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Teaching Design to Civil and Architectural Engineering Students—a Diagram-Based Approach*

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In contrast to the extensive theoretical field that investigates the concept of the architectural diagram, certain aspects of the diagram's practical applications have been overlooked. Therefore, the research presented examines the potential of using diagrams as a specific form of graphic representation for teaching design to civil and architectural engineering students, through an empirical experiment conducted in a studio course environment. The research is based on the mixed methods approach, where the efficiency of the diagrams is tested through quantitative and qualitative analyses of sketchbooks, questionnaires and course observations. Through the application of diagrams, an emphasis is placed on the design process versus the final product of designing, thus deepening the understanding of the complexity of the architectural discipline. The results obtained show that diagrams support and improve the design process for novices, thus confirming their significant role in education, but also evidencing their importance as a means for developing complex design skills. Furthermore, our results demonstrate that the reorganization of the course positively influences learning and design processes, as well as their outcomes, whereas new modes of representation have a significant contribution.

Keywords: architectural engineering; civil engineering; engineering education; design process; design studio; diagramming techniques

1. Introduction

In recent years, there has been an increasing interest in studying student learning processes. In their seminal article, Dym et al. state that "design is both a mechanism for learning and in itself a learning process" [1, p. 112]. Therefore, the various operationalizations of the design procedures in the educational context enable researchers to examine the process of acquiring design skills. In this regard, the present study set out to investigate the usefulness of diagrams in learning the basics of architectural designing. In architecture, the diagram is a fundamental device that is almost impossible to describe without falling into the banal and obvious; to put it in simple terms, a diagram is the architecture of an idea or entity [2, p. 18]. Investigating previous research on diagrams in disciplines ranging from cognitive science and psychology to computer science and artificial intelligence, Purchase [3] noted that empirical studies of diagram comprehension are most common. Furthermore, she reported that a wide range of diagram types has been examined empirically, with the main goal of researching the participants' understanding and use of diagrams. Although extensive research has been carried out on diagrams, there is no single study that seeks, through many different aspects, to consider the possibility of acquiring the skills of architectural design through the use of diagrams. In this respect, the present research aims at expanding knowledge in the area which has not been sufficiently investigated. This study differs from the previous ones by trying to examine the application of the diagram in all phases of the design process.

The particularity of this research is reflected in the fact that its participants are students of civil and architectural engineering who, within the framework of the course described below, should learn the basics of architectural design. Through the utilization of the diagrammatic methods and drawings, this research strives to examine the potential of such an approach for supporting and enhancing the novices' design process. Considering the overview of the previous studies, the research data are drawn from three main sources: the students' sketchbooks, questionnaires and course observations. This study provides significant insight into the nature of the diagram, especially from the aspect of its practical application. Furthermore, the research establishes a context for process-oriented engineering education through the examination of the generation and definition of ideas using graphic means. Finally, the research contribution lies in the intention to understand the novices' designing process better.

The remainder of this paper is structured as follows. The first section lays out the theoretical background of the research and introduces the research question, objectives and hypotheses. The second section describes the conducted study, the participants, the methods used, as well as how the data were analysed. The subsequent section presents the findings of qualitative and quantitative analyses carried out to meet the research objectives,

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while section four discusses and interprets the key findings and relates them to the existing field of knowledge. Finally, we present our closing remarks and establish possible directions for future research.

2. Theoretical framework

2.1 Graphic representations in design and engineering

Graphic representations have always played a pivotal role within design and engineering disciplines [4], as sketches, drawings, images and models are the basic tools of designers and engineers to clarify the ideas and concepts they are considering. The design drawing is "an iterative and interactive act involving recording ideas, recognizing functions and meaning in the drawings, and finding new forms and adapting them into the design" [5, p. 135]. The sketching process can be defined as a way of visualizing a mental idea that makes the invisible visible [6]. According to Senturer and Istek [7], without representational media, it is impossible to carry out any design activity.

Designers think about design processes when they sketch the objects they are designing [1]. In the literature, there is a clear link between design thinking and graphic representations. The term 'design thinking' [8] refers to the study of designer practices [9] and is defined as an analytical and creative process that engages an individual in the possibilities of experimenting, creating models and prototypes, collecting feedback and redesign [10]. The concept of design thinking is not solely related to design, in many engineering disciplines this notion has immense importance. Dym et al. [1, p. 104] note that design thinking reflects the complex processes of inquiry and learning performed by designers. According to Cicalò [11], graphic techniques and methods should not be viewed solely as functional tools to produce images that represent reality, but rather as tools for empowering thinking. Peponis et al. [12] state that design thinking is documented through different types of drawings, as drawings are necessary to explain design decisions, focus on significant design features or evaluate designs relative to a set of criteria. The same authors argue that, if the design is the outcome of thinking, the drawings implicitly document the way of thinking [12].

Designing often starts with a diagram that gradually turns into a more complex graphic display by adding details. These diagrams facilitate the consideration, dialogue and self-criticism of designers and therefore serve the purpose of presenting and testing the designer's intention. In other words, the diagrams serve as the primary means of thinking and solving problems [5, 13]. Burke identifies a diagram as a key form of visual thinking in architecture, as it performs work considered central to design research and the production of innovation [14, p. 347]. The progressive use of diagrams in architecture is synchronic to the development of the theory of communication and to the first meaningful computational developments in the mid-twentieth century [15]. Alexander's diagrammatic problem decomposition in the form of patterns [16], Wittkower's nine-square-grid diagrams of Palladian villas [17] and Rowe's diagrams of Le Corbusier's villas [18] represent the origins of a diagrammatic approach to the study of architecture. The diagrams have become part of contemporary architectural discourse and practice, particularly through the work of paradigmatic architects such as Bernard Tschumi, Peter Eisenman, Rem Koolhaas, SANAA, and Ben van Berkel among others [19].

In the field of graphic representations, various definitions of the diagram can be found [3, 5, 20–24]. Hasan Eilouti provides the most comprehensive description in which: ". . . a diagram is understood as a form of data visualization that abstractly and graphically uses geometric elements (e.g., lines, nodes, circles, rectangles and arrows) and textual annotations to represent structure, hierarchy, enclosure and/or sequence of design products, as well as their related functions, processes and activities" [25, p. 84]. Diagrams can be distinguished from other types of graphical representations by their essentially abstract, propositional nature, and their embodiment of graphic defaults [26]. The difference between diagrams and design drawings cannot be clearly defined. However, we can point to several guidelines that can help us differentiate these concepts. A diagram usually uses geometric elements to abstractly represent natural and artificial phenomena, building components, human behaviour, and territorial boundaries of space [20, 21]. A diagram also represents abstractly without giving detailed descriptions of scale or realistic pictorial representations. On the contrary, a design drawing does not use symbols or more complex forms of abstraction and is generally about spatial form [20]. As stated by Vidler [27], a diagram is not a sketch—therefore it evokes nothing; it is not a plan—therefore it cannot be built. It is a kind of delineation, a neutral zone, where certain relations are mapped precisely but without qualitative information. The advantage of diagrams lies in their ability to simplify the consideration of formal and conceptual qualities by minimizing the elements presented. Their essence is analysis. Consequently, any drawing can be considered diagrammatic in the sense that it involves a process of abstraction and a corresponding reduction of information [22].

