Analysis of Scaled Prototyping Using Modular Construction Systems as a Bridge Between the Design and Implement Phases of the CDIO Framework

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ABSTRACT

Between conceptual design and the physical construction of a system there is an interval in which decisions have already been made but have not yet been confronted with the actual behaviour of components. Errors occurring in that interval are costly because they are discovered late, when the definitive prototype has already been built and correcting it requires starting over. This article analyses a curricular experience in which scaled prototyping using modular construction systems was deliberately placed within that interval as an intermediate validation stage in the CDIO II Project course of the Electronic Engineering programme at the University of Quindío. The aim is to examine what kind of design faults low-fidelity prototyping detects before definitive construction, and how that early detection reshapes the formative process. The experience took place during the second semester of 2023 with student teams addressing needs identified in their environment, following a seven-stage prescriptive linear design sequence. More than twenty prototypes were produced with applications in agro-industry, access control, irrigation, security and mobility assistance. Documentary analysis of the projects made it possible to classify the faults detected at the scaled prototyping stage: calibration errors, routing failures in transport subsystems, inadequate sensor placement, and dimensioning problems. Findings suggest that the formative value of low-fidelity prototyping lies not in representing the final product but in the early exposure of design assumptions that students had not made explicit.

Keywords: prototyping, CDIO framework, engineering design, active learning, scalability.

INTRODUCTION

Engineering design courses are typically organized around a seemingly natural sequence: the problem is defined, a solution is designed, and then it is built and tested. This sequence works well until the construction phase. That is when difficulties arise that the design failed to anticipate—and they appear at the worst possible moment, as time and materials have already been consumed. The student discovers that a sensor is positioned where it cannot take the necessary readings, that a transport mechanism diverts the material before it reaches the measurement point, or that proportions which worked on the blueprint do not work once the object actually exists.

The CDIO framework organizes engineering education around the conceive-design-implement-operate cycle and positions the integrative project as a central learning space (Crawley et al., 2014). While the framework precisely describes what must occur in each phase, it leaves the issue of the transition between them open. The shift from design to implementation is particularly delicate, as it entails transforming an abstract representation into an object subject to the constraints of the physical world—and it is precisely this conversion where unexpected challenges arise.

The literature on prototyping has examined this transition in detail. A prototype is not merely a preliminary version of a product; it is an instrument of inquiry whose purpose determines its form and level of fidelity (Lauff et al., 2018; Camburn et al., 2017). A low-fidelity prototype—built using materials different from those of the final product and at a scale other than the definitive one—can answer questions that a high-fidelity prototype would address only later and at a higher cost. Furthermore, Gerber and Carroll (2012) documented a significant psychological effect in educational contexts: rapid prototyping reduces the fear of failure and increases the willingness to experiment, precisely because the object being built is not precious.

This research focuses on that specific stage. In the CDIO Project II course within the Electronic Engineering program at the University of Quindío, a mandatory intermediate phase was introduced between conceptual design and final construction; during this phase, each team must physically realize its proposal at scale using a modular construction system. The tool employed is Estralandia—a playful, educational system of Colombian origin that provides modular structures for assembling mechanical and electronic systems at scale and allows for the integration of microcontrollers, sensors, and actuators. Its function in the course is not recreational in the strict sense; rather, it serves to subject the design to testing before any necessary corrections become costly.

While there is abundant literature on project-based learning in engineering and established literature on prototyping theory, there is a scarcity of documentation regarding curricular sequences that incorporate low-fidelity prototyping as a mandatory, assessable stage within the CDIO framework—specifically documenting the failures that this stage actually enables one to detect. Therefore, the aim of this manuscript is to analyze scaled prototyping using modular construction systems as a bridge between the Design and Implement phases of the CDIO framework.

THEORETICAL FRAMEWORK

Design and implementation phases within the CDIO framework

The CDIO framework defines the design phase as the creation of the plan, drawings, and algorithms describing what is to be implemented, and the implementation phase as the transformation of that design into the product—encompassing manufacturing, coding, integration, and testing (Crawley et al., 2014). The framework's standards mandate design-build experiences integrated into the curriculum, as well as the workspaces required to facilitate them (Malmqvist et al., 2020).

This formulation is clear but omits an element that practice reveals to be decisive: a moment of commitment exists between the two phases. Once definitive construction begins, revising the design entails backtracking. Classic literature on engineering design methodology has acknowledged this issue and proposed iterative processes specifically to mitigate it (Pahl & Beitz, 2007; Cross, 2008; Ulrich & Eppinger, 2012). However, in a semester-long course, unrestricted iteration is a luxury; time is fixed, and the number of possible cycles is limited. The practical question, then, is not how many iterations to perform, but rather where to position them for maximum effectiveness.

