education sciences

MDPI

Article

Application and Assessment of an Experiential Deformation Approach as a Didactive Tool of Truss Structures in Architectural Engineering

Maristella E. Voutetaki

Department of Architectural Engineering, School of Engineering, Democritus University of Thrace, 67100 Xanthi, Greece; mvouteta@arch.duth.gr

Abstract: Experiential learning methods are advantageous for students as they motivate them to comprehend structural concepts without complex calculations, enhancing their inherent understanding of static principles. This research introduces a novel, cost-effective haptic didactic tool to enhance the approach to teaching trusses to students in a School of Architecture. The primary goal is to address challenges associated with the complexities of teaching structural systems within the context of architectural education. The proposed approach is related to the most critical issue, which is the state in which the individual elements are under applied load, compression, or tension. The approach explores the deformation of the truss elements and establishes a connection between their visible deformation and the stress they develop under various loads. As a didactic tool, this approach offers an alternative perspective to help students understand truss function under various loads. Also, an assessment procedure of learning outcomes and satisfaction indices has been structured to validate the impact on students on the proposed educational procedure. The findings underscore the significant educational efficiency of the proposed procedure as a sustainable way to connect the structural engineering challenges arising during design courses and creative skills in architecture engineering.

Keywords: experiential learning; truss model; structural engineering; architectural engineering; workshop activity process (WAP); truss design process (TDP); experiential deformation approach (EDA); mutual teaching; collaborative learning

Citation: Voutetaki, M.E. Application and Assessment of an Experiential Deformation Approach as a Didactive Tool of Truss Structures in Architectural Engineering. *Educ. Sci.* **2024**, *14*, 354. https://doi.org/10.3390/educsci14040354

Academic Editor: Da Yang Tan

Received: 30 December 2023
Revised: 19 March 2024
Accepted: 25 March 2024
Published: 28 March 2024

1. Introduction

Experiential learning plays a significant role in the field of contemporary pedagogical methodologies. In contrast to conventional teacher-centered learning approaches that employ relatively passive strategies, this method sets the student as the central teaching point, assuming a more active role in acquiring knowledge through experiential engagement [1–3]. The learning process can be optimized through the transformative approach of experiential engagement, as developed by the founder of experiential learning theory [4–6].

1.1. Teaching Structural Engineering in Architecture Using Experiential Learning

Educating architecture students presents inherent challenges. In the conceptual learning of engineering science, it is well known that architecture students encounter difficulty comprehending the fundamental concepts of structural engineering science concepts [7,8]. In the context of structural engineering science courses, practical teaching methods play a crucial role in imparting a tangible, physical dimension to the understanding of structures and construction systems. Experiential learning, identified as a promising pedagogical approach at the academic level, explicitly addresses the conceptual learning aspects of architectural courses. Through active involvement with actual structural engineering data, students acquire metacognitive skills directly applicable to the challenges architects encounter in real-life conditions [9]. These methods align with the principles of a student-centered approach, which emphasize the importance of active participation, autonomy, and critical thinking. Teaching techniques included discussion, question-and-answer, working in groups, brainstorming, simulation, role play, and practice to promote active learning and student engagement within the educational environment, reflecting a commitment to student-centered and adult learning principles [10].

The time constraints within architectural curricula and numerous obligations across various courses limit the time to provide structural engineering knowledge. Additionally, the distinct separation of structural engineering subjects from construction and design-oriented ones increases students' difficulty connecting real-world design challenges and structural design concepts during design courses. The learning-by-doing approach is expanded into creative practices by utilizing engineering constructs. The didactic approach is fundamental to addressing structural engineering education primarily from architectural perspectives, promoting a transdisciplinary interchange [11,12].

1.2. Integrated Learning Approaches for Enhancing Structural Understanding in Architecture

Integrated learning approaches are essential to improve understanding of structural concepts in architecture. Students can understand complex structural principles by combining various educational methods, such as hands-on experiences with physical models, collaborative problem-solving in group settings, and theoretical discussions in classroom settings. This integrated approach allows students to explore structural concepts from multiple perspectives, enhancing their learning and promoting more profound understanding.

1.2.1. Experiential Learning: Learning through Physical Models

Structural engineering design requires an understanding of the relationships between principles of statics, such as equilibrium conditions, force vectors, support reactions, and the analysis of structural elements under various loading conditions. In this context, the construction and the iterative development of physical models play a fundamental role in the conceptual phase of the design process. Physical models are vital in architecture [12] for exploring experimental ideas holistically and effectively, including building awareness regarding the optimum use of materials and resources. The use of physical and digital models in this pedagogic approach successfully engaged students, promoting the integration of structural parameters in early architectural design stages and simultaneously creating a common ground for architects and engineers towards an interdisciplinary practice and education [13].

In the study of Vrodissi et al. [14], the foundational concept of structure is introduced in the initial stages of the design process, and contextual constraints are then integrated to underscore the intrinsic connection between structure and space. The objective is to explore structural engineering concepts within an inclusive design perspective and transform the structural concept into a meaningful architectural idea.

Consequently, teaching the structure only by discussing it is not a solution to the problem as it does not answer the issues that arise during architectural design. Based on the findings of the study of Montes et al. [15], they introduce a new way to teach engineering mechanics in architecture degrees, using everyday objects within their reach to build an object or structure that must remain in a "creative balance", and this will serve as an inspiration for new buildings. The equilibrium challenge uniquely promotes intuition and creativity, crucial aspects for the future development of architects within their profession. The obtained results underscore the efficacy of the methodology, proving how students perceive these exercises as an enjoyable means of learning through experimentation.

1.2.2. Sustainable Learning: Learning through Collaborative Environments

In higher education, collaborative learning is critical for qualifying students with the skills to handle complicated challenges. It is also helpful to combine collaborative learning with learning by teaching to investigate and receive more advantages relevant to sustainable education. It recognizes and introduces the importance of diverse perspectives and expertise in handling complicated issues [16,17]. Essential learning pedagogies to integrate sustainability in engineering education are student-centered, experiential, problem-based, constructive, and transformative learning approaches. The above approaches enhance interdisciplinary knowledge, collaboration, problem-solving skills, and critical thinking, making it suitable for combining sustainability into engineering curricula. By engaging in those processes, students acknowledge their learning and personal needs and develop strategies to fulfill them [18].

The study of Dominguez et al. [19] focuses on a practical experiment rooted in real-world contexts. It reveals a distinction between theoretical knowledge and its practical implementation. This discrepancy underscores the necessity for increased hands-on activities within the curriculum. The study emphasizes integrating physics and mathematics through modeling and adopting a student-centered approach. Also, the collaborative nature of these activities enhances the overall learning experience. Meaningful dialogues within small groups have played a crucial role in the students' successful construction of models. Teachers can enhance students' motivation in sustainable development education by offering autonomy, encouraging reflection on future roles, fostering community collaboration, and enabling personalized learning aligned with individual goals and interests [20]. Implementing sustainable teaching methods can improve the linkage between various course content and curricula.

1.3. Truss Physical Models

Sadowski and Jankowski 2021, utilized a physical 2D truss model to teach structural systems to architecture students. The applied method of visualizing the forces using LED lights was clear and can also be helpful in teaching structural engineering students, enabling the understanding of the work of individual elements of the truss. The surveyed students showed great interest in the project as well as recommended its use in further teaching [21]. Frequently, structural engineering science courses are founded on the comprehension of fundamental theoretical principles, vectors, forces, moments of forces, bending moments, equilibrium, etc. Pursuing a similar objective [22], Bigoni et al., 2012, constructed a simple 3D physical Warren-type truss model to effectively understand trusses' structural behavior.

Allen and Zalewski 2012, maintain that design intuition resides in the subconscious and can be cultivated or suppressed through years of exposure and association. They emphasize a critical perspective of pedagogical approaches within polytechnic institutions, focusing on calculating structures with specific static schemes. However, they contend that the core challenge lies in shaping a structure to optimize static and aesthetic outcomes. The form of a structure is a direct result of comprehensive considerations involving the object's function and the spatial distribution of forces. The significance of the design intuition asserts its derivation from a synthesis of life experiences, soft skills, and professional insights. The flow of forces method significantly changed the qualitative approach to teaching and designing structural systems generally. It referred to the graphic visualization of the invisible network of internal forces, making it a helpful approach for learning without using calculations. The structural behavior can only be represented by two types of internal forces: compression and tension, which, being mutually perpendicular to each other, create an orthogonal system of stress trajectories [23].

1.4. Assessment of the Educational Process

A critical aspect of the educational process involves assessing students to provide feedback. Richardson et al. [24,25] created a tool that can efficiently and reliably measure students' conceptual understanding of the strength of materials. They aimed to validate and ensure the reliability of inventories through student group administration and response validation via interviews and assessment procedures. Montes et al. [26] used an ad hoc questionnaire to evaluate the effectiveness of their methodology in improving students' understanding of physics concepts. The questions were designed to assess the students' knowledge and perception of the activities. The above approaches deviate from traditional classroom dynamics and transform the evaluation methodology of the subject. Furthermore, critical self-reflection on teaching can lead to the transformation and the adoption of alternative teaching practices since the critically reflective process is a critical point for enhancing an academic's pedagogical, curriculum, and instructional knowledge [27]. In engineering education, rubrics are used for grading and receiving feedback during active learning and hands-on activities. These evaluative tools clarify to students the expectations embedded in the success criteria for their final learning outcomes. Assessment procedures help students better understand the educational steps. The observable action provides evidence of achieving the task, thus maximizing the usefulness of the assessment procedure in teaching interventions [28,29].

The Critical Incident Questionnaire (CIQ) is a well-known tool that allows teachers to carry out reflective work [30]. It identifies the significant situations that the students face during the teaching process. It stimulates the teacher's decision-making capacity and response to face the teaching procedure strategically and innovatively. Also, as an intervention tool, it is helpful to raise the awareness of those involved, assess the actions triggered, and propose alternative actions for similar contingencies [31]. The CIQ is an effective qualitative instrument to assess critical reflection and critical incidents during learning [32] and may assist instructors in determining student engagement and the impact of the instructor's teaching [33]. Stephen Brookfield suggests that the journey to uncovering the value of teaching involves engaging in critical reflection; it operates as a feedback tool for educators to improve the teaching procedure.

