Development of a Computerized Simulator for Direct Current Machine Control: Integration of Design Thinking and Information Systems Design in Industrial Automation

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Abstract—This document describes the role of Information Systems Analysis and Design (ISAD) and Design Thinking (DT) in the development of a computerized simulator for direct current machines within the Electrical Machines Laboratory at the National University of Colombia, Bogotá campus. A brief description of both methodologies, the developed simulator, and the physical environment of the Laboratory where it is implemented is provided. Design Thinking (DT) and Information Systems Analysis and Design (ISAD) are complementary methodologies that have proven effective in developing technological solutions, particularly in industrial automation. This paper presents the application of these methodologies in the simulator's development. The simulator not only replicates basic operating conditions and wiring of involved components but also integrates advanced automatic control techniques, simulation, and uncertainty quantification methods for enhanced reliability assessment.

Index Terms—Software Development, Design Thinking, Electrical Machinery, Simulation, Uncertainty Quantification, Control Systems.

I. Introduction

Design Thinking (DT) as a project development strategy has gained popularity in educational environments, promoted as a means to achieve solutions through collaboration and empathy. On the other hand, Information Systems Analysis and Design (ISAD) focuses on developing solutions to problems where custom software is the final, [1].

Given previous experience in developing computerized simulators for electrical machinery and the expanding popularity of DT, it is necessary to develop a methodology that leverages the advantages DT can offer, [2].

Computerized simulators are essential in an Electrical Machinery Laboratory as they allow the replication of basic operating conditions and wiring between involved components. Improper handling of these elements in a real environment can lead to accidents causing damage to both humans and infrastructure, [3].

A model that complements ISAD with DT characteristics emerges as a hybrid strategy for developing a computerized simulator, building on previous experience with similar projects. While ISAD focuses more on finding ways to solve problems through software implementation, DT brings to the table the consideration of other items that cannot necessarily be recreated on a computer but should be taken into account, [4], [5].

The developed simulator focuses on replicating the basic speed measurement characteristics of a direct current machine, including connections to a power board and control and protection devices, [6].

We introduce the Integrated Techno-Empathic Framework (ITEF), which serves as a mapping function between the divergent ideation of DT and the convergent implementation of ISAD. Furthermore, we implement a specific armature-controlled DC motor model including epistemic uncertainty, ensuring that the simulator prepares students for non-ideal industrial conditions.

II. The Integrated Techno-Empathic Framework (ITEF)

To integrate DT and ISAD effectively, we formalize the process as a transformation of the requirement space $\mathcal{R}$.

Definition 1 (Requirement Space). Let $\mathcal{R}_t$ be the set of identified system requirements at time t. The objective of the software development process is to minimize the distance $d(\mathcal{R}_t, \mathcal{S}_{opt})$, where $\mathcal{S}_{opt}$ is the optimal solution set.

The ITEF model maps the five stages of DT (Empathize, Define, Ideate, Prototype, Test) directly to the ISAD phases (Analysis, Design, Development, Implementation, Feedback) through a transformation matrix $\mathbf{T}_H$, see Table I.

Lemma 1 (Convergence of Requirements). If the feedback loop gain K_{fb} in the Test/Feedback phase satisfies $0 < K_{fb} < 1$, the requirement set $\mathcal{R}$ converges to a stable subset $\mathcal{R}_{stable}$ as the iteration index $k \to \infty$.

Table I
ITEF Mapping: Integration of Design Thinking Stages with ISAD Phases. Source: created by the authors.

DT Stage (U_i)	ISAD Phase	Mathematical Output
Empathize	Analysis	Requirement Set $\mathcal{R}_0$
Define	Analysis	Boundary Constraints $\mathcal{C}$
Ideate	Design	Candidate Set $\mathcal{S}_{cand}$
Prototype	Development	Solver Selection ϵ_{global}
Test	Implementation	Feedback Gain K_{fb}

Proof. Let the error in requirement identification be $e_k = \mathcal{R}_k - \mathcal{R}_{true}$. The update rule in the ITEF model is given by $e_{k+1} = (1 - \alpha K_{fb})e_k$, where α is the efficiency of the Empathize stage. For $|1 - \alpha K_{fb}| < 1$, $\lim_{k\to\infty} e_k = 0$. ■ □

This lemma drives our development strategy: rather than a single pass, the simulator underwent three specific iterations where α was maximized through direct student interviews, reducing the "Empathize" uncertainty U_1.