The diagrams show the topology, shape, size, and position, which is why they differ from diagrams in other domains that normally contain one or two of these characteristics in order to convey the meaning [5]. Architects use diagrams to clarify both specific projects and general design principles [28]. Châtelet [29] claims that diagrams are concrete abstractions since they take visualised form while abstractly representing chosen parts of the world. Due to this abstract feature of the diagram, the designer can avoid premature thinking about the details [30]. In the diagram, the aesthetic form is usually of secondary significance, in order to show the essential principles of an idea or relations between objects [31].

2.2 Design and engineering education

Design education deals with both teaching how to design and guiding students to recognize individual ways of designing [32]. Accordingly, researchers have always seen the studio as a main pedagogical framework for teaching design [33–42]. The studio promotes critical, creative problem solving, or what has become known as 'design thinking' [43, 44]. The studio concept is based on constructivist methodology, which considers learning to be an active process where a learner constructs knowledge through practice and interaction with the environment [45]. Or, as put forward by Little and Cardenas [46], the pedagogical approach in the studio is based upon the idea that self-teaching is the best way for students to take on difficult and challenging tasks. To enable this, a complex design task is assigned, for which the solution requires a set of skills that students do not possess at the outset. Often the design task is open-ended, which allows students to find their own way to solve a given problem, as well as to offer a unique solution [46].

Donald Schön was the first to recognize the integrative value of studio approaches as models for other professional education [47, 48]. This view is supported by Boyer and Mitgang, who claim that "architectural education is a model that holds valuable insights and lessons for all of higher education" [43, p. 5]. Various studies have assessed the efficacy of exposing engineers to the design studio pedagogies used in architecture. For example, Arens et al. [49, p. 5] argue that the design studio is particularly suitable for engineering education due to its efforts to link art and science through 'learning-by-doing' experience. A recent study by Chance et al. [50] showed that such an approach can improve student learning, as well as help students practice high order skills.

A challenging task in engineering education is the organization of a problem-based introductory course [51]. Likewise, educators in the fields of design and architecture meet with similar problems. A profound insight into the way of acquisition of design knowledge by novice designers is provided by Curry [34], based on the understanding of design as a cumulative developmental process. According to Curry [34, p. 644], a key aspect of a pedagogical approach is the identification of the right design methodology for the student at the appropriate stage. Farivarsadri [36] performed an in-depth analysis of an introductory architectural studio and noted that one of the objectives of such a course should be to overcome communication obstacles where students have difficulty communicating their ideas to others. Cognitive load of beginners can be greatly reduced by introducing procedural frameworks, thus providing a more effective way of learning complex cognitive tasks than conventional problem solving [52]. Developing teaching techniques based on this cognitive architecture, while recognizing its advantages and constraints, greatly facilitates the acquisition of an expert level of practice [34]. Similarly, Oxman [41] argued that, in order to further develop design education, the learning task needs to be redirected from a product-oriented approach toward a cognitive-based one. Taking this into account, the present paper offers an alternative educational approach, based on the process of design rather than on the final product.

2.3 The diagram-based approach in designing

As modes of representation, visualization, communication and research, diagrams significantly contribute to professional design practice. For example, Alexander [53, pp. 84–85] describes the diagram as the starting point of the synthesis of design, where the design is presented as linking program requests with the corresponding diagrams, arguing that "any pattern that is abstracted from a real situation, conveying the physical influence of certain demands or forces, is a diagram". Laseau [54] defines diagrams as an abstract graphic language, resembling a verbal language, which consists of rules and vocabulary. In addition, Lockard [55] argues that a diagrammatic approach can be used to investigate design solutions and interact with visual information.

In the context of the present research, the recognition of the importance of the diagrams in design and related disciplines, which was pointed out by Gross and Do [56], distinguishes as a key stance. Some books intended for the education of novice architectural designers [54, 57, 58] focus on a variety of drawing methods and techniques, among which the diagramming process is an essential method. In their seminal book *Precedents in Architecture* [59], Clark and Pause demonstrated the essence of the diagrammatic approach by graphically analysing over 100 of the most prominent buildings to compare their formal properties. Likewise, Balmer and Swisher [28] described diagramming as an intellectual method of analysis in the service of architectural study. They argued that the most effective way to introduce design thinking to novice designers is to study and practice the use of diagrams. It is these attitudes that justify the diagram-based approach to design teaching applied in the present research.

Three key studies have investigated the potential of diagrams in the context of architectural education. The first systematic study of the application of diagrams in the studio was reported by Clayton [60], and it provided a diagramming vocabulary aiming to guide students into an appreciation of aesthetic principles. This study showed that the diagrammatic approach resulted in increased sophistication and abstract aesthetic intentions in the students' designs; furthermore, it indicated that diagrams help students to operationalize their knowledge. Later, Hasan Eilouti [25, 61] developed a set of conceptual and operative diagrams and introduced them to students to help them visualize, develop and present the various procedures associated with design derivation processes. The results of this study supported the positive impact of diagrams on improving the students' achievements and their learning skills. Ultimately, the detailed examination of conceptual diagrams conducted by Dogan [62] investigated how such diagrams might help students to see relationships between a concept and space and coordinate their mutual development. Dogan's study focused on the initial phases of the design process, with the intention to teach the students how to manipulate diagrams at a generic level to reach conceptual and spatial breakthroughs. The evidence presented in this study suggested that the concept-driven approach may enable students to manage the design process better. This study also proved that the students acquired a better understanding of the design process by working with conceptual diagrams.

2.4 Research questions, objectives and hypotheses

With the literature review in mind, the aim of this paper is to address the following question: does the diagramming aid in generating solutions to design problems? To answer the question, the empirical study was designed to examine whether, and to what extent, the diagram-based approach improves and promotes the design process in the studio course. Our main objective is to investigate whether students of architectural and civil engineering might benefit from the use of the diagram as a tool in the process of designing. In addition, our secondary objective is to organize a course based on a studio model in a more structured manner, with clearly defined rules and constraints, since it has been indicated by some prominent researchers that a studio lacks rigour and better coordination [36–39, 41, 63–67]. In parallel with the first two objectives, the underlying objective is to teach students how to express their ideas visually, rather than verbally, using diagrammatic techniques.

