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Cognitive Comparison of design methods in the conceptual phase

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Abstract

The initial phases of design, known as the conceptual design phases, are often associated with hand sketching, while parametric tools are reserved for the later, more developed stages of design. This paper examines the potentials of using parametric tools in the early design phases in comparison to widely utilized hand sketching. It is intended to find out the impacts of using parametric tools on the cognitive behaviors and the satisfaction of self-assessment levels of the designers. An experimental study was conducted with a group of graduate architecture students using Grasshopper, the findings of which are analyzed through a content-oriented coding scheme, together with protocol analyses. Significant differences are found between cognitive behaviors of the participants in using hand sketching and Grasshopper. The findings show that all of the participants consider Grasshopper as a useful conceptual design tool that may be utilized in early design phases, in contrast to its wide popularity in the late stages of design.

Keywords

Design cognition, parametric design, hand sketching, conceptual design phase, computational design, protocol analysis

Parametric modeling tools in general and Grasshopper (operating with Rhino 3D) in particular have been widely used in the design process for the past few decades. However, their use is more associated with later phases of the design process. While sketching is often associated with conceptual design,[1–3] parametric tools are seen as suitable for the further detailed design processes.[4–10] In the conceptual phase, often design ideas are generated and assessed quickly one after the other. Usually, this is done by producing quick sketches of the ideas. Parametric tools are often conceived to be too powerful, too complex, and too demanding for this stage and are reserved for the later phases of design, especially for after the design begins to take shape.

Thus, particularly in these early stages of design, when the conceptualization takes place and quick sketches are produced to test the initial design ideas, designers seem to be preferring hand sketching. Goldschmidt[11] expressed that hand sketches are very important in design activity for conveying designers'

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thoughts, and they are necessary and effective tools for the dialectic thinking process of designers. Sketching is especially effective in the conceptual design phase for defining, developing, revising, and combining the varied ideas easily and quickly. Sketches are considered to be the conceptual design medium itself, generating and supporting creative ideas,[12,13] and continually offer iterative design processes that allow designers to assess and reconsider different alternatives and results.[14–16]

In terms of the cognitive aspect of design, Schön[17] examined the relationship between designers and hand sketches. Designers quickly create various ideas and put these ideas on paper while sketching. They can examine and assess their own sketches while transferring ideas from their minds to paper and discover unexpected ways of solving design problems. Therefore, hand sketching enables the designer to explore unintended outcomes and enables them to think back on what has been done in the design process. In this regard, Schön[17] defined the design activity as a "reflective practice" within his "reflection-in-action approach." This approach has been often used in the design field to investigate and evaluate the cognitive aspect of the design process.[18,19] Goldschmidt[11] expressed that there is a dialogue between designer's "seeing that" and "seeing as," where "seeing that" is reflective criticism and "seeing as" is the analogical reasoning and reinterpretation of the sketch. One of the reasons why hand sketching is considered as a cognitive process is that sketches have continuously varying and unexpected contents, especially in the conceptual design phase.

In the last decades, the use of sketches has been greatly influenced by the emergence of computer tools and the growing interest in digital technologies, leading to discussions on whether sketches will continue to be an integral part of the design process or be replaced by digital technologies.[20–22] Goldschmidt[23] argues that hand sketches cannot easily be replaced and removed because of their cognitive benefits in the conceptual design phase. It is then worth investigating how new technologies, such as parametric modeling tools, may be used and contribute to this phase.

In order to explore the effects of parametric tools on the conceptual design phase, the cognitive processes of the designers in hand sketching and in using parametric tools are studied, compared, and analyzed. Despite the extensive literature on the cognitive behaviors of designers while hand sketching, the role of parametric tools in terms of design cognition has not been thoroughly examined. The study by Lee et al.[24] offered strategies for adopting parametric design for creating creative solutions. In line with their study, this study is based on cognitive research on a parametric tool (Grasshopper) in comparison to hand sketching to assess the potential of parametric tools in the conceptual design phase. As such, the study aims at answering the following three questions: *first*, whether parametric tools are capable of contributing to the early design phase and what their potentials are; *second*, how the media (hand sketching and parametric tools) may be used together in the conceptual design phase, and how parametric tools differ from hand sketching in supporting different design strategies (the problem-driven and solution-driven approaches); *third*, how parametric tools support the cognitive processes of the designers and whether they have them produce more cognitive activities, and if so what are those specific activities.

Research methodology

Within this conception, a study was conducted using hand sketching and Grasshopper in the conceptual design phase. The study was carried out by six participants, who are graduate students of a master of science in architecture program. Following a pilot study, a design session, where the participants were asked to fulfill a conceptual design task, was carried out and the session was monitored. Protocol analysis is carried out to investigate the cognitive behaviors of the designers.

Protocol analysis

Protocol analysis is widely used to understand how designers design and mainly aims at exploring the cognitive processes of designers.[25–27] Protocol analysis consists of two consecutive procedures: data collection and data analysis. There are basically two approaches for data collection: "concurrent" and "retrospective."[27] Although each approach aims at revealing cognitive behaviors of designers, they differ in terms of the collection type and the content of verbal data. In order to obtain verbal data with concurrent protocol analysis (C.PA), the participants are asked to design and verbalize their thoughts simultaneously. In this method, participants are expected to express their thoughts while they are dealing with a design problem. Participants have limited time to express their thoughts while designing in the experiment. Constraints caused by concurrency prevent the simultaneous interpretation of the design process.[27] On the other hand, in retrospective protocol analysis (R.PA), the verbal data is obtained from verbalization of a participant's recall of thinking after s/he completes the design task. When designers finish the design task, they are asked to report about the design process and reflect on what they did in the experiment. In most of the cases, after participants complete the experiment, they watch their recordings and videotapes of the design sessions to remember their design activities. These visual records are utilized as clues during retrospective verbalization to remind participants how they designed during the experiment.

Although there are studies in which the efficiency of hand sketching and parametric modeling tools is studied separately, there are few studies that study the efficiency of both, through protocol analysis methods. Table 1 shows some of those studies. The average sample size for these studies is 7.

L. Hay et al.[25] carried out a comprehensive study for reporting the protocol analysis studies that focus especially on the cognitive approach of conceptual design process. They investigated 47 protocol analysis studies on architectural design, product design engineering, and also engineering design. The total number of participants in these studies is 350 designers. In each study, the number of participants in the studies ranged from 1 to 36, and the participants' average number was 7.

Table 1. Examples of various protocol analysis studies.