1.5. Purpose of This Article

This study aims to alleviate architecture students' challenges in understanding structural engineering by using practical simulations involving simple materials or easily accessible structural components. During educational practice at the Department of Architectural Engineering of the Democritus University of Thrace in Greece, the author prepared various structural simulations during courses and workshops [34]. Because of the difficulties faced in understanding structural concepts, it is necessary to find ways to enhance the students' understanding of these issues. Also, to bridge structural and synthetic courses in the preceding workshops, it became evident that students derived great satisfaction from hands-on experimentation with fundamental tangible materials. This realization prompted the idea of creating a specialized workshop exclusively dedicated to delving deeper into truss operation.

The objective of this study is to select specific teaching model configurations to test and try, providing the students with an opportunity to develop a more profound comprehension of the operational principles of trusses. The truss structure represents a fundamental structure in which the elements operate exclusively in either compression or tension. It is an ideal didactic example for architecture students, facilitating comprehension of various concepts in the engineering structures course syllabus.

The investigation evaluates the implementation of the didactic tool, examining the efficacy of experiential and mutual learning in structural engineering education through a hands-on workshop. To achieve and evaluate the results of the workshop, targeted questionnaires and feedback worksheets were developed to assess experiential students' performance and metacognitive skills before and after the workshop. The findings reveal a substantial enhancement in students' comprehension of concepts, team collaboration, communication skills, and critical thinking following the workshop. This suggests that experiential workshops hold considerable promise as valuable resources for enhancing structural engineering education for architects. The paper concludes by endorsing the more extensive integration of such workshops into the curriculum of architectural schools offering structural courses.

The novelty in the present work is the development of a simple, accessible, cost-effective, sustainable, and practical truss didactic tool designed to promote a deep comprehension of the structural engineering concepts of trusses. Finally, the entire process is evaluated to obtain relevant information that can be used to improve the educational procedure in the future.

2. Methodology of the Truss Design Process and Evaluation of the Workshop

2.1. Participants and Pedagogy Methodology

This study involved the participation of 50 first-year Architecture School students. The students were grouped into 8 groups, actively collaborating to coordinate experiential truss simulations as outlined in a provided worksheet. Each group was assigned a leader, who was a higher-year student, to assist with the education procedure. For this reason, besides the experiential teaching method, this approach is integrated with mutual learning, creating a synergistic educational environment. In this combined framework, students actively engage in hands-on experiences while participating in collaborative learning activities.

In mutual learning, students teaching each other is alternatively recognized as "learning through teaching". This concept is not new and has historical precedence in educational methodologies. Mutual learning is a crucial approach to enhancing learning effectiveness and can increase conventional educational methods [35]. Collaborative learning, characterized by active student–teacher engagement and group-based problem solving, deviates from traditional teaching methods. This approach, emphasizing teamwork and communication, is particularly beneficial for sustainable education. The emphasis on collective strengths and weaknesses within groups contributes to a sustainable educational framework that prepares students to navigate and contribute to a more sustainable future [36]. Fiorella and Mayer 2014 [37] investigate whether the learning outcome is more effective when students prepare to teach compared to when students prepare for a test. The results show that preparation for teaching can be an effective learning strategy even without training or interaction with another student.

It is worth mentioning that the students had no truss experience except the day before they attended a course regarding the theoretical fundamental structural principles of trusses. Conversely, the leader had successfully completed exams on trusses in the previous year. Nevertheless, an extra session dedicated exclusively to student leaders was conducted a day before the workshop. The purpose of this session was to provide detailed information about the educational procedure and the aim of the workshop, enabling leaders to refresh their understanding and disseminate more effectively to others throughout the workshop.

2.2. Workshop Activity Progress (WAP)

The WAP was designed to encourage the students to attend the procedure effectively. It is evaluated through custom-made questionnaires to offer an overview of performance concerning learning outcomes achieved. The WAP contains the Truss Design Process (TDP) as a foundational section, which introduces the Experiential Deformation Approach (EDA) utilized to assemble visual transformations to the loaded trusses. Specific teaching truss model configurations are selected to test and try. The assessment procedure was recorded from the initiation of the workshop to its end. Four custom-made questionnaires were formulated for comprehensive analysis and evaluation to assess the efficacy of the workshop concerning its influence on educational effectiveness and learning outcomes. Figure 1 outlines the steps of the WAP and the respective duration. The entire process lasts approximately three hours. The WAP consists of seven steps. Initially, students are organized into groups, each group receiving a kit with the necessary materials. Following this, the first questionnaire is distributed. The central phase of the WAP, known as TDP, is initiated and occupies the majority of the time. Finally, the evaluation process occurs, involving three designated questionnaires. The duration of each step is referred to in Figure 1 and analyzed in each relevant section.

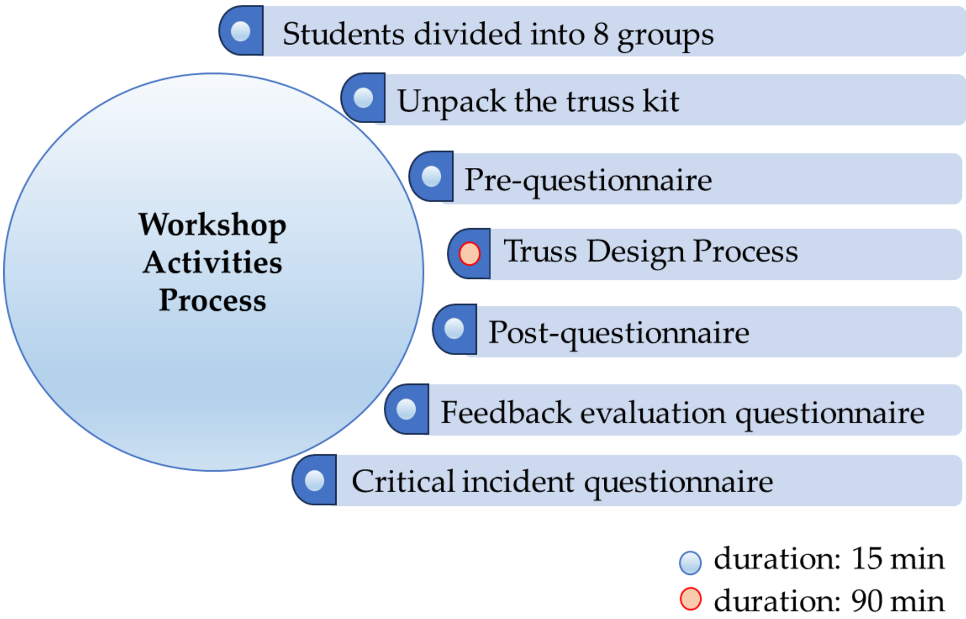


Figure 1. Workshop Activities Progress WAP, includes Truss Design Process TDP.

2.2.1. Materials and Implementation of Truss Models

Students were divided into groups. Each group was provided with a toolkit containing the essential material for constructing the truss, as shown in Figure 2. The toolkit contains 7 steel elements, 2–3 elastic bands (EB), some ropes, 5 fastening sets, 2 supports to implement a pin, a brick to represent a roller, and a worksheet with instructions. These materials are carefully selected using sustainable approaches. Each material is fully reusable without consuming energy during its use. A period of 15 min is provided for the exploration of materials.

Figure 2. Toolkit. During the Truss Design Process TDP.

The fundamental configuration of the 2D truss is a triangular assembly of pin joints connected to straight structural elements made of metal, representing well-known variances of the Warren truss, two types of variations, M and W (Figure 3). Implementing a 180-degree rotational adjustment from the M type can result in the W type as an alternative design using the same materials. Both trusses are statically determined and supported by a roller and a pin. The supports are positioned at the lower nodes as a supported beam for the M type and an overhanging for the W type. Structural elements of a truss are subjected to either compression or tension when the external concentrated load is applied at their pin-joint connections. Three types of loads distinguished by their variations are applied during the workshop: concentrated loads oriented towards gravity (G), concentrated loads opposing gravity (−G), and lateral loads (L).

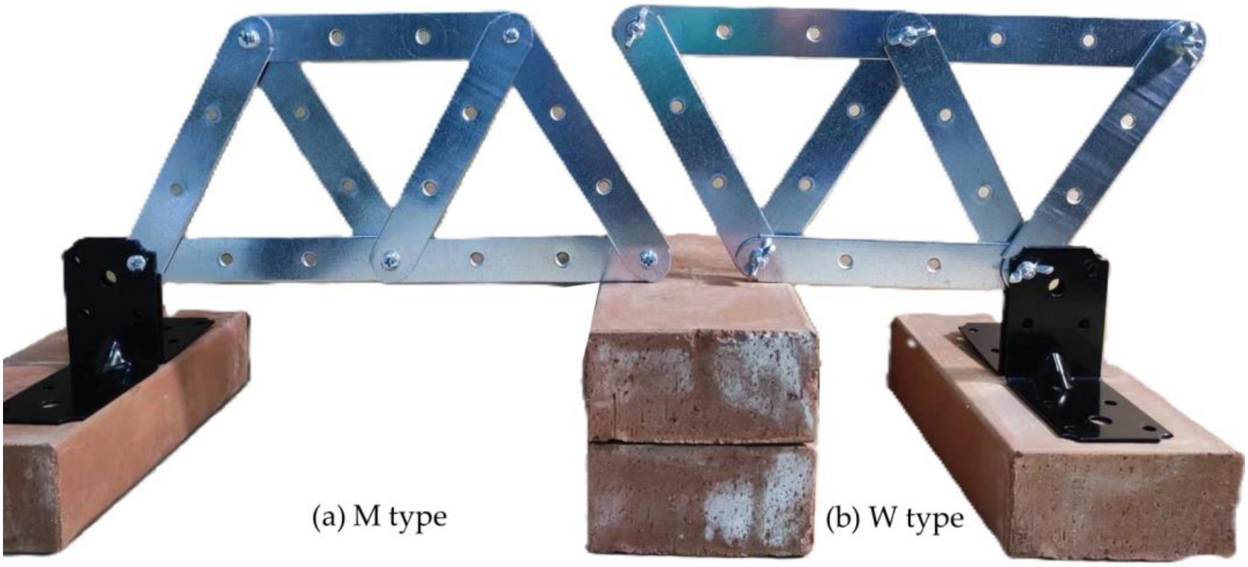


Figure 3. Configurations of the tested 2D Warren trusses: (**a**) M type and (**b**) W type.