III. The Role of Design Thinking as a Generalized Parameter in Project Development

The National Learning Institute of Costa Rica, [7], provides a general idea of Design Thinking as a means for collectively solving problems, offering solutions and improvements based on empathy. It goes beyond problem-solving, becoming a source for implementing values and attitudes that will benefit the entire Institution, [8], [9]. This methodology establishes a set of steps for constructing projects aimed at solving problems arising in daily life.

Fig. 1 shows the stages of DT. In the first stage (Empathize), a need arises from the personal experience of those who wish to highlight the existence of a difficulty that must be eliminated or its consequences mitigated. Publicizing the existence of a problem is fundamental since its solution is a collective construction.

The next stage (Define) requires delimiting the problem and its possible solutions, [10], [11]. Resource scarcity will limit the definition of solutions since all Institutions encourage their members to reduce the amount of resources currently used.

Ideating solutions is a consideration that must be made collectively, as there may be solutions or items to consider that were not initially envisioned, [11], [12].

Prototyping a solution, whether tangible, regulatory, software, etc., requires specialized knowledge and development skills. Objective criteria must be considered to estimate whether its operation meets initial expectations, although in this stage, data is obtained under controlled conditions that are not necessarily real.

The evaluation stage implies reviewing the prototype's action on the problem that originated its development, i.e., under real conditions. Fig. 1 implies that, despite generating a solution, a re-evaluation is necessary to empathize with problems arising from the search for the solution.

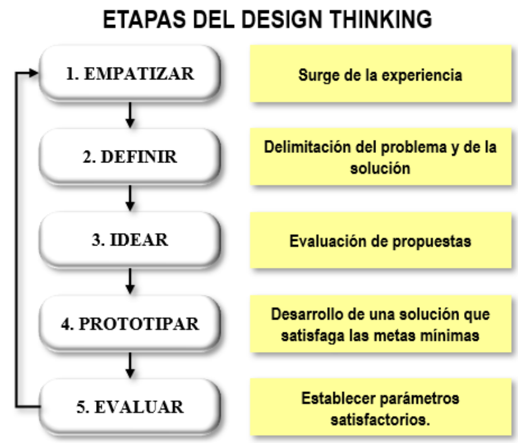

Figure 1. Stages of Design Thinking and their fundamental activities. Source: created by the authors.

A. Mathematical Formulation of Uncertainty in Design Thinking

To consider a mathematical formulation of uncertainty in Design Thinking, we can model the uncertainty U in the DT process, considering that each stage introduces an uncertainty factor. This factor affects the final solution. Thus, the total uncertainty U can be expressed as a function of the uncertainties in each aforementioned stage (1), [13], [14]:

$$U = \sum_{i=1}^{5} U_i \tag{1}$$

where U_i represents the uncertainty in each DT stage, defined as follows:

- U_1: Uncertainty in the Empathize stage, related to correctly identifying the problem
- U_2: Uncertainty in the Define stage, associated with optimally or suboptimally delimiting the problem and its possible solutions
- U_3: Uncertainty in the Ideate stage, related to generating solutions conceived for innovation
- U_4: Uncertainty in the Prototype stage, associated with the technical and practical feasibility of the proposed prototype
- U_5: Uncertainty in the Test stage, related to the solution's effectiveness under non-ideal or real conditions

Furthermore, a correction factor α can be introduced into the modeling. This factor represents the team's ability to reduce uncertainty in each stage (2):

$$U = \sum_{i=1}^{5} \alpha_i U_i \tag{2}$$

where α_i is a correction factor ranging between 0 and 1, depending on the team's effectiveness in reducing uncertainty in stage i.

B. Advanced Uncertainty Quantification Methods

For more sophisticated uncertainty analysis, we can employ Bayesian approaches (3):

$$P(U|\mathcal{D}) = \frac{P(\mathcal{D}|U)P(U)}{P(\mathcal{D})} \tag{3}$$

where $P(U|\mathcal{D})$ is the posterior distribution of uncertainty given data $\mathcal{D}$, $P(\mathcal{D}|U)$ is the likelihood, and $P(U)$ is the prior distribution.

The total uncertainty can also be modeled using Monte Carlo methods (4):

$$U_{\text{total}} = \frac{1}{N} \sum_{i=1}^{N} f(U_i^{(j)}) \tag{4}$$

where N is the number of Monte Carlo samples and $U_i^{(j)}$ represents the j-th sample of uncertainty in stage i.

