Rethinking Structural Design Education through Boundary Conditions and Design Flexibility in PBL

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Abstract

This study addresses the pedagogical challenge of balancing design freedom and instructional structure in architectural engineering education through the strategic use of boundary conditions. In typical Problem-Based Learning (PBL) settings, students often face unclear task scopes or overly rigid design constraints, which can hinder creativity or reduce engagement. To overcome this, the study proposes a structured PBL model that incorporates adjustable boundary conditions to guide, rather than limit, student learning. Drawing from both structural engineering principles and educational theory, the model uses written and visual design guides to define parameters within which students work. Three types of PBL projects—task, discipline, and problem—are discussed as scalable formats offering varying degrees of design flexibility. In practice, task-based projects were primarily implemented, with discipline projects explored to test adaptability. Hands-on scaled modeling activities enabled students to experiment with different building technologies and evaluate material behavior, strengthening their understanding of real-world construction constraints. Findings suggest that controlled flexibility not only supports technical learning but also enhances motivation and critical thinking. This boundary-based framework allows instructors to recalibrate project complexity according to course goals. Future research may examine how digital platforms such as BIM can expand the adaptability and interdisciplinary potential of this model in broader curricular settings.

Keywords: Problem-based learning, boundary conditions, architectural engineering pedagogy, design constraints and flexibility, curriculum innovation .

Introduction

Contemporary architectural engineering education emphasizes not only technical expertise but also a wide range of transferable skills such as interdisciplinary collaboration, communication, adaptability, and sustainability awareness (Kolmos & Graaff, 2015; NAE, 2004; OECD, 2021; Warin, 2015). As the complexity of built environments increases, graduates are expected to be equipped with capabilities that go beyond structural and material knowledge. Professional organizations and accreditation bodies worldwide increasingly emphasize the importance of innovation, real-world problem-solving, and cross-disciplinary teamwork (ABET, 2023; Pantazidou & Nair, 1999). These evolving expectations have led to the widespread adoption of active learning methodologies, particularly in Science, Technology, Engineering, and Mathematics (STEM) fields, where deeper engagement and knowledge retention are crucial (Freeman et al., 2014; Prince, 2004). Within this context, problem-based learning (PBL) has become a prominent pedagogical model due to its ability to immerse students in realistic scenarios and promote the development of critical engineering competencies (Kolmos et al., 2015).

Based on this theoretical foundation and the need for a concrete implementation model in architectural engineering, the authors designed a problem-based learning (PBL) framework to enhance instruction in building component design. The pedagogical structure draws from key concepts such as prefabrication, the open building approach (Cuperus, 2001; Habraken, 1961; Troyer, 1998), and prescriptive construction codes (Mehta, 2008; Sanchez-Garrido et al., 2023). The educational model integrates five structural technologies—timber framing, cold-formed steel framing, reinforced concrete prefabrication, autoclaved aerated concrete panels, and structural insulated panel systems—grouped as either stick-built or panelised systems. These building technologies form the foundation of a PBL-driven curriculum module embedded within an undergraduate architectural engineering course. Components of this previously proposed educational model in architectural engineering are depicted in Figure 1.

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The course examined in this paper, "Architectural Materials and Methods of Building Construction," was redesigned using a modular approach that combines lectures, hands-on tasks, discussion-based learning, and PBL. The course targets sophomore-level students who typically lack formal structural analysis training; therefore, prescriptive codes, rather than computational models, guide the learning activities. Foundational knowledge on construction systems is delivered through preparatory lectures and modules before students enter the PBL block. To successfully engage with the PBL tasks, students must understand not only the structural systems involved but also the constraints and expectations inherent to the assignment. This learning environment is characterized by a complex pedagogical framework that integrates structural systems, construction methodologies, and design tasks across different building types. To manage and evaluate this complexity, the current study adopts the concept of boundary conditions as a unifying lens that defines the scope and operational limits within the learning environment. This theoretical framing provides clarity on the extent of student freedom, task structure, and material constraints, all of which impact design flexibility and student outcomes.

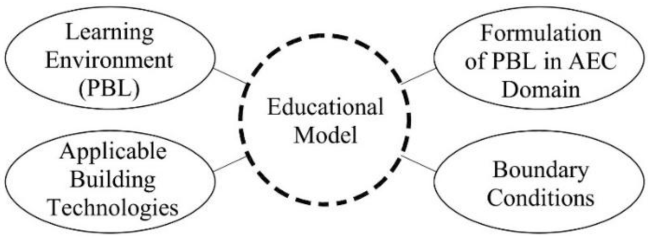


Figure 1. Components of the educational model for stick-built and panelized building systems.

