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Full Length Article

Real-time interaction of physical models and generative AI in the architectural design process (hybrid design studio experiments – HDS)

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ABSTRACT

This study aims to experimentally examine the simultaneous real-time use of physical models and generative AI tools in architectural design. Distinguishing itself from prior sequential hybrid studies, this research introduces a real-time reciprocal loop between tactile and digital tools. The studio included two sequential design experiments: one with contextual constraints and one without. Methodologically, the study adopted a Design-Based Research framework, utilizing student surveys to evaluate the effectiveness of the hybrid approach. In addition, expert opinions were obtained to support pedagogical inferences and to evaluate student outcomes. Findings indicate that while physical model-making remains the dominant driver for design realization compared to prompt writing, both tools function supportively. Furthermore, most students reported that predefined contextual constraints were more productive. Ultimately, the study contributes to design pedagogy by demonstrating that real-time hybridization fosters reflection-in-action, while structured constraints act as essential catalysts for creative focus in AI-integrated workflows.

1. Introduction

Design is an action shaped by problem-solving and optimization processes, as an effort to transform the current state into the desired one [1]. In this process, the designer is defined as the representative of the ideas to be realized and a "unifier" who deals with dynamics such as uncertainty and conflict [2]. The designer transforms the design situation into an alternative state, taking constraints into account, in order to make it satisfactory [3]. Design is not only about objects but also a means of intervention in the world [4]. The three-stage structure of design processes, consisting of draft proposal, schematic design, and detailed design, is complex due to the analysis-synthesis-evaluation-decision cycle. At the same time, this structure requires decisions to be made under constraints [5]. The aforementioned approaches reveal the complexity and multidimensional nature of design.

In architectural design processes, shape grammars and genetic algorithms are considered pioneers of computational methods [6]. Computational thinking, which utilizes computational design tools and methods to generate solutions to complex problems, is employed as a useful approach for problem-solving [7,8]. With this approach, people can produce alternative outcomes with similar inputs [9]. Through the advent of generative AI (GAI) models such as "Large Language Models" (LLM) and "Latent Diffusion Model" (LDM), which are deep learning (DL) tools, designers can produce complex architectural outputs with text, visual, or parametric inputs [10–12]. In the digital age, the act of designing has transformed, as Oxman [13] points out, through the hybrid relationship established between the architect and the machine. Algorithmic design, parametric modeling, and the AI tools commonly used today have expanded the creative and analytical capacity of the design process.

In architecture, physical models remain an important design tool despite the digital revolution [14]. Models have long been used as one of the fundamental tools for perceiving space and embodying design ideas. Models are not merely a technical part of design but also an integral part of architectural thinking [15]. Model making in architecture allows the discovery of the design itself; it serves to test elements of the space, such as scale, proportion, and materials, to make errors visible, and to stimulate creativity [16]. It is widely recognized that models are most effective in the early stages of architectural design, but achieve the highest success when supported by hybrid tools such as sketches [17]. Today, models are used only for aesthetic and structural evaluations. In the design process, using models, user needs, and context analysis are neglected in the advanced stages of design. Models are closed to user feedback throughout the design process. Therefore, the use of hybrid

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tools in design is considered important [18].

Computer-aided architectural design (CAAD) tools provide speed and precision unlike physical models, but carry the risk of distancing themselves from tactile experience [19]. In contrast, the combined use of digital and physical design tools establishes a link between creative intuition and algorithmic optimization [20]. GAI offers designers new possibilities such as parametric design, data analysis, and probability-based scenario generation. With digital design tools, the concept of "computable creativity" and human-centered design processes in architectural design have been enriched [13]. However, it is known that digital tools alone fall short in supporting cognitive processes. At this point, hybrid tools overcome the limitations of individual tools by supporting creativity, problem solving, and alternative production in conceptual stages, thereby improving design quality [21]. Today's digital transformation in design does not render physical design tools such as models obsolete, but rather makes them part of a hybrid design methodology [13]. This approach not only preserves the traditional use of models but also makes them an active component of a data-driven design language.

Architectural education progresses in parallel with the architectural design process that takes place in practice. It is important to establish the relationship between the transformation occurring in architectural design and education [2,22,23]. This process is supported by current design tools. Today, the design process and design education can be realized with tools such as VR (virtual reality), AR (augmented reality), and MR (mixed reality) [24,25] and with the help of prompt writing offered by GAI tools [26]. Regarding the integration of GAI into architecture education, students are seen to be eager and active in this area, while educators are hesitant due to the lack of a defined pedagogical framework [27]. Okagbue et al. [28] argue that AI makes the learning process more efficient by supporting traditional education with digital systems. However, the lack of evaluation standards and methods for AI-supported systems negatively affects the process of integrating these systems into the education system [29]. Although developments in AI create new opportunities in education, it is important to maintain a critical approach to its impact on pedagogical practices. This is because the effects of current approaches on creativity and design thinking, which are fundamental skills that students need to acquire, remain uncertain [30]. The prompt-based research model is reshaping the traditional 'design-based research' approach [31]. However, traditional methods such as hand drawing and physical models continue to contribute. For an effective studio, a hybrid approach is recommended [32]. It is known that traditional studios are limited by linear pedagogies and constrain creativity, while non-traditional studios produce collaboration with digital tools and create their own context [33]. With this observation, the number of hybrid design studies using multiple design tools together in architecture education and design processes has increased in recent years [34–38]. These approaches use different design tools sequentially at different stages of the design process.

Tong et al. [37] used AI tools to generate images from perspective drawings created by students. The results were evaluated by students and tutors. It was demonstrated that current AI tools can assist in producing more effective and understandable visuals for design products. Liu et al. [39] visualized cognitive maps produced by students' hand drawings using the Midjourney tool. Their findings revealed that GAI balanced the design outputs of students with different cognitive orientations. The results indicated that students became more eager to use AI in their future work. Özorhon et al. [38] visualized hand drawings and section models using AI tools. They demonstrated that using AI alongside traditional tools significantly supports the development of student projects. Basarir [40] demonstrates that AI integration in architectural education transforms design processes and that students gain an interactive learning experience with physical models while developing "smart prototypes". In this process, models become not only static representations, but also dynamic interfaces fed by data. Students use AI tools in hybrid studios to support their design decisions with real-time data analysis [40]. However, despite these advancements, most hybrid models in architectural education tend to create linear workflows. Although there are studies investigating the impact of hybrid design tools on architectural education, approaches examining the effects of using these tools in simultaneous real-time are quite rare. The architectural design process fundamentally emerges as the designer's practice of thinking while acting [2]. This approach, called "reflection-in-action," refers to the student's immediate response to their design intervention and the thinking process intertwined with action. This study proposes a hybrid design method that operationalizes the reflection-in-action approach. This method distinguishes itself from other studies by uniquely enabling simultaneous real-time interaction between physical models and GAI outputs.