Four distinct configurations for each truss model are selected due to the truss's inherent symmetry and the requirement to substitute a maximum of two EBs simultaneously. Twenty-four configurations are generated to systematically investigate the structural behavior of the two truss model configurations. In Figure 4, the schematic form of the twenty-four configurations can be seen with dotted circles in the positions in which elements are substituted by EBs. In order to apply a concentrated load, a rope is affixed to the specific joint as illustrated by the red vector where the arrow shows the direction. Students note a (+) or (−) inside dotted circles to indicate tension or compression, respectively.

Figures 5 and 6 depict some selected configurations of the Warren-type trusses, M and W, at un-load UL and on-load OL cases, respectively. It is apparent when an element replaced by an EB is in compression (−) or tension (+) under the specific applied load. The yellow rope represents the applied force on a joint.

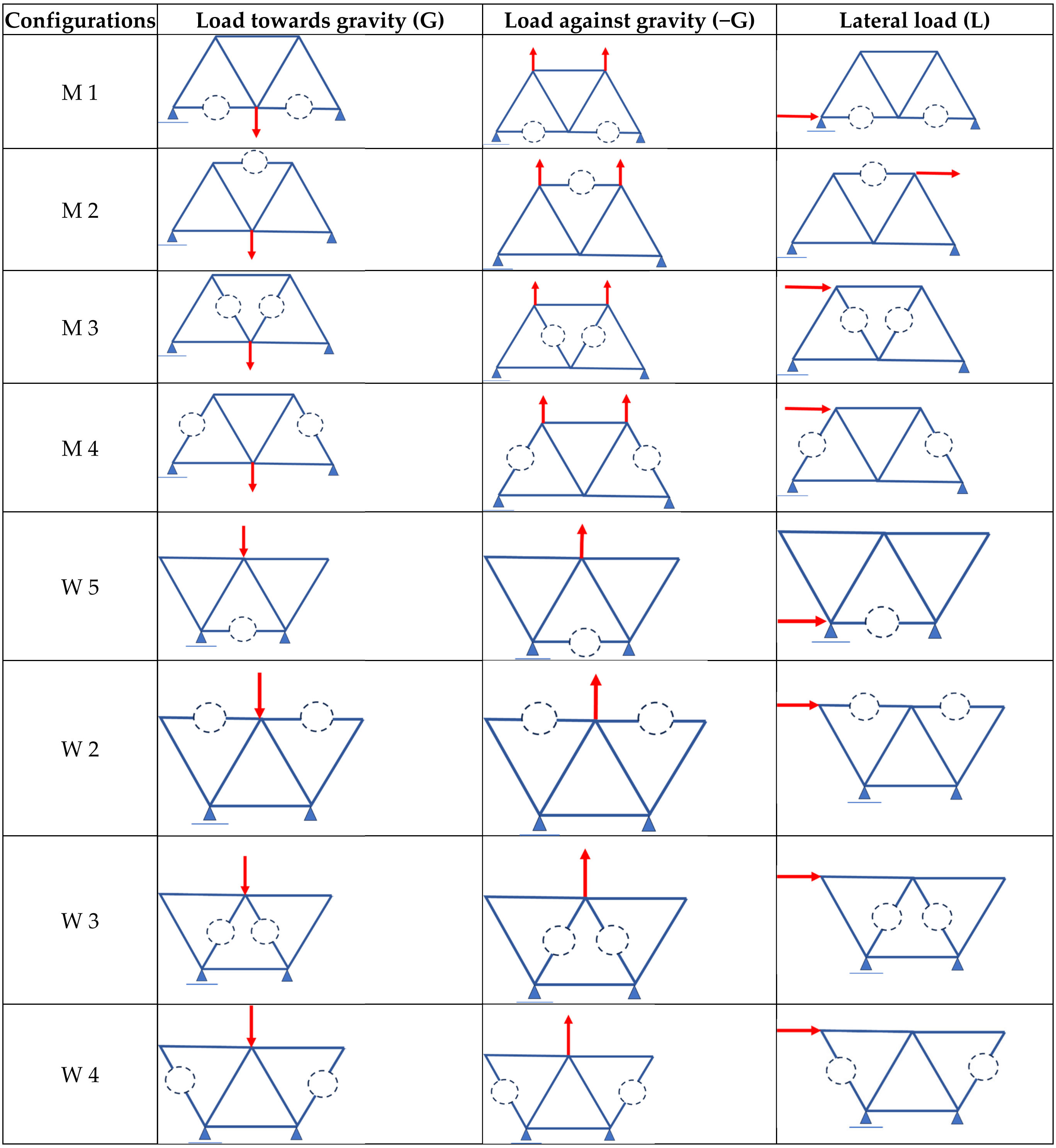


Figure 4. Schematic form of the twenty-four truss configurations.

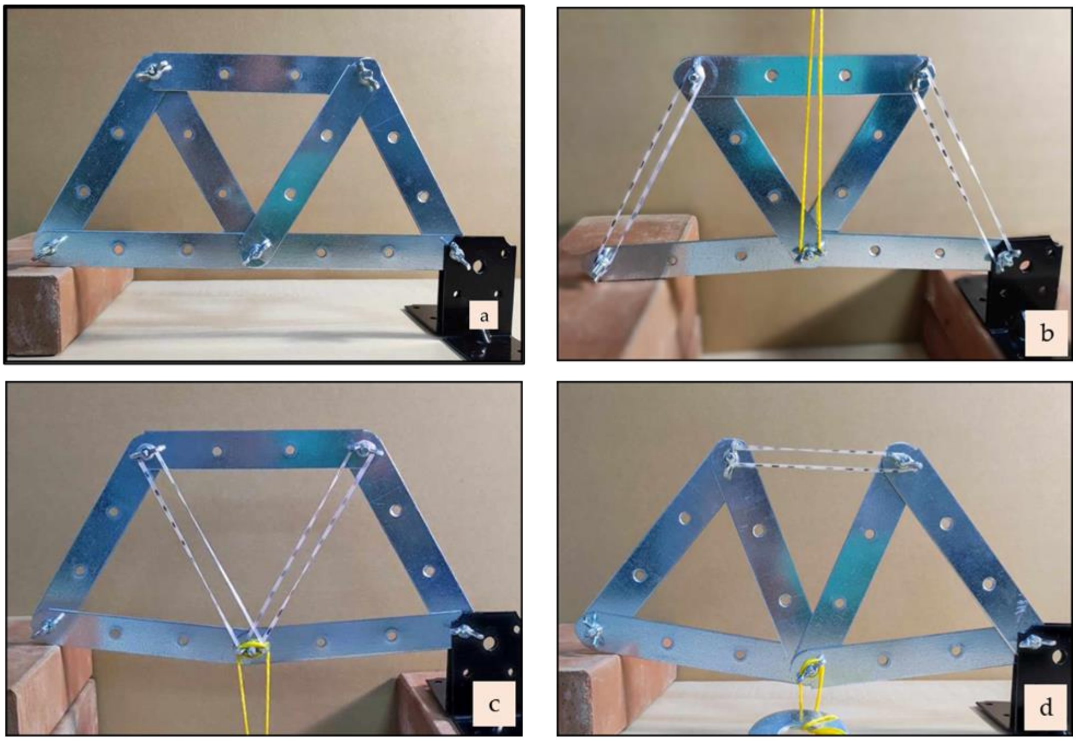


Figure 5. Selected configurations for M-type truss: (**a**) M UL-type truss, (**b**) M4(−G) OL diagonal external element replaced, (**c**) M3G OL diagonal internal elements replaced, and (**d**) M2G OL top element replaced.

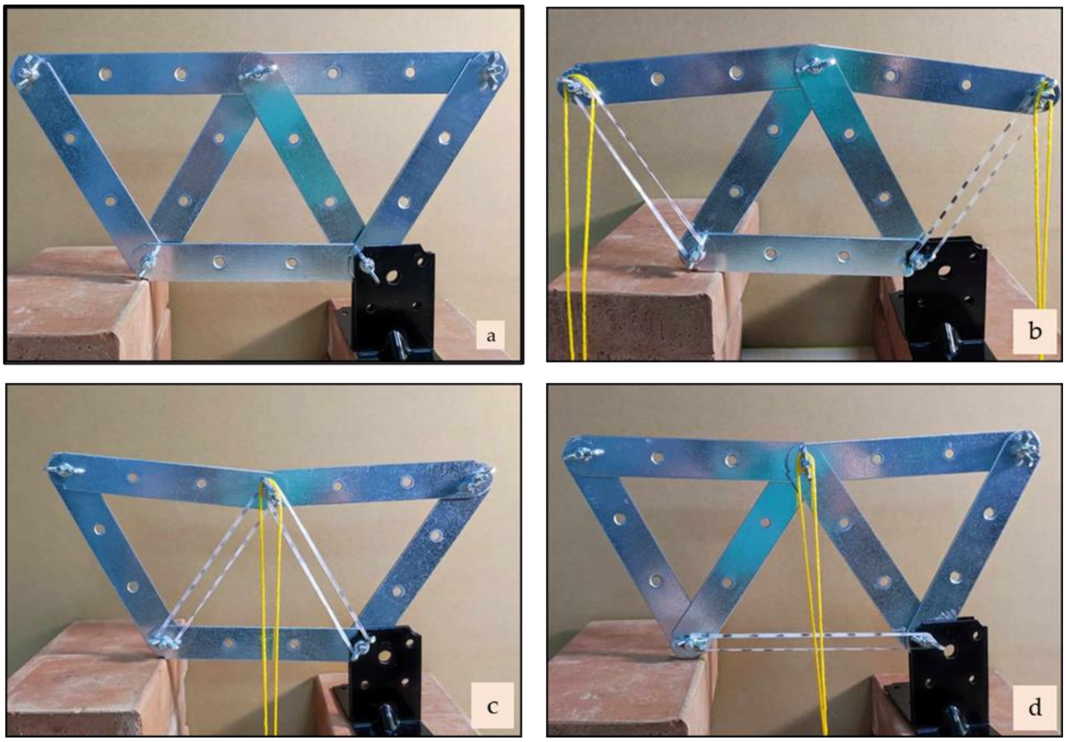


Figure 6. Selected configurations for W-type truss: (**a**) W UL-type truss, (**b**) W4G OL diagonal external elements replaced, (**c**) W3G OL diagonal internal elements replaced, and (**d**) W1G OL bottom element replaced.