The current study builds directly on two earlier studies by the authors that explored the use of PBL in architectural engineering education, focusing specifically on framing systems and building components (Yıldırım & Baur, 2014a; 2014b). In those studies, student feedback was systematically collected through surveys and structured observation, providing insight into how students perceive task complexity, interdisciplinary coordination, and time management under constrained conditions. These findings revealed specific challenges in navigating multiple layers of decision-making, particularly when students lacked clear guidance on scope boundaries and evaluation criteria. Such challenges are well-documented in engineering education research (Kolmos et al., 2015; Mills & Treagust, 2003), and align with the need for more explicitly defined learning frameworks. As a response, the current study introduces the boundary conditions framework to structure and clarify the pedagogical environment in which students operate. This refinement addresses earlier shortcomings and aims to enhance both student engagement and measurable learning outcomes.

As an outcome of this process, the research question posed in this study is as follows: What is the link between design flexibility and the type of PBL project? The hypothesis is that design flexibility and boundary conditions are directly proportional within the learning environment of building structural systems. This study defines "boundary conditions" as any limiting parameters—prescriptive, spatial, material, or procedural—that influence students' design decisions within a learning task. Although the survey results from previous work are not directly analysed here, they serve as the foundational input for developing the educational model discussed in this paper. By exploring how boundary conditions shape student engagement, task complexity, and learning outcomes, this study aims to contribute to a more structured and adaptable approach to PBL in architectural engineering education.

Materials & Methods

Theoretical Basis of PBL Framework

Problem-based learning (PBL) has continued to evolve as a student-centered approach that fosters active engagement and critical thinking, particularly in engineering and architectural education (Antepohl, & Herzig, 1999; Kolmos et al., 2015). PBL bridges the gap between theoretical instruction and practical application by placing students in scenarios that mirror real-world complexities. In this learning model, problems are not merely exercises but serve as the foundation for identifying knowledge gaps and promoting deep learning (Klegeris & Hurren, 2011; Servant-Miklos, 2019). Students take an active role in their learning process, collaborating in groups, reflecting on problem contexts, and synthesizing information to generate design solutions (Kuo et al., 2021).

Unlike traditional teacher-centered models, PBL requires instructors to act as facilitators who guide rather than dictate the learning process. Educators manage group dynamics, encourage discussion, and prompt inquiry rather than delivering prepackaged knowledge (Savery, 2006). These characteristics align with John Dewey's "learning by doing" philosophy, which remains a cornerstone of active learning practices (Forrester, 2004; Koschmann, 2014; Menendez et al., 2019). Recent literature emphasizes that effective PBL implementation depends heavily on context, including institutional culture, available resources, and student background (Chen et al., 2021; Mann et al., 2020).

Similar courses are present in the curricula of architectural and civil engineering departments globally, though implementation strategies vary depending on institutional and regional contexts (Kim et al., 2024; Naveh et al., 2022; Shekhar & Borrego, 2017). The current study builds upon these varied applications by examining a specific PBL initiative developed in an architectural engineering program, with a particular focus on the structural systems and building component design. A detailed account of how this study extends prior applications is integrated into the following sections.

To better understand how learning activities in PBL settings relate to student design outcomes, this study adopts a methodological framework that investigates two main parameters: the type of PBL activity and the role of boundary conditions in shaping the educational model. These two elements form the basis for the structure of this section. Subsection 2.1 provides a review of existing PBL activity types in engineering education, while Subsection 2.2 focuses on the boundaries within which these activities occur and how such constraints affect design flexibility and pedagogical effectiveness.

PBL Applications in Engineering and Architecture Education

Problem-Based Learning (PBL) has become a widely accepted pedagogical approach in engineering education for its capacity to develop students' ability to address complex, ill-defined problems. Its alignment with real-world challenges makes it especially relevant to the evolving demands of engineering practice (Bizjak, 2008; Canavan, 2008; Deng & Liu, 2023; Fapohundaa et al. 2023; Sarkawi et al., 2024; Sukacke et al., 2022). Active learning environments structured around PBL enhance students' readiness for professional settings that require collaboration, communication, and critical thinking (Fogg & Fendley, 2024; Patnawar, 2023).

Although PBL is not a new concept, its application in architectural and civil engineering programs has gained renewed pedagogical interest. Architectural engineering curricula increasingly incorporate design-oriented strategies to help students engage with the layered complexity of building design and construction. Studies show that PBL fosters deeper conceptual learning and encourages exploratory design approaches in architectural contexts (Kolmos et al., 2015).