IV. General Aspects of Information Systems Analysis and Design

According to [15], ISAD emerged as a methodology for developing solutions involving software development. It consists of stages that, once overcome, cannot be returned to previous ones. Fig. 2 shows the general scheme of ISAD.

Figure 2. Stages of ISAD. Source: created by the authors.

The Analysis Phase seeks to understand, describe, and document the system as it currently is, without proposing solutions to the arisen problems. Although institution members provide important information, a neutral and objective viewpoint is sought since they have biased opinions that could compromise the project.

In the Design Phase, sketches of items considered as solutions to the problems found in the analysis phase are elaborated. Several paths may exist, the most popular being the elaboration of schematics of what will be new software. This stage may also involve the use of prototypes (a strategy useful when a previous system with similar initial problems has been designed) and the agreement between the developer and end-users about the characteristics to be modified in the current system.

The Development Phase consists of implementing the characteristics agreed with end-users in the software. Here, it must be considered that only what has been worked on in the Design Phase is taken into account, and no last-minute changes are allowed since a change, however small, could trigger the modification of most of the elaborated source code, causing considerable economic losses and delays in the project execution schedule.

Current software development embeds source code testing at the syntax level, generally performed with data supplied by institution members. The Implementation Phase is the critical stage of the entire project since it seeks that end-users use the new system and abandon the previous one.

The Feedback Phase is an exercise that cannot be absolutely controlled: factors beyond the work team's will (such as planned obsolescence or changes in Legislation) make necessary the re-evaluation of any solution involving software development. It should not be confused with corrections made to the project related to developer guarantees, which are mandatory to ensure system operation under the conditions agreed upon in the Design Phase.

A. Stability Analysis

The simulator implements a closed-loop PID controller. To ensure the simulation remains valid under uncertainty, we prove the following:

Theorem 1 (Lyapunov Stability under Bounded Noise). Let $V(\mathbf{x}) = \mathbf{x}^T\mathbf{P}\mathbf{x}$ be a Lyapunov candidate for the noise-free system. If the noise covariance $\Sigma < \frac{\lambda_{min}(\mathbf{Q})}{2\lambda_{max}(\mathbf{P})}$, the system remains mean-square bounded.

Proof. The derivative of V along the trajectories of the system is (5):

$$\mathcal{L}V = -\mathbf{x}^T\mathbf{Q}\mathbf{x} + \text{Tr}(\mathbf{G}^T\mathbf{P}\mathbf{G}) \tag{5}$$

where $\mathbf{G}$ is the noise coupling matrix. For stability, we require $\mathbb{E}[\mathcal{L}V] < 0$ outside a bounded region. This holds if the noise term is dominated by the dissipation term $-\mathbf{x}^T\mathbf{Q}\mathbf{x}$. ■ □

This theorem is critical for the simulator's logic; if user-defined parameters result in noise levels violating Theorem 1, the simulator triggers a "System Unstable" warning, a feature not present in previous deterministic simulators, in this way it can be simulated in a DC Machine and Control System Specifications showed in Table II.

Table II
Simulated DC Machine and Control System Specifications. Source: created by the authors.

Parameter / Device	Specification / Type
Machine Type	Separately Excited DC Motor
Control Strategy	Armature Voltage Control (Cascade PID)
Power Rating (P_{nom})	2.5 kW
Nominal Voltage (V_a)	220 V DC
Protection Device	Thermomagnetic Circuit Breaker (Curve C)
Speed Sensor	Optical Tachometer ($\pm$0.5% uncertainty)
Solver Integration	Runge-Kutta 4th Order ($h = 10^{-4}s$)

V. Uncertainty Quantification in System Development

To address the inherent uncertainties in both DT and ISAD methodologies, we incorporate advanced uncertainty quantification techniques. For the simulator development, we consider both aleatoric (statistical) and epistemic (systematic) uncertainties.

A. Aleatoric Uncertainty Formulation

The aleatoric uncertainty in system measurements can be modeled using Gaussian processes (6):

$$U_a = \sigma^2 \mathbf{K}(\mathbf{X}, \mathbf{X}') \tag{6}$$

where σ^2 represents the measurement variance and $\mathbf{K}$ is the covariance matrix between input points $\mathbf{X}$ and $\mathbf{X}'$.