Based on the above said, we hypothesise that the use of diagrams will stimulate the design process, increase the number of initial ideas and the quality of design outcomes. Our main hypothesis is that while explicitly instructed to use the diagram-based approach, students could experience advancement in the quality of their design process and of the final product. Within our secondary hypothesis, we speculate that the number of diagrams drawn will be directly related to the quality of the students' work during the semester and will affect their understanding of the design process. While the diagram has received considerable recognition in the theoretical discourse on architecture and design, few studies examine it directly as a design tool. Thus, in addition to the hypotheses, this paper also intends to relate the extensive theoretical field of research on diagrams to a more practical application of diagramming techniques.

3. The study

This study is envisaged as quasi-experimental design research that combines a careful and purposeful combination of both qualitative and quantitative observations and analyses which were beneficial for responding to the research objectives. In order to be able to draw some conclusions about very complex components of the design process, our intention was to collect multiple sets of data using different research methods in such a way that the resulting mixture has multiple and complementary strengths and nonoverlapping weaknesses, which is generally considered as the fundamental principle of mixed research [68]. Therefore, the present study combines the following approaches: (1) the qualitative analysis of findings from the students' sketchbooks, (2) the quantitative visual content analysis from the sketchbooks, (3) the descriptive statistical analysis of the questionnaires and (4) the qualitative studio observations intended to further examine and critically evaluate the diagram-based approach to teaching design.

3.1 Research participants and the design task

The students (n = 29; 12 females and 17 males) who took part in the study were all second-year undergraduate students, between 20 and 34 years of age, with no previous experience in a design studio. The study was conducted in the school year 2016/17, within the course *Design of a Family House*, which is mandatory for all students in the *Architectural Engineering* programme (19 participants), but it is open as an elective course for students in the *Civil Engineering* programme (10 participants). Both programmes are part of the undergraduate studies at the Faculty of Civil Engineering Subotica, University of Novi Sad. The course *Design of a Family House* was established in 2013 when a new study programme *Architectural Engineering* passed the accreditation. The primary goal of this programme is to combine the acquisition of technical and design skills within the engineering faculty.

Considering that the course in which the research was carried out belongs to the field of architectural education, but in a broader context its participants are educated and trained as engineers, it seems advisable to use the previously described studio model for learning the basics of design. According to Mandala et al. [69, p. 1315], efficient development of students' design thinking abilities requires the introduction of creative practices such as problem-based learning, appropriate feedback and fostering reflexive skills. All these aspects can be covered successfully through the studio course which grounds are taken from the domain of design education.

The assignment given to the students was to design a single-family detached house, based on the given project brief slightly differing for each student. At the beginning of the semester, students were introduced to the diagrams and were also provided with a set of diagrammatic examples, so the students could understand what diagrams look like and how they operate. The students were also presented with a detailed studio schedule containing information about successive design phases, along with the description of each diagrammatic exercise which is to be applied during the project development. The assigned tasks were of the open-ended type; thus, the students were encouraged to explore additional solutions before immersing themselves in the development of the final proposition.

3.2 Studio course organization

The intention of the course presented was to establish the basic principles of architectural design. Students' lack of drawing and model-making skills, as well as their inability to understand the design process itself, make a formulation of an initial design studio a highly demanding task for the studio instructors [36]. Since all the participants might be considered novices [70], with no requisite domain-specific knowledge for approaching design problems, the instructors made a significant effort to introduce the design methodology and provide phases of problem-solving. The given design task meant designing in a context-free environment requiring the lowest level of design skills to complete, with an emphasis on the plan organisation and functional examinations [34]. The authors believe that these exact factors might most fully be explored and understood through the diagrammatic approach to architectural designing. In order to provide an understanding of design to the students, the course was based on 'first principles', where design proceeds from identifying requirements and necessary functions to providing appropriate forms or structures [71].

The studio work consisted of five stages, where the theoretical content presented in the course lectures was always supported by practical applications. The design phases on the basis of which the course was organized are in accordance with Goel [72], who identified four stages in the design process—problem structuring, preliminary design, design refinement and detailed design. In our study, the analysis of form was viewed as a distinct phase, to determine the potential of the diagram in the study of the three-dimensional space. To teach the basics of architectural design, we tried to understand students' learning processes. In that sense, it has been noted that there are many advantages in applying diagrams to traditional types of graphic representations. The work on the design task was accompanied by diagrammatic exercises, the purpose of which was to emphasize certain aspects of the overall project. The series of different diagrammatic exercises (given in Table 1) was based on the comprehensive literature review dealing with various types of diagrams and their application in designing [28, 59–61]. Table 1 also presents the course phases and their duration in weeks. The diagram-based tasks in each project phase aimed to elucidate the complexity of both design problems and processes in architecture, through which the students were to develop skills of manipulating spatial relationships; develop skills of graphic representations necessary for the interpretation and communication of their architectural intentions and, above all, to enable the students to include rigorous analytical studies in their design processes. The course instructors insisted that the students present their ideas thoroughly and convincingly by means of various graphic representations, i.e., rather graphically than verbally.

There were no intermediary submission dates in the studio, only a completion date. The window for the study was set to a period of 15 weeks. Participation in the diagram-based exercises was mandatory to pass the course. However, the students had the opportunity to opt out from having their projects included in the study. Nevertheless, no student

Table 1. List of diagrammatic exercises for each project stage

Course phase	Weeks	Suggested diagram-based analyses
Research and analysis	2–4	• users' activities • space required for activities • performative sequencing (24-hour period) • precedent analysis
Preliminary schematic design	5–6	• concept mapping • plan/spatial relationships • spatial deployment of zones • scheme of circulation • space links
Development and refinement	7–9	• conceptual diagram / *parti* • hierarchy of spaces • serving and served space • public, semi-private and private spaces • plan arrangement and area size • levels of connection between inner and outer space • illumination
Form analysis	10–11	• structure, symmetry, balance • element and the whole • repetition, addition, subtraction • volumes and forms
Finalization	12–15	• representational diagram • post facto explications

requested that his/her projects, sketchbooks or questionnaire answers be excluded from the study.

3.3 Procedure, instruments and data analysis

The sketchbooks present the self-documentation of the students' work and contain traces of their learning and design processes. Students were strongly advised to make a conscious effort to record their design processes in the sketchbooks. To provide the descriptive and interpretive validity of our examinations, as well as to avoid researcher bias, the analyses of the sketchbooks were carried out by two experienced external researchers from our Faculty. These researchers were provided with detailed explanations regarding the research being conducted, the concept of architectural diagrams, and the analysis criteria. After the sketchbooks had been submitted, a few principal aspects in the students' design processes were investigated; namely, we examined: (1) whether the students used diagrams to help them generate design solutions; (2) whether the applied diagrams facilitated the design process; (3) how many diagrams and of what type were drawn; (4) whether students employed any diagrams which were not described in the given course information, i.e. whether they developed their own diagrammatic strategies; and (5) whether the students used the diagram as an analytical or as a generative tool in the design process.