In particular, hands-on methods such as scaled modelling support the translation of structural concepts into tangible outcomes. This tactile engagement improves student comprehension and supports long-term retention. Its effectiveness has been demonstrated in various structure-focused courses (Hidayat et. al, 2024; Vrontissi, 2015). PBL is also prevalent in capstone and design studio settings, which often frame learning around open-ended problems. Implementation models range from discipline-specific formats to interdisciplinary integrations (Mann et al., 2020), though adoption varies based on institutional and curricular readiness (Miklos & Kolmos, 2022).

Several architecture schools—such as Newcastle University (Australia) and Delft University (Netherlands)—were among the first to adapt PBL from medical education, with a focus on fostering design autonomy and critical inquiry (Banerjee, 1996; Smith et al., 2005). These early cases emphasized the benefit of embedding preparatory content before full immersion into PBL tasks.

From a methodological standpoint, three core PBL project types are commonly recognized: task projects, discipline projects, and problem projects (Graaff & Kolmos, 2003). Each offers a different balance between structure and freedom, with increasing flexibility leading to greater design openness. This typology informs the discussion of boundary conditions and design freedom in architectural engineering education.

In the current study, these project types serve as a lens to examine how pedagogical boundaries influence student autonomy and engagement. This provides the foundation for the next subsection, which explores boundary conditions in more detail.

Boundary Conditions in PBL from Structural and Pedagogical Perspectives

The concept of boundary conditions originates from mathematics, fluid mechanics, and engineering disciplines, where it typically refers to constraints or known values applied to the edges of a system in order to solve boundary value problems (Cadence, n.d.; Erochko, 2020; Karimpour & Rahmatalla, 2020; Simscale n.d.; Wikipedia, n.d.). In structural engineering, a boundary condition is defined as a location on a structure where either displacement or external force is specified. These constraints are essential to ensure solvability in static or dynamic structural analysis problems (Raney et al., 2015). For example, a beam supported by a hinge or fixed end has specific boundary conditions that directly affect internal force distribution and structural behaviour. In educational curricula, including civil and architectural engineering programs, boundary conditions are introduced through structural analysis courses to help students model realistic behaviour of buildings under various loads.

However, boundary conditions also take on a conceptual and methodological role in educational theory and design-based research. In organizational and educational theory development, boundary conditions define the limits or contextual scope of a theory—answering where, when, and for whom the theory applies (Busse et al., 2017). These conceptual boundaries are not physical constraints but rather methodological parameters that establish the relevance and generalizability of an approach or intervention. In recent literature on built environment pedagogy, such boundaries are seen as a framework to define the scope and applicability of design interventions and their evaluation (Sokol et al., 2022).

In the context of this study, the term boundary condition is intentionally used with dual meaning—drawing from both its technical roots in structural engineering and its methodological role in educational design. This dual usage mirrors the interdisciplinary nature of architectural engineering education, where engineering knowledge intersects with project-based pedagogies (Kolmos & Graaff, 2015).

To avoid confusion, the distinction is made explicit: Structural boundary conditions refer to the physical constraints applied to structural systems in analysis and design (e.g., fixed, pinned, roller supports). Pedagogical boundary conditions, as used in this study, refer to the predefined limits of the PBL activity—such as the scope of the project task, type of building system, and degree of design freedom provided to students.

In the proposed educational model, these pedagogical boundary conditions are articulated through instructional materials such as handouts and design guides. These documents define the boundaries of the PBL activity in two main ways: 1) Design Flexibility of Structural Systems: The type of structural system (e.g., frame, wall, slab) and the extent to which students can modify or select these systems based on performance goals and building type. 2) Constraints and Specifications for the PBL Activity: These include the selected building type, design criteria, material choices, site assumptions, and performance requirements.

By establishing clear boundary conditions in both the engineering and pedagogical sense, the activity helps students develop realistic and applicable design solutions while staying within a structured learning framework. This also ensures alignment with the learning objectives and assessment criteria of the course. As such, the boundary conditions become both a teaching tool and a reflection of the complexity students will encounter in their future professional roles.

Integrating Design Flexibility into PBL: A Case from Architectural Engineering Education

The classroom activity and its theoretical foundation were implemented in a course titled Building Construction at a mid-western public university in the United States (Yıldırım & Baur, 2014a and 2014b). At the beginning of the semester, a PBL-based task was introduced to students as an individual design project. The scope of the task included predefined building types and structural technologies. Despite these defined parameters, students were encouraged to generate unique design solutions within the provided framework, allowing them to explore their own design paths.