B. Epistemic Uncertainty Formulation

The epistemic uncertainty arising from model limitations can be expressed as (7):

$$U_e = \int p(\mathbf{w}|\mathcal{D}) \cdot \mathrm{Var}[f(\mathbf{x};\mathbf{w})] d\mathbf{w} \tag{7}$$

where $p(\mathbf{w}|\mathcal{D})$ is the posterior distribution of model parameters given data $\mathcal{D}$, and $f(\mathbf{x};\mathbf{w})$ represents the simulator's prediction function.

C. Total Uncertainty Composition

The combined uncertainty for the simulator predictions can be formulated as (8):

$$U_{\text{total}} = U_a + U_e + U_{\text{model}} + U_{\text{parametric}} \tag{8}$$

where:

- U_{model} represents model structure uncertainty
- $U_{\text{parametric}}$ accounts for parameter estimation uncertainty

D. Bayesian Uncertainty Quantification

We employ Bayesian inference for uncertainty propagation (9):

$$p(y|\mathbf{x}, \mathcal{D}) = \int p(y|\mathbf{x}, \mathbf{w}) p(\mathbf{w}|\mathcal{D}) d\mathbf{w} \tag{9}$$

This approach allows us to quantify prediction uncertainties through posterior predictive distributions.

VI. Laboratory of Electrical Machines at National University of Colombia

The Laboratory of Electrical Machines is one of those within the Faculty of Engineering, located in Building 411 on the campus of the National University of Colombia - Bogotá D.C. (see Fig. 3).

Figure 3. Entrance to Building 411 - Laboratories of Electrical and Mechanical Engineering at National University of Colombia - Bogotá Campus. Source: created by the authors.

This building is well-known as it serves as a meeting point not only for Electrical Engineering students and graduates but also for other programs such as Mechanical Engineering, Electronic Engineering, Mechatronics Engineering, among others, since their laboratories are also located there. They are physically delimited, feature specialized machinery, and their operations follow Occupational Health and Safety guidelines. Consequently, all members of the University Community visiting these facilities are required to use safety equipment and follow regulations that they would also encounter in current industrial environments.

Within the Electrical Machines Laboratory, there are electrical devices such as motors and generators used at industrial levels, and devices for their control and power supply (see Fig. 4).

The environment of the Electrical Machines Laboratory does not differ from an industrial one; it is properly signposted and clean. The regulations to comply with range from the use of safety implements to the prohibition of food consumption. Generally, students learn to operate industrial electrical machines under operating conditions that ensure acceptable energy consumption performance.

VII. Virtual Laboratory for D.C. Machine

The background directly involves the authors of this document as they have been those who have developed and directed projects of this nature:

- Virtual Laboratory of Single-Phase Transformer. Undergraduate thesis that recreates connections and data collection from tests.

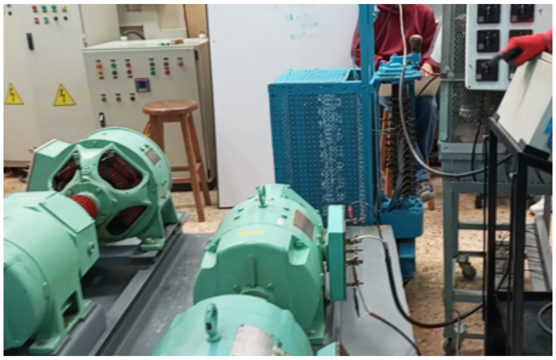

Figure 4. Interior of the Electrical Machines Laboratory at National University of Colombia - Bogotá Campus. Source: created by the authors.

- Virtual Laboratory of Asynchronous Machine.
- Virtual Laboratory of Synchronous Machine.
- Professional Skills Evaluation System SECAP.

The methodology used for developing all these solutions was ISAD, and although the basic needs for their development are the same (reducing costs and risks in electrical machinery operation), their physical operating fundamentals and applications in industry are different.

Within the Electrical Energy Conversion classes (subject developed in the Electrical Machines Laboratory), there is a set of activities where the operation of one type of machinery at a time is evaluated. To complete the simulators used in this class, it is necessary to build a Virtual Laboratory for Direct Current Machine.

