs. Additionally, cutting-edge industrial-grade equipment such as PLCs should be introduced based on the university's disciplinary strengths, exposing students to real-world industrial technology ecosystems and broadening their technical horizons [14].

4.2. Implementing a modern management model characterized by "smart openness and data-driven decision-making"

To elevate laboratory construction and management to new heights, coordinated efforts must be made across three dimensions: system development, management mechanisms, and evaluation incentives. For instance:

(1) An integrated laboratory information management system should be established, with core functional modules encompassing access control, equipment reservations, consumables requisitioning, fault reporting, data statistics, and security monitoring. Students can reserve lab benches and borrow instruments via a mobile app or web portal, enabling one-click service. Simultaneously, the system automatically records equipment utilization rates, failure rates, and other metrics. Through data analysis, administrators can accurately assess equipment configuration rationality, optimize consumables procurement plans, and provide data support for teaching reforms;

(2) Fully implement an open management operation mechanism. While ensuring scheduled teaching activities, maximize laboratory access hours, including evenings and weekends, by permitting cross-disciplinary and cross-grade student entry. Beyond mandatory experiments, laboratories will offer diverse, abundant elective projects for student selection. Students are actively encouraged to propose independent experimental topics aligned with their interests and research directions. To support students in conducting independent innovation experiments, the laboratory will establish a "Project Mentor System." This system will assign specialized mentors to each student's independent innovation project, providing comprehensive and detailed guidance throughout all stages: experimental design, implementation, and problem-solving;

(3) We will reform the experimental teaching evaluation and incentive mechanisms by establishing a diversified assessment system. This system will incorporate pre-experiment preparation and operational compliance into overall grades, utilize information systems to track student participation and contributions, and introduce awards such as the "Experimental Teaching Achievement Award." Achievements like guiding academic competitions will serve as the key criteria for professional title evaluations and performance assessments, thereby stimulating the intrinsic motivation of the teaching team [15].

4.3. Build a dual-qualified faculty team that combines full-time and part-time instructors with outstanding capabilities

To strengthen the development of the experimental teaching faculty, a dual-pronged approach combining internal cultivation and external recruitment is essential. At the internal cultivation and advancement level, establish a regular training mechanism to periodically organize faculty participation in training on new technologies, equipment, and teaching methods. Simultaneously, encourage and fund experimental instructors to undertake visits, exchanges, and job shadowing at high-level domestic and international universities or renowned enterprises. We must also promote mutual growth between teaching and research by encouraging laboratory instructors to engage in research projects, transforming research outcomes into comprehensive and research-oriented laboratory programs, and support them in summarizing experiences from laboratory management and teaching reforms, applying for teaching research projects, and publishing papers on pedagogical innovation. Regarding external recruitment and resource sharing, we should flexibly recruit industry experts by appointing senior corporate engineers and technical directors as industry mentors or adjunct professors. They should be invited to regularly deliver lectures on campus, supervise graduation projects, and collaborate on experimental development, thereby introducing cutting-edge engineering case studies and practical expertise into the academic environment. Concurrently, establish joint university-industry laboratories through collaborations with leading enterprises. Companies provide equipment, technical expertise, and training support, while the university contributes facilities and talent resources. This approach not only enhances hardware capabilities but also cultivates a permanent cohort of industry mentors [16].

4.4. Establish a safety assurance system characterized by "full participation and end-to-end controllability"

To fortify laboratory safety defenses, a systematic approach must be implemented across three dimensions: institutional culture, technical controls, and emergency response as listed:

(1) Prioritize institutional frameworks and cultural norms: On one hand, establish a robust safety accountability system by clearly defining responsibilities at all levels, including the college, laboratory directors, faculty advisors, administrative staff, and students, through signed safety agreements that enforce the principle of "whoever uses is responsible, whoever manages supervises." Additionally, cultivate a safety-conscious laboratory culture. Conduct regular safety awareness campaigns through new student orientation, safety knowledge competitions, promotional posters, and WeChat official account posts. Implement safety knowledge assessments as a mandatory prerequisite for laboratory access, where individuals who fail the assessment are prohibited from entering;

(2) Prioritize both technical and human safeguards: Strengthen safety infrastructure by equipping every lab with adequate firefighting equipment, emergency medical kits, and emergency power-off buttons. Physically isolate high-voltage experimental zones with warning signage and provide protective gear for high-frequency/high-voltage experiments. Implement intelligent safety monitoring by installing video surveillance and smoke detectors for real-time alerts. Equip critical devices with smart power management systems for automatic overcurrent, overvoltage, and leakage protection, integrated with management systems to log abnormal operations;

(3) Emergency management and response must be strengthened. Detailed contingency plans for incidents such as electric shock, fire, and chemical spills should be developed and prominently displayed.

Additionally, at least one full-scale fire evacuation and first-aid drill involving all personnel should be conducted each semester to ensure faculty and students are familiar with escape routes and basic first-aid techniques, thereby effectively enhancing practical capabilities for handling emergencies [17].

5. Conclusion

The construction and management of electrical and electronic laboratories constitute a complex systemic endeavor involving philosophy, technology, institutional frameworks, and culture. Their modernization is by no means an overnight transformation. This paper systematically constructs a four-pronged reform framework, grounded in a "hybrid hardware platform," driven by an "intelligent and open management model," anchored by a "dual-qualified faculty," and safeguarded by a "comprehensive safety system covering all personnel and processes."

This framework aims to achieve as follows:

(1) Meet multi-tiered teaching demands from fundamental verification to cutting-edge innovation through tiered hardware development;

(2) Unlock laboratory resource potential and stimulate faculty-student initiative via information-driven and open management reforms;

(3) Cultivate a dual-qualified faculty pool proficient in both theory and practice;

(4) Fortify the lifeline of sustainable laboratory development through a safety system emphasizing both cultural values and technological safeguards.

Looking ahead, with the rapid advancement of technologies such as artificial intelligence, big data, 5G, and the Internet of Things, electrical and electronics laboratories will inevitably evolve toward greater intelligence, networking, and personalization. Only by adhering to the principles of "student-centeredness, competency-based education, and safety as the bottom line," and through continuous exploration and bold implementation, can electrical and electronic laboratories truly become the cradle for cultivating outstanding engineering talent. This will contribute indispensable educational strength to China's transformation from a major manufacturing nation to a manufacturing powerhouse.

Disclosure statement

The author declares no conflict of interest.

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