Design flexibility was a key pedagogical tool in this activity. Providing students with a spectrum of allowable solutions fostered ownership over their design processes and promoted creativity. Importantly, the design domain itself inherently constitutes a complex problem space. Thus, imposing strict limitations on design choices directly constrains students' capacity for problem-solving. To avoid this, the instructional model deliberately encouraged a shift from task-oriented projects—characterized by pre-defined outcomes—toward discipline-oriented projects that offer more autonomy and complexity. This transition allows students to engage more deeply with the problem space and develop advanced design strategies.

This conceptual shift is illustrated in Figure 2, where design flexibility emerges from the intersection of building type (e.g., rectilinear, diagonal) and building technology (e.g., stick-built, panelised). The diagram highlights how varying levels of planning and freedom (task vs. discipline projects) exist within the overlapping domains of technical constraints and typological decisions. The entire process is enclosed within a broader PBL context, underscoring the educational strategy behind this instructional model.

The use of boundary conditions also played a central role in framing the task. These were defined through a "Design Guide" and other supporting materials distributed to the students. The guide outlined the limits of the task environment, including specifications for building systems, materials, span dimensions, and performance expectations. This instructional strategy enabled the simulation of real-world design constraints, encouraging students to make informed decisions under bounded conditions—similar to how they would in professional practice.

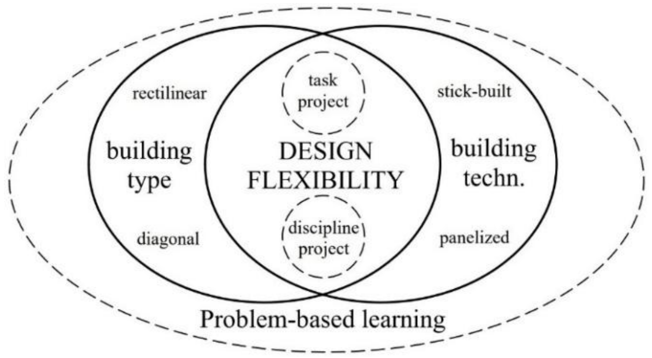


Figure 2. Conceptual framework of design flexibility in a PBL context, based on the interplay between building types, technologies, and project typologies

In this educational setup, boundary conditions referred not only to structural supports or force-displacement constraints—as used in structural analysis—but also to the pedagogical framework that shapes the limits and expectations of the learning task. This dual usage aligns with the theoretical framing discussed earlier in Section 2.2, where boundary conditions help define the scope, roles, and contextual limits of a problem-based task in architectural engineering education.

By integrating both flexible design options and clearly articulated boundary conditions, the case study aimed to simulate the complexity of real-world architectural design problems while maintaining the pedagogical structure necessary for effective learning.

Relation of PBL Project Type and Design Flexibility

Student motivation is strongly influenced by their level of engagement, and as evidenced in previous studies (Yıldırım & Baur, 2014), this engagement is enhanced when students are granted design flexibility. In other words, when students have opportunities to explore alternative design solutions beyond strict boundaries, they become more invested in the learning process. This is particularly evident in Problem-Based Learning (PBL) environments, where design is not only a pedagogical tool but also a complex problem domain in itself. Limiting design scope too narrowly may hinder students' ability to practice critical thinking and creative problem-solving. Therefore, the transition from task project to discipline project is intentional—it seeks to balance technical rigor with flexibility, thereby cultivating a richer learning experience.

In this case study, three categories of PBL project types were developed to represent varying degrees of design flexibility: task project, discipline project, and problem project. These categories align with increasing levels of complexity and open-endedness. A visual framework illustrating this gradation is presented in Figure 3.

Task projects are framed around typical housing units that comply with prescriptive codes and provide clear structural guidelines. These projects emphasize basic engineering principles such as load distribution and structural stability. The goal here is to simplify the problem space for initial comprehension. In this phase, students typically work with rectangular building types—commonly accepted as structurally efficient and compliant with standard codes. Approximately half of the floor plan in these designs is dedicated to support systems, while the remaining portion allows for limited flexibility within predefined constraints.

As students progress to discipline projects, they are encouraged to apply the foundational knowledge from task projects to more complex configurations. These discipline projects still maintain some boundary conditions (e.g., code compliance or construction technique), but now allow for more "out-of-the-box" design thinking. These projects challenge students to depart from typical patterns and explore unique architectural solutions while still respecting the principles of structural design.