Constraints in architectural design act as filters for design solutions and serve as a stimulating factor in the problem-solving process [5]. Studies on the role of constraints in the architectural design process show that contextual constraints are not only limiting but also guiding elements of the creative process [3]. In a study by Ibrahim et al. [41], the space between two structures was defined as a constraint, and shape grammars were used to fill this space, investigating the effect of this constraint on students. Pauwels et al. [3] investigated the effect of constraints such as context, orientation, accessibility, and budget on students' design process. Tezel and Casakin [42] conducted two different studies with interior architecture students, covering different types of constraints such as concept, form, ergonomics, and design performance. By changing the constraints between the two studies, they demonstrated that design approaches change along with the constraints. In architectural design, context is not merely a physical environment but also functions as a framework that shapes the designer's decision-making and creative mechanisms. However, studies revealing changes in students' design approaches when contextual constraints vary are quite limited. Therefore, the study aims to test the differences between designs developed in a predefined context and a self-defined context, in addition to the simultaneous and real-time approach. The dual experimental design constructed in the study is pedagogically significant for observing and analyzing how structured (predefined context) and unstructured (self-defined context) problem-solving processes can be transformed in design education.

The study investigates the effectiveness of a new design methodology that integrates the production capacity of physical models created during the architectural design process with GAI models. To this end, the potential of physical models and the GAI tool were used together in the architectural design process. The original value of the study derives from the simultaneous and interactive use of physical models and GAI-based design tools in the developed hybrid design studio (HDS). The questions investigated in the study fall under two main headings. Alongside the effectiveness of hybrid tools, the research questions measure the response of the HDS and designers to the change in context constraints made in the design process.

- The first topic is hybrid design. Can a hybrid design process be created that students can actively and simultaneously use with physical and digital design tools? Can architectural models and GAI tools be complementary tools in the architectural design process? Which tool plays a more effective role in the designs produced with this collaboration?
- The second topic investigates how HDS is affected by the architectural context. Can the context of the architectural element to be designed be defined using generative AI tools? What is the impact of architectural context and design constraints on the HDS process?

The HDS conducted as part of this research involved reconfiguring design tools to enable simultaneous and real-time interaction. To evaluate the hybrid method, the design process and survey responses of 26 participants in the studio (HDS) conducted at XXX University were analyzed. The study was also supported by expert evaluations from 12

faculty members at the XXX University School of Architecture. Participants' experiences during the workshop process were recorded. After the workshop, participants were given a survey to evaluate the HDS. This recorded data was subsequently shared with the experts. The experts provided architectural evaluations of the results obtained from the HDS and were asked about the pedagogical contributions of the study. The study aimed to integrate physical and digital tools. The impact of this integration on creative processes and design decisions was measured using data obtained from participants. The measurement results demonstrated that simultaneous and real-time design with physical and digital tools is feasible and that this combination has positive effects. Additionally, it was observed that the students adapted to the changes in the design process introduced by the two experiments. However, given that the study was based on a one-day workshop with a limited sample group, the findings cannot be generalized to the broader field of design education. Instead, the research is presented as an exploratory pilot study aimed at understanding the applicability of the proposed concurrent methodology and its qualitative impact on student groups. Fig. 1 shows the framework of the study.

2. Method

It is essential to examine the effectiveness of hybrid studios in architecture and design education and their impact on solving design problems. In this study, an experimental method within the Design-Based Research (DBR) framework was adopted to investigate the potential of GAI-based design tools in the architectural design process [43–45]. Guided by this framework, the HDS setup was developed to address the identified research questions. The findings were discussed by synthesizing process observations, quantitative data, post-experiment surveys, and expert opinions.

A workshop titled "Hybrid Design Studio (HDS)" was held at the Faculty of Architecture at XXX University. The workshop began with a knowledge-sharing session on design practices using generative AI tools. Participating students formed a total of six teams to take part in the workshop. During the workshop, the teams created physical models, and architectural visuals were produced using GAI within the scope of the work, based on those models. In the first experiment of the study, teams were asked to develop designs within a predefined context. In the second experiment (self-defined context), teams were encouraged to create their own contexts and obtain final visuals with a freer design approach. The experimental setup and workshop processes designed within the scope of the study are described below.

2.1. Hybrid Design Studio (HDS) experiment environment

The experimental setup used in HDS enables the production of architectural visuals by simultaneously processing prompts that reveal the conceptual structure of the design with physical models produced tactilely. In the literature, it is emphasized that LDM-based models are effective in creating architectural design alternatives [12] and enabling rapid iteration during the concept phase [10]. To achieve these objectives, a custom workflow was established within the ComfyUI [46] interface. In this workflow, physical model images and prompts were used as input. The process begins with the real-time capture of physical model images in the experimental environment using a camera. These images are transferred to the digital environment via the 'ComfyUI' [46] interface. The images are pre-processed using a depth map extraction method that allows the architectural form to be processed with minimal loss in the models. The 'DepthAnything V2′ [47] model is employed to extract depth maps, which subsequently condition the ControlNet [48] network. Simultaneously, textual inputs are structured into three distinct categories. These are "Architectural Design Prompt," "Context Prompt," and "Visual Quality Prompt." These are concatenated and processed via Clip Text Encoder [49]. By synthesizing physical model visuals and prompts through Stable Diffusion XL Turbo [50], which was selected for its low-latency visual synthesis capabilities, architectural design visuals are generated in real time (Fig. 2). Furthermore, this setup enabled the entire design process, the generated design alternatives, and the design inputs to be recorded.

2.2. Case study: Hybrid Design Studio (HDS)

Students participating in the workshop were selected on a voluntary basis from each of the 1st to 4th years at XXX University. Since the study methodology required physical model-making and prompt-writing to progress simultaneously, it was requested that teams of at least 4 participants be formed. These teams included at least 2 participants responsible for physical model-making and at least 2 for prompt-writing, ensuring that 1st-, 2nd-, 3rd-, and 4th-year students were distributed evenly across each team. According to the specified criteria, the 26 students participating in the workshop formed 6 teams. The distribution of participants by team and grade is shown in Table 1. The design tools were introduced to the teams, and the workshop requirements were explained. After the briefing, the teams were given time to meet, assign tasks, and determine their design strategies. The processes of the two experiments are shown in Fig. 3.