Year	Author	Field	Method	Medium	Experiment time	Number of participants
1997	Suwa and Tversky[18]	Architecture	R.PA	Hand sketching	45 min	9
2001	Won, P[28]	Industrial design	R. PA	Hand-digital sketching tools	1 h	2
2001	Bilda, Z[29]	Interior Architecture	R. PA	Hand-digital sketching tools	3 h	6
2001	Kavaklı and Gero[30]	Architecture	R.PA	Hand sketching	1 h	2
2010	Tang et al[31]	Industrial design	C.PA	Hand sketching-geometric tools	1 h	20
2013	Sun et al[32]	Engineering	R.PA	Digital sketching	Open-ended	15
2015	Lee et al[33]	Architecture	R.PA	Parametric tools	1 h	4
2015	Yu, R. and Gero, J[34]	Architecture	C.PA	Parametric-geometric tools	1 h	8
2017	Tahsiri et al[35]	Architecture	C.PA	Hand sketching-geometric tools	40 min	5
2017	Shih et al[36]	Architecture	C.PA	Hand sketching-geometric tools	75 min	6
2018	Lee et al[37]	Industrial design	C.PA	Hand-digital sketching tools	60 min	8

R. PA = retrospective protocol analysis.
C.PA = concurrent protocol analysis.

Content-Oriented coding

The main paradigms of approaching to the design process are *the rational problem solving process*[38] and *process of reflection-in-action.*[17] The first one involves analysis, observation, and generalizability, whereas the second one involves framing of the problem, taking action, and improving the current situation.[19] The first one corresponds to the process-oriented protocol analysis, and the second one corresponds to the content-oriented approach. In this study, the content-oriented approach to qualitative coding is applied to multimodal documentation of design sessions through transcripts of verbal and recorded activities. Segments are identified and coded as different types of cognitive actions associated with design concept development. The purpose of segmentation is to divide the whole verbal data into smaller parts named as *segments*. Partitioning the protocol according to the coding scheme makes it possible to organize and analyze the protocol easily and clearly. The segmentations indicate the changes in the design intent and action of the designer. Each segment corresponds to a different design intention in the design process. The following table demonstrates participant 4's segments as a sample (Table 2).

Suwa et al.'s[39] coding scheme is one of the most well-known content-oriented coding schemes associated with the content-oriented approach that aims to reveal the contents of what designers see, attend to, think of, and retrieve from memory while designing. It is used by various researchers.[33,37,40] In this coding scheme, four cognitive action categories are devised: *physical*, *perceptual*, *functional,* and *conceptual*, in order to show information processing in human cognition. Each action category is divided further into subcategories and each subcategory is specified with a code for analyzing the verbal data. As Suwa et al.'s[39] coding scheme was devised for hand sketching, in order to make it more suitable for a parametric design environment, subaction categories were revised. Bilda[29] and Lee et al.'s[33,41] coding schemes were utilized to achieve a revised scheme comprising digital actions (Figure 1).

A partial example of the coding scheme based on the encoded actions of the segments is shown in Figure 2. Although all of the conceptual and functional actions were encoded from the verbal reports of the participants, the vast majority of the physical and perceptual actions were obtained from the video recordings in the experiment.

Table 2. A sample of segmented protocols (Participant 4).

Segment	Protocols
12	I wanted to understand the scale so I tried to create some points at 3 meters and according to that, I arranged other points' heights. Here...Place the points in the z axis. Iam playing with them (points) in top view now. Because in a design we should be aware of the plan view, not only sections or evaluations. So I am thinking about all of the views and revising the heights of the points again
13	Here, I aimed to locate the entrances, I wanted to design to be, and I wanted everyone to enter this project from all views so I designed some openings in here. I am thinking about his (enterance) when Iam rotating this shape. Yes...I am changing the direction in there for creating different shapes
14	After that , now, I am giving thickness to pipe lines. I changed the pipe lines radii and arranged them. I want to design thin lines, thin structure. Beacuse I don't want it to be a heavy design. Do not want hese steel parts to be too dominate in this design. The structure would otehrwise be too heavy so I made them thin.
15	Then, I created delaunay meshes with the pipe lines. It (delaunay triangles) is for making surfaces. I bought these surfaces in line with each other. I was trying to create closed spaces. I like these triangle parts.
16	Now I am thinking about the general shape that becomes like a shell structur. Yes, it (structure) is closed. Ican mae openings wherever I want but in the end, it will be only like a shell structure even if I create furniture for standing or something like taht with the triangulated shape. But I did not want to be like that. It is too planar and I do not like it. Beacause of that I added more volume.

ACTION CATEGORY	SUBCATEGORY	ACTION ID	DESCRIPTION
PHYSICAL	Create	Dcg	Creating new geometry/depiction
		Dcp	Creating new parameter*
		Dcr	Creating new rule*
	Modify	Dmg	Modifying the geometry/depiction
		Dmp	Modifying the parameter*
		Dmr	Modifying the rule*
	Erase	Deg	Erasing a geometry/depiction
		Dep	Erasing a parameter*
		Der	Erasing a rule*
PERCEPTUAL	Features	Pfg	Attending to visual features of a new geometry (shape, size, angle etc.)
		Pfa	Attending to the graphical depiction of the algorithm*
	Relations	Prs	Attending to spatial relations among elements (proximity, alignment, intersection, etc.)
		Prl	Attending to the links between the parameters*
		Prg	Discovering a space as ground
	View	Pvf	Attending to the feature of a view in 3D (imagery or graphical)
FUNCTIONAL	Implement	Fn	Associating a new depiction, feature or relation with a specific function that was previously thought or newly discovered
		Fi	Implementing of a function independently of geometries
		Fi-re	Re-interpretation of a function
	Reactions	Fri	Exploring the issues of interactions between artefacts and people/nature (functions, tool-user relation, or psychological reactions)
CONCEPTUAL	Goal setting	Cg	The intentions designers want to achieve
	Retrieve knowledge	Ck	Retrieving knowledge from memory
	Evaluation	Ce	Making preferential and aesthetic evaluations (like-dislike, good-bad, beautiful-ugly, etc.)

* For parametric design environment only (Grasshopper)

Figure 1. Coding scheme of cognitive actions.