At the upper level of design freedom lies the problem project, where constraints are minimized and creativity is maximized. This format promotes an open-ended inquiry model, asking students to identify, frame, and solve architectural problems that may not have one correct answer. The lack of predefined boundaries in this type allows for full engagement with both form and system logic, helping students internalize structural reasoning while exploring innovative solutions.

Team-based work is emphasized across all project types, cultivating soft skills such as communication, collaboration, and leadership. According to student feedback, this layered approach provided a clearer sense of progression and supported their design development across different complexity levels.

Figure 3 below graphically represents this progressive relationship among project types, boundary conditions, and design freedom. As students progress from task projects (c) to discipline projects (b), and eventually to problem projects (a), the degree of design freedom increases, and boundaries—often determined by building types or prescriptive codes—are gradually lifted to support out-of-the-box thinking.

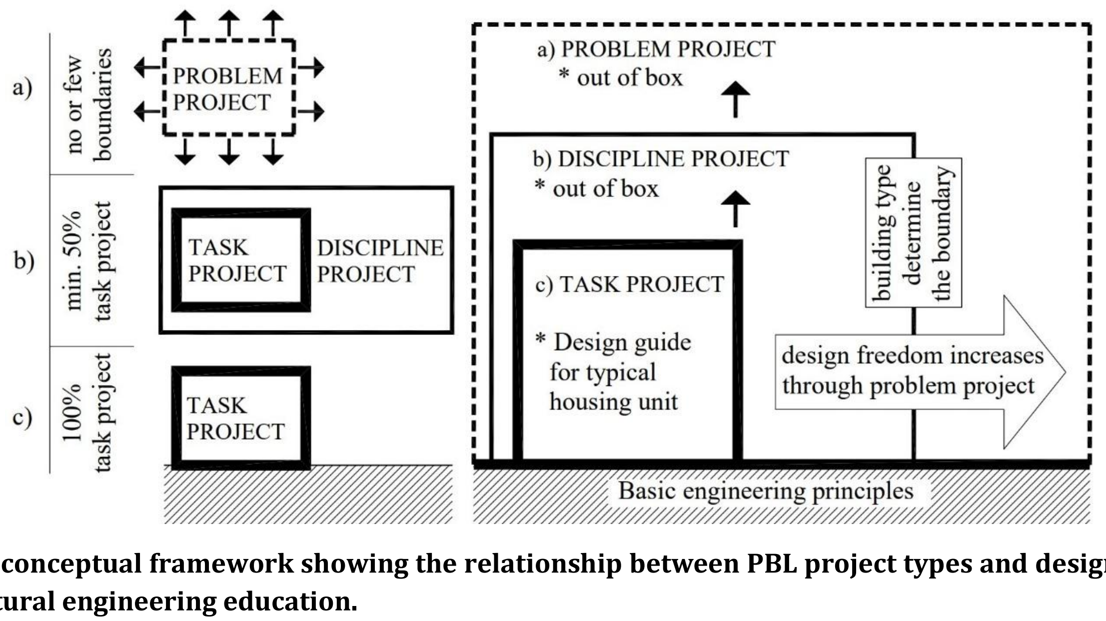


Figure 3. A conceptual framework showing the relationship between PBL project types and design flexibility in architectural engineering education.

Boundary Conditions in Task-Based PBL and Their Transition Toward Discipline Projects

In this activity, the framework for prefabricated construction is introduced through stick-built and panelised building systems. These systems establish the foundational boundary conditions that guide students throughout their PBL tasks. While implementation details may vary between courses, the pedagogical structure and core intent of the activity remain consistent.

Students begin with a design guide supported by written and visual documentation that emphasizes dimensional coordination, interface control, and construction logic. Within this context, twelve key parameters—ranging from decision-making levels to expected learning outcomes—form a flexible yet structured framework for guiding project-based learning. Figure 4 illustrates this framework through two interrelated diagrams. Figure 4a presents a scope–challenge map that positions each of the twelve parameters across two axes: design scope (horizontal) and challenge level (vertical). For instance, modular coordination and dimensional coordination are categorized as high-challenge but moderate in scope, while activity steps and types of building components occupy both high-scope and high-challenge zones. Figure 4b provides a flowchart of the instructional sequence, outlining how boundary conditions are applied and gradually relaxed to transition from task-based projects toward more flexible, discipline-specific work.

This methodology is operationalized through a four-stage instructional workflow: a) Orientation; The instructor introduces the educational model, student roles, and overall activity sequence, b) Design framework; Students engage in modular form development and dimensional coordination, c) Design Development; Prefabrication technologies and components are applied to develop structural layouts, d) Designs are assessed based on structural principles, evaluation criteria, and learning outcomes.