In Experiment 1, students designed a weekend home using

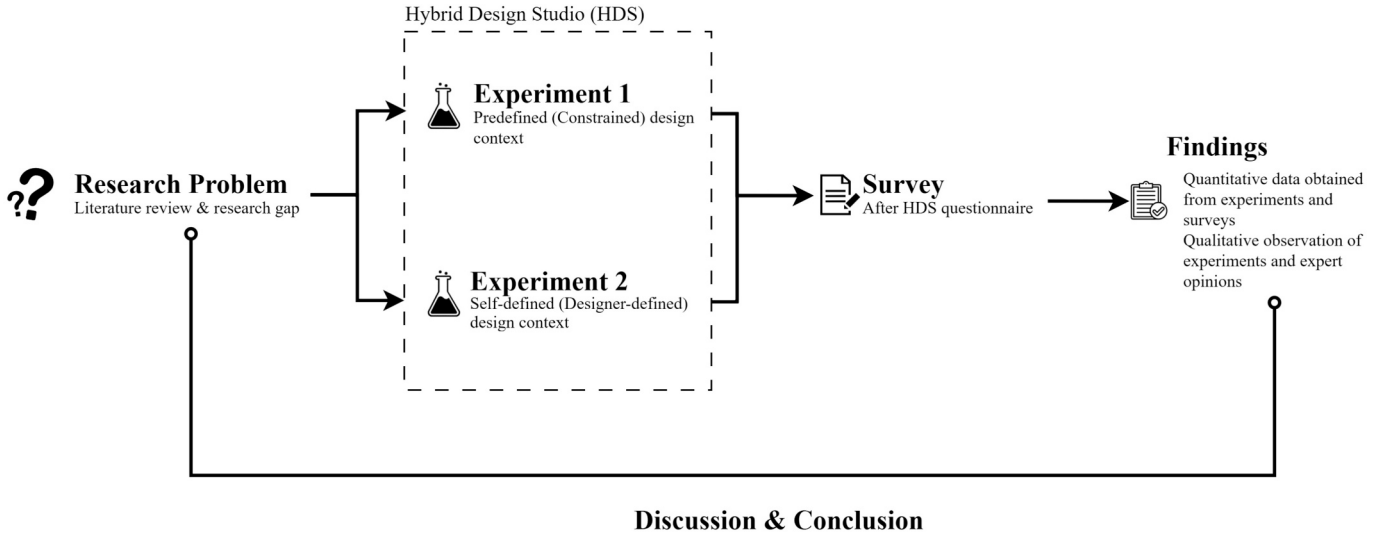


Fig. 1. Framework of study.

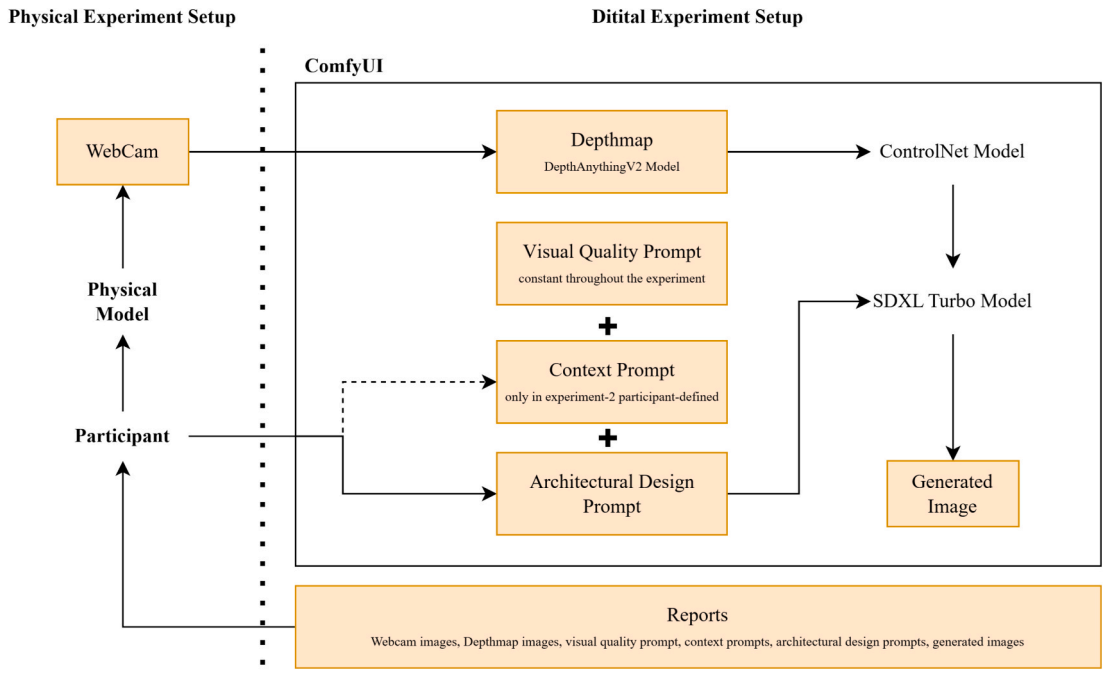


Fig. 2. Physical and digital workflow of HDS. (The orange boxes show the inputs and outputs included in the experiment report.)

Table 1
Number of participants, distribution among teams.

Team/ Year	Team-1	Team-2	Team-3	Team-4	Team-5	Team-6	Total
First Year	0	1	1	1	1	0	4
Second Year	1	1	1	1	1	2	7
Third Year	2	1	1	2	0	1	7
Fourth Year	1	1	1	1	3	1	8
Total	4	4	4	5	5	4	26

predefined context prompts that remained unchanged throughout the process. The visual representation of the context expected for the teams' designs, along with the prompts used to obtain it, is shown in Table 2. Architectural design prompts were determined by the teams prior to the design experiment. Experiment 1, conducted within the scope of the workshop, tested the students' approaches to predefined problems. The teams were expected to make preliminary preparations and finalize their architectural design decisions before starting the experiment. Each team produced initial prompts and models for architectural design as part of their preliminary preparation. The teams experienced the 10-minute hybrid design studio in the specified order. The principle of co-evolution of problem–solution spaces [51] and the adoption of a faster