Prototyping as an instrument of inquiry

Recent research on prototyping has shifted the emphasis from the object itself to its purpose. Based on an empirical study in industrial settings, Lauff et al. (2018) demonstrated that prototypes serve various functions—such as communicating, exploring, validating, and aligning team expectations—and that the appropriate level of fidelity depends on which of these functions is being pursued. Camburn et al. (2017) systematized the state of the art regarding prototyping strategies and techniques, establishing that the choice of fidelity level, scale, and degree of subsystem integration constitutes a design decision in its own right, rather than a merely instrumental matter.

A low-fidelity prototype possesses a counterintuitive property that explains its utility: because it does not resemble the final product, it compels the team to explicitly define which aspect of the system is being represented. When a team builds a scaled-down transport mechanism using modular parts, they cannot evaluate the finish or material strength; however, they can assess the geometry of the path, the sequence of

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operations, and the coherence between what the sensors are intended to detect and what they can actually detect from their specific positions. The limitations of the tool define the scope of the question.

Gerber and Carroll (2012) also documented the affective dimension of this practice: low-fidelity prototyping reduces the perception of risk associated with error, increases the sense of progress, and fosters a willingness to discard an alternative. In engineering education, where students tend to commit to their initial idea early on, this effect has direct pedagogical implications.

Modular construction systems in engineering education

Modular construction systems offer standardized parts that can be assembled without specialized tools and allow for disassembly and reassembly. Their educational value lies in the relationship between the cost of modification and the willingness to modify: when undoing an assembly takes only minutes, students experiment with alternatives they would not attempt if reversing the process took days.

Estralandia—the system used in the study—is one such environment, developed in Colombia to teach engineering and technology concepts through the construction of scaled-down mechanical and electronic systems. It provides modular structures that enable the creation of functional prototypes and supports the integration of microcontrollers, sensors, and electromechanical components, transforming the prototype from a mere geometric model into a system with observable behavior.

Inductive learning and concrete experience

The instructional sequence analyzed corresponds to what Prince and Felder (2006) term inductive teaching methods: those that begin with a problem, a case, or an observation and lead from there to principles, rather than presenting the theory first and applying it later. Their review of the available evidence concludes that these methods outperform deductive ones in developing thinking skills and ensuring long-term retention, although they require greater effort from instructors and trigger initial resistance among students accustomed to lecture-based instruction.

The psychological basis of the sequence lies in experiential learning theory, according to which knowledge is generated through the transformation of experience via a cycle comprising concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 2015). The scale prototype serves as the object that enables the concrete experience; without it, reflective observation would focus on representations rather than behaviors.

Schön (1983) contributed a notion that is complementary and particularly relevant to this case: that of a "reflective conversation with the situation," in which the designer does not apply a method but rather acts upon the material, observes how it responds, and reformulates their understanding of the problem based on that response. A modular prototype is a material that responds quickly.

METHODOLOGY

Research approach and type

The research adopts a qualitative approach based on the systematization of experience, involving a documentary analysis of the outputs generated by the teams. The aim is not to measure the intervention's effect on an outcome, but rather to reconstruct the implemented didactic sequence and categorize the design flaws revealed during the scale-model prototyping stage. This scope is explicitly defined because it determines the limitations of the conclusions: the report presents a substantiated description rather than an estimate of efficacy.

Population and sample

The experience took place during the second semester of 2023 in the CDIO Project II course within the Electronic Engineering program at the University of Quindío in Armenia, Colombia, involving 35 students.

The students were organized into teams and presented with an initial challenge based on a need identified in their own environment, thereby situating the exercise in the realm of authentic problems rather than standard classroom problem statements.

Methodological development

The process followed a prescriptive linear design model organized into seven stages, with the scaled prototyping stage deliberately positioned between conceptual design and functional prototype development. Table 1 describes the sequence.

Table 1. Didactic sequence of the CDIO Project II course, featuring an intermediate scale-model prototyping stage.