After the implementation of diagrammatic methods in their design process, students were asked to provide feedback through a structured anonymous questionnaire, which was conducted after the designs had been submitted for final evaluation, to guarantee more objectivity in the responses. The questions had been designed to assess the students' reflections and evaluations of the diagram-based approach to designing. The questionnaire consisted of 15 questions, divided into three sections. The introductory part contained four questions and was focused on the self-evaluation of the students' performance during the course. The substantial part of the questionnaire centred on the students' evaluation of a diagram-based approach to architectural design, and it consisted of nine questions. The final two questions addressed the students' general satisfaction with the organization of the studio course. The list of questions is provided in Fig. 5. Finally, a section for additional comments was also provided. Fully anchored 5-point rating scales (5 = strongly agree; 4 = agree; 3 = neither agree nor disagree; 2 = disagree; 1 = strongly disagree) were used for all the questions, with a neutral option available to avoid forced choices. The data obtained from the questionnaires were analysed by employing descriptive statistics. Then, in order to examine the statistical significance of the responses in relation to the neutral value of 3, we conducted a t-test for which the explanation and the results are given in the following section.

Although most of the material for qualitative and quantitative analyses came from the sketchbooks and the questionnaires, the qualitative observations of the design process in the studio were indispensable to the further investigation of the research

Table 2. Number and percentage of diagrams drawn in each design phase, along with the measures of central tendency and the standard deviation

	Research and analysis	Preliminary schem. design	Development and refinement	Formal analysis	Finalization	Σ
Sum of diagrams	**240** (18.1%)	**304** (24.7%)	**456** (34.9%)	**297** (21.5%)	**17** (0.9%)	**1314** (100%)
Mean	8.28	10.48	15.72	10.24	0.59	45.31
Median	8	12	16	9	0	44
Std. dev.	4.40	4.66	7.60	7.58	1.24	20.97

questions. To provide trustworthiness of qualitative research, observations were carried out by multiple researchers who were taking extensive field notes during the studio hours. The first author participated in the studio as an instructor and observer, accompanied by two graduate students who acted as observers. The use of multiple observers allowed cross-checking of observations to make sure that observations are credible. During the progress of the course, we were observing the general behaviour of the students, their motivation and commitment in the studio, their flexibility towards new approaches to architectural designing, their willingness to understand diagrams as a potentially useful tool in the design process, as well as their ability to deliberately manipulate different diagrams and to express their ideas graphically.

4. Findings

To represent our findings in the best way, the following section will be further divided to show the results obtained from the sketchbooks, the questionnaires, and studio observations. Since the nature of these sources is different, they are assessed separately, but together they form a whole for the better understanding of the potential of a diagram-based approach.

4.1 Quantitative and qualitative results from the sketchbooks

As described in the previous section, sketchbooks were carefully studied to detect every successive diagram drawn. Subsequently, each diagram was examined and categorized according to the appropriate course phase. The sum of diagrams drawn in each phase and their percentage in relation to the total number of the diagrams drawn is shown in Table 2. This table also shows mean and median values, as well as the standard deviation for the number of diagrams in each design phase.

To get a more detailed insight into the quantitative results obtained from the sketchbooks, the box plot chart given in Fig. 1 shows the maximum and the minimum number of diagrams drawn per student at a certain design phase, as well as the median value, and the quartiles of 25% and 75%.

It is notable that the largest number of diagrams (456 diagrams, or 34.9%) belongs to the *Development and refinement* phase (Fig. 2). This is followed

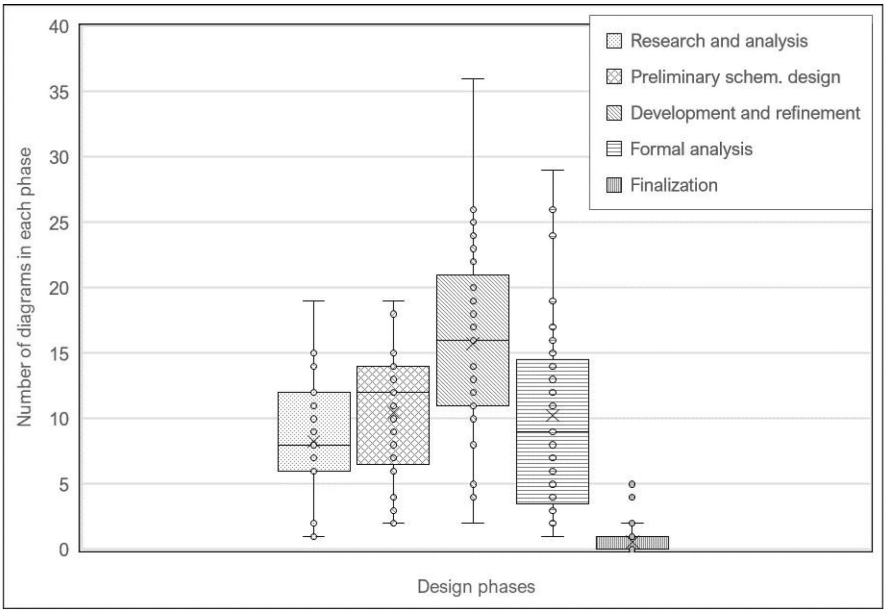

Fig. 1. Box plot chart of quantitative visual content analysis from the sketchbooks.

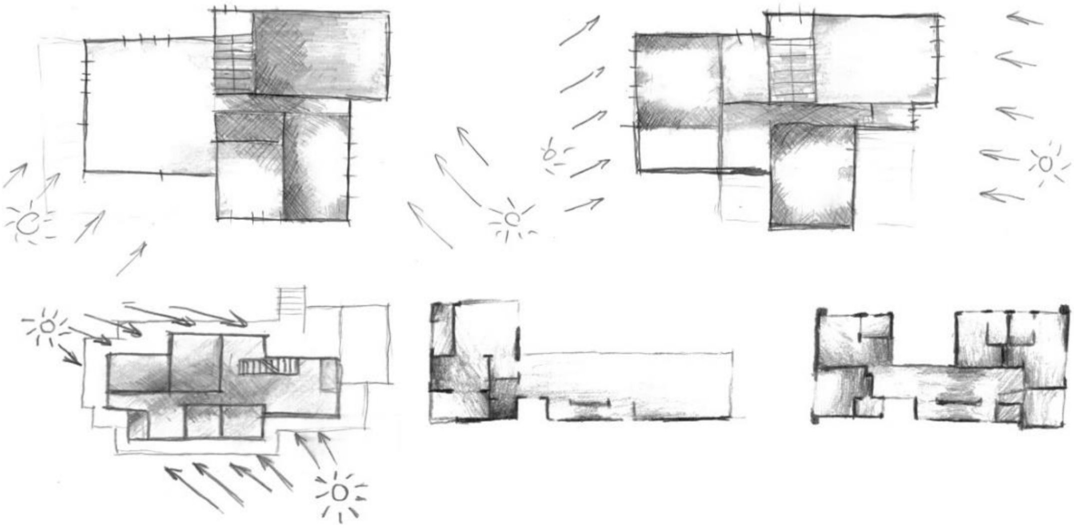

Fig. 2. Illustrative examples of illumination diagrams drawn in the Development and refinement phase.

by an almost equal distribution of the number of diagrams drawn during the *Preliminary schematic design* phase (Fig. 3) and the *Formal analysis* phase (Fig. 4), where students drew 304 diagrams (24.7%) and 297 diagrams (21.5%), respectively. During the *Research and analysis* phase, the students drew 240 diagrams (18.1% out of the total number). Surprisingly, an extremely small number of diagrams was drawn throughout the *Finalization* phase, i.e., only 17 diagrams, which represents an insignificant 0.9% of the total number of diagrams drawn.