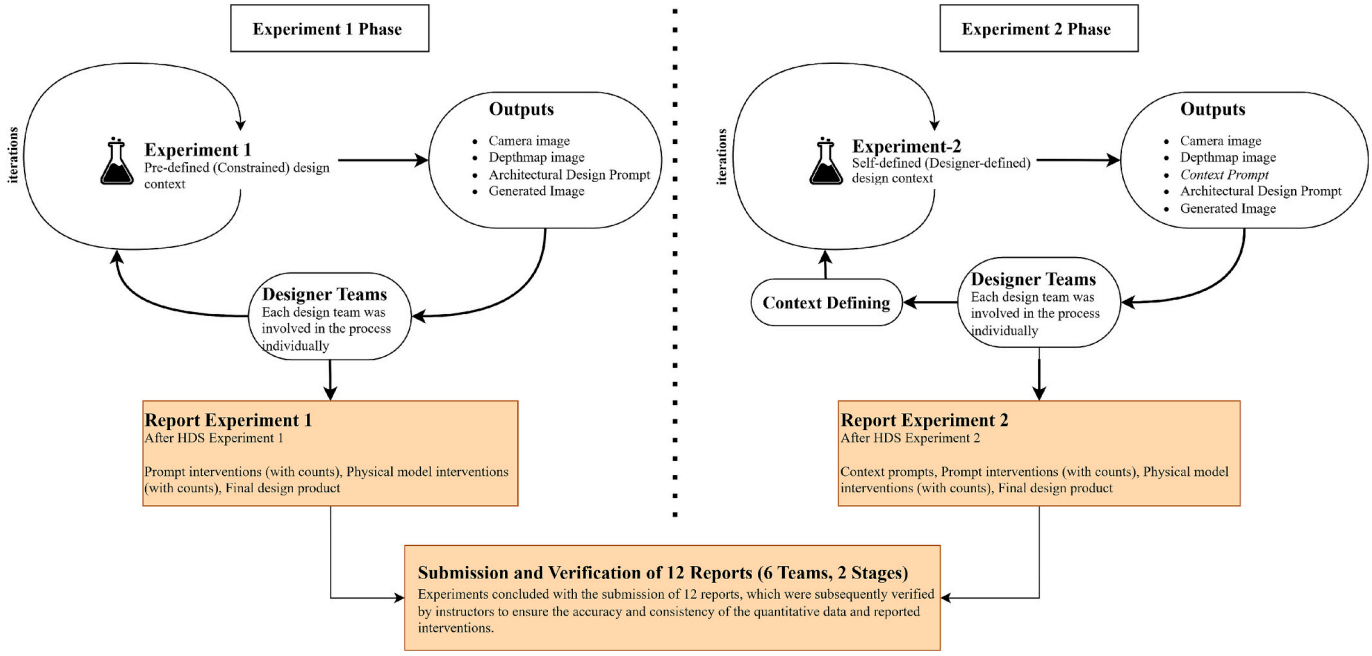


Fig. 3. The processes of the two experiments performed at HDS.

Table 2
Experiment 1 context image (left), visual quality prompt (middle), and context prompt (right).

Context Image	Visual Quality Prompt	Context Prompt
	cinematic composition, ultra-realistic, photorealistic, HDR, high detail, realistic textures, professional photography	near a tranquil lake, positioned on a flat land in front of the water, serene atmosphere, distant mountain range in the background, soft fog covering the horizon, light scattered clouds in the sky, warm golden hour lighting, sunset reflections on the lake

building approach to think faster [52] were instrumental in limiting the duration to 10 min. Due to the limited time, students were encouraged to adopt an intuitive design approach by establishing rapid cycles between physical models and GAI outputs, rather than focusing on technical details. Throughout the study, the model, the depth map generated from the model, and the design visual produced by combining the depth map and prompts were interactively advanced by all teams. Examples of the instant products created during the process are shown in Table 3. After the design processes were completed, the teams' input and output data were sent to them. The teams processed each action that resulted in a visual change in the depth map data as a physical model intervention. Similarly, changes applied to architectural design prompts ensuring uninterrupted, meaningful word and sentence structures were processed as prompt interventions. The teams determined and reported the number of interventions they made to update and modify their designs on the models and prompts, as well as the final design product they produced. Experiment 1 concluded with the submission of these reports. The quantitative data provided by the teams were also verified by the instructors, ensuring that the number of interventions reported by all teams was accurate and consistent.

In the Experiment 2 phase of the study, unlike Experiment 1, teams were expected to create their own context prompts to define the context in which they would design. The context prompts created by the teams were tested in the experimental setup prepared before Experiment 2 began. Context prompts were created only at the beginning of the experiment and were kept unchanged throughout the process, similar to Experiment 1. The visual context images are shown in Table 4. In accordance with the synthetic context prompts, Experiment 2 observed the teams' approaches to the context and design problem they had identified themselves. The teams were given time for preliminary preparation and, as in Experiment 1, were expected to prepare their initial model and prompts. The teams also experienced HDS in 10-minute intervals in Experiment 2. Experiment 2 concluded with the identification of the interventions they applied to the models and prompts, the determination of their final designs from among the architectural products they produced during the HDS process, and the creation of reports. Consistent with the methodology in Experiment 1, actions resulting in visual changes to the depth map were processed as model interventions, while changes ensuring uninterrupted, meaningful word and sentence structures were processed as prompt interventions. Finally, the quantitative data provided by the teams were verified by the instructors to ensure the accuracy and consistency of the reported interventions.

A survey was administered following two experiments conducted in the studio. Students were given a survey consisting of five 5-point Likert-scale questions and 1 two-option question to evaluate the HDS. The survey consists of questions measuring the impact of physical model and prompt interventions applied in HDS on the design, as well as questions measuring the difference between Experiment 1 and Experiment 2. The evaluation survey was completed by 26 students who participated in HDS. Expert opinions were gathered to evaluate the workshop process and its outputs. This process took place in two stages. First stage involved architectural evaluations of the designs produced. In this stage, four questions were asked for both experiments. In the second stage, experts acted as observers, reviewing the students' products and reports to gather pedagogical insights about the overall work. Finally, they were asked for their opinions on integrating HDS into the architectural design studio.

3. Findings and observations

The teams' design activities were monitored throughout the HDS workshop. Data collection encompassed the number of design steps, physical model interventions, and the quantity and content of prompts sent to the GAI model. At the conclusion of both experiments, interventions made by each team during the ten-minute intervals were identified and categorized. Examination of the results revealed a total of 476 interventions in the HDS process (Table 5, Fig. 4), comprising 39.5% architectural design prompts and 60.50% model interventions. In Experiment 1, where the design area was restricted by predefined context prompts, the total number of interventions was calculated as 205. Of these, 37.07% (76) were prompts and 62.93% (129) were model interventions. Team 1 recorded the highest rate of prompt interventions (28.95%), while Team 4 recorded the lowest (5.26%). Model intervention rates in this phase ranged between 15.50% and 18.60%. In the Experiment 2 phase, the removal of context restrictions allowed for a customizable at the team level and rendering the process unconstrained. This phase recorded a total of 271 interventions, of which 41.33% (112) were prompts and 58.67% (159) were model interventions. Regarding specific team performance in Experiment 2, the prompt intervention rate ranged from a low of 4.46% (Team 3) to a high of 25.89% (Team 6). Similarly, model intervention rates varied between 10.69% (Teams 4 and 5) and 27.04% (Team 2). Consequently, significant quantitative differences were observed between the two phases. In Experiment 2, the total number of interventions increased by 32.2%, with specific increases of 23.26% in model interventions and 47.37% in prompt interventions compared to Experiment 1.

The final design products selected by the participating teams from the design visuals created during Experiment 1 (left) and Experiment 2 (right) are presented in Table 6. A comparative visual analysis reveals distinct design patterns emerged between the two phases. While the predefined constraints in Experiment 1 resulted in formally cohesive and controlled solutions, the self-defined contexts in Experiment 2 led to considerably more stylistically diverse and structurally exploratory designs. Architectural model images and architectural design prompts corresponding to these studies are presented in Fig. S2-5 in the supplementary materials. Overall expert evaluations indicate that, although the unconstrained approach in Experiment 2 fostered greater experimental diversity, the guided nature of Experiment 1 yielded results that were perceived as more balanced in terms of traditional architectural criteria (Table 6).

The workshop process was evaluated using a survey administered to

Table 3
The model created by team-2 in Experiment 1 (left), the momentary depth map (middle), and the momentary design output obtained (right).