2.2.2. Experiential Deformation Approach (EDA)

When a structure is subjected to various forces or loads, it may deform, which can be either elastic or permanent, depending on the material properties and the magnitude of the applied loading. Deformation in the context of structures refers to the change in dimensions or shape of a structure under the influence of external forces, loads, or environmental conditions. Understanding and predicting deformation are crucial for ensuring the structural integrity and safety of a building or any other engineering structure.

Trusses are very helpful didactic examples in visualizing internal forces and their flow. Due to their design properties, truss elements theoretically develop only axial forces, i.e., compression or tension. Understanding the deformation of a truss under various load conditions is crucial for designing stable systems. Engineers analyze the forces acting on each element to ensure they remain within acceptable limits to prevent catastrophic failure.

The framework for understanding the TDP was organized to motivate the students and illustrated in Figure 7. The workflow in this figure illustrates the steps of TDP and the learning outcomes represented by interactive cogwheels, emphasizing the collaborative and interconnected components working together to achieve comprehensive and evolving knowledge and skills. At the beginning of the procedure, students are prompted to form a triangular and a rectangular shape representing a truss. Subsequently, students are required to evaluate the configurations to determine their stability. Students are tasked with providing a solution by transforming it into a stable configuration. An element is added with or without the leader's assistance, dividing the square into two triangles, ensuring stability. In the next step, they try to replace the additional truss element with an EB. When loads are applied to the joints using the EB's EDA, it becomes visible whether the EB is under tension due to elongation or under compression due to reduced length (Table 1, example 4). In the next step, they are motivated to construct a free Warren-type truss and try to find different ways to support it, as depicted in Figure 8. The Warren truss is commonly used because of its simplicity and efficient structural performance. It is characterized by equal-sized members or a series of equilateral triangles. The students were encouraged to use pin and roller supports. After that, they replace one or two truss elements with EBs. When applying loads to the trusses, visual changes can be observed in the form of the trusses. It is easy to observe the changes, for example, when applying a load, how it affects the geometry and deformation of the truss, and how it redistributes the forces inside. Upon completing the TDP using the deformation approach, students should be able to define and comprehend the fundamental concepts related to equilibrium, such as forces, vectors, and the conditions for static equilibrium and understand the fundamental differences between compression and tension behavior in elements and structures. This work focuses on a first-semester course when Structural Engineering is initially taught. The course includes trusses, constituting 30% of the overall syllabus. At the same time, the theory of trusses encloses fundamental principles of mechanics, including Newton's laws, forces and components, vectors, moment of forces, equilibrium, free body diagrams, types of supports of a structure, and the equilibrium of a particle or a body. Consequently, it is significant that the learning outcomes related to the trusses' issues encompass over 50% of the total course curriculum.

The loads on the joints of the elements influence the deformation of an element of a truss. Understanding how loads or forces flow into the truss is essential for predicting deformation accurately. An essential part of this study involves an approach dedicated to identifying the state the elements are under (compression or tension) using the proposed EDA. The EDA is based on the assumption that replacing a truss element with an EB will show the deformation when a load is added. Upon applying a load, the observable deformation of the EB or EBs serves as an indication of the mechanical behavior of the truss element replaced by the corresponding EB.

Figures 9 and 10 depict selected configurations of the two Warren-type trusses M and W at the un-load and on-load cases, respectively, using EDA. The deformation of the EBs represents the tension or compression of the truss element replaced by an EB. In

Figure 9, three particular cases are presented. The first case represents the compressive behavior of the top truss element substituted by an EB under gravity load. The second case demonstrates complex behavior due to the lateral applied force. One diagonal internal element is under compression, while the other is under tension. In the case of the lateral load changing direction, the behavior changes, respectively. In the third case, a dual substitution of two truss elements with EBs is observed. The gravity direction of the applied force influences tension in both elements similarly, as is evident due to the deformation of the EBs. Yellow lines represent the border of the initial length of the truss element, while the dotted red lines represent the deformed state of the truss element. In every case, the deformation represents the state under which the individual element is under tension or compression and is marked as (+) or (−). In some cases, the deformation of the element can be visible at two edges. In those cases, a red dotted line can be seen at two edges. Figure 10 illustrates three specific additional cases related to the W type.

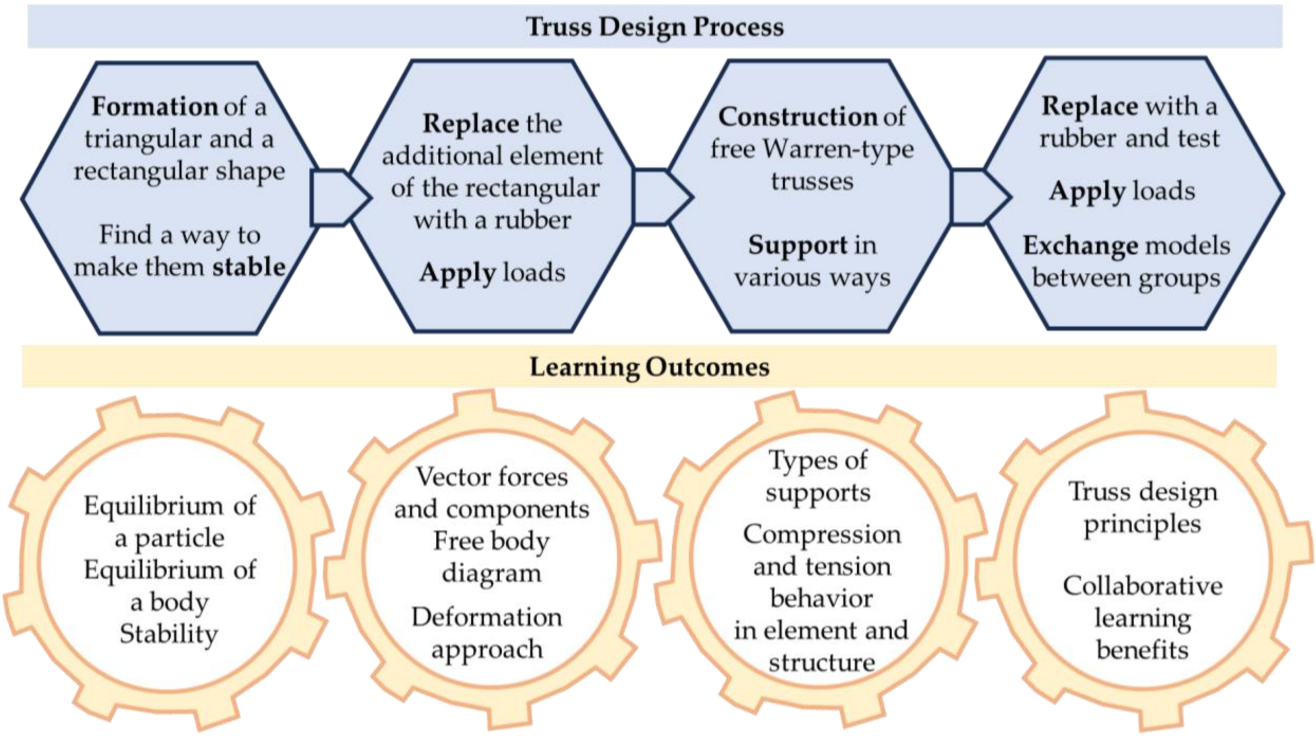


Figure 7. Basic Steps of the Truss Design Process and Learning Outcomes.

Table 1. Multiple-choice questions for the pre- and post-questionnaire and the success rates. The correct answers have been underlined.