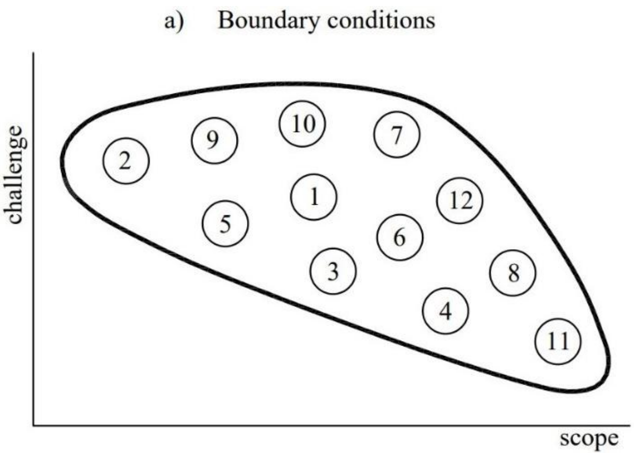
This structured yet adaptable system enables students to explore both technical requirements and creative possibilities in component-based architectural design. The use of modular units fosters a range of design solutions, reducing redundancy and encouraging individualized team outcomes.

Moreover, building types created by combining these modular units are also used as reference examples in discipline-specific designs. This approach enables students to move beyond the limitations of task-based housing models. The same modular methodology can be extended to discipline projects depending on the level of design freedom granted by the instructor.

Ultimately, this flexibility allows instructors to recalibrate the depth and openness of learning activities by adjusting the boundary conditions. Each of the twelve parameters functions as a dynamic lever—by altering just one (e.g., modular system scope or evaluation criteria), the project type can shift toward higher complexity and student autonomy. In doing so, the PBL environment becomes more tailored to course objectives and student readiness.

Findings and Reflections on PBL Application

This section presents findings and reflections derived from the implementation of the proposed PBL educational model. The evaluation is organized into three key areas: (1) learning outcomes observed during the activity, (2) specific challenges encountered throughout the implementation process, and (3) considerations for potential future research. These categories aim to offer both analytical insight and practical implications. The outcomes reported here may contribute to improving this educational framework and guiding the development of similar curricula in architectural engineering and related disciplines.



	b) Flowchart
Orientation	1) Educational model 2) Levels of decision making 3) Steps of the activity
Design Framework	4) Types of building form 5) Modular (grid) system and dimensions 6) Dimensional coordination
Design Development	7) Level of industrialization in building 8) Types of building technology 9) Types of building components
Iteration and Evaluation	10) Basic principles of building technologies 11) Evaluation methodology 12) Learning outcomes

Figure 4. Boundary conditions and instructional flow of PBL tasks in structural systems. (a) Scope-challenge map. (b) Instructional flowchart.

Learning Outcomes in PBL Activities

Since the PBL activity involving stick-built and panelised building systems includes the hands-on assembly of scaled architectural models, the selection and evaluation of appropriate educational materials became an integral part of the learning process. In this context, "educational materials" refer specifically to the physical model-making materials used by students. The quality of the learning experience was found to be closely related to the properties of these materials, including their availability, affordability, ease of use (workability), and the quality of the final model outcomes.

Students experimented with seven different materials while modelling five distinct building technologies. Based on their modelling experience, they assessed each material according to the aforementioned criteria. This exercise allowed students to reflect on material performance and develop critical thinking about construction technologies and real-world constraints. The methodological foundation of this assessment is based on previous findings by the authors, which were revisited and adapted within the scope of the current study to align with experiential learning goals (Yildirim & Baur, 2014a; 2014b).

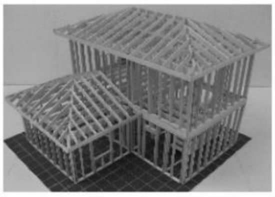
As a result of the hands-on modelling exercises conducted within the PBL framework, students re-evaluated various model-making materials based on their real-world performance during the activity. Table 1 summarizes the observed strengths and weaknesses of each material in terms of availability, affordability, workability, and the quality of the final product. This reassessment process served not only as a reflection tool but also as a core learning outcome, encouraging students to critically analyse material behaviour and its implications in architectural construction.