Segment-12

Action Category	Action ID	Content
Physical	Dmg Dmp Dmp Dmg	 playing points revising height
Perceptual	Pfg Pvg Pvf Prs	3 meters in z axis
Conceptual	Cg Cg Ck Ck Ck	tried to create wanted to understand in top view should be aware of the plan view thinking about all the views

Segment-13

Action Category	Action ID	Content
Physical	Dmg Dmp Dmp Dmg Dcr	rotating this shape
Perceptual	Prs Pvf	changing the direction
Functional	Fn Fn Fri	entrances openings everyone to enter this project
Conceptual	Cg Ce	aimed to locate different shape

Segment-14

Action Category	Action ID	Content
Physical	Dmg Dmg Dcp Dcr Der	arrange pipelines change the pipeline radii
Perceptual	Pfg Pfg Pfg Pfa Prl	thin lines thicknesses steel
Conceptual	Cg Ce Ce Ck	I want to design too heavy too dominant these steel parts to be too dominant

Segment-15

Action Category	Action ID	Content
Physical	Dcp Dcp Dmp Dcr	delaunay mesh pipeline
Perceptual	Prs Prs Prg Pfg	make surfaces brought these surfaces in line create spaces triangle parts
Functional	Fn	closed space
Conceptual	Cg Ce	I was trying to create I like these

Segment-16

Action Category	Action ID	Content
Physical	Dcp Dcp Dep Dcr Dcr Dcr	
Perceptual	Pfg Pfg Pfa Prl	triangulated shape I added more volume
Functional	Fn Fn Fi	it (structure) is closed openings create furniture for standing
Conceptual	Cg Ce Ck Ce	I am thinking the general shape But I did not want to be like that it will be only like a shell structure too planar

Figure 2. Partial sample of the encoded segments.

The study

The study group consisted of six graduate architecture students, all with undergraduate architecture degrees in 4 + 2 programs. They were randomly selected from the 10 students, who are enrolled in a graduate program of architecture. The selection of such a group of students is made to ensure that their levels of design skills are similar. Previous protocol analysis studies on the cognitive behaviors of designers are usually handled with a relatively small group of participants (min 2 max 20 participants) (Table 1), but they provide an in-depth study of the samples and rich data.[42,43] Such limited number of participants is preferred in protocol analyses, as very large data sets are produced.[31] Although protocol analysis focuses on a limited sample size, it allows for a thorough and comprehensive examination of each sample. Consistent with past research studies in this area, this study is conducted with a limited sample size, providing insight as the information collected and analyzed is of high quality and in-depth. However, it is important to note that the findings of this study cannot be generalized to describe the behaviors of a larger population. Yet, despite this limitation, studying the behaviors of a limited sample in-depth can help us gain a better understanding of the process, as in similar studies.

The participants were initially asked to answer some questions about their level of knowledge in using Grasshopper and hand sketching. All had completed courses involving hand sketching in their undergraduate programs. Five of them had prior knowledge about Grasshopper, having previously carried out projects using the software. The remaining group took courses on Grasshopper, but they did not use the software for design purposes before. Thus, the participants are grouped as "experienced" and "inexperienced". All of the participants (in pilot study and main study) were female, and they volunteered to participate in this study (Table 3).

Pilot study. Four participants, different from those who participated in the main study, joined in the pilot study. Two days before the pilot study, a training session on Grasshopper was held. The training session lasted for 4 h. The aim of this training session was to tutor the participants and show them advanced examples done with the software. The training focused on the surface tools, the most-used parameters, menu items, and components in Grasshopper. The pilot study facilitated the evaluation of the following factors: The sufficiency of the time for subjects, appropriateness of research setting location, conditions and software programs, the adequacy of technical devices such as cameras and videotapes, adequacy of design briefs, and the convenience of the coding scheme. As a result of this pilot study, the design brief, time, and computer lab conditions were found to be appropriate for the subjects and the coding scheme proved to be efficient (Figure 3). However, the training session had a negative impact on the inexperienced participants. It had a direct influence, and students tried to make similar designs to the ones they did in the training section, instead of exploring the potentials of the software and hence was cancelled for the main study. The power analysis made by the G*Power 3.1.9.6. software for the cognitive actions in the pilot study (with four participants) demonstrated the following results. Mean ± Std. for D, P, F, and C, respectively, are as follows: for sketching: Deviation (31.25 ± 2.5, 31.5 ± 8.06, 18.25 ± 5.95 and 29.25 ± 3.63) and for Grasshopper: Deviation (154.25 ± 17.57, 88.75 ± 10.44, 45.5 ± 9.79, 45.25 ± 5.63). Impact power calculated over the values is 3.498. The power for D, P, F, and C actions is 9.8, 6.138, 3.363, and 3.377, respectively, and alpha (α) is 0.05. Therefore, the minimum sample size was determined to be four for D and six for P, F, and C, to be evenly distributed among the groups.

Main study. In the main study, the participants were free to use hand sketching and Grasshopper alternatively, switching in between as much and as often as they required. Debut software was used to record the changes in the designers' computer screens while they used Grasshopper. These recordings were useful for the

Table 3. General profile of the participants.

	Subjects	Gender	Age	Year	Experience in GR	CGPA
Policy study	1	F	24	(2nd year) graduate student	Inexperienced	3.17
	2	F	23	(2nd year) graduate student	Inexperienced	3.06
	3	F	23	(1st year) graduate student	Experienced	3.37
	4	F	23	(1st year) graduate student	Experienced	3.14
Main Experiment	P1	F	24	(2nd year) graduate student	Inexperienced	2.98
	P2	F	22	(1st year) graduate student	Inexperienced	3.31
	P3	F	24	(1st year) graduate student	Inexperienced	3.44
	P4	F	26	(2nd year) graduate student	Experienced	3.71
	P5	F	22	(1st year) graduate student	Experienced	3.04
	P6	F	22	(1st year) graduate student	Experienced	3.42

Figure 3. Experiment setting (the computer lab).

participants to recall their design process. Three video cameras were located above the tables, positioned between every two participants. These recordings were used in the retrospective interview sections.

Before beginning with the main study, each participant completed a survey about their educational background and level of experience in using Grasshopper. A design brief was distributed to the participants, and they were given 15 min to examine the brief before getting on with the task. The process was composed of one design session. The participants had 1 hour to design. The differences in seconds were ignored. The design task was a shelter on campus, a self-standing structure to house 15–20 people underneath, protecting them from the weather conditions. The site given for the shelter was one of the large lawn areas on campus, reserved for recreational purposes. The design task was rather simple, to encourage the participants to do different concept explorations. The participants were expected to come up with conceptual designs, rather than detailed drawings. The day after the main experiment, each participant was allocated a different time interval to carry out the interviews. The participants were requested to watch their individual recordings of the design process in order to recall their design activities.

Findings

The post-task questionnaire revealed that the participants were satisfied with using Grasshopper and with the designs they produced in the end through Grasshopper (Figure 4). Their assessment of Grasshopper indicated that the medium aided them to generate different design alternatives, quicker and easier than they would have generated through hand sketching.

Inexperienced users started off with hand sketching, whereas experienced users directly started off with Grasshopper. Inexperienced users started off with hand sketching, while experienced users directly started designing in Grasshopper. Two of the experienced users switch to hand sketching once in between Grasshopper sessions, while one other switches twice. As seen in Figure 5, the hand sketches of both the inexperienced and experienced users depict directions, notes, and priorities they have for designing.

The results of the protocol analysis depict the participants' cognitive behaviors in detail. While examining the protocol analysis data, various quantitative definitions were used, such as frequencies, percentages, and statistical analyses. In this examination, the Mann–Whitney U test was conducted, to compare differences between two independent groups and see whether there are statistically significant differences (Tables 4 and 5).

Segmentation session

Segmentation provides separation of the design process in terms of designers' goals and intentions. In other words, segments indicate that designers have taken a new decision or their intentions have changed in the

Figure 4. Responses to the post-task questionnaire.

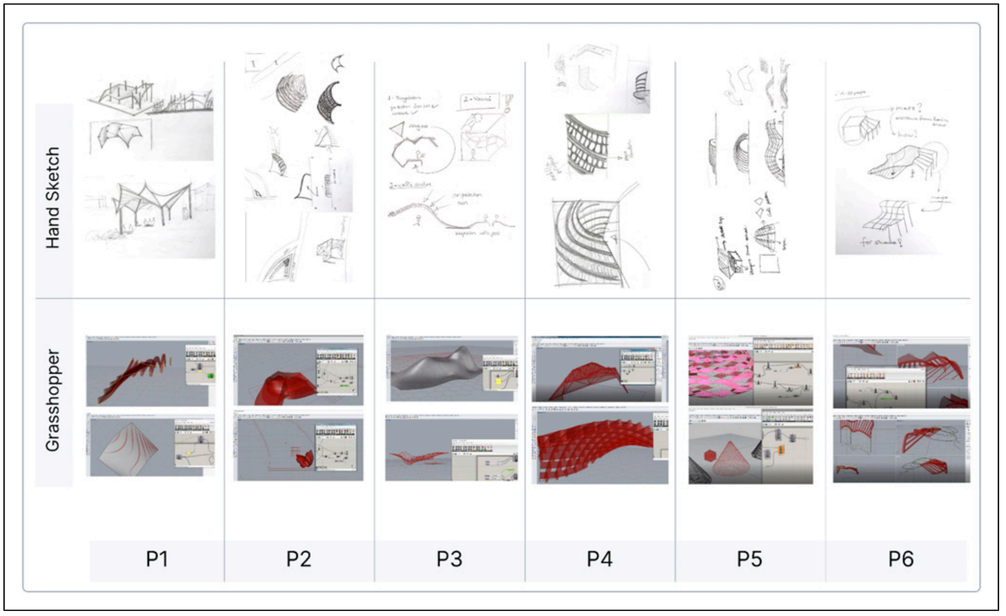

Figure 5. Hand sketches and parametric designs produced by the participants.

design process. Due to the emergence of a new segment through a new decision, designers' perspectives and problem-solving methods can be discovered. In this study, each participant had a different number of segments while using each media. This differentiation has revealed that designers' decision-making and problem-solving processes vary. Results demonstrated that the total number of segments in Grasshopper (231) was higher than in hand sketching (140). The average number of segments is 38.5 in Grasshopper and 23.3 in hand sketching.

The design session was divided into parts in terms of the participants' switching points between the two media. All inexperienced users began their design processes with hand sketching, whereas experienced users preferred to start with Grasshopper. Similarly, while the inexperienced participants ended the design process with hand sketching, the experienced designers finalized the process with Grasshopper. The experienced group had more segments in total than the inexperienced group. Experienced participants had more segments in Grasshopper than in hand sketching, and it was the opposite for the inexperienced participants.

Segmentation enables decomposing the design problem into episodes of goals and subgoals that the designers attend to obtain in the design session, which also reflect the designer's intentions in solving the design problem (Table 2). Experienced participants' segmenting of the design process had a common decreasing pattern (Figure 6). The high numbers of segments at the beginning of the design process show that the participant plays among different alternatives to achieve the best design solution. With the first shift between the two tools, it is assumed that the participant knows what to do next. This results in a decrease in the number of segments because the intentions or goals would now have fewer shifts than the beginning of the design process. Inexperienced participants' problem-solving behaviors depict mixed patterns. There is an increase in the total segment numbers of two participants while there is a decrease for the other participant.

All participants have different time periods of using Grasshopper and hand sketching. While the previous figures represent the switching points between the two tools, the following figure shows the time spent using

Table 4. Distribution of D, P, F, and C actions.

	Sketching		Grasshopper		Total	
	F	%	f	%	f	%
D-actions	348	24.25	1087	75.75	1435	100
P-actions	193	21.18	718	78.82	911	100
F-actions	160	46.78	182	53.22	342	100
C-actions	202	30.10	469	69.90	671	100

Table 5. Mann–Whitney U test—percentage distribution of action categories.

	Sessions						Significance	
	Sketching (M, SD, Media)			Grasshopper (M, SD, Media)			Z	p
Physical	37.21	4.60	36.83	43.03	3.22	43.40	−2.082	**0.037**
Perceptual	23.89	4.65	25.13	35.23	5.39	33.30	−2.882	**0.004**
Functional	17.93	3.92	18.78	5.81	3.06	5.20	−2.882	**0.004**
Conceptual	21.11	4.98	20.50	16.25	3.52	15.55	−1.922	0.056

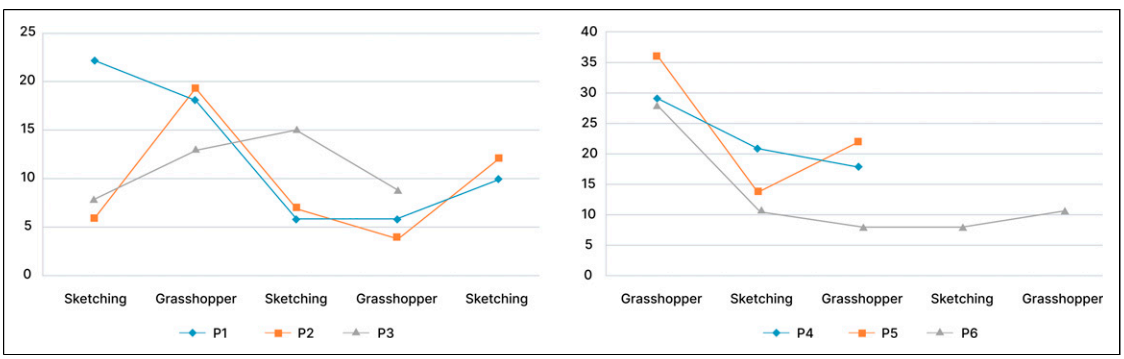

Figure 6. Total number of segments in hand sketching and Grasshopper for the experienced and inexperienced groups.

either medium by experienced and inexperienced users (Figure 7). The time spent hand-sketching and the number of times hand sketching is utilized are less in experienced users.

Action categories

Cognitive actions (D: physical, P: perceptual, F: functional, and C: conceptual) of each participant were encoded according to the coding scheme. In order to analyze the cognitive action categories, subcategories, and individual action codes, the data was normalized as percentiles of the total number of actions. Figure 8 shows the general percentages of the total hand sketching and Grasshopper actions. 72% of the total actions are related to Grasshopper and 28% are related to hand sketching.

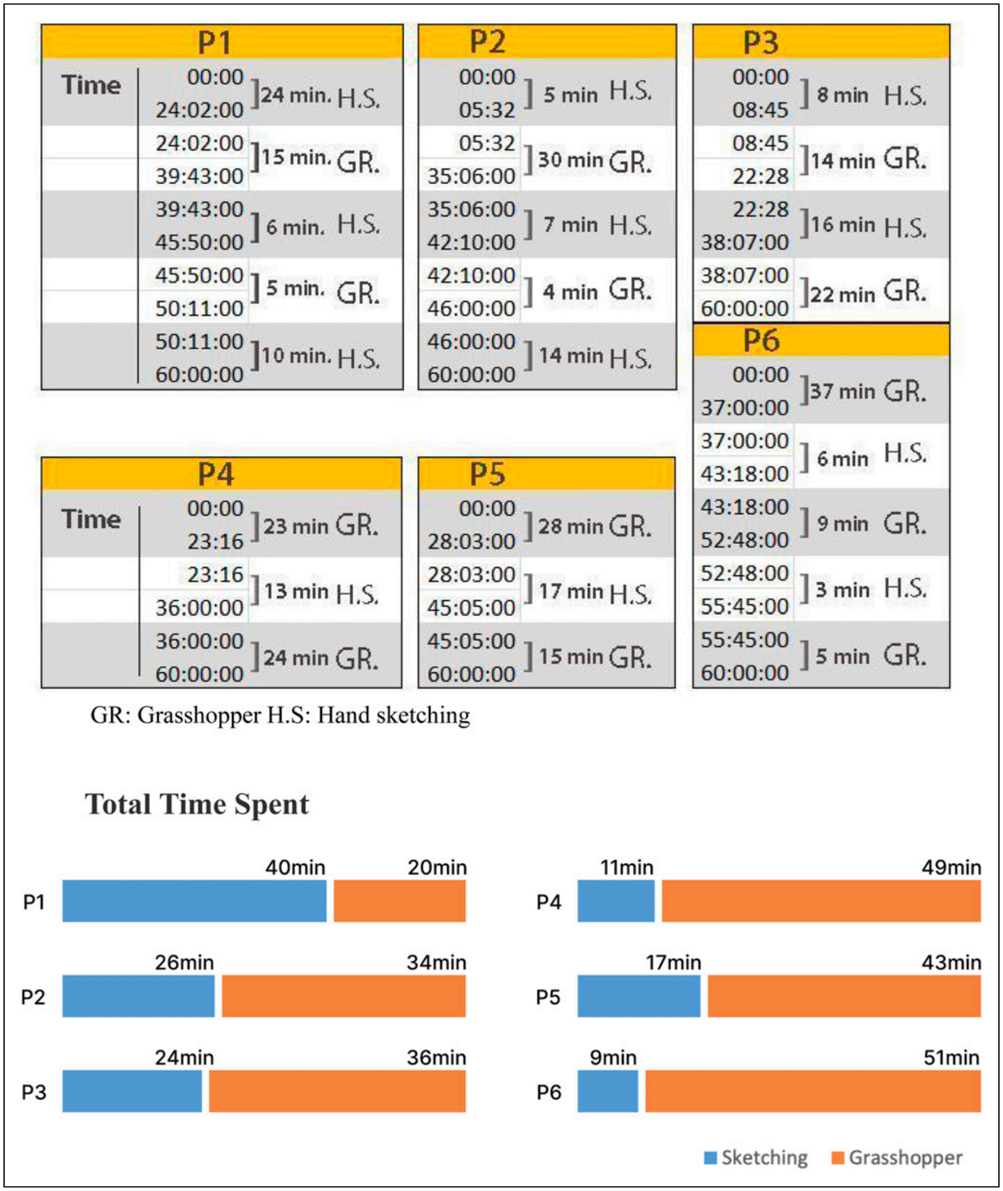

Figure 7. Time spent in using Grasshopper and hand sketching throughout the design session.

The total numbers of cognitive actions in the design session for each individual participant are displayed in Figure 9. Experienced participants' cognitive actions have a common increasing pattern, and the total number of cognitive actions is higher in Grasshopper than in hand sketching. Experienced participants have either frequently added new features to their existing designs to achieve the optimal solution or have begun designing from scratch. Inexperienced participants also had more actions in Grasshopper, except for one. Inexperienced users have a higher number of cognitive actions in Grasshopper even though their segment numbers in Grasshopper are lower than in hand sketching.

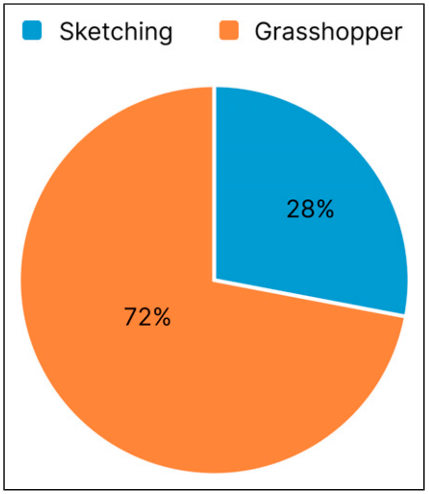

Figure 8. Distribution of the hand sketching and Grasshopper actions.

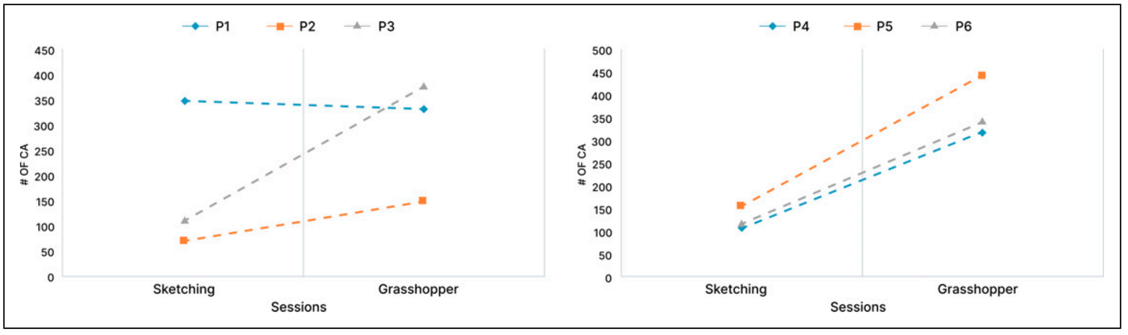

Figure 9. Cognitive actions of experienced and inexperienced participants.

Table 4 indicates the distribution of action category scores and percentages throughout the design process. All action categories have higher scores in Grasshopper than in hand sketching. The results indicate that participants engaged mostly in physical actions (D-actions) in Grasshopper and in the overall design session.

Table 5 shows that the mean for physical actions is statistically significant ($z = -2.082$; $p = 0.037 < 0.05$). Similarly, there is a meaningful difference among the percentages of perceptual actions ($z = -2.882$; $p = 0.004 < 0.05$). While the mean number of physical actions and the perceptual actions is higher in Grasshopper ($M = 43.03$, $SD = 3.22$; $M = 35.23$, $SD = 5.39$, respectively), functional mean score is higher in hand sketching ($M = 17.93$, $SD = 3.92$). The mean conceptual actions are not statistically different ($z = -1.922$; $p > 0.05$).

Action subcategories

Subcategory distributions of four cognitive actions in the design process are represented in Figure 10. Differences are high for modify, erase, relation, view, and implement actions. Most dominant action subcategory is *create,* both for experienced and inexperienced users.

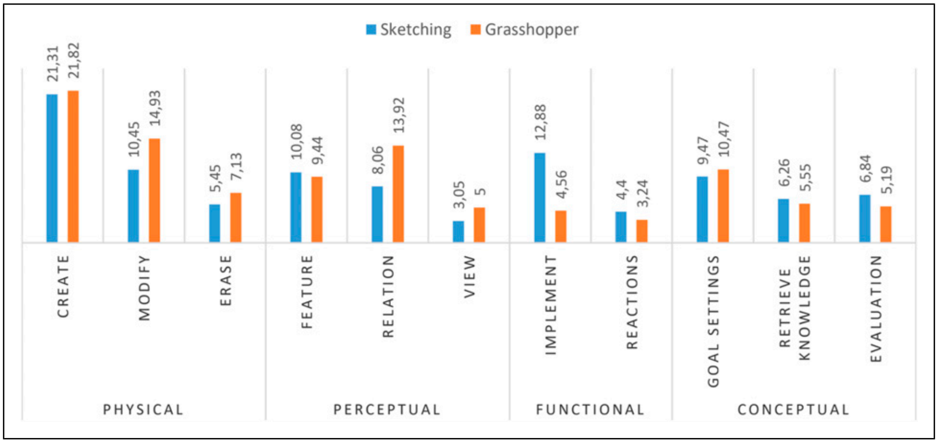

Figure 10. Distribution of action subcategories.

Table 6. Mann–Whitney U test—percentage distribution of action subcategories.

	Sessions						Significance	
	Sketching (M, SD, Media)			Grasshopper (M, SD, Media)			Z	*p*
Create	21.31	2.04	21.15	21.82	4.76	21.81	−0.320	0.749
Modify	10.45	2.16	10.75	14.93	3.47	15.36	−2.242	**0.025**
Erase	5.45	1.54	5.20	7.13	2.34	7.75	−1.282	0.200
Feature	10.08	2.96	10.75	9.44	1.94	9.17	−0.484	0.629
Relation	8.06	2.77	8.75	13.92	2.36	13.75	−2.722	**0.006**
View	3.05	0.99	2.55	5.00	0.44	5.05	−2.732	**0.006**
Implement	12.88	2.87	12.80	4.56	1.66	4.25	−2.882	**0.004**
Reactions	4.40	1.35	4.50	3.24	1.59	3.12	−1.441	0.150
Goal settings	9.47	1.20	10.40	10.47	2.40	10.51	−0.321	0.748
Retrieve knowledge	6.26	2.20	5.65	5.55	1.73	5.85	−0.480	0.631
Evaluation	6.84	3.09	5.90	5.19	2.12	5.80	−0.641	0.522

The results of the Mann–Whitney U test show that *modify, relation, view,* and *implement* rank score averages are statistically significant as seen in Table 6 ($p < 0.05$). The mean score of *modify* (M = 14.93 SD = 3.47), the mean score of *relations* (M = 13.92 SD = 2.36), and also the mean score of *view* (M = 5.00 SD = 0.44) are higher in Grasshopper, while the mean score of *implement* is higher in hand sketching (M = 12.88 SD = 2.87). The rest of the subcategories did not indicate any statistically significant differences.

Table 7 indicates whether the percentages of action categories and segments are more in Grasshopper or in hand sketching. Red color represents the statistically significant values.

Discussions

In this study, it was hypothesized that parametric tools may contribute to the conceptual design phase. As stated in the research questions, the possible contributions of parametric tools were analyzed in terms of *first*, in their capacities of contributing to the early design phase; *second*, in the differences of parametric tools from

Table 7. General distribution of subcategory actions.

	Cognitive subcategory actions										
	Physical			Perceptual			Functional		Conceptional		
	Create	Modify	Erase	Feature	Reliation	View	Implement	Reactions	Goal setting	Retrieve Knowledge	Evaluation
Grasshopper	x	x	x		x	x			x		x
Handsketching							x	x		x	

hand sketching in supporting different design strategies (the problem-driven and solution-driven approaches); *third*, in supporting the cognitive processes of the designers. In order to facilitate the indications of the findings, the discussions may be grouped as follows:

Segmentation session

1-) Experienced users produced more design variations, alternatives and results. In the post-study reports all the participants showed a great deal of satisfaction with the designs they produced.

There is a difference in the average numbers of segments among the inexperienced and experienced participants. Experienced participants had more segments (206) in total and in Grasshopper (152) while inexperienced participants had more segments in hand sketching (86) than in Grasshopper (79). These differences occurred according to the change of aims, intentions, and decision making of the participants. Experienced participants produced many design alternatives related to the design task while searching for a form or solving a problem (Figure 11). In line with Khamis et al.[44] (2022), who suggest that parametric tools are capable of generating solution alternatives at the early stages of design, the participants in this study also experimented with different alternatives.

2-) In parametric design, the solution-driven approach (rather than the problem-driven approach) is more effective for supporting variational thinking in the conceptual design phase. Experienced users tend to think more solution-driven in the whole process, whereas inexperienced users do not tend to use a single strategy.

The segmentation process showed the number of times designers switched between the two media and helped to model the specific problem-solving processes of the designers. The segment numbers of the experienced participants decreased from the beginning to the end of the design session. They switched to hand sketching one or two times in the whole process, utilizing Grasshopper as the main tool and hand sketching as a supportive tool. Experienced users set the initial goals primarily and worked on numerous variations, while inexperienced users focused on specific designs (Figure 12). Experienced participants worked on their design solutions with a top-down perspective[45] with Grasshopper. The findings are in line with Lee et al.,[41] who worked with two novice and two expert architects on the conceptual design of a high-rise building in 1 hour and found out that the solution-driven approach (rather than the problem-driven approach) is more effective for supporting creative outcomes as well as divergent thinking (*p*.20).

Lee and Ostwald[46] (2020) suggest that the solution-reflecting strategy involves a cycle of evaluation of the geometry and changing of parameters accordingly. This is reflected in the high total scores for geometric and algorithmic actions in Grasshopper (Figure 13). Also, when analyzed separately, the percentages of algorithmic actions (Dcp + Dcr + Dmp + Dmr + Dep + Der) are higher than the geometric actions (Dcg + Dmg + Deg).

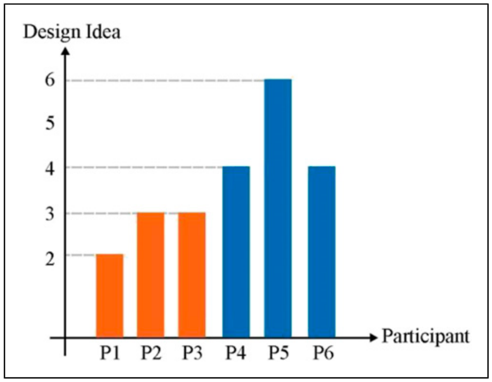

Figure 11. Number of design ideas.

On the other hand, inexperienced users had an increase in total segment numbers (except P1). Two of the inexperienced users increased their segment numbers and changed their intentions radically, when they switched to Grasshopper. These fluctuations in the number of segmentations between the two groups of participants show that they have different problem-solving strategies. While the experienced users tend to engage in a solution-driven approach, the inexperienced users had mixed tendencies.

The relatively higher segmentation numbers in Grasshopper indicate that the designers' goals and intentions changed more frequently while using the parametric tool. Participants generated more ideas as Grasshopper provided a suitable environment for concept production, supporting variational thinking. The finding is in line with Stavric and Marina,[47] who state that visual editors such as Grasshopper enable designers to explore non-standard forms. Also, the inexperienced users stated that they would have preferred to use Grasshopper more, if they were more experienced in using it. It can hence be suggested that algorithmic design thinking and parametric design tools to be more integrated into architectural education, in line with the suggestions of previous studies of Stavric and Marina[47] and Aish and Hanna.[48]

Cognitive behaviors of the participants

> 3-) Parametric design tools support and enhance all cognitive actions (physical, perceptual, functional, conceptual) of the designer and support the conceptual design phase as much as hand sketching. Cognitive activities were found more diverse and higher in using Grasshopper for both user groups.

An associative interpretation and discussion are held between the results of the protocol analysis. The results show that the experienced participants' cognitive actions increased while using Grasshopper, and the total number of cognitive actions was higher in Grasshopper than in hand sketching. This pattern matched up with the total number of segments in Grasshopper. This is not unexpected as Grasshopper allows designers to produce a large number of alternatives and try different solutions in a short time.[49,50] The positive effects of Grasshopper resulting from the algorithmic framework can be observed in both the high number of cognitive actions and the high satisfaction levels of the experienced participants. Similarly, inexperienced participants also had more cognitive actions in Grasshopper than in hand sketching.

All action categories have higher scores in Grasshopper than in hand sketching numerically. They are mostly associated with the physical actions (D actions). The reason that Grasshopper's percentages are higher in each cognitive action category may indicate that Grasshopper is not just a "form searching tool" but also a

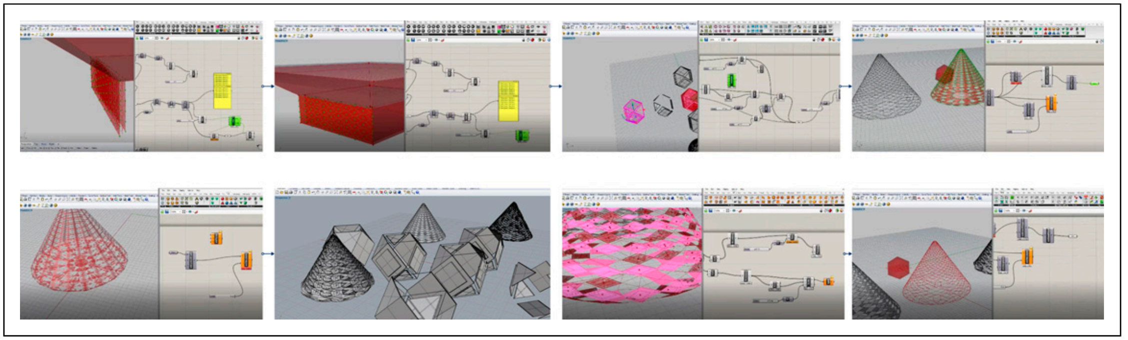

Figure 12. Sample variations by one of the participants (P5).

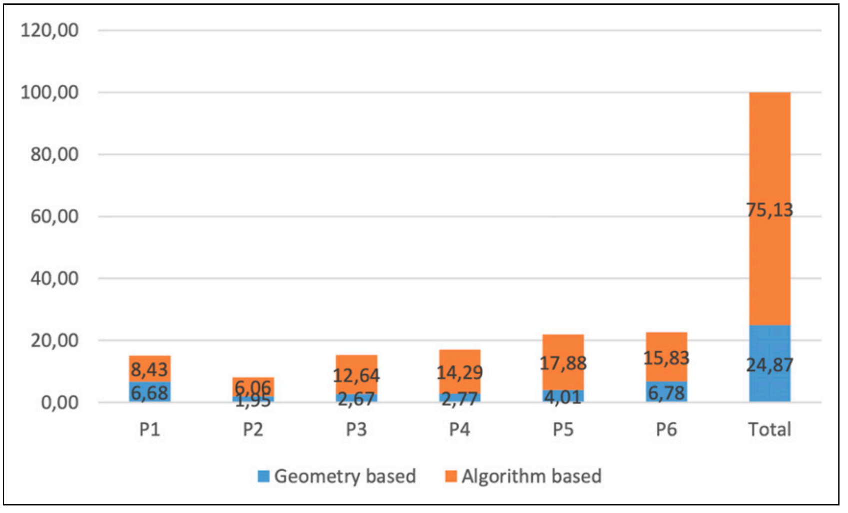

Figure 13. Distribution of geometry- and algorithm-based codes in Physical and Perceptual actions in Grasshopper.

tool that supports and enhances all cognitive behaviors of the designer. When the participants' statements are taken into consideration, the finding that all participants gave Grasshopper full score in terms of usability and efficiency is consistent with the high cognitive behaviors.

4-) D (physical) and P (perceptual) actions were statistically significant in using Grasshopper, while F (functional) actions were found to be statistically significant in using hand sketching, revealing that designers mostly associated spatial relations effectively when they work with Grasshopper, while hand sketching was useful to allow exploring the functional characteristics of design components.

5-) In using Grasshopper, the most common cognitive actions were modifying the geometry or an algorithm, viewing different perspectives and thinking about the relations between the components. In hand sketching, the most popular cognitive activity was implementing a role or a function.

Physical (D) actions. The results indicate that the average percentage of D actions is higher in Grasshopper (43.03%) than in hand sketching (37.21%). This significant difference is mostly dependent on the frequency of *modify* and *erase* actions. With Grasshopper, the participants could reveal different design alternatives. The finding about *modify* action indicates that Grasshopper showing different variations of a design solution in a short time is a factor in preference in the conceptual design phase. The frequency of *modify* action is analyzed through the subcategories of Dcg, Dmg, and Deg (Table 1). Dcg is related to making a new depiction or generating an initial geometry in both media, corresponding to the creation of new lines, walls, columns, objects, or arrow symbols that represent a relation between these elements. Dmg deals with the modification of the existing geometry/depictions such as copying a geometry, revising the shape, and moving or rotating a geometry are included in this subcategory. If a designer uses an expression such as "I extend this curve," Dmg is coded as the associated action. Moreover, in hand sketching, tracing over a depiction on a new sheet of paper can be perceived as Dmg. Lastly, Deg is the deletion of the previously generated geometry/depictions in Grasshopper and in hand sketching. However, in Grasshopper, the content of D actions is slightly different than hand sketching. If the designer drops a component onto the algorithm space, that is, Grasshopper's canvas screen, this action implies the generation of a new parameter coded as Dcp. If the designer connects the parameters through wire-network, it refers to creation of a rule coded as Dcr. The same reasoning applies to modifying and erasing the parameters and rules in Grasshopper. While changing the value of a parameter that affects the geometry directly refers to the modification of a parameter coded as Dmp, changing the existing connections between the parameters without erasing implies modification of a rule is coded as Dmr. Likewise, deleting a parameter is coded as Dep, and disconnecting the link between the parameters is denoted as the action of erasing a rule Der.

Perceptual (P) actions. The average frequency of P actions of the participants is higher in Grasshopper (35.23%) than in hand sketching (23.89%). This is largely due to the high results in the *relation* and *view* subcategories. The finding that the *relation* subcategory having a higher value can be supported by the idea that parametric modeling tools can promote generation of spatial relations between the design elements better and directs the designer to relational thinking.

The *view* subcategory emphasizes the importance of 3D visualization in the form-finding process. All participants were able to make evaluations and different modifications in 3D view while generating different forms. They preferred to see the 3D view, from all angles and viewpoints, while externalizing the design idea.

Functional (F) actions. The results show that the average percentage of the F actions is higher in hand sketching (%17.93) than in Grasshopper (%5.81). This statistically significant difference is mostly dependent on the frequency of *implement* action. It can be asserted that the hand sketches allow designers to think more holistically in the design process.

Conceptual (C) actions. C actions represent the semantic level of the participants in the design process. The average percentages of the C actions differ between individuals within the inexperienced and experienced groups. The reason for this is that C actions are related to the subjective evaluations of the users about the design solutions and to their past knowledge. The difference of the C actions between hand sketching and Grasshopper is close to being statistically significant ($p = 0.056$). This might support the claim that, since Grasshopper is a visual algorithmic tool, it requires as much conceptual actions as hand sketching.

Conclusion

This study reviews the potentials and contributions of parametric modeling tools in the conceptual design phase, in comparison to hand sketching, by indicating the cognitive activities of the designers and their satisfaction levels about Grasshopper, a parametric tool operating with Rhino 3D software. This review is based on an experimental study, the results of which were obtained from the protocol analyses with content-oriented approach. The aim is to contribute to the research field, where despite the extensive research on the cognitive behaviors of designers while hand sketching, research on the role of parametric tools in design in terms of cognition is to be explored.

The findings indicate that all participants find using Grasshopper in the initial design phase more effective, in terms of *perceiving and solving the design problem*, *utilizing and managing time*, *generating different alternatives,* and *considering the relations of the design elements*. The findings show that there is an increasing trend in the cognitive actions of the designers while using Grasshopper, and the total number of cognitive actions is higher in Grasshopper than in hand sketching. This shows that Grasshopper is not merely a tool for form searching but also a tool that supports and enhances all the cognitive behaviors of the designer in the conceptual design phase.

In comparing the effects of hand sketching and parametric tools in generating concepts, the findings support the idea that parametric modeling tools can promote generation. The findings do not suggest a replacement of hand sketches in the conceptual design phase but indicate that parametric design tools may support this phase strongly. The results show that prior knowledge and experience in using the parametric design tool is an effective factor in the success of using the tool in the conceptual design phase.

This study is one of the few efforts to compare hand sketching and Grasshopper by a content-oriented protocol analysis. The implemented research methodology provided insights into various aspects of designers' cognitive behaviors in terms of the use of these two media. The coding scheme developed for this study is hoped to be beneficial for the field of design research. Further research on the raised issues would facilitate more implications for improving such tools, education, and architectural practice at large.

In order to provide contribution to further studies, the research limitations of the present empirical study should be taken into account. This study comprised six female participants with different expertise levels in using Grasshopper. For further studies, an increased number of participants and a more balanced gender distribution are suggested to enrich the findings. None of the similar studies nor this study introduce a discussion on the gender-based differences (if any) in the results. Considering the fact that similar studies do not even disclose gender information of the sample group, it would be interesting to have future studies concentrate on the impacts of gender differences on the findings. On the other hand, although the expertise level in using Grasshopper is diverse in the sample of this study, their level of design experience is homogeneous. Future studies may involve sampled populations with different design experience levels. In addition to that, in this study, the designers participated individually and did not collaborate. Further studies may involve teamwork and discuss the results. This study has focused on one parametric modeling tool, Grasshopper, a visual algorithm editor, in the conceptual design phase. However, there are various other parametric modeling tools which may be utilized. The use of different tools, such as textual algorithm editors, and/or Building Information Modeling (BIM) tools would be beneficial to further explore the potential and advantages of adopting digital tools in the conceptual design phase.

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