Figure of the Question	Question	Pre-Questionnaire Success Rate	Post-Questionnaire Success Rate
	1. Which configuration appears to be stable? (A) Rectangular (B) Triangular (C) None	40.82%	89.74%

Table 1. *Cont.*

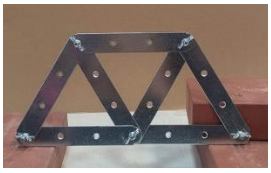
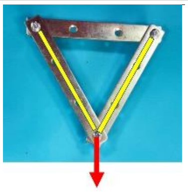
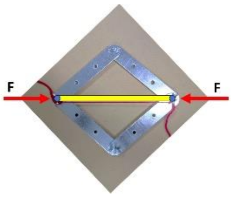
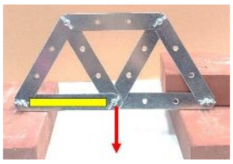
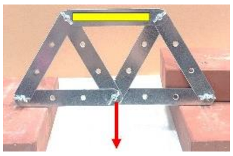
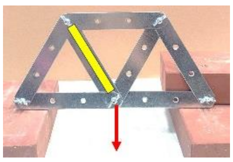
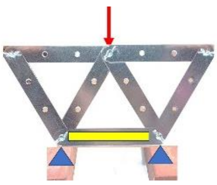
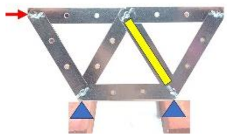
Figure of the Question	Question	Pre-Questionnaire Success Rate	Post-Questionnaire Success Rate
	2. How can you construct this truss? (A) Connecting 8 elements (B) Connecting 2 triangles with 1 element (C) Connecting 3 triangles	77.55%	89.74%
	3. What is the condition of the yellow components, under the applied force? (A) Compression (B) Tension (C) Zero	65.32%	94.87%
	4. What is the condition of the yellow components, under the applied force? (A) Compression (B) Tension (C) Zero	75.51%	94.87%
	5. What is the condition of the yellow components, under the applied force? (A) Compression (B) Tension (C) Zero	14.28%	86.74%
	6. What is the condition of the yellow components, under the applied force? (A) Compression (B) Tension (C) Zero	22.45%	92.31%
	7. What is the condition of the yellow components, under the applied force? (A) Compression (B) Tension (C) Zero	61.22	89.74
	8. What is the condition of the yellow components, under the applied force? (A) Compression (B) Tension (C) Zero	22.45%	87.18%
	9. What is the condition of the yellow components, under the applied force? (A) Compression (B) Tension (C) Zero	34.69%	84.62%

Table 1. *Cont.*

Figure of the Question	Question	Pre-Questionnaire Success Rate	Post-Questionnaire Success Rate
	10. What is the condition of the yellow components, under the applied force? (A) Compression (B) Tension (C) Zero	42.53%	74.36%

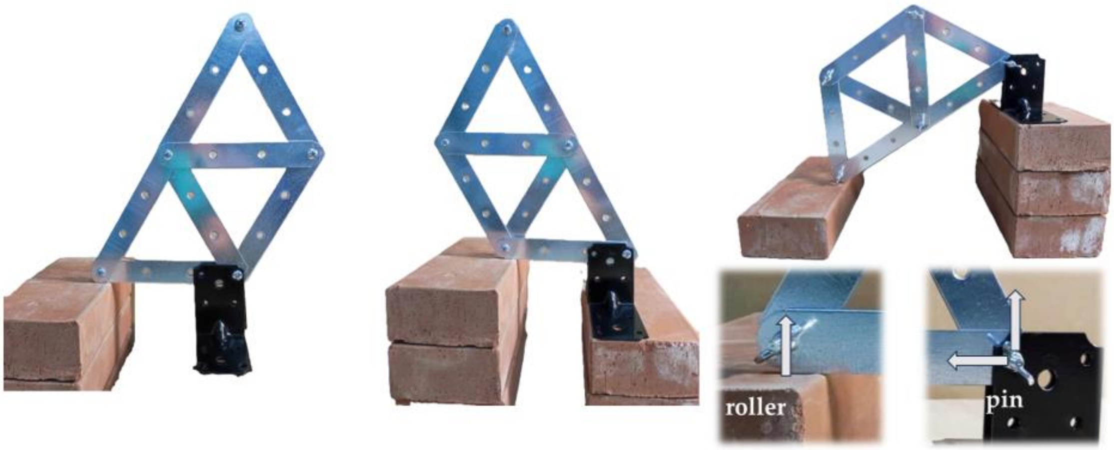


Figure 8. Warren-type truss supported in various ways, using a roller and a pin.

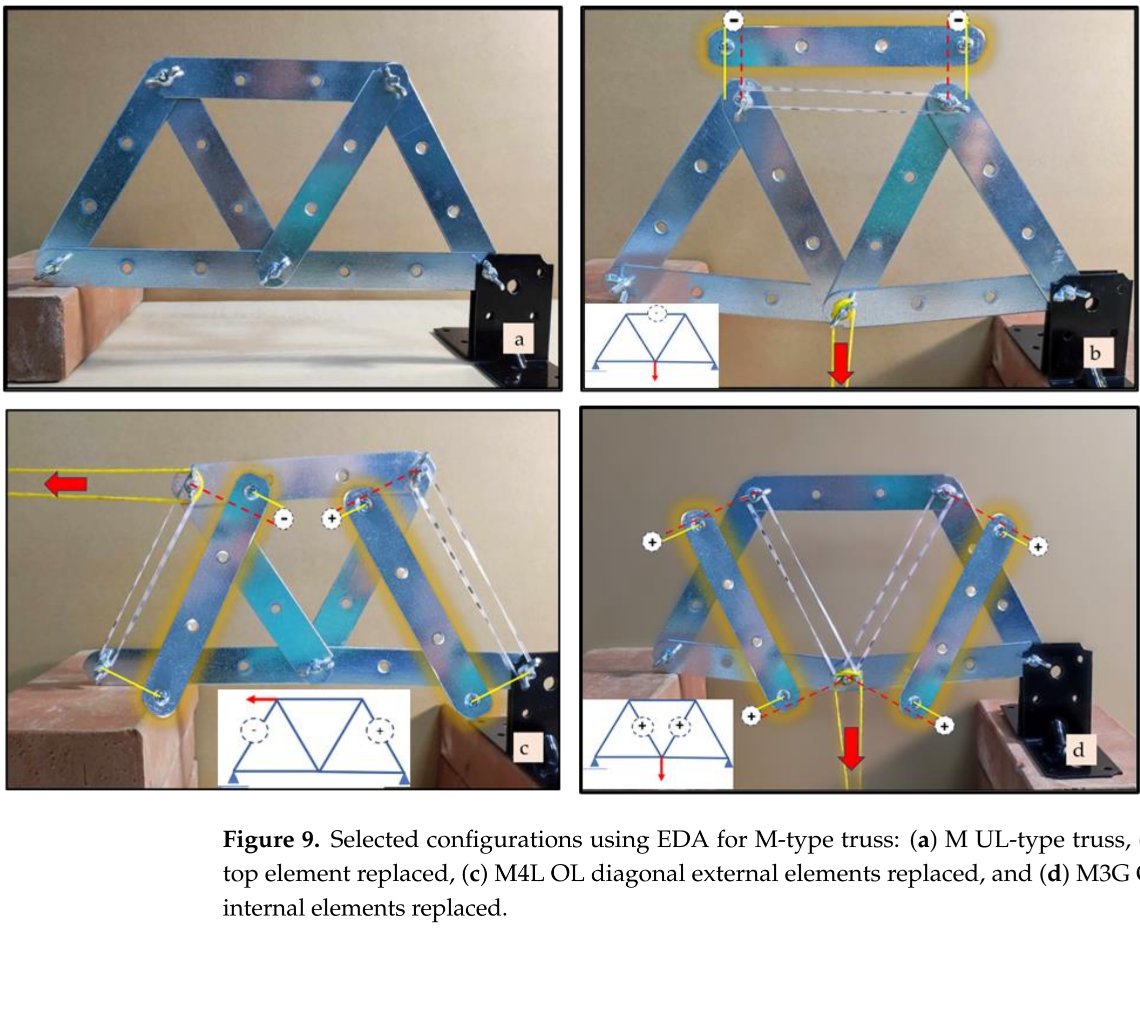


Figure 9. Selected configurations using EDA for M-type truss: (**a**) M UL-type truss, (**b**) M2G OL top element replaced, (**c**) M4L OL diagonal external elements replaced, and (**d**) M3G OL diagonal internal elements replaced.

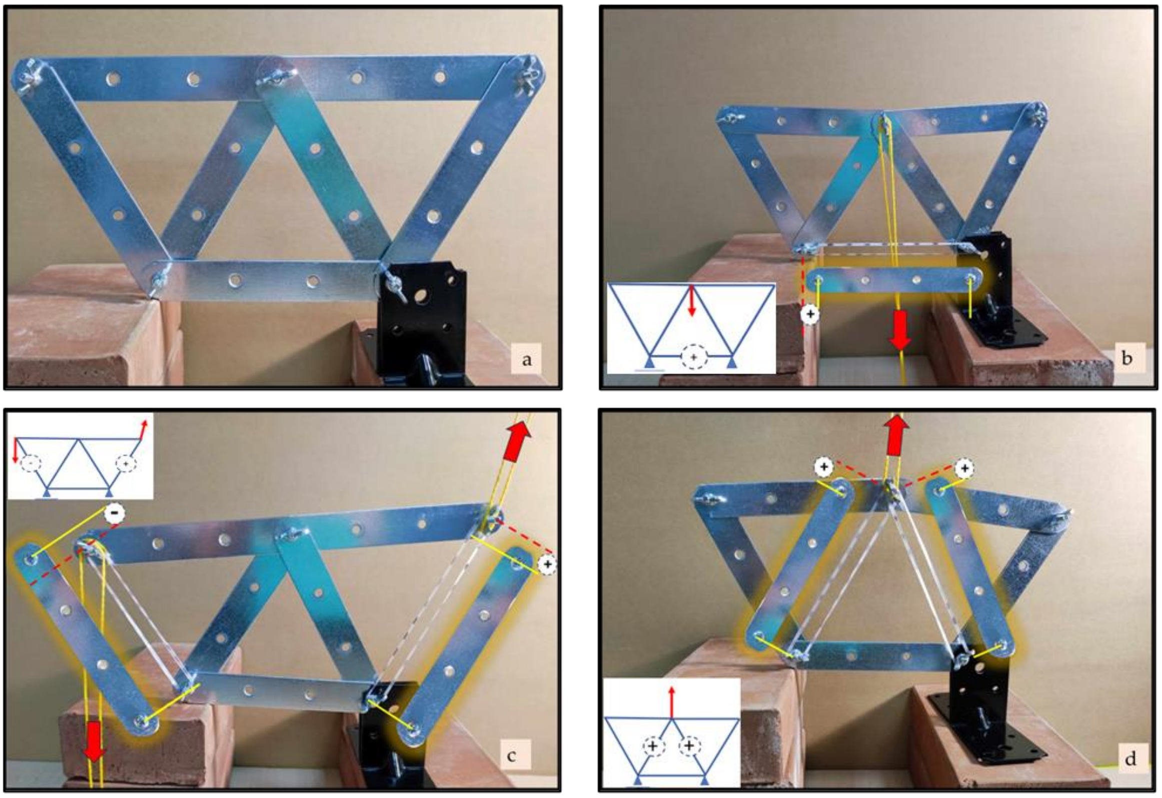


Figure 10. Selected configurations using EDA for W-type truss: (**a**) W UL-type truss, (**b**) W1G OL bottom element replaced, (**c**) W4G and (−G) OL external diagonal elements replaced, and (**d**) W3(−G) OL internal elements replaced.