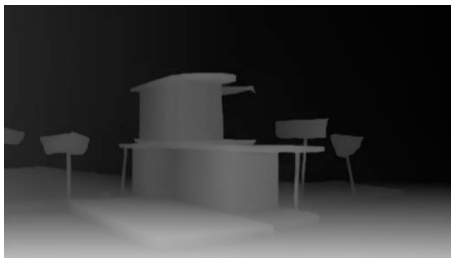
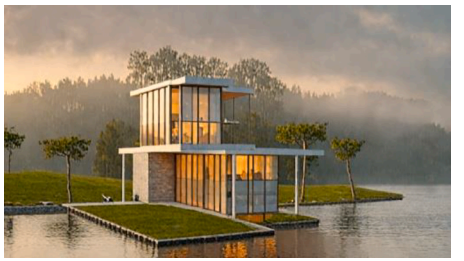
Webcam Input	DepthMap	Generated Image
		

Table 4
Visuals of the contexts created by teams in Experiment 2 (Context prompt and the visual representation of the context are shown in Fig. S1 in the Supplementary Materials).

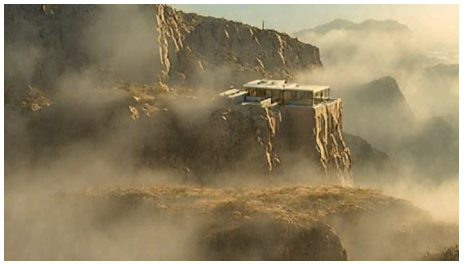
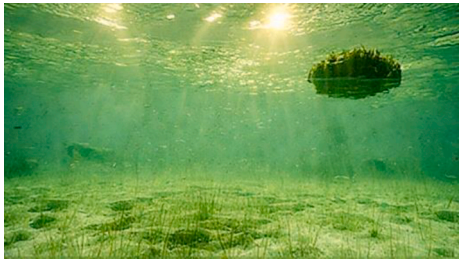
Team-1	Team-2	Team-3
		
Team-4	**Team-5**	**Team-6**
		

Table 5
The number and total of team interventions in design tools in Experiment 1 and Experiment 2 at HDS (When contextual constraints were removed, the total number of interventions increased by approximately 32%).

Hybrid Design Studio (HDS)	Team 1	Team-2	Team-3	Team 4	Team 5	Team 6	**Total**
Experiment 1	46	41	25	25	34	34	**205**
Experiment 2	54	66	33	29	33	56	**271**
Total	100	107	58	54	67	90	**476**

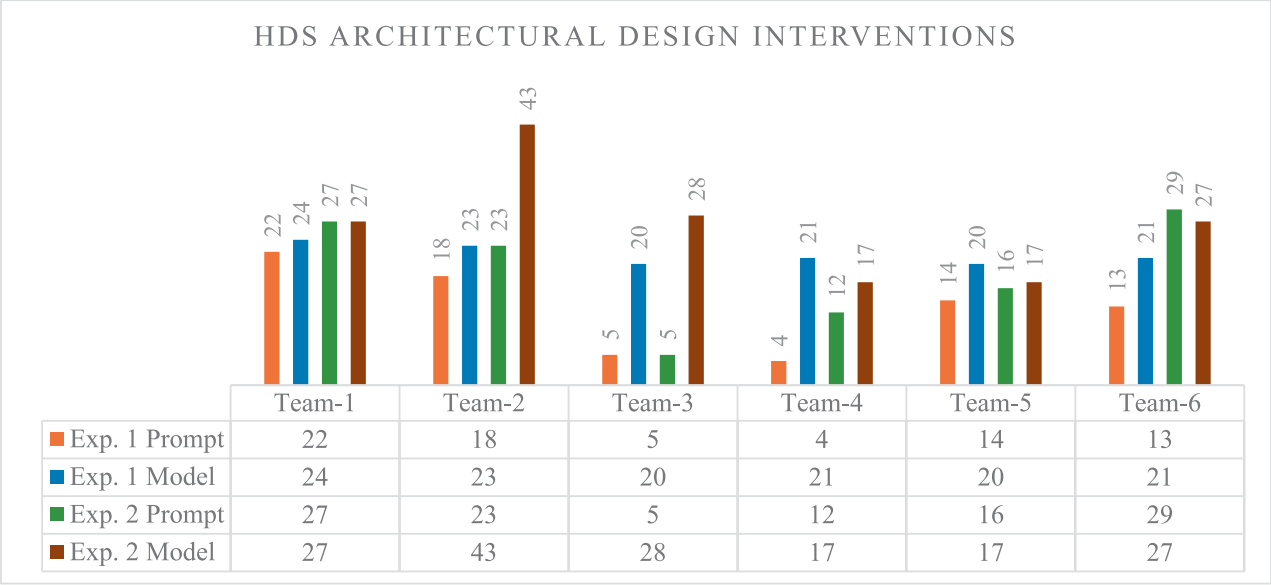


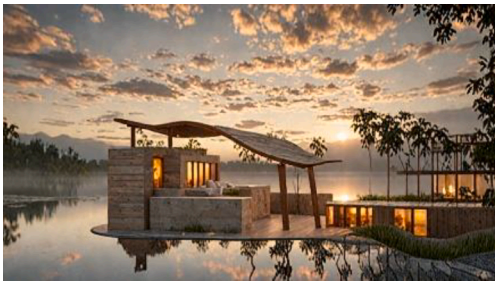
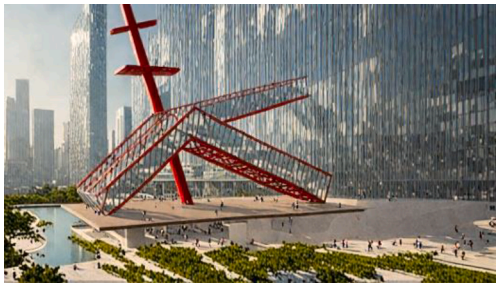
Fig. 4. Interventions by teams on models and prompts in the HDS (Team-3 and team-4 intervened minimally in the prompts throughout the process, but intervened more in the physical model).

the students upon completion. The survey consisted of 5-point Likert-scale questions [53] and one multiple-choice question. These questions were constructed based on two factors: the first examined the effectiveness of the physical modelling and GAI methods used in HDS, while the second tested the impact of removing the predefined context prompts during the Experiment 2 phase. Internal consistency tests were conducted for all structured survey questions and the two factors (Table 7). Additionally, the mean scores for these two factors were examined using a dependent-samples *t*-test, and the significance value was found to be less than $p = 0.05$, indicating a statistically significant difference between the factors. This statistical divergence aligns with the visual patterns observed in the design outcomes; it suggests that the students perceived the unconstrained context in Experiment 2 as a distinct methodological shift, which corresponding to the emergence of more stylistically diverse and structurally exploratory designs.