The Virtual Laboratory for Direct Current Machine (VL-DCM) has been available since mid-September 2025. Its scheme is shown in Fig. 5 (Appendix). Through an initial menu, the user develops evaluation activities ranging from the selection of measurement equipment and occupational health and safety, wiring development and step sequence, to data collection, [16].

The VL-DCM consists of four modules:

- Equipment evaluation: In real life, the user must go to the Warehouse to obtain the items they desire, where the storekeeper does not make suggestions and only dispatches what is requested. In the simulator, the user has a list with all components that can be found in the Warehouse and must choose only those required. To achieve approval of this item, the user must choose only what is needed without selecting something unnecessary or omitting some indispensable element. Fig. 6 (Appendix) shows the module used in this stage. Similarly, the user must perform an evaluation of occupational health and safety equipment selection.
- Wiring evaluation: In real life, students must interact with electrical machines, control devices, and power boards, which are at fixed points and must be connected to each other through cables. The laboratory terminals do not have labels or terminals that prevent user errors as in computer assembly (many of its connectors can only be coupled in one way). Making an error when making these connections within the laboratory is probable and can cause serious damage. In the Virtual Laboratory, the user has the image of the components, distributed in the laboratory, and buttons that recreate the cables. The system gives its approval only when all cables are properly connected to the terminals. Fig. 7 (Appendix) shows the module used in this stage.
- Energization evaluation: In real life, a series of steps must be followed to properly energize the DC machine. In the simulator, a sequence of activities indicated in a list must be performed, operating switches through a click. When this task is performed adequately, the system permits continuing to the next one. Once all steps are completed, authorization for data collection is given. Fig. 8 (Appendix) shows the module used in this stage.
- Data collection: In real life, measurement instruments such as the multimeter or tachometer are used to perform measurements (which depend on the resistance that the student adjusts with the rheostat). In the simulator, the rheostat is a slide (representing the independent variable of the measurements) and yields voltage and angular velocity data. Fig. 9 (Appendix) shows the module used in this stage.

VIII. Uncertainty Propagation in Measurement Systems and Comparative Results Between Design Thinking and Information Systems Analysis

The data collection module incorporates uncertainty quantification for measurement accuracy. The angular velocity measurement uncertainty can be modeled as (10):

$$\sigma_\omega = \sqrt{\left(\frac{\partial\omega}{\partial V}\right)^2 \sigma_V^2 + \left(\frac{\partial\omega}{\partial R}\right)^2 \sigma_R^2 + \sigma_{\text{cal}}^2} \qquad (10)$$

where:

- σ_V is the voltage measurement uncertainty
- σ_R is the resistance setting uncertainty
- σ_{cal} is the calibration uncertainty

The relationship between angular velocity and electrical parameters follows the DC machine equation (11):

$$\omega = \frac{V - I_a R_a}{K\phi} \qquad (11)$$

where I_a is armature current, R_a is armature resistance, and $K\phi$ is the machine constant.

In this way, it is possible to get a Comparison of Control Performance Metrics: Deterministic vs. Stochastic (UQ) Simulation, Table III (Appendix).

Given previous experiences, DT is better in initial stages as it integrates different actors more naturally, whose contributions are more general. Since they have no preconceived ideas, they can expose information that otherwise would have been forgotten.

One problem with DT is that it allows feedback at any stage of the process. Contractually, ISAD is more adequate as it allows a temporal delimitation that can be understood by anyone involved in the process. Emphasis must be placed on the inconvenience of the DT ideal of permanent feedback: requirements can only be evaluated and proposed in the Analysis Phase because, when translated into terms of modules to be developed, they generate delays.

Given the contractual nature of software projects and the need for evaluation within companies, ISAD forces the documentation of development stages. Therefore, documentation development allows generating data that can be used for process evaluation to improve the development of future projects.

Given the empathetic approach, DT is better than ISAD when evaluating feedback from newly built systems. It should be noted that the consequences of using solutions (especially if they involve software) cannot be foreseen, and generally, externalities are detected more easily by end-users (and not by developers), [15], [16].

IX. System Reliability and Uncertainty Analysis

The overall system reliability can be quantified using a probabilistic approach. The probability of successful operation P_s considering all uncertainty sources is (12):

$$P_s = \prod_{i=1}^{n}(1 - p_{f,i}) \cdot \exp\left(-\int_0^t \lambda(\tau)d\tau\right) \qquad (12)$$

where $p_{f,i}$ is the failure probability of component i and $\lambda(\tau)$ is the time-dependent failure rate.