2.2.3. Workshop Evaluation

In the next step of the WAP, each group member receives an assessment worksheet containing multiple-choice questions via the university's e-learning platform. Students are given 15 min to answer. Directly after answering the questionnaire, students immediately confirm the percentage of correct answers, gaining insight into their current level of knowledge. All students realize their initial level of knowledge on fundamental principles of trusses. This is identified as a pre-questionnaire.

In the next step, the TDP initiates. It lasts about one and a half hours, as described in detail in the previous subsection. At the end of the TDF, each group member receives an identical assessment worksheet to the pre-questionnaire for immediate feedback on their comprehension of the truss operation developed during the TDP. Students are given 15 min to answer, the same time as the pre-questionnaire. This is identified as a post-questionnaire. The aforementioned pre- and post-questionnaires illustrate the advancement in knowledge acquisition from WAP.

The CIQ was customized to address the diverse needs of learners across various educational levels [38]. A hard-copy anonymous CIQ consisting of 5 questions with free-text answers was given during the WAP to gather valuable insights and reflections from participants.

Finally, an additional questionnaire was provided to assess both the satisfaction and the level of comprehension estimated by the students themselves. Through this questionnaire, students provide valuable feedback on their experience during the WAP by responding to five questions concerning their interest, difficulty level, comprehension, team collaboration success, feelings and thoughts about the WAP, and metacognitive skills they developed. The well-known Likert scale [39], containing an odd number of characteristic values, was used for this. In the current study, the participants were presented with a five-point scale where 1 is "strongly disagree" and 5 is "strongly agree", and were given 15 min to answer.

3. Results

The results are divided into three sections. The extensive comparative analysis of the pre-and post-questionnaire reveals the performance of the students' learning outcomes. The second section presents the results from the feedback evaluation of the Likert-type questionnaire, which shows the students' feedback about the process. The third section shows selected statements extracted from the anonymous CIQ, which were reported and analyzed.

3.1. Results of the Pre- and Post-Questionnaire

The pre-questionnaire consisted of 10 questions, which were designed to assess the students' knowledge and perception of the activities. The questions were structured in relation to the challenges proposed in the WAP, and the students were required to choose the correct answer between three multiple-choice options. The post-test results were analyzed to determine the effectiveness of the proposed approach in helping students understand the concepts of structural engineering in trusses.

Table 1 shows the pre- and post-questionnaire comprehension questions with their multiple-choice responses and the results of the corresponding success rates. The correct answers have been underlined. The success rate in the post-questionnaire, in general, demonstrates a notable increase compared to the corresponding success rates observed before the workshop. The results of the post-questionnaire indicate that the majority of responses are highly successful, above 85%. The other ones have a discrepancy improvement of about 20–30%.

It is worth mentioning that the analytical results for each student, about the pre- and post-results, demonstrated noticeable progress without any exception. In this direction, in the case of the first question, a considerable number of students (59.18%) provided incorrect answers despite the topic of triangular stability being theoretically covered in class. However, a significantly improved percentage (89.74%) responded correctly in the post-questionnaire. This underscores the importance of students comprehending the mechanics through a haptic hands-on procedure.

Notably, in the post-questionnaire, each student demonstrated significant improvement. It is worth mentioning that the pre-questionnaire's initial performance levels exhibited a range from 2 to 9, while in the post-questionnaire, the observed range extended from 5 to 10. Students can validate the percentage of correct responses in the pre-questionnaire at the same time via the e-learning platform; thus, the pre-questionnaire may serve as a motivational factor, prompting them to concentrate during the WAP to improve their performance in the post-questionnaire.

3.2. Results of the Feedback Evaluation of the Likert-Type Questionnaire

In addition to the previous pre- and post-questionnaire, the students were also required to rate their level of agreement with each statement on a Likert scale questionnaire. The questionnaire consisted of five questions, which were designed to evaluate the WAP in terms of the impact on education, concluding satisfaction, and comprehension indicators among the students. Figures 11–15 depict the answers, where 1 means "Strongly Disagree", 2 means "Disagree", 3 means "Neutral", 4 means "Agree", and 5 means "Strongly Agree".

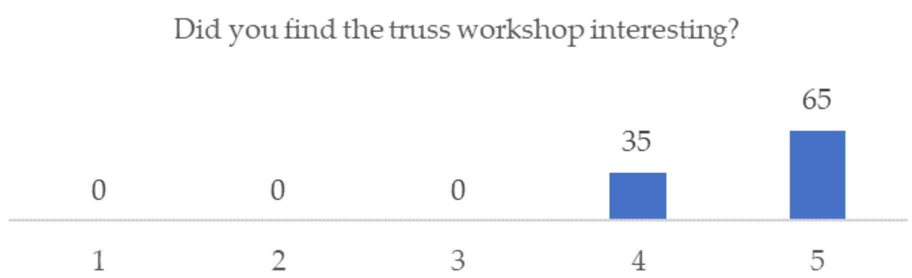


Figure 11. First question of the satisfaction and comprehension questionnaire on a Likert scale.

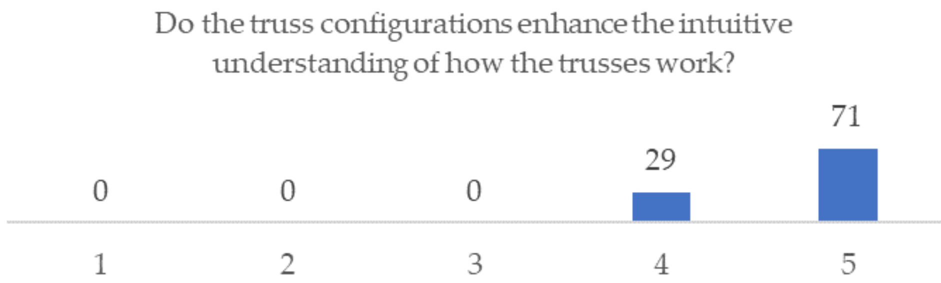


Figure 12. Second question of the satisfaction and comprehension questionnaire on a Likert scale.

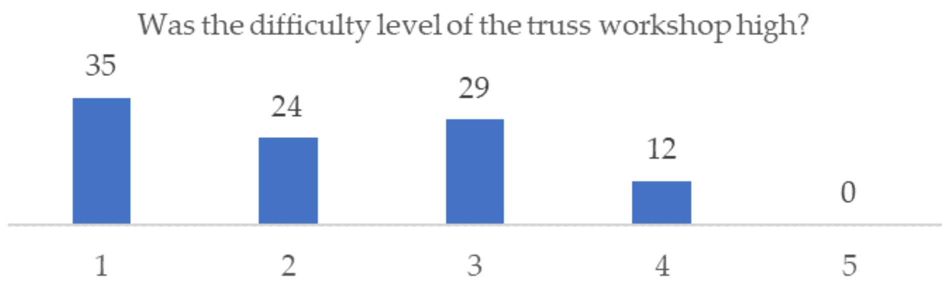


Figure 13. Third question of the satisfaction and comprehension questionnaire on a Likert scale.

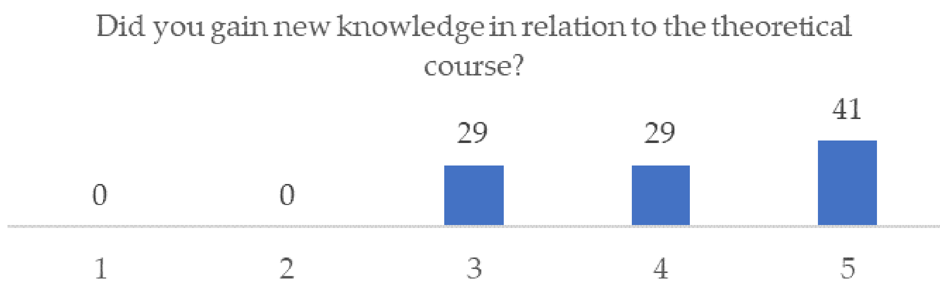


Figure 14. Fourth question of the satisfaction and comprehension questionnaire on a Likert scale.

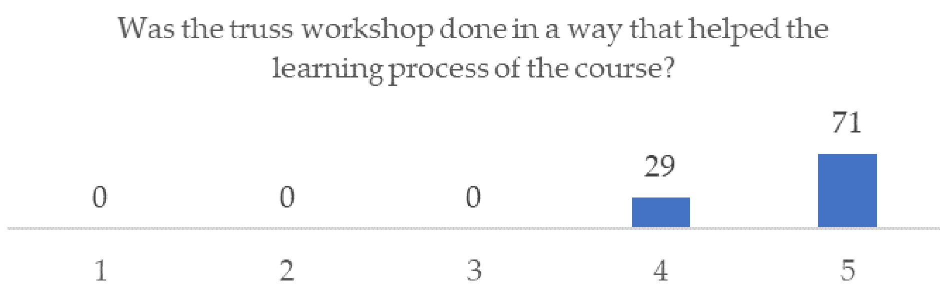


Figure 15. Fifth question of the satisfaction and comprehension questionnaire on a Likert scale.

Questions:

1. Did you find the truss workshop interesting?
2. Do the truss configurations enhance the intuitive understanding of how the trusses work?
3. Was the difficulty level of the truss workshop high?
4. Did you gain additional knowledge related to the theoretical course from the workshop?
5. Was the truss workshop done in a way that helped the course's learning process?