Furthermore, we can observe that, on average, the students drew approximately 45 diagrams during their design processes. However, it is of considerable importance to point out that this number deviates significantly (SD = 20.97) from the mean number of the diagrams drawn, thus we can remark that some students performed poorly in the aspect of developing their design proposals with diagrams. On the other hand, a few students put in an outstanding performance in relation to the mean number of diagrams drawn. These students achieved the best result in terms of the quality of their solutions, as well. The correlation between the

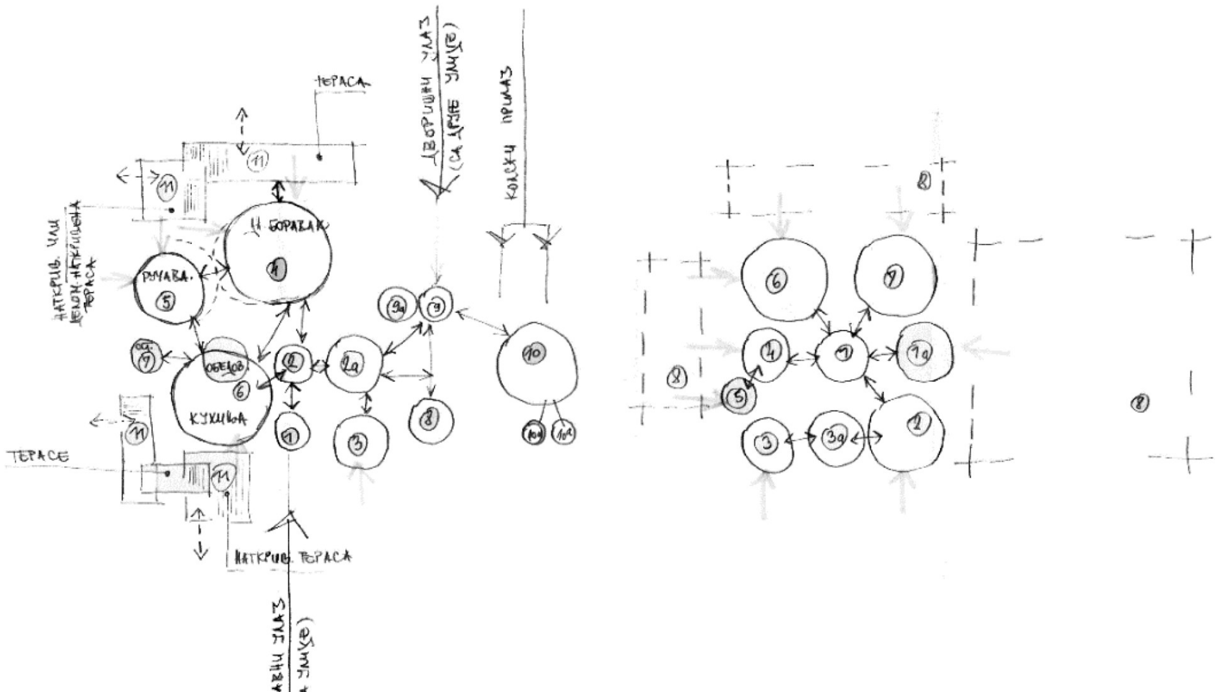

Fig. 3. Illustrative examples of circulation diagrams drawn in the Pre-design programming phase.

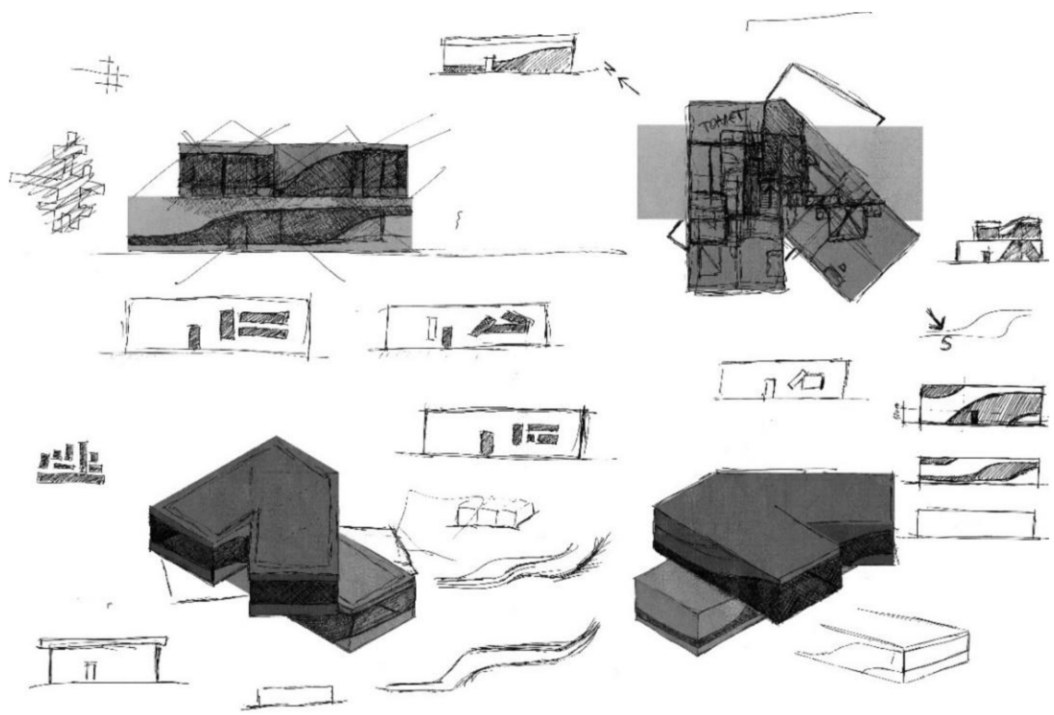

Fig. 4. Illustrative examples of form diagrams drawn in the Formal analysis phase.

total number of the diagrams drawn and the final grade achieved in the course was determined using a Spearman's correlation test that showed a relatively high coefficient of correlation between these variables ($\rho = 0.871$).