The uncertainty in performance metrics can be assessed using Monte Carlo simulation (13):

$$U_{\text{system}} = \frac{1}{N}\sum_{j=1}^{N}\left|\frac{y_j - \hat{y}_j}{\hat{y}_j}\right| \qquad (13)$$

where y_j are simulated values and $\hat{y}_j$ are expected values.

X. Conclusions

While ISAD has a collaborative and empathetic approach, DT proposes a more generalized approach. Its stages and methodology are more suitable for interdisciplinary projects, but the stage-by-stage parameters of ISAD are more appropriate for controlling and documenting any software process. ISAD allows adequate control of time and resources in the computerized simulator development project. DT is better in initial evaluation activities (needs) and feedback (post-implementation).

Thus, the developed simulator focuses on speed measurement of a direct current machine, integrating connections to a power board and control and protection devices. The DT methodology allowed identifying the needs of end-users (students and teachers) through an empathetic approach, while ISAD ensured structured and documented software development. This hybrid approach not only optimized the development process but also allowed the creation of a system that can be used for teaching and research in automatic control of industrial systems.

Furthermore, the simulator incorporates system modeling, simulation, and optimization techniques, making it a valuable tool for training in industrial automation and the study of advanced control systems. The integration of these methodologies and techniques demonstrates how the use of DT and ISAD can improve the development of technological solutions in the field of control engineering and industrial informatics.

The incorporation of uncertainty quantification methods provides a robust framework for assessing system reliability and performance under varying conditions, enhancing the educational value and practical applicability of the simulator.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Appendix

Table III
Comparison of Control Performance Metrics: Deterministic vs. Stochastic (UQ) Simulation. Source: created by the authors.

Metric	Deterministic (Ideal)	Stochastic (VL-DCM)
Rise Time (t_r)	1.2 s	1.4 ± 0.2 s
Overshoot (M_p)	4.5 %	6.8 ± 1.1 %
Steady State Error (e_{ss})	0.0 %	0.5 ± 0.3 %
Stability Margin	Infinite	Bounded (Theorem 1)

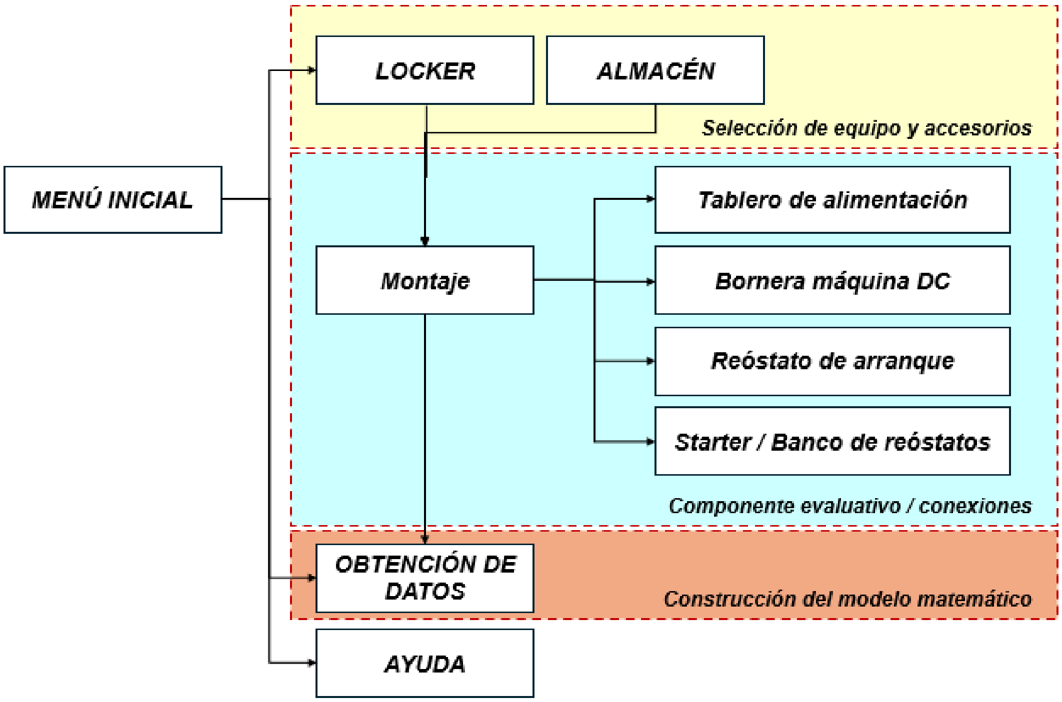

Figure 5. General scheme of the Virtual Laboratory for D.C. Machine. Source: created by the authors.