The workshop implemented in the first year of the architecture degree has significantly influenced the methodology of addressing subjects and knowledge. It was observed that 100% of participants agreed that they found the truss workshop interesting, of which 65% strongly agreed. During the workshop, the vast majority of students strongly agreed that the learning procedure enhanced their intuitive understanding of how the trusses work. Consequently, everybody agreed that the workshop effectively helped the intended purpose of the learning procedure.

Most of the students disagreed that the difficulty level of the workshop was high. Of them, 70% gained new knowledge relative to the theoretical course. All of them agreed that the way the workshop was carried out helped the learning process of the course.

In general, according to the questionnaire, the learning procedure during the workshop was easy, efficient, and interesting.

3.3. Results of the Critical Incident Questionnaire (CIQ)

The students were required to complete a custom-made CIQ. The Critical Incident Survey is based on a survey by Stephen Brookfield and consists of asking students to reflect on the critical moments they remember from the WAP and TDP. The questionnaire is tailored to fit the requirements of the truss workshop. There were five questions and typical comments from the students are as follows. Answers are arranged in order of their frequency, with the most common ones appearing first.

1. At what moment in WAP did you feel most engaged with what was happening and better understand the operation of the truss?

…"after a significant experiential example"…
…"during the experiential activity"…
…"when the leader explains"…
…"with the use of EBs" … "instead of elements"…
…"when I saw them happening"…
…"when I understand the operation of the EBs…during applying forces"…
…"when I grasp with my hands"…
…"when I saw them happening"…
…"when we actually used in practice what we had learned in theory"…

2. At what moment in WAP were you most distanced from what was happening and felt confused about the operation of the truss?

…"at the beginning"…"before leader explain"…
…"at a significant configuration"…
…"I didn't feel"…
…"just when I finished the first questionnaire"…

3. What action that anyone (teacher or student) took did you find most affirming or helpful?

…"the replacement of elements with EBs"…
…"the leaders explain the workshop"…
…"all were useful" … "we understand better the operation of the trusses"…
…"the conversation during the workshop"…
…"my participation at the workshop"…
…"when the leader demonstrates the operation of the mini truss"…"hand-on demonstration"…
…"none"…
…"movements of the rope"…"apply forces on the truss"…

4. What action that anyone took during the WAP that puzzled or confused you?

…"none"…
…"when we tightened the screws enough"…"we had to apply a huge amount of load to see deformation"…
…"the brick"…"when the truss was unstable on the brick"…
…"I don't remember"…
…"at a significant configuration"…
…"guess without explanation"…
…"the workshop only helps me, but I feel confused during the theoretical course"…
…"none, I feel confused about the course but not so much anymore"…

5. What aspect of the WAP surprised you the most?

…“I realized compression tension and”…
…“that the leaders could explain very clearly”…“and understable”…
…“I started to understand physics”….
…“how truss works”…
…“how easy it was”…
…“the effect of the loads on trusses”…
…“It was relatively easy”…
…“create a truss on a small scale”…
…“the way the elements moving”…
…“now I can understand better the exercises”…
…“at the end from 4/10, I got 10/10”…
…“the practice of theory”…
…“It was very experiential and understandable”…
…“interesting workshop”…
…“sometimes it was compression or tension, and I wouldn’t expect”…

The most significant feedback received from all of the above answers was the role of the leader. It was critical in all steps of the WAP. Students feel most engaged with what happened and better understand the truss operation after a significant experiential example and generally during the experimental activity.

It is very important that many students felt confused about the operation of the truss at the beginning and before giving explanations. Many of them did not feel confused at all, and some after having finished the first questionnaire. This is somewhat expected because they were invited to answer the questionnaire without having any experience first, except for the theoretical course the day before, which was captured from the pre-questionnaire.

The replacement of the elements with the EBs was found to be the most helpful action. As they stated, they understood the operation of the trusses better after the WAP. It was very helpful to interact with all of the participants while having conversations and exchanging aspects. Most of the students replied “*that no action was taken during the workshop, which is puzzling or confusing me*”, although there are two replies worth discussing. The first was about “*the screws fastening very tight, and they couldn’t use the trusses properly when applying loads*”. During the WAP, most of the students realized that it is not the tightness of the joints that makes the truss stable but the triangular configuration. The second was about “*when the truss was unstable on the brick*”. The truss teaching model represents a simple 2D physical model, designed to be affordable, utilizing readily available materials for its construction. Due to the above issues, it was necessary to consider and discuss certain assumptions during the WAP. Despite the fact that the majority of students comprehended the assumptions, both observations were considered for the optimization of the next workshop.

Their greatest surprise occurred when they recognized how a truss works in practice and the development of compression, tension, and no tension in the elements, which is visible due to using EDA. Many of them refer to how easy it was and how experiential and understandable it was.

Some replays show that they can now better understand the physics and the exercises. This is an important outcome that may improve their performance in the course’s final exam.

4. Discussion—Advantages, Limitations, and Future Work

The application and effectiveness of a practical, experiential approach in teaching structural engineering within the architectural environment are discussed. This approach contributes to the pedagogical strategies, learning outcomes, and overall impact of employing a hands-on methodology in the educational engineering process.

The workshops performed during the first year of the architecture degree have significantly influenced the methodology used to address subjects and knowledge. Departing from traditional teaching methods, the workshops encourage learning through experimentation and practical application instead of memorization, and they have been a real achievement in motivating student participation in their learning [15,40], as Table 1 reveals. The teaching approach scales affordably to larger classes with increased material needs due to low material costs. It demonstrates adaptability to various educational environments, adapting to different levels of student populations, backgrounds, and abilities. It contains flexibility to distinct educational levels in school, undergraduate, polytechnic institutions, and STEAM (science, technology, engineering, arts, and mathematics) programs [15].

An alternative evaluation approach for assessing the effectiveness of the proposed experimental procedure in enhancing the learning process could involve comparing the results of two student groups regarding their comprehension of truss behavior: Group A, which participated in the proposed experiential procedure, and Group B, which engaged in a theoretical course covering the same content but presented through theoretical instruction rather than hands-on experience.

Active learning based on mutual and collaborative learning promotes a positive attitude towards learning, as disclosed by the CIQs.

Each group participates in a model exchange procedure where they share their respective designs with other groups. During this exchange (see Figure 2), each group is tasked with completing all the marked circles in the models provided by the other groups. This collaborative activity promotes knowledge sharing, cross-evaluation, and a collective effort to enhance the overall quality of each model. By engaging in this reciprocal exchange and addressing the marked circles in other models, groups can benefit from diverse perspectives, insights, and expertise, contributing to a more comprehensive and refined final result.

A limitation is imposed when replacing more than two EBs due to the model's unstable condition. Despite that limitation, students can concentrate more thoroughly on each case. Simultaneously, they can collaborate directly with other groups who replace different elements. Cooperation among the groups is supported to achieve a comprehensive supervisory overview.

Despite its limitations, this portable truss didactic tool demonstrates flexibility, allowing all students to use it easily during the WAP. In contrast, other methods that demand bulky equipment limit student participation in the hands-on experience. It is possible in future work to replace the EBs with springs, or if the elements are too long, replace them with a force meter to directly measure the amount of compression or tension developed.

The learning outcomes of the process are many and are fulfilled by collaborative learning benefits. Among these benefits are enhanced critical thinking skills, improved communication abilities, and the development of effective teamwork and interpersonal skills. Collaborative learning also facilitates a deeper understanding of diverse perspectives and encourages active engagement with course material.

5. Conclusions and Further Developments

This study introduces an experiential, low-cost, and sustainable didactic tool, to enhance the teaching procedure of structural engineering in Architectural Studies. The proposed model can be easily demonstrated during a course using accessible materials. A WAP was developed to assess the TDP and its effectiveness in students' comprehension of trusses. The students actively collaborate in experiential procedures to deepen their understanding of structural engineering topics. The WAP results indicate that students profoundly comprehend the behavior of truss elements under various loads. The suggested EDA involves observing visual changes in trusses and understanding the impact of loads on geometry and deformation. Deformation represents the state of the truss elements (under compression or under tension).

The combination of experiential and mutual pedagogical methodologies enhances the overall learning experience by applying practical skills through real-world applications and promoting the exchange of knowledge and insights among near-equivalents.

In general, the success rate in the post-questionnaire demonstrates a notable increase compared to the corresponding success rates of the pre-questionnaire. Specifically, an average of 80.0% responded correctly in the post-questionnaire, a significant improvement compared to 45.7% in the pre-questionnaire.

Notably, the anonymous CIQ indicates that students found the learning process easy, effective, and enjoyable. Their engagement was exceptionally high during experiential activities and in the practical application of theoretical concepts. The workshop improved students' understanding of structural concepts and positively influenced their learning experience and engagement with the subject, as depicted in the questionnaire. The EDSA suggests an effective didactic tool for teaching structural engineering in architecture, improving students' learning outcomes in this field, and providing a deeper connection between structural and architectural design parameters.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and in line with university ethical guidelines on human research laid out at https://duth.gr/en/Services/Commitees/Research-Ethics-Committee-REC. The anonymity of all participants is rigorously maintained throughout the research process. Identifiable information is treated with the utmost care, and only authorized personnel have access to such data. The collected data will be stored securely, and confidentiality measures will be strictly observed. The author is committed to upholding the ethical principles and legal requirements governing this research project. Any deviations from the approved protocols will be promptly reported to the Institutional Review Board for further review and guidance. This declaration is made in good faith, with full acknowledgment of the responsibilities associated with conducting research in a manner that ensures both the scientific validity of the study and the protection of the rights and privacy of all participants involved.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data are not publicly available due to ethical restrictions.

Conflicts of Interest: The author declares no conflicts of interest.