While qualitatively observing the sketchbooks, we formed a few distinct impressions of the students' design process. Namely, we recognized that all students tried to use diagrams to generate their design solutions. However, only some students (17 out of 29) managed to employ diagrams towards the creation of a solution. Students did not develop their own strategies for implementing diagrams in the design process, meaning they only used those diagrams suggested by the studio instructor. Although the diagrams from the sketchbooks suggest some generative attributes, the students failed to utilize those as such, and they preferred using diagrams exclusively as an analytical device.

4.2 Quantitative results obtained from the questionnaires

The graph chart showing the overall results of the analysed questionnaires is given in Fig. 5. The purpose of the introductory part of the questionnaire (Q1–Q4) was to examine the self-evaluation of the students' performance in the studio. Most students (72.4%) were confident while working on their projects, while eight students (27.6%) reported a neutral stance towards this question. If we observe the students' motivation, we can claim that it was on a significantly high level, with a mean value of 4.48 (strongly agree = 55.2%, agree = 37.9%, neutral = 6.9%). Then, over two-thirds of the students (strongly agree = 34.5%, agree = 41.4%) reported that they had carried out their tasks responsibly, although four students (13.8%) responded neutrally, and three (10.3%) expressed disagreement with this assertion. When asked whether they tried to implement diagrams in their design process, 27 out of 29 students reported positive answers and two responded neutrally. This result was also confirmed by the sketchbooks analysis.

Let us now look at the substantial part of the questionnaire (Q5–Q13), where the obtained results show students' predominant satisfaction with the diagram-based approach to design. Our results demonstrate that the students found diagrams most useful when searching for a concept to drive their design solution ($\bar{x} = 4.24$). Then, the analysis that the students considered equally important was the one involving diagrams for the spatial organization ($\bar{x} = 4.24$). This is followed by diagrams in the phase of Development and refinement ($\bar{x} = 4.00$), as well as the ones in the Formal analysis ($\bar{x} = 3.97$). Although the mean value of the answers to these two questions was relatively high, in both cases there are two negative responses. The least useful was diagrammatic precedent analysis ($\bar{x} = 3.86$). Additionally, all students claimed that they had understood the concept of the architectural diagram and agreed upon the statement that the approach adopted

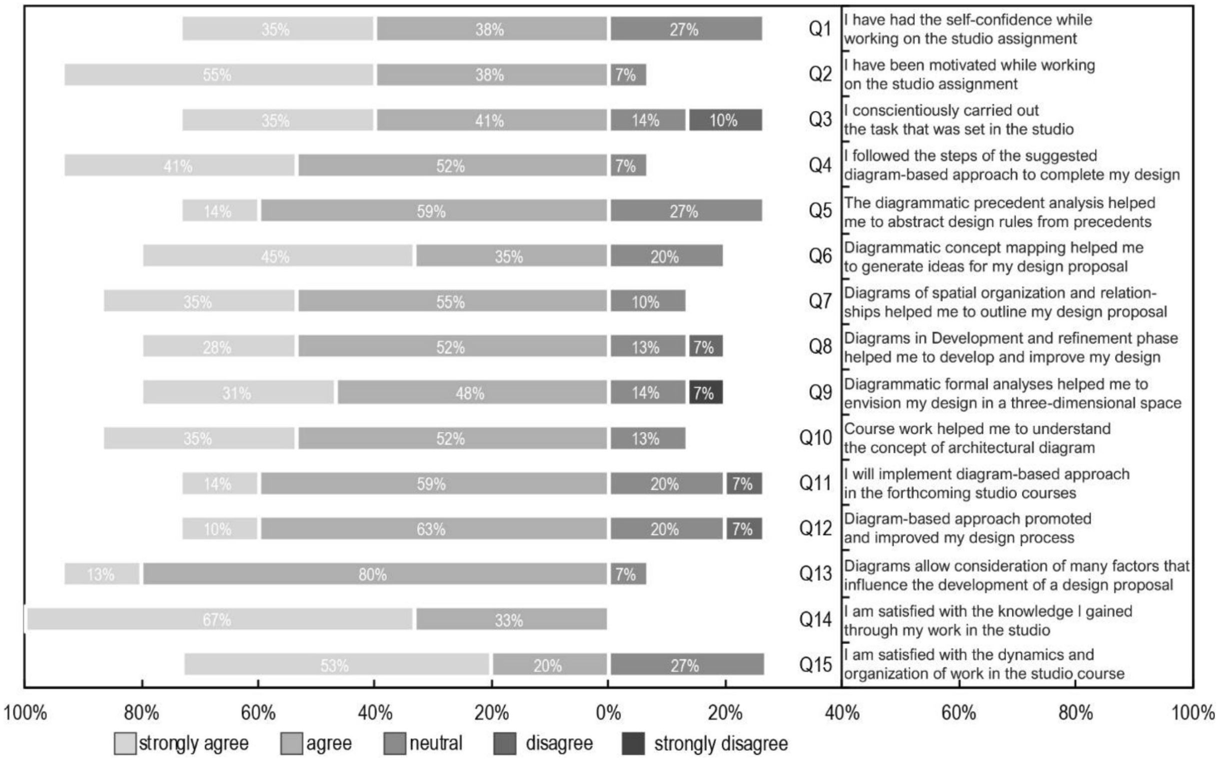

Fig. 5. Overall results of the questionnaires.

Table 3. One-sample test

	Test Value = 3					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Q1	7.207	28	0.000	1.069	0.77	1.37
Q2	12.602	28	0.000	1.483	1.24	1.72
Q3	5.588	28	0.000	1.000	0.63	1.37
Q4	11.797	28	0.000	1.345	1.11	1.58
Q5	7.260	28	0.000	0.862	0.62	1.11
Q6	8.502	28	0.000	1.241	0.94	1.54
Q7	10.518	28	0.000	1.241	1.00	1.48
Q8	6.372	28	0.000	1.000	0.68	1.32
Q9	4.944	28	0.000	0.966	0.57	1.37
Q10	9.628	28	0.000	1.207	0.95	1.46
Q11	5.521	28	0.000	0.793	0.50	1.09
Q12	5.525	28	0.000	0.759	0.48	1.04
Q13	12.581	28	0.000	1.069	0.89	1.24
Q14	19.326	28	0.000	1.690	1.51	1.87
Q15	7.663	28	0.000	1.241	0.91	1.57

stimulated their design process ($\bar{x}$ = 3.76). Moreover, 21 students (strongly agree = 13.8%, agree = 58.6%) stated their intention to continue with the diagram application in the upcoming courses, while six students were neutral and two rejected this claim. Ultimately, we can analyse the results of the final part of the questionnaire (Q14–Q15), where the students reported a significantly high level of contentment with both the knowledge gained in the studio ($\bar{x}$ = 4.69), and the dynamics and organization of the course ($\bar{x}$ = 4.24).