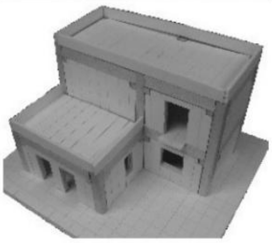
For instance, the timber framing system was effectively modelled using balsa wood at a 1:20 scale, while the cold-formed steel framing (CFS) system was tested at various scales such as 1:10, 1:20, 1:25, and 1:32 using materials like aluminium profiles, aluminium foil, and plastic model profiles. Despite initial assumptions, some materials proved ineffective: aluminium foil and versatile paper were particularly challenging due to assembly difficulties and lack of structural integrity. These realizations were derived directly from students' modelling attempts, leading to a deeper understanding of practical constraints in construction.

Similarly, reinforced concrete (RC) prefabricated systems and panelised approaches were modelled using foam board and 3D-printed plastic components at scales such as 1:20, 1:32, and 1:50. Students also observed how certain materials imposed limitations or provided advantages in replicating real-world systems. For example, while aluminium profiles yielded realistic and durable results, they were harder to manipulate without additional equipment.

The modelling activity fostered collaborative learning, problem-solving, and reflection on design-to-construction translation. Moreover, it enabled a tangible comparison of material behaviour, which students reported as instrumental in grasping structural logic. The compiled assessments (see Table 1) not only document material performance but also represent one of the core learning outcomes of the PBL process.

Table 1. Reassessment of model-making materials based-on learning outcomes.





	Material	Applicable building technology	Notes			
			Available	Affordable	Workable	Results
1	**Balsa wood**	Timber framing system	X	X	X	V
2	**Foamboard**	RC prefabricated, AAC panel, SIP systems	X	X	X	S
3	**Aluminum profile**	CFS framing system		X		V
4	**Aluminum foil**	CFS framing system	X	X		F
5	**Versatile paper**	CFS framing system	X	X		F
6	**Stock-ready plastic model profiles**	CFS framing system	X	X	X	V
7	**3D Printer (plastic)**	RC prefabricated, AAC panel, CFS framing system	X			E

P = Poor, F = Fair, S = Satisfactory, V = Very Good, E = Excellent

Addressing Pedagogical and Structural Challenges through Flexible PBL Design

Students generally expressed satisfaction with the PBL activity, as reported in earlier research by the authors, where comparative feedback suggested that the PBL approach had a more beneficial impact than traditional lecture-based learning environments (Yildirim & Baur, 2014a; 2014b). While that study included direct survey data, this paper reinterprets those findings from a pedagogical design perspective, emphasizing structural and material-related flexibility within PBL settings.

A recurring challenge identified by students is the lack of variety in building types and technologies over consecutive semesters. Performing the same design and construction tasks annually can lead to a sense of monotony. Enhancing flexibility in PBL activities helps avoid this repetition, strengthens engagement, and supports deeper, longer-term retention of knowledge. Flexibility becomes particularly relevant when examining two key aspects of the PBL model: building type and building technology.

Each of these aspects presents its own distinct challenges. On the side of building types, limitations are often imposed by prescriptive codes and standardized typologies embedded in architectural design guides. On the technology side, the main difficulty lies in sourcing workable and scalable model-making materials that reflect real-world construction systems. A strategic response to these constraints involves re-framing the project: shifting from a narrowly defined "task project" to a broader "discipline project," in which structural freedom and conceptual integrity are encouraged while still aligning with educational goals.

Figure 5 summarizes how such challenges can be addressed, and what effects these solutions have on student learning outcomes. For instance, the use of stock-ready plastic profiles in modelling cold-formed steel systems enables greater material flexibility and technical accuracy, which in turn leads to increased student satisfaction and a more meaningful engagement with the PBL process. Similarly, allowing broader interpretation of prescriptive codes empowers students to apply their technical knowledge with structural foresight gained from traditional coursework.

By introducing manageable forms of flexibility in both design parameters and modelling materials, the PBL framework can better support student autonomy, critical thinking, and applied problem-solving — essential qualities for emerging professionals in architecture and construction fields.

Directions for Further Research through Course Integration and Digital Platforms

Building Information Modelling (BIM) has become increasingly central in the Architecture, Engineering, and Construction (AEC) sector, offering substantial improvements in project coordination, stakeholder communication, and design integration. Over the last decade, with the rise of mobile computing and tablet-based tools, BIM has evolved into a powerful digital infrastructure that supports centralized data environments and collaborative workflows.

Within the scope of this study, which emphasizes educational implementation, coordination and communication skills have emerged as essential competencies for architectural engineering students. These are particularly relevant in project-based learning (PBL) contexts, where active engagement, interdisciplinary thinking, and real-time problem-solving are key components of the learning process.