The survey questions are grouped under two main headings. Q1, Q2, and Q5 determine the effectiveness of the physical models and architectural design prompts used in the design, while Q3, Q4 (Table 8), and the two-option question shown in Table 9 determine the effects of the differences between Experiment 1 and Experiment 2. Based on the responses to the questions related to the first heading, the impact of architectural design prompts on design development was calculated as 4.27/5 (Q1). The impact of model-making, another supportive tool used in HDS, on design development was calculated as 4.62/5 (Q2). The average response to the question of whether there was a difference between the two tools used was measured as 2.00/5 (Q5). The fact that the results from Q1 and Q2 exceed 4.2 indicates that model-making and prompt-writing have a strong influence on the results. However, the fact that the average score obtained from Q2 is higher than that from Q1 indicates that model-making has a more significant influence on the results. The low score obtained from Q5 shows that there are observable differences between the two tools. The second category of survey questions examines contextual constraints. In Experiment 1, designs were made using predefined contexts, whereas in Experiment 2, teams developed their contexts using their own context prompts. The value indicating that the context prompts created by the students helped to achieve a better design output was calculated as 4.15/5 (Q3). The response to the question investigating whether there were any differences between the two experiments was calculated as 2.19/5 (Q4). Finally, a two-choice question (Q6) measured at which stage students produced more effective designs. 69.2% of students (18/26) thought they were more effective at designing in a predefined context, while 30.8% (8/26) thought they were more effective at designing in a self-defined context. This difference parallels Q4, which shows differences between the two experiments. This situation demonstrates that the context factor plays a decisive role in shaping the effectiveness of the design process. The 38.4% difference obtained from Q6 shows that the uncertainty inherent in the self-defined context (Experiment 2) can complicate the creative process, whereas the predefined context (Experiment 1) facilitates the concretization of the process by accelerating students' decision-making within a limited time.

To examine the relationship between survey data, Pearson correlation tests were performed between questions, and metrics for intra- and inter-factor relationships were created. When correlations were examined, it was observed that the questions established meaningful relationships both within and outside the factors (Table 10). In the first factor (see Table 7), the relationship between Q1–Q2 (effects of prompt and model-based design development) ($r = 0.7438$, $p = 0.0001$) constitutes the strongest significant relationship. Participants who believe that architectural design prompts have a strong effect on design generally believe that model making has an even stronger effect on design. The relationships between Q1–Q5 ($R = 0.4783$, $p = 0.0135$) and Q2–Q5

Table 6
HDS Experiment 1 the selected design image (left), HDS Experiment 2 the selected design image (right) The averages of the experimental stages evaluated by experts in terms of visual quality, architectural originality, form and proportions, and contextual harmony are 3.77/5 for Experiment 1 and 3.48/5 for Experiment 2 (The evaluation questions and expert answers are shown in Table S1 in the supplementary materials).

TEAM	Experiment 1 (Expert Score: 3,77/5)	Experiment 2 (Expert Score: 3,48/5)
TEAM-1		
TEAM-2		
TEAM-3		
TEAM-4		
TEAM-5		

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Table 6 (*continued*)

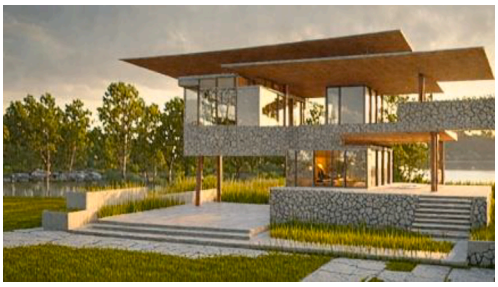
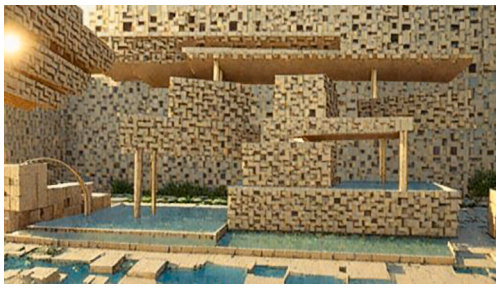
TEAM	Experiment 1 (Expert Score: 3,77/5)	Experiment 2 (Expert Score: 3,48/5)
TEAM-6		

Table 7
Cronbach's Alpha values and standard deviations for the factors and the entire survey (The internal consistency of the survey is 0.7875, Paired-Samples T-Test on Inter-Factor Scores p = 0.0008, Chi-Square Test of Independence for Inter-Factor Relationship p = 0.8620).

Scale	Number of items	Cronbach's alpha	Min. total score	Max. total score	Standard deviation	Score mean
Factor 1 (Q1, Q2, Q5)	3	0.7731	8	13	1.6572	3.6282
Factor 2 (Q3, Q4)	2	0.7252	3	8	1.2631	3.1731
Total Scale (Q1 − Q5)	5	0.7875	13	21	2.5189	3.4462

Table 8
Survey questions and their mean values.

Likert-type questions (abbreviated as Q)	Mean
Q1: Architectural design prompts have been influential in the development of the design.	4,27
Q2: Model making has been effective in the development of the design.	4,62
Q3: Creating context prompts allowed me to create better designs.	4,15
Q4: There was no difference in the development of the design between the first experiment and the second experiment.	2,19
Q5: There was no difference between interfering with the prompt and intervening in the model when designing.	2,00

Table 9
Two-option survey question and answers.

Two-choice question	Experiment 1	Experiment 2
Q6: Which stage do you think you design more effectively?	%69,2 (18)	%30,8 (8)

(R = 0.4044, p = 0.0405) are moderately significant. These relationships indicate that participants who believe both prompts and models contribute significantly to design perceive a difference between the effects of prompts and models on design development. In the second factor, the Q3–Q4 relationship (R = 0.5818, p = 0.0018) is strong and significant. Participants who perceive the effect of the constrained context on the design as high indicate that removing the context constraint between experiments affects the design process. Furthermore, there are moderate cross-relationships between the factors. The Q1–Q4 relationship suggests that architectural design prompts may be related to the perception of differences between the two experiments. The Q1–Q3 relationship suggests that design prompts influence context prompts. The Q2–Q3 relationship suggests that models and context may contribute jointly. Although these relationships between factors are not directly related to the research objective, they are important findings.

In the HDS process, expert opinions were included alongside student self-assessments to better understand the impact of models and prompts on design and the differences across experiments. The final architectural design visuals created by the students were shared with and evaluated by faculty members teaching at the xxx University School of Architecture for expert opinion. Expert opinions were scored on a scale of 1–5 in terms of the visual quality, architectural originality, form and proportions, and contextual harmony of the designs produced. The averages of the 12 expert opinions are given in Table S1. Looking at the evaluation criteria (Fig. 5), it is seen that Experiment 1 (3.92/5) has higher averages than Experiment 2 (2.83/5), especially in terms of visual quality (4.25/5) and form-proportion (3.92/5). In terms of contextual harmony, Experiment 1 (3.33/5) is slightly higher than Experiment 2 (3.00/5), but both experiments have average values in contextual harmony. Experiment 2 is viewed more positively than Experiment 1 (3.58/5) in terms of architectural originality (4.16/5). Differences in the average scores were observed between experiments. Experiment 1 has a higher architectural evaluation (3.77/5 average) than Experiment 2 (3.48/5).