Stage	Activity	Associated CDIO phase	Product
1	Problem definition based on environmental need and analysis of functional requirements	Conceive	Problem statement and requirements matrix
2	Conceptual design: identification of functions, inputs, outputs, and constraints through functional analysis and block diagrams.	To design	Black-box functional specification
3	Decomposition of the system into subsystems and allocation of functions	To design	White-box functional specification
4	Preliminary design and construction of a modular-system scale prototype, integrating microcontrollers, sensors, and electromechanical components.	Design / Implement	Exploratory scale model
5	Desarrollo del prototipo funcional con incorporación de programación, control y automatización	Implementar	Functional prototype
6	Integration with the specific environment and performance evaluation under simulated conditions.	Implement / Operate	Testing and Adjustment Report
7	Presentation of results to teachers and peers	Operate	Presentation and report on lessons learned

Source: Prepared by the author.

Stage 4 is the central focus of this analysis. Its mandatory and assessable nature distinguishes it from an optional layout exercise: no team may proceed to functional prototype construction without having subjected its design to scale testing and documented the resulting adjustments.

Assessment instruments and techniques

The products were evaluated using rubrics that assessed five criteria: solution creativity, prototype functionality, level of technological integration, suitability for the intended environment, and scalability potential. Feedback was provided by course instructors and peers during the presentation stage.

Analysis and triangulation of information

The analysis and triangulation of information were conducted based on the documentation for each project: problem statements, functional specifications, records from the scale-model prototyping stage, and final reports. Design flaws identified during stage 4 were coded inductively—grouped into categories based on the nature of the error—and the coding was reviewed by a second researcher.

RESULTS

Overview of the projects

The teams developed more than twenty prototypes with diverse applications, including smart irrigation systems, home alarm systems, automatic dispensers, and assistive mechanisms for people with reduced mobility. Table 2 details the most precisely documented cases, which underpin the analysis in the following section.

Table 2. Documented projects and the contribution of the scaled prototyping stage

Proyect	Application scenario	Contribution of the scaled prototyping stage
Automated transport and measurement system for parchment coffee	Coffee agro-industry	Simulation of grain flow and determination of control points
Vehicle counter for Gate No. 4 of the University of Quindío	Institutional access control	Site-scale sizing and sensor placement optimization
Pig feed dispenser	Bengala Farm, University of Quindío	Performance evaluation of the dosing mechanism prior to construction
Heating system for piglets	Bengala Farm, University of Quindío	Iteration from the black-box specification to the final 1:100 scale prototype.
Rabbit food dispenser	Bengala Farm, University of Quindío	Verification of the delivery mechanism and sizing
Security system for the program's laboratories	Academic program infrastructure	Test of the coverage and arrangement of the detection elements

Source: Prepared by the author based on course project documentation, second semester of 2023.

Agro-industrial application: heating system for piglets

The piglet heating project at the Bengala Experimental Farm allows for the observation of the entire process. The team began with a "black box" functional specification, representing the system by its inputs and outputs without detailing its internal workings. Next, they developed a "transparent box" specification, breaking the system down into subsystems and assigning functions to each. Based on this, they built initial exploratory prototypes using a modular system—which underwent successive modifications—ultimately arriving at a 1:100 scale prototype that integrates a temperature sensor, a heating control unit, and a display.

The significant aspect of this case is not the product itself, but the transition between representations. Moving from the black box to the transparent box is a conceptual operation that students often resolve on paper in a way that is plausible yet incomplete. Building a scale model compels them to complete the design, because a subsystem described merely by a label in a diagram must—in the actual assembly—occupy physical space, connect with other components, and perform an observable function.

Analysis and classification of detected faults

Document analysis made it possible to group the design flaws identified during the scale-model prototyping stage into four categories, as shown in Table 3.

Table 3. Categories of design flaws detected during the scale prototyping stage

Category	Description	Illustrative case
Calibration errors	The correspondence between the physical quantity and the instrument reading does not behave as the design assumed.	Calibration of the weighing system for parchment coffee transport
Addressing faults	The transported material or element does not follow the path intended by the design.	Routing of grain transport to the measurement point
Improper sensor placement	From its position, the sensor cannot observe the variable it is supposed to measure, or it observes it with interference.	Sensor layout at the gate's vehicle counter
Sizing issues	The planned proportions or spaces prove unfeasible when the system is realized.	Scaling of dosing systems and the vehicle counter

Source: Prepared by the authors based on project documentation.

It is evident that the four categories share a noteworthy trait: none of them stems from a calculation error. They are errors of assumption. In each instance, the student had implicitly assumed that a certain relationship would hold, that a path would follow the expected course, or that a specific position would suffice. The scale prototype did not correct a flawed calculation; instead, it revealed a premise that had never been put to the test.