Further research can explore how the boundaries and flexibility of PBL models might be expanded or redefined through two complementary pathways:

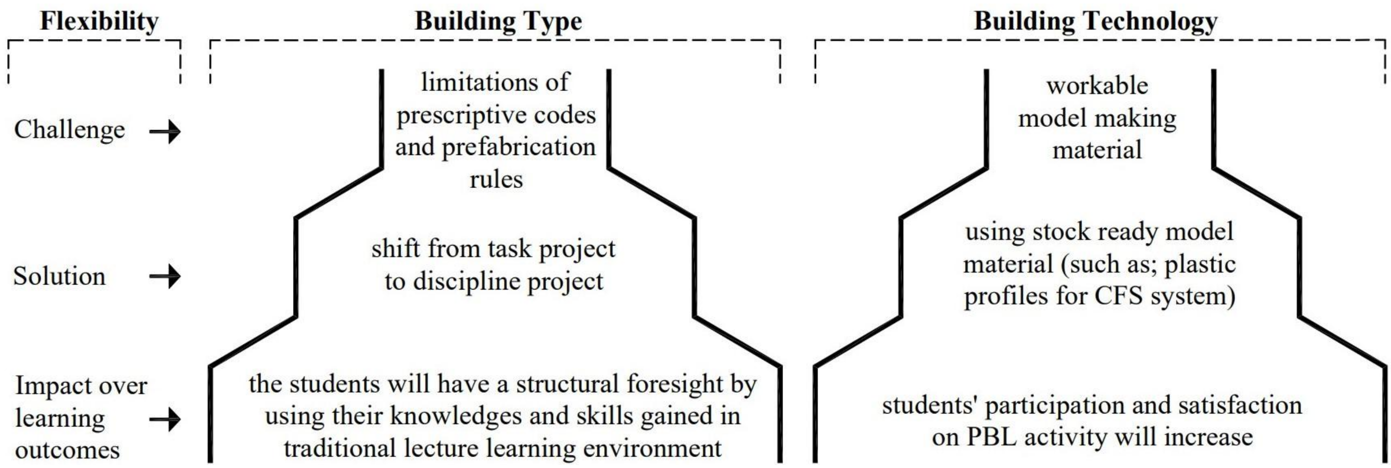


Figure 5. Challenges, solutions, and impacts on learning outcomes through maintaining flexibility.

- Extension into additional courses: The current educational model may be applied beyond design studios to include related building technology courses, enabling cross-course comparison and fostering broader interdisciplinary learning.
- Integration with digital platforms: Embedding PBL activities into BIM-based environments offers an alternative to traditional hands-on methods. While differing in format, both approaches share core values of feedback-driven iteration, active participation, and collaborative design. Comparative studies could examine how platform-based flexibility influences learning outcomes and student engagement.

In conclusion, aligning PBL models with technological developments (such as BIM) offers new avenues for expanding its pedagogical boundaries. Future studies may investigate how these integrations influence student autonomy, knowledge retention, and real-world preparedness across multiple learning contexts.

Conclusion

This study proposed a boundary condition–based educational model that integrates design flexibility into problem-based learning (PBL) environments in architectural engineering education. By framing instructional constraints through written and visual design guides, the model provided a structured yet flexible approach that supported both student autonomy and technical rigor. Boundary conditions, in both structural and pedagogical terms, served not as limitations but as guiding parameters that enabled deeper engagement with complex design challenges.

The model's progression from task-based to discipline-oriented project types illustrates how design flexibility can be gradually expanded while remaining aligned with course objectives. Although task projects were primarily implemented, limited applications of discipline projects provided insight into how increased autonomy and scope affect student motivation and performance. Varying project parameters—such as building type and construction system—was shown to mitigate repetitive patterns and foster longer-term knowledge retention.

Hands-on modelling activities using diverse materials enabled students to evaluate structural feasibility, construction logic, and material behaviour. These experiences bridged conceptual understanding and practical application, encouraging reflective thinking and problem-solving through tangible design processes. Material performance assessments became not only a feedback mechanism but also a central learning outcome.

Moreover, the ability of instructors to recalibrate the scope of PBL activities by adjusting specific boundary parameters proved essential for addressing varying student readiness and maintaining course adaptability. This study affirms that clearly articulated, adaptable boundary conditions enhance the effectiveness of PBL by linking pedagogical structure with creative freedom.

Future research may explore how digital learning platforms, particularly Building Information Modelling (BIM), can further extend this model, and how flexibility across tools, materials, and project types influences learning outcomes, interdisciplinary collaboration, and student agency in architectural engineering education.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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