When expert opinions are examined, it is observed that the attributes of form and proportions exhibit parallelism with visual quality. Considering that physical models have a greater influence on form and proportions, while prompts have a stronger impact on visual quality, this indicates that physical models and prompts mutually influence each other during the design process. Examining the score difference between Experiment 1 and Experiment 2 reveals that the predefined context has a positive impact on the final product. However, architectural originality and different approaches are observed to be considerably more effective in Experiment 2. This situation parallels the participants' choice of

Table 10
Pearson correlation matrix (it is observed that the two factors consisting of Q1-Q2-Q5 and Q3-Q4 questions establish meaningful relationships within themselves).

Pearson correlation	Q1	Q2	Q3	Q4	Q5
Q1	1.00	**R = 0.7438 (p = 0.0001)**	**R = 0.4170 (p = 0.0341)**	**R = 0.4927 (p = 0.0105)**	**R = 0.4783 (p = 0.0135)**
Q2	**R = 0.7438 (p = 0.0001)**	1.00	**R = 0.4052 (p = 0.0400)**	R = 0.2126 (p = 0.2972)	**R = 0.4044 (p = 0.0405)**
Q3	**R = 0.4170 (p = 0.0341)**	**R = 0.4052 (p = 0.0400)**	1.00	**R = 0.5818 (p = 0.0018)**	R = 0.2944 (p = 0.1443)
Q4	**R = 0.4927 (p = 0.0105)**	R = 0.2126 (p = 0.2972)	**R = 0.5818 (p = 0.0018)**	1.00	R = 0.2733 (p = 0.1767)
Q5	**R = 0.4783 (p = 0.0135)**	**R = 0.4044 (p = 0.0405)**	R = 0.2944 (p = 0.1443)	R = 0.2733 (p = 0.1767)	1.00

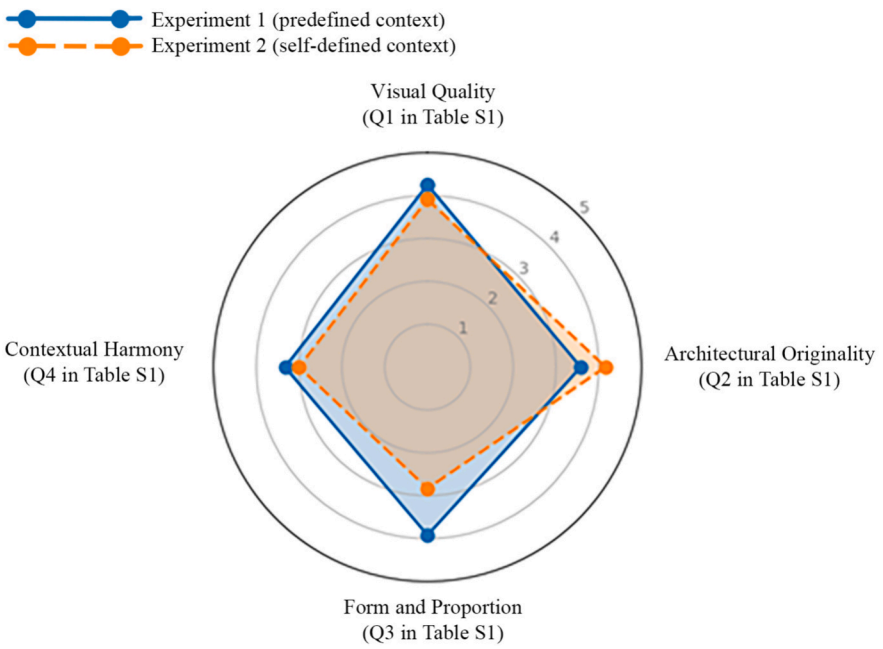


Fig. 5. Comparative analysis of two experiments on expert evaluation criteria (Comparative visualization of design performance indicators; the blue line represents the predefined context (Experiment 1), while the orange dashed line represents the self-defined context (Experiment 2)).

experiment stage question in the two-option question (see Table 9) and the question showing that the teams creating the context prompts exhibited more effective behaviors in the design (see Table 8, Q3).

In addition to the quantitative evaluation of design outcomes, experts acted as observers by reviewing the students' products and reports to gather pedagogical insights regarding the overall workflow. Their opinions on the integration of HDS into the architectural design studio were collected (see Table S2 for the specific question and detailed responses). Qualitative data obtained from experts were classified using thematic content analysis to identify common viewpoints and recurring patterns. The results indicate that opinions largely clustered around the main themes of 'Enhancement of Design Exploration' (75%), 'Pedagogical Contribution' (58.3%), and 'Necessity of the Hybrid Method' (50%) (Table 11). This distribution suggests a general consensus on the potential of the method to enrich the design process while maintaining the complementary role of physical modeling.

Aligning these findings with the research aims highlights two key outcomes. First, the simultaneous real-time approach proved effective: physical modeling acted as the primary driver, while prompt writing served as a strong supporting tool. Second, regarding contextual constraints, predefined contexts accelerated decision-making by reducing uncertainty. In contrast, self-defined contexts demonstrated GAI's potential for conceptual definition, despite the challenges of managing an open-ended design process.

Table 11
Thematic analysis of expert opinions (the dominant theme is enhancement of design exploration with a 75% rate).

Theme	Frequency (f)	Percentage (%)	Sub-concepts	Related experts
Enhancement of Design Exploration	9	%75	Generation of alternatives, Increased creativity, Process acceleration, Daring experimentation	Expert-1, Expert-3, Expert-4, Expert-5, Expert-6, Expert-8, Expert-10, Expert-11, Expert-12
Pedagogical Contribution	7	%58,3	3D thinking skills, Perception of proportion/scale, New horizons/ vision, Integration into education	Expert-2, Expert-3, Expert-5, Expert-7, Expert-9, Expert-11, Expert-12
Necessity of the Hybrid Method	6	%50	Insufficiency of AI alone, Complementarity of model & AI, Impact of simultaneous use	Expert-2, Expert-4, Expert-5, Expert-8, Expert-10, Expert-12

4. Discussion

Within the scope of this study, the simultaneity and reciprocal interaction of design tools used in HDS, as well as the effect of contextual constraints on the hybrid design process, were investigated. Current studies indicate that hybrid design approaches are more effective than the use of single design tools [33–38]. For instance, while recent research by Tong et al. [37] and Özorhon et al. [38] has explored the sequential integration of GAI and physical tools in architectural education, the HDS framework distinguishes itself by focusing on real-time interaction. This study provided the opportunity to experience physical models and GAI tools simultaneously. The presence of 288 models and 188 prompt interventions across Experiment 1 and Experiment 2 provides evidence that the two tools can be used interactively and simultaneously. Looking at the survey responses, the fact that Q1 and Q2 scores are above 4 indicates that the combined use of these two tools positively affected the process. In the HDS process, 60.5% of the total number of interventions were model interventions, and 39.5% were prompt interventions. The results of 4.22/5 (Q1) and 4.62/5 (Q2) in the survey show that model making has a higher impact on design development than prompt writing. At the same time, the average of 2.00/5 (Q5) indicates that designing with two tools is different. These findings are consistent with Driscoll [14], who states that model making is still an effective design tool today. The importance of model making in design is preserved with hybrid design systems that combine digital tools with physical tools such as models [18]. Meanwhile, as Oxman [13] states,

digital transformation does not make physical tools redundant, but rather incorporates them into a hybrid methodology.