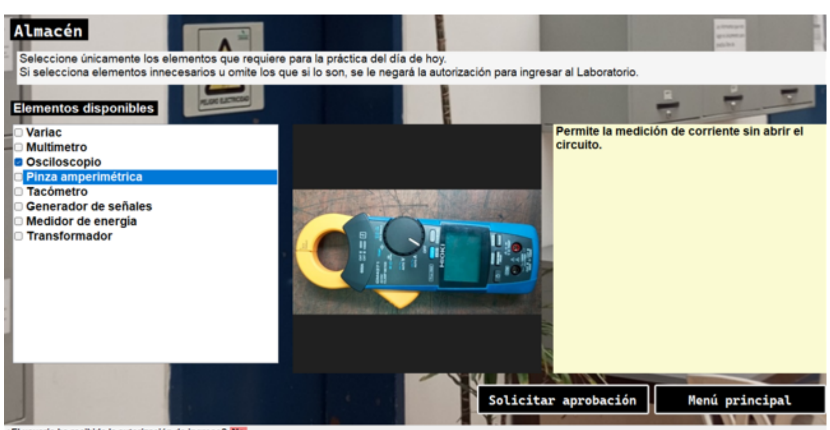

Figure 6. Equipment selection evaluation module of the Virtual Laboratory for D.C. Machine. Source: created by the authors.

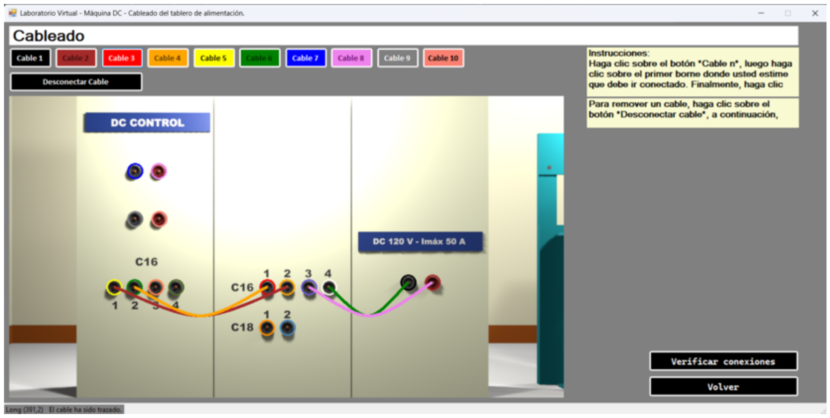

Figure 7. Wiring evaluation of the Virtual Laboratory for D.C. Machine. Source: created by the authors.

Figure 8. Step-by-step evaluation of the Virtual Laboratory for D.C. Machine. Source: created by the authors.

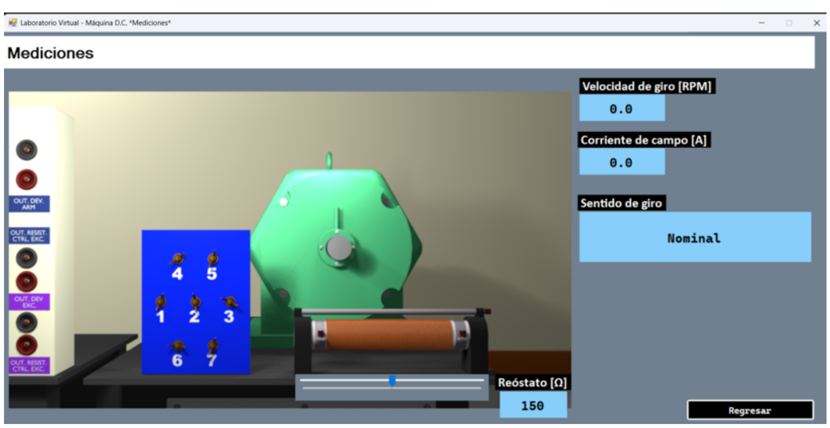

Figure 9. Speed data acquisition of the DC Machine in the Virtual Laboratory for D.C. Machine. Source: created by the authors.