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Interactive generative system supporting participatory house design

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ABSTRACT

This paper deals with the issue of supporting the participation of non-expert users in the house design process with the use of digital tools. The research aimed to verify the feasibility of an interactive generative system verifying and guaranteeing design solutions' correctness. A computer tool, HOPLA-Home Planner, was developed, and its usability was tested with non-experts. This research revealed a demand from non-expert users for an interactive generative system allowing them to customize and verify various house layout configurations. The presented method can be implemented in a design practice that employs participatory house design, reducing the design process time and related costs while maintaining direct contact with the client. Future research should confront the identified non-expert desire to customize house designs with architects' willingness to implement computer-aided participatory house design.

1. Introduction

Research on computer-aided design participation in housing has gained considerable momentum over the last two decades due to the popularization of computer techniques among professionals and the general public.

Currently, nonexpert users have broad access to professional design tools. In addition to specialized software for engineers, free and easy-to-use editors are directly addressed to nonexperts, for example SketchUp [1], Floorplanner [2], or Planner 5D [3]. Additionally, the entertainment industry responded to the demand for tools that enable people to create their designs, as exemplified by Sims [4], Second Life [5] and Minecraft [6]. Such computer tools can encourage nonprofessionals to design but mislead people who embrace the possibility of designing homes solely on their own. The software does not guarantee the acquisition of projects that are possible to build and does not assure its users that their created solutions are error-free. While these design tools might allow people to design a home, they do not support the materialization of building the designed home.

Unlike design software and games that simulate the process of designing, computer tools supporting design participation ensure the correctness and feasibility of the obtained design solutions. Several approaches in the research field have been proposed to address this issue.

Duarte proposed guaranteeing the correctness of design solutions using a generative system based on discursive grammar [7]. The system consists of two grammars: the first grammar is responsible for generating design briefs based on user data, and the second grammar provides rules for generating designs in a particular style [8]. A set of heuristics guided the generation of the designs towards the solution that matches the brief. The user could accept the solution or reject it and generate a new solution after changing the information used to form the brief.

Other authors employed predesigned modules from which the design proposal was generated. Rau-Chaplin, MacKay-Lyons, and Spierenburg proposed generating house layouts from a library of room tiles [9]. Solutions could be customized by replacing the room tiles, which created challenges in maintaining a reasonable plan. The authors proposed relying on the user's superior knowledge of their needs and common sense to overcome this issue. Huang and Krawczyk also utilized predesigned house modules to generate design solutions [10]. To ensure the correctness of customization, the user was allowed to select different room layouts only from compatible “space tiles,” which were a priori verified by the authors. Mohamed used a similar customization approach in his PREFAB 2.0 tool, which allowed a user to choose from the preselected alternative layouts for selected rooms [11].

Khalili-Araghi and Kolarevic proposed a dimensional customization system to guarantee that customized house designs comply with the design rules [12]. The tool allowed changes in the indicated parameters of the predesigned houses. Design rules were embedded into a three-dimensional model as constraints, allowing modification of the dimensions of the building within the designated ranges.

An alternative approach to computer-aided design participation of

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houses was proposed by Weinzapfel and Negroponte [13], following the ideas of the French architect Yona Friedman. Aiming to allow people to design their own houses without any intermediary creating the design solution for them, they equipped YONA software with procedures that verify users' decisions and guide them through the design process. In a similar approach proposed by McLeish in his participative design platform, customization of homes was achieved with a tangible user interface [14]. To support users in designing on their own and provide safety measures, the tool was equipped with a computational design critic verifying the correctness of the obtained design solutions. Difficulties with implementing such a module led to substituting it with a design expert who evaluates and gives feedback in real-time from a remote location.