To measure the impact of the contextual constraint on the design process, two experiments were conducted: one with a contextual constraint and one without. In Experiment 2, it was found that students could generate architectural design contexts using the prompts they developed (see Table 4). As another output of HDS, when comparing Experiment 1 and Experiment 2, it was observed that the total number of interventions increased by 32.2% from 205 to 271 in Experiment 2. This situation parallels the 4.15/5 response given to Q3. Furthermore, the differences between the Experiment 1 and Experiment 2 processes are supported by Q4 (2.19/5) in the questionnaire. As identified by Tezel and Casakin [42], Q4 shows that design approaches change with changing constraints. However, the data obtained from Q6 indicates that students performed more effective design in the Experiment 1 phase. As mentioned by Lawson [5], the sequential two experiments conducted in HDS support that architectural design constraints act as filters in design solutions. It is seen that the constraining filter also limits intervention during design. The idea that students design more effectively in experiments with contextual constraints can be linked to the view that constraints are guiding elements in creative processes, as stated in the research by Pauwells et al. [3]. In Experiment 2, the removal of the contextual constraint also brought with it a new design problem for the students to solve. This circumstance has made it difficult to achieve the desired design solution, leading to an increase in the search for alternatives.

4.1. Pedagogical Takeaways

The findings of this study provide opportunities for pedagogical implications in architectural design education. Physical models continue to be important tools that enable students to represent their ideas concretely in the early design stages. This enduring relevance aligns with the content analysis, where 50% of the experts drew attention to the 'Necessity of the Hybrid Method,' suggesting that AI tools benefit significantly from the tactile grounding of physical models [18]. First, physical models used simultaneously with the GAI tool enable students to test their abstract ideas, positively contributing to visual thinking and reflective design practice in a manner that supports Schon's [2] concept of “reflection-in-action”. This has accelerated the thought process, which previously took a long time to concretize. Notably, a prominent theme in the expert feedback was the ‘Enhancement of Design Exploration’; 75% of the experts indicated that the hybrid workflow appeared to accelerate the design process and encourage the exploration of more daring alternatives. It broadens students' horizons in terms of combining technology with the concept of design and increases their interest in similar hybrid methods. Furthermore, the ability to instantly observe the effect of the visuals obtained as a result of the study on proportion, scale, and form has enabled students to understand the possible effects of their design interventions more quickly. Qualitative data obtained from expert opinions showed that the simultaneous use of two- and three-dimensional environments contributed to the development of students struggling with three-dimensional thinking (Table S2). In this context, 58.3% of the experts touched upon the aspect of ‘Pedagogical Contribution,’ noting that the method offers support for addressing challenges related to 3D visualization and scale comprehension. Secondly, predefined contextual constraints (Experiment 1) provide a production space that guides creativity rather than limiting it [3]. Processes that occur without constraints (Experiment 2), on the other hand, carry the risk of increasing uncertainties and problems that need to be solved in the design process. The hybrid approach used in the research has the potential to accelerate trial-and-error processes by encouraging a continuous feedback loop between human reasoning and machine production. This makes it possible to quickly generate ideas about more alternative design scenarios and test the potential effects of design inputs in a very short time. Through this interaction, a new environment is proposed in studio-based design pedagogy by simultaneously revealing students' analytical and intuitive thinking styles. However, despite their potential positive effects, AI tools continue to carry risks due to the lack of comprehensive research on their impact on developing students' fundamental skills [29]. As research on hybrid design approaches increases, our knowledge base on the benefits and limitations of current tools will continue to grow.

5. Conclusion

The concept of design and the act of designing are, by nature, complex. Tools that facilitate CAAD processes, leveraging increasingly powerful hardware, have evolved over time, giving rise to alternative design approaches. Today, in addition to the CAAD and computational thinking processes, the contribution of AI-supported generative models to design actions is being researched. Within the scope of this study, the effect of the simultaneous coexistence of GAI and physical models in real time on the architectural design process was investigated in the developed HDS. Through the advent of the two-way hybrid design cycle that includes models and prompts, the design process is accelerated, and design alternatives are effectively incorporated into the process. Designers have the opportunity to select the desired design product from the numerous options offered by GAI. The effectiveness of these productions and the impact of design constraints on the process were evaluated by applying the selected methods within the scope of the study.

- The findings of the study reveal that the integration of physical and digital tools enriches design production processes. In the design experiments, which involved the simultaneous and interactive use of architectural model production and AI prompts, it was observed that the tools supported design practice by feeding off each other. It was determined that the impact of models on the final product was higher than that of prompts in HDS. Familiarity with the tools learned within traditional design practice is seen as the reason for this finding.
- In Experiment 2, unlike Experiment 1, students also created their own context prompts. The difference between the two experiments, namely the personalization of the design context, accelerated the hybrid design process. While leaving the design context to the teams increased the search for alternatives, it was noted that it made access to the final product more difficult. Therefore, most participants concluded that the Experiment 1 phase, where the design problem was defined, was more efficient. Design processes were carried out without deviating from the defined context in both phases. It was observed that teams were able to generate their own context within a short period of time and design within those contexts. For this reason, it is concluded that GAI models can easily simulate synthetic or real contexts.

It is important to acknowledge the limitations that define the scope of this research. Since this study was conducted as a single-day workshop with a group of 26 students, it should be viewed as a preliminary exploration rather than a definitive conclusion. Consequently, the ability to generalize these findings is currently limited, and future studies should aim to verify these results with larger participant groups. However, the HDS framework, which was developed using the DBR methodology, offers a highly flexible structure. This structure preserves the core collaboration between physical models and GAI, even as specific technologies change over time. This adaptability ensures that the method remains reliable, allowing future researchers to quickly discover and test innovative hybrid design processes.

Moving forward, this study points toward clear paths for further development. The approach can be expanded through workshops that span multiple sessions or different institutions to test how well it applies across diverse educational and cultural environments. Furthermore,

tracking students' progress over a longer period is essential to reveal the lasting effects of this method on their cognitive and creative skills. Additionally, the HDS approach holds significant potential for integration with new technologies, such as Virtual Reality (VR). Using VR alongside or instead of physical models in future versions could deepen students' interaction with form and spatial visualization. Ultimately, synchronizing AI-supported production with physical models demonstrates that architectural design is evolving into a truly hybrid discipline, which will require deeper cooperation between different disciplines in future academic studies.

6. Ethical approval and informed consent statements

Ethical committee approval has been obtained for this study.

7. Data availability statement

The data that support the findings of this study are available on request from the author(s).

8. Declaration of generative AI in scientific writing

No generative AI was used in the scientific paper. Everything in the study was created by the authors.

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CRediT authorship contribution statement

Barış Mert Karasu: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adil Yirmibeş:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.asej.2026.104198.

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