In order to check if the results for each questionnaire item (Q1–Q15) deviate significantly from the average value of 3 (neutral response), we conducted a t-test and set the following hypothesis: H_0: $\mu_0 = 3$, H_1: $\mu \neq 3$. The results were considered significant at the level of 95% (p = 0.05). As we can see from the Table 3, all p-values are less than the significance level of α = 5% (0.05), which means that the zero hypothesis H_0 is rejected at the significance level of 5% and that the alternative hypothesis H_1 is accepted. On this basis, we can claim that the results of the questionnaire shown in Fig. 5 differ significantly from the average value of 3 for each question. These results show a high level of agreement with our hypotheses, as will be discussed later.

4.3 Studio observations

To acquire a deeper understanding of the results from the sketchbooks and the questionnaires, we made careful informal observations of the students' behaviour and design processes in the studio. One issue which arose at the beginning of the course was that most of the students encountered problems representing their ideas. Although strongly advised to display their ideas graphically, almost all students chose to express themselves verbally. Thus, we noticed that students have difficulties with understanding the essence of the design process, and especially with entering that process. To overcome this problem the students were shown, through theoretical and practical work, step-by-step procedures on how to shape one's ideas. After several weeks, the intensity of this issue decreased, so we attribute this result to the more structured approach in the preliminary phase of the design. However, even at the end of the course, it was evident that some students (n = 12) still struggled with the graphical representation of their ideas. These were the students who drew the least number of diagrams.

We also noticed that students cease to consider alternatives as soon as they reach an acceptable solution. This observation indicates that the students judge the design process as a search for one solution, rather than considering more potential solutions for comparing and selecting one of the highest quality. From the aspect of motivation, observations evidenced that all students were motivated for work and learning in the studio, which is consistent with the self-evaluation in the questionnaires. Given that the participants of this study are considered novices, we observed the considerable flexibility towards new approaches to designing as well as the willingness to understand and apply diagrammatic methods. At the end of the course, however, the students were still unable to use fully the potential of diagrammatic methods in developing design solutions. Therefore, it can reasonably be concluded that although diagrams are a powerful tool for improving student design process, it is not a universal technique that can remove all obstacles to learning.

Overall, together with our qualitative and quantitative analyses, the observations support the role of diagrams in the enhancement of designing and learning processes. The adopted approach enabled the students to understand their design intentions better, to grasp the importance of the simultaneous thinking and designing, and most importantly, to be fully focused at each stage of design, rather than concentrating on the final product.

5. Discussion

This study aimed to examine whether the application of diagrammatic methods in a studio environment can positively affect the students' design processes and design outcomes. The results from the quantitative analysis of the students' sketchbooks (Table 2; Fig. 1) showed that over a third of the total number of diagrams drawn belonged to the Development and refinement phase of the projects. While working in this stage, students were developing their schematic design, applying requested modifications and providing detailed floor plans based on the previous functional examinations. It can, therefore, be assumed that diagrams in this phase were most significant for solving the spatial organization. Öztürk and Türkkan [73] have also acknowledged the importance of this phase in a structured design process since it provides an actual frame for design and involves the expression of design ideas into spatial compositions.

The number of diagrams drawn in other project phases was nearly evenly distributed, except for the Finalization phase. One surprising observation to emerge from the sketchbooks was the small number of diagrams drawn in the final phase of the students' design processes. This result is consistent with Yang's findings [74, p. 7] that showed a general trend in the distribution of drawings—fewer in the beginning, most in the middle, and then a significant decline at the very end of the course. This also accords with the observations of Shekhar and Borrego [75], who noted that activities implemented at the end of the semester receive less student interest. Furthermore, from this finding, we can make some general assumptions about the students' design processes. According to our understanding, this result might be related to the students' predominant use of the diagram as an analytical tool, which resulted in the largest number of diagrams drawn in the analytical phases of design. Despite the fact that previous research refers to multiple interpretations and applications of diagrams [14, 76–79], the participants in this study focused on the diagram's characteristic of enabling easier analysis of a large number of data affecting the design process. Although the sketchbooks indicated some generative attributes of the drawn diagrams, it is the analytical aspect that prevails.

Supplementary analysis of the sketchbooks and observations of the students' design process in the studio revealed that diagrams were used to frame and visualise design problems, to develop concepts, to facilitate problem-solving and for revising and refining ideas. These results confirm the association between the relatively unstructured drawings (as the diagrams), and the problem decomposition into spatial relations, as put forward by Purcell and Gero [80, p. 409]. Additionally, the use of diagrams as a specific type of drawings for facilitating visual thinking is consistent with earlier studies. Our findings confirm that students use diagrammatic drawings for thinking, developing design ideas and solving problems, as proposed by Akalin and Sezal [81]. This also accords with the understanding that designers use graphical representations to generate forms rather than to externalise pre-existing ideas, as argued by Goldschmidt [82].

Another interesting finding is the direct relationship between the number of diagrams drawn and the success of their application in the design process. Our quantitative analyses and observations unambiguously suggest that students who drew the largest number of diagrams are those who used their potential to the greatest extent. This is in accord with a recent study indicating that the more initial drawings are produced, the more nuances will tend to be revealed in the final result, thus nuances are directly proportionate to how often graphic strategies are used [83]. Likewise, our results support the evidence from the previous studies [74, 84] which state that there is a positive correlation between the total number of sketches created during the design process and the final design outcome. According to this evidence, we can infer that the application of diagrammatic techniques in a studio positively affects the students' design process.

The overall results from the questionnaires confirmed and further substantiated the ones from the sketchbooks. Nevertheless, it is necessary to point out a few key findings that deepen our understanding of the applied approach. The students' evaluation in the questionnaires showed that they consider the diagram most helpful in the concept-seeking phase of the design process, which is consistent with the results of Dogan [62], who recognized that diagrams in the conceptual phase of designing help relate abstract ideas to generic spatial schemes. On the other hand, the students evaluated the diagrammatic precedent analysis as least useful for developing their design solutions. This finding contrasts with that of Akin [63], who argued that precedent studies are extremely important in evaluating ideas and generating new ideas by abstracting design rules from precedents. However, the same author also pointed out that a certain skill of recognizing abstract concepts in explicit physical designs is something that students must learn in school [63, p. 410]. It seems likely that, in the case of our participants, this factor is responsible for the poor evaluation of the precedent analysis. Our result corroborates the ideas of Casakin and Goldschmidt [85], who suggested that novices fail to transfer abstract relations from precedents and are unable to distinguish between representations of relevant concepts and source examples. This finding has important implications for the development of future introductory courses since it suggests that students should be taught how to extract essential ideas from precedent studies.