Student perception and product projection

Students responded positively to the use of the modular system and highlighted three aspects: the opportunity to experiment without fear of making mistakes, the ease of visualizing ideas that had previously existed only as descriptions, and the way in which collaboratively handling the prototype facilitated teamwork. These three observations align with the effects documented by Gerber and Carroll (2012) in their study on the psychological experience of prototyping.

Several prototypes were selected for presentation at internal fairs and institutional events, opening up the possibility of their continuation as research or entrepreneurial projects. Although this potential for future development was not among the course objectives, it suggests that the scale prototyping stage also enhances the communicability of the proposals.

DISCUSSION

The central analysis of this systematization can be briefly stated: the scale prototyping stage did not detect calculation errors but rather unstated assumptions. This distinction has pedagogical consequences that extend beyond the case analyzed. A calculation error is corrected by reviewing the procedure and is, in formative terms, of little interest. An unstated assumption reveals a reasoning habit: the student progressed from the diagram to the construction without questioning what they were taking for granted. Making this habit visible is a higher-order formative objective than simply correcting a calculation.

The result is consistent with characterizing the prototype as an instrument of inquiry rather than as a preliminary version of the product (Lauff et al., 2018; Camburn et al., 2017). If the prototype were understood as a preview of the final result, a 1:100 scale model built with modular parts would have little value because it does not resemble the final system in either materials or dimensions. Its usefulness stems precisely from the fact that it does not try to be like anything else: low fidelity defines which questions it can answer and, in doing so, formulates them.

The stage's placement within the sequence is crucial. Positioning it before the conceptual design phase would turn it into an aimless exploration, while placing it after final construction would render it useless. Its value hinges on occurring at a point where the design is sufficiently specified for testing yet not so far advanced that revision would be costly. This observation suggests that the transferable contribution of the experience lies not in the tool employed, but in the position it occupies within the sequence.

This case offers a nuance to the existing literature on inductive methods. Prince and Felder (2006) noted that such methods often trigger initial resistance among students. In the experience analyzed here, however, no such resistance emerged; a plausible explanation is that the modular system's hands-on nature reduces perceived uncertainty by yielding a tangible result quickly. Nevertheless, this interpretation cannot be substantiated by the available evidence and should be regarded as a hypothesis for future research.

The study's limitations must be stated without qualification. It involves the systematization of an experience within a single course and semester, lacking a comparison group, pre- and post-performance measurements, and frequency records that would allow for weighing the relative importance of each failure category. Student perceptions were gathered informally. Consequently, no causal claims regarding the effectiveness of the mechanism can be substantiated by these data. What the study offers is a documented description of a sequence and a classification of the failures that emerged from it.

CONCLUSIONS

An analysis of the documented projects reveals four types of failures: calibration errors, routing faults in transport subsystems, improper sensor placement, and sizing issues. None of these are calculation errors; rather, they all stem from design assumptions that the student had not made explicit.

The instructional sequence described in Table 1—specifically the inclusion of a low-fidelity prototyping stage as a mandatory, graded step between conceptual design and final construction—has a significant impact on various processes, particularly in the agro-industrial sector. It is this sequencing, rather than the specific tool employed, that is transferable to other programs; any modular construction system allowing for rapid assembly and cost-free disassembly would serve an equivalent purpose.

Recording the frequency of each failure category in future cohorts would allow the classification to be converted into a quantified result. Administering a formal perception instrument at the end of the course would replace instructor observations with evidence. Comparing teams that undergo the scale-model prototyping stage with those that proceed directly to construction would make it possible to estimate the net effect of the intervention; however, its implementation raises ethical considerations that would need to be addressed beforehand, as it would entail depriving one group of students of a stage presumed to be beneficial.

ETHICAL CONSIDERATIONS

Ethical approval: The proposal was endorsed by the Faculty of Engineering's bioethics committee. At no point was work conducted involving animals or human subjects.

Student academic outputs are used with the express authorization of their authors. Images of prototypes included in the manuscript must not allow for the identification of individuals without written consent. Authorship of the developments belongs to the teams that built them**.**

Conflict of interest: The authors declare no conflict of interest**.**

Data Availability

Declaration: Prior publication. A preliminary version of this study was presented as a paper at the ACOFI 2025 International Engineering Education Meeting (DOI 10.26507/paper.4212). The present manuscript is an original text that expands upon that version regarding the theoretical framework, methodological approach, and analysis; it also incorporates a classification of the detected failures that was not included in the conference paper. It does not reproduce the text or figures from that document.

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