Nomenclature

WAP	Workshop Activity Process
TDP	Truss Design Process
EDA	Experiential Deformation Approach
CIQ	Critical Incident Questionnaire
EB	Elastic Band
UL	Un-Load
OL	On-Load

References

1. Fűz, N. Out-of-School Learning in Hungarian Primary Education: Practice and Barriers. *J. Exp. Educ.* **2018**, *41*, 277–294. [CrossRef]
2. Radloff, J.; Capobianco, B.M. Investigating Elementary Teachers' Tensions and Mitigating Strategies Related to Integrating Engineering Design-Based Science Instruction. *Res. Sci. Educ.* **2021**, *51*, 213–232. [CrossRef]
3. Daniel, S. A Phenomenographic Outcome Space for Ways of Experiencing Lecturing. *High. Educ. Res. Dev.* **2022**, *41*, 681–698. [CrossRef]
4. Kolb, A.Y.; Kolb, D.A. Experiential Learning Theory as a Guide for Experiential Educators in Higher Education. *Exp. Learn. Teach. High. Educ.* **2022**, *1*, 38. [CrossRef]
5. Miettinen, R. The Concept of Experiential Learning and John Dewey's Theory of Reflective Thought and Action. *Int. J. Lifelong Educ.* **2000**, *19*, 54–72. [CrossRef]
6. Seaman, J.; Brown, M.; Quay, J. The Evolution of Experiential Learning Theory: Tracing Lines of Research in the JEE. *J. Exp. Educ.* **2017**, *40*, NP1–NP21. [CrossRef]
7. Charleson, A. *Structure as Architecture: A Source Book for Architects and Structural Engineers*, 2nd ed.; Routledge: London, UK, 2014. [CrossRef]
8. Ji, T.; Bell, A.J.; Ellis, B.R. *Understanding and Using Structural Concepts*; CRC Press: Boca Raton, FL, USA, 2015.

9. Justo, E.; Delgado, A.; Llorente-Cejudo, C.; Aguilar, R.; Cabero-Almenara, J. The Effectiveness of Physical and Virtual Manipulatives on Learning and Motivation in Structural Engineering. *J. Eng. Educ.* **2022**, *111*, 813–851. [CrossRef]
10. Aikaterini, T.; Gioti, L. Evaluating University Pedagogy: Teacher and Student Perspectives. *Eur. J. Educ. Stud.* **2022**, *9*, 200–217. [CrossRef]
11. Vrontissi, M.; Castellón, J.J.; Acunto, P.D. "Constructing Equilibrium": A Methodological Approach to Teach Structural Design in Architecture. In Proceedings of the IV International Conference on Structural Engineering Education Structural Engineering Education without Borders, Madrid, Spain, 20–22 June 2018. Available online: https://www.researchgate.net/publication/329267609 (accessed on 29 November 2018).
12. Kowalski, S.; Samól, P.; Szczepański, J. Physical Models in the Education of Architectural History. *World Trans. Eng. Technol. Educ.* **2022**, *20*, 251–257.
13. Castellón González, J.J. Structural Models in Architectural Education: Experimental Explorations between the Physical and the Digital Realms. In *Structures and Architecture A Viable Urban Perspective?* CRC Press: Boca Raton, FL, USA, 2022; pp. 202–209. [CrossRef]
14. Vrontissi, M.; Castellón González, J.J.; D'acunto, P.; Monzó, L.E.; Schwartz, J. Constructing Structural Concepts by Means of Physical Models. In Proceedings of the IASS Annual Symposia, IASS 2018 Boston Symposium: Approaches for Conceptual Structural Design, Boston, MA, USA, 16–20 July 2018. [CrossRef]
15. Montés, N.; Hilario, L.; Rivera, J.; López, Á.; Ferrer, T.; Verdejo, P.; Juan, I.; Ábalos, A. The Equilibrium Challenge, a New Way to Teach Engineering Mechanics in Architecture Degrees. *Educ. Sci.* **2023**, *13*, 398. [CrossRef]
16. Zhou, X.; Chen, L.H.; Chen, C.L. Collaborative Learning by Teaching: A Pedagogy between Learner-Centered and Learner-Driven. *Sustainability* **2019**, *11*, 1174. [CrossRef]
17. Herranen, J.; Vesterinen, V.M.; Aksela, M. From Learner-Centered to Learner-Driven Sustainability Education. *Sustainability* **2018**, *10*, 2190. [CrossRef]
18. Guerra, A. Integration of Sustainability in Engineering Education: Why Is PBL an Answer? *Int. J. Sustain. High. Educ.* **2017**, *18*, 436–454. [CrossRef]
19. Dominguez, A.; De la Garza, J.; Quezada-Espinoza, M.; Zavala, G. Integration of Physics and Mathematics in STEM Education: Use of Modeling. *Educ. Sci.* **2023**, *14*, 20. [CrossRef]
20. Mulder, K.F.; Ferrer, D.; Coral, J.S.; Kordas, O.; Nikiforovich, E.; Pereverza, K. Motivating Students and Lecturers for Education in Sustainable Development. *Int. J. Sustain. High. Educ.* **2015**, *16*, 385–401. [CrossRef]
21. Sadowski, K.; Jankowski, S. Learning Statics by Visualizing Forces on the Example of a Physical Model of a Truss. *Buildings* **2021**, *11*, 395. [CrossRef]
22. Bigoni, D.; Corso, F.D.; Misseroni, D.; Tommasini, M. A Teaching Model for Truss Structures. *Eur. J. Phys.* **2012**, *33*, 1179–1186. [CrossRef]
23. Edward, A.; Waclaw, Z. *Form and Forces: Designing Efficient, Expressive Structures*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2012.
24. Richardson, J.; Steif, P.; Morgan, J.; Dantzler, J. Development of a Concept Inventory for Strength of Materials. In Proceedings of the 33rd Annual Frontiers in Education, FIE, Westminster, CO, USA, 5–8 November 2003; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2003; Volume 1, pp. T3D29–T3D33. [CrossRef]
25. Richardson, J.; Morgan, J.; Evans, D. Development of an Engineering Strength of Material Conceptinventory Assessment Instrument. In Proceedings of the 31st Annual Frontiers in Education Conference. Impact on Engineering and Science Education, Reno, NV, USA, 10–13 October 2001; Volume 2, pp. F2A–F24. [CrossRef]
26. Montés, N.; Aloy, P.; Ferrer, T.; Romero, P.D.; Barquero, S.; Carbonell, A.M. EXPLORIA, STEAM Education at University Level as a New Way to Teach Engineering Mechanics in an Integrated Learning Process. *Appl. Sci.* **2022**, *12*, 5105. [CrossRef]
27. Kedraka, K.; Rotidi, G. University Pedagogy: A New Culture Is Emerging in Greek Higher Education. *Int. J. High. Educ.* **2017**, *6*, 147. [CrossRef]
28. Lur, K.T.; Tan, D.Y.; Cheah, C.W.; Lee, C.H. Connecting Design and Engineering Physics with Reverse Engineering. In Proceedings of the IEEE Global Engineering Education Conference, EDUCON, Tunis, Tunisia, 28–31 March 2022; IEEE Computer Society: Washington, DC, USA, 2022; Volume 2022, pp. 571–578. [CrossRef]
29. Tan, D.Y.; Cheah, C.W.; Lee, C.H. Reverse Engineering Pedagogy as an Educational Tool to Promote Symbiosis between Design and Physics. In Proceedings of the TALE 2021—IEEE International Conference on Engineering, Technology and Education, Wuhan, China, 5–8 December 2021; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2021; pp. 780–784. [CrossRef]
30. Brookfield, S. Critically Reflective Practice. *J. Contin. Educ. Health Prof.* **1998**, *18*, 197–205. [CrossRef]
31. María, M.; Campillay, D. Use of the Critical Incident Survey as a Reflection on the Teaching-Learning Process. *Int. J. Mech. Eng.* **2022**, *7*, 669–674.
32. Gilstrap, D.L.; Dupree, J. Assessing Learning, Critical Reflection, and Quality Educational Outcomes: The Critical Incident Questionnaire. *Coll. Res. Libr.* **2008**, *69*, 407–426. [CrossRef]
33. Vaughn, S.M.; Luther, V.L.; Baiden, F. *Practice and Evidence of Scholarship of Teaching and Learning in Higher Education*; Pestlhe, Centre for Teaching and Learning University of Oxford: Oxford, UK, 2020; Volume 14, No. 1; pp. 37–58.

34. Voutetaki, M.E.; Thomoglou, A.K. Experiential Learning in Architectural Engineering School through the Hands-on Workshop: Practically without Calculations. In Proceedings of the International Conference on Electronics, Engineering Physics and Earth Science (EEPES 2023), Kavala, Greece, 21–23 June 2023.
35. Blandin, B.; Lietaer, B. Mutual Learning: A Systemic Increase in Learning Efficiency to Prepare for the Challenges of the Twenty-First Century. *AI Soc.* **2013**, *28*, 329–338. [CrossRef]
36. Gamage, K.A.A.; Ekanayake, S.Y.; Dehideniya, S.C.P. Embedding Sustainability in Learning and Teaching: Lessons Learned and Moving Forward-Approaches in STEM Higher Education Programmes. *Educ. Sci.* **2022**, *12*, 225. [CrossRef]
37. Fiorella, L.; Mayer, R.E. Role of Expectations and Explanations in Learning by Teaching. *Contemp. Educ. Psychol.* **2014**, *39*, 75–85. [CrossRef]
38. Keefer, J.M. *The Critical Incident Questionnaire (CIQ): From Research to the Critical Incident Questionnaire (CIQ): From Research to Practice and Back again Practice and Back again*; New Prairie Press: Manhattan, KS, USA, 2009. Available online: https://newprairiepress.org/aerc (accessed on 18 December 2015).
39. Dauzón-Ledesma, L.; Izquierdo, J. Language Learning Investment in Higher Education: Validation and Implementation of a Likert-Scale Questionnaire in the Context of Compulsory EFL Learning. *Educ. Sci.* **2023**, *13*, 370. [CrossRef]
40. Salemi, M.K. An Illustrated Case for Active Learning. *S. Econ. J.* **2002**, *68*, 721–731. [CrossRef]