While observing the students' design processes in the studio, we noticed that the students considered designing as a search for a single solution. This outcome can be attributed to the fact that the participants in this study are novices, without previous experience in a studio, which leads us to understanding that they are still unable to perceive design as a necessary cyclical structure. This observation correlates well with the ones of Newstetter and McCracken [86], who recognized that students envisage design as a linear process, and they stop considering alternatives as soon as they have one potential solution. Our observations are also consistent with those of Kowaltowski et al. [38], who found that students usually cling to their first design solution and are reluctant to abandon it, even if potential problems are pointed out.

As noted previously, at the end of the studio course the students did not reach the point of using the full potential of the diagram. This finding confirms the relationship between abstract knowledge and diagrammatic skills, as proposed by Purcell and Gero [80]. These authors pointed out that the different aspects of problem-solving must be closely integrated, and that abstract knowledge coevolves with skills of producing and using diagrams. In the context of our research, the participants lacked a meaningful understanding of the design process, which prevented them from fully utilizing the diagram. Such a situation is well explained in the literature, where Uluoğlu [67] claims that education is a long-term investment and it may not be possible to observe its outcomes within a limited time interval. Our results are also in accord with a recent study of Mandala et al. [69] indicating that novice designers do not yet possess the design skills necessary to explore design space, frame the problem and work towards an acceptable solution. The studio observations also showed that the students have difficulties in communicating and representing their ideas, which is in accord with the study of Farivarsadri [36] who pointed out that one of the obstacles in achieving the objectives of a studio course lies in the students' lack of communication skills. In accordance with the remarks of this author and with our observations, this problem can be overcome if students are instructed on how to display their ideas graphically by learning a common graphic vocabulary of design.

In general, our results provide further support for the argument from the previous studies that diagrams promote the design process [25, 60–62] and point out the capability of the diagram-based approach in an introductory studio course. By applying the diagram-based approach, the students seemed much more connected to the design process. Therefore, we can claim that our first hypothesis was verified. As for our second hypothesis, we assumed that the number of the drawn diagrams would be directly related to the quality of the students' results and their understanding of the design process. The analyses carried out within the framework of empirical research confirmed this assumption, which implies that the diagramming activities indeed improve the quality of students' design processes and outcomes. Regarding our research objectives, we examined the possibility of applying diagrams in the context of an architectural studio, during a course that was based on clearly defined rules and constraints. We found that the reorganization of the course positively influences learning and design processes, as well as their outcomes, whereas new modes of representation while insisting on the visual displaying of ideas, have a significant contribution.

Although the previous research already analysed the possibility of applying the diagram in the context of architectural education, this study further broadens our knowledge of this phenomenon since it focuses on the diagram as an exclusive tool in all stages of the design process. The approach presented enables us, in comparison to the previous studies, to examine the possibilities of diagrams from several aspects and through various analyses, which inevitably leads to a better understanding of the subject matter. This combination of findings promotes the comprehension of the complex nature of architectural diagrams and provides support for the conceptual premise on the essential role of the diagram in the creation of works of architecture. In summary, then, the results provide clear evidence of the significance of the diagram in the design process, and a wealth of insights into characterising a students' design process.

In addition to the results closely related to the application of the diagrams in the design process, this research enabled the adoption of conclusions regarding the appropriate pedagogical approach for teaching novices in design and engineering disciplines. Since not all students have been able to apply a diagram in creating a solution, nor have they developed new strategies for applying the diagram, it can be assumed that there are some differences between the course requirements and its specifications. Course requirements indicate what needs to be achieved during the course, while the specifications explain how the requirements can be reached. It can, therefore, be argued that instructors must constantly review the curriculum as well as their approach, and continuously improve courses to provide students with the best possible learning conditions through pedagogical methodologies that match the current level of student skills. As for the present research, this could mean that it is the task of the instructor to further clarify the concept of an architectural diagram to students in order to maximize the results of its application.

However, the authors recognize some limitations regarding this study. The presented findings may be somewhat limited due to the small sample size ($n = 29$), which restricted the chance to conduct a more rigorous statistical analysis, thus reducing the reliability of the results. Then, due to its scope, our study does not include the comparison between an experimental and a control group to determine how diagrams affect student learning. It would be interesting to examine how the design process of novices develops with and without the use of diagrams, which will be conducted in future work. It can also be argued that the concept of diagrams is too abstract to digest in a 15-week period since the participants in this study are novices in an introductory studio course. Therefore, it is important to bear in mind that potential bias may arise due to both lack of knowledge of the design process and of experience. Nevertheless, we presume that the results shown generated some insights and allowed discussion and that they can point to certain trends and advantages of using the diagrammatic approach in learning architectural design, as well as to difficulties that might appear in this case.

6. Conclusions and future work

To sum up, we designed and presented an experiment in the studio to examine empirically the potential of the diagram-based approach in teaching design to architectural and civil engineering students. Taken together, our results suggest that diagrams promote and enhance the design process of novice designers. The upshot of this is the possibility of improving design education and acquisition of design skills by offering process-oriented introductory courses, with emphasis on the representation and the elaboration of ideas through graphic displays. This paper highlights the importance of diagrammatic representations and provides insight into the design processes of novices. The contribution of our study lies in the detailed consideration of the process of applying diagrams at each stage of design. These findings add to a growing body of research on diagrams, and substantially to our understanding of their practical application, which has been recognized as an insufficiently investigated aspect in the study of diagrams. While the approach adopted limits the generalizability of the findings to other scenarios, the insights presented in this work are not specific to particular courses and may be applied to other course settings.

Also, the obtained results give us an insight into the pedagogical approach that we have applied in teaching and show us that it is our task, as instructors, to reconsider our curriculum and our assumptions about the process of student learning. The applied diagram-based approach is only the first step in studying the possibility of utilising diagrams in acquiring the skills of architectural design. Based on the obtained findings, we will be able to further develop our approach to the curriculum and to the introductory design studio, and in subsequent studies more specifically examine the role of diagrams. Even though there are some limitations in this study, we believe our work could present a general theoretical and practical framework for examining the role of graphic representations in the students' design process. Our data suggest that diagrams could be used to enhance the acquisition of complex skills that are inherent to architectural practice. In our view, these results constitute an initial step towards understanding the practical uses of diagrammatic methods. Consequently, we are confident that our results may improve the knowledge of the perplexing nature of the architectural diagrams.

We hope that our research will be of benefit to researchers dealing with similar subject matter, but at the same time, we believe that it can aid instructors in the organization of studio courses. To deepen our knowledge, we intend to conduct similar experiments with students of higher-level studios, to compare and hopefully confirm our findings. Since our results are promising, they should also be validated by the larger sample size. Consequently, further studies in the current topic are therefore required to establish a clear picture of the role of the diagram in the design process.

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