Parallel to advances in research, numerous house builders operating in North America developed online configurators, such as Living Homes [15], Blu Homes [16], Connect Homes [17], and Pennwest Homes [18], and Toll Brothers [19]. These tools guaranteed the correctness of designs through the use of predefined solutions. The scope of the available modifications was verified in advance to ensure the feasibility of all changes offered. Moreover, online access to these configurators allows monitoring of their usage and obtain solutions, which are also verified at ordering. The need to ensure the correctness of all possible combinations of configurations limits the number of modifications and often restrains the possibility of modifying the layout of a house and focusing users' attention on the selection of finishing materials and appliances.

Inviting nonexpert users to participate in the design process requires ensuring that outcomes can be built without design errors. Weinzapfel and Negroponte [13] proposed transferring this responsibility to users while the tool was supposed to assist them. Kolarevic suggested that the lack of popularization of mass customization in housing relates to the reluctance of users to take responsibility for designing their homes [20]. Participants might want to have infinite freedom in designing, but if they are not convinced that the outcome is feasible, they would not decide on its realization.

In the traditional participatory design process, the guarantee of the correctness of projects is ensured by the involved architect. In the iterative process, the architect prepares a design proposal, presents it and discusses it with the client, and updates the design based on the expectations expressed by the client. The process is time consuming as it requires the architect to update the design and meet the client multiple times, and the number of design iterations is limited by the client's budget.

Computer-aided design participation can minimize the personal involvement of architects in such a process while transferring the correctness guarantee to the tool. Online home configurators available on the market ensure the correctness through predefined, verified in advance solutions that often result in limiting offered modification possibilities. Duarte [7] showed the possibility of using generative design to expand the range of possible design solutions. Generative design can significantly expand the scope of design outcomes while guaranteeing their correctness with the formalized rules but can simultaneously limit the participation of the users to the acceptance of the produced results. Modifying the generated solution by non-expert users can be challenging, as shown by Rau-Chaplin, MacKay-Lyons, and Spierenburg [9]. The intuitiveness of the tool depends on the provided user interface enabling interaction with the generative procedure. McLeish [14] showed the difficulties of integrating a user-friendly interface with the computer procedure responsible for the correctness guarantee. This research sought a method for interactive computer-aided design participation that supports users and verifies and corrects their decisions if needed. The aim was to develop a tool to generate alternative design solutions in response to user requirements and allow interaction and flexible customization of house layouts. This research was aimed at verifying the feasibility of an interactive generative system supporting the process of participatory design and guaranteeing the quality and safety of solutions. Therefore, the objective was firstly to develop a computer-aided design participation tool for the mass customization of houses, and secondly test its usability, and assess the potential of nonexpert users' participation in the self-configuration of house designs and their attitude towards design customization in general.

2. Methods

The research was planned with the use of computer tool developed in two stages: 1. development of the method of computer-aided design participation and validation of typology of alternative solutions with a physical mockup, 2. development of a generative design system with user interfaces and its usability testing. This research proposes the use of generative design to provide a large scope of correct design solutions and support users in verifying their design decisions. Therefore, a method of computer-aided participation for single-family house design allowing flexible configuration of spaces was proposed. That method was used to develop a computer tool consisting of two core elements: a generative design system responsible for producing design solutions in response to user input with respect to formalized architectural design rules and a user interface allowing to introduce data and control the process interactively.

To verify the feasibility of the proposed method in supporting the participatory design process, usability tests, in the form of a design task to be performed by the research participants using a developed tool, were prepared.

2.1. Computer-aided design participation

Participatory design invites nonexpert users to make active decisions about the future use of space. Nonexpert users do not need expertise or professional education in design, but will want their personal feelings, opinions and needs to be reflected in the final outcome. Based on the authors' experience in designing houses with clients' participation it was hypothesized that for nonexpert users, one of the most important aspects of the house design process is the customization of the building layout. To address this functionality, the proposed method is based on the idea of shattering the building into smaller functional parts. Modules representing different house spaces are arranged linearly in two bays of a house. Such an arrangement allows for flexible reconfiguration of spaces. The physical mockup was used to verify the practicality of this approach (Fig. 1).

To allow nonprofessional users to safely arrange the layout of a house, the tool needs to guarantee the correctness of the outcomes with

Fig. 1. Exploration of house design possibilities via a physical mockup, photo: Krystian Kwieciński.

formalized design rules. The proposed method aimed to use generative procedures to produce designs fulfilling such rules and to verify users' design decisions. Therefore, the system consists of two elements: a user interface, which allows the introduction of design expectations and the control of the design process, and a generative design system that is responsible for verifying user input and generating solutions in relation to it.

Following the proposed method, a computer tool that supports design participation is aimed at:

- streamlining customization of single-family house designs by actively involving users
- providing solutions that meet various users' expectations
- allowing for flexible modification of solutions
- eliminating incorrect solutions and proposing alternatives.

2.2. Generative design system

The developed generative design system uses the concept of hierarchical decomposition of a house floorplan into bays, zones, and rooms (Fig. 2). The rooms are presented with colored and named matrices of 60 by 60 cm (about 1.97 ft) modules. Rooms are grouped into zones which are distributed in two bays. House layout is longitudinally divided into separate bays. The system operates on a set of 9 possible functional modules [vestibule (ve), toilet (to), kitchen (ki), dining room (di), living room (li), home office (ho), master bedroom (bed), single bedroom (bes), and bathroom (bat)], of which some modules may be used multiple times. Each room's dimensions are multiples of the base module (M) dimension of 60 cm. Possible room widths are presented in Fig. 3. The rooms have the same depth of seven modules, with the exception of the rooms preceded by a hall allowing internal communication in the building. Such rooms have the depth of 5 modules. The hall is located in the bay where the vestibule is located.

The generative design system is based on context-free grammars. In mathematical linguistic grammar is defined as systems $G = (V, T, P, S)$, where: (a) V is a finite set of nonterminal symbols, (b) T is a finite set of terminal symbols, (c) P is a finite set of productions, and (d) $S \in V$ is the initial symbol of the grammar. Productions of the grammar are usually denoted $X_0 \rightarrow X_1X_2 \cdots X_n$, where $X_0 \in V$, $X_1X_2 \cdots X_n \in V \cup T$, c.f. [21]. Grammars having all productions with X_0 being a nonterminal symbol are context-free grammars.

A derivation in a grammar is a finite sequence of strings of nonterminal and terminal symbols such that: (a) the first string in this sequence is the initial symbol of the grammar and (b) for any two consecutive strings in the sequence, the later one is obtained from the former one applying a production by replacing a substring of the former string equal to the left-hand side of the production with the right-hand side of the production. The last element of the string is derivable in the grammar.

For a context-free grammar a derivation can be outlined in a form of derivation tree, i.e. (a) the root of the tree is labelled with the initial symbol of the grammar and (b) for any internal vertex labelled by the left side of a production, its children are labelled by symbols of the right side of the production.

Developed context-free grammar rules control the syntactic structure of the house layout. The initial productions of the grammar create the topmost level of the hierarchy defining floors of the building, which are divided into bays.

<building>	→	*<floor> <buidling>*
	→	*<floor>*
<floor>	→	*<bay1> <bay2>*

The fallowing part of the grammar divides bays into zones: the entrance zone (z_entrance), the semipublic zone (z_semipublic), and the private zone (z_private). Zones allow room grouping in relation to the degree of their privateness and guarantee that rooms from one zone are not placed inside another zone.

<bay1>	→	*<z_entrance> <bay1>*
	→	*<z_semipublic> <bay1>*
	→	*<z_private> <bay1>*
	→	*<z_entrance>*
	→	*<z_semipublic>*
	→	*<z_private>*
<bay2>	→	*<z_entrance> <bay2>*
	→	*<z_semipublic> <bay2>*
	→	*<z_private> <bay2>*
	→	*<z_entrance>*
	→	*<z_semipublic>*
	→	*<z_private>*

Fig. 2. Detailed house floorplan (left side) and its hierarchical decomposition (right side) into bays, zones and rooms: vestibule (ve), toilet (to), kitchen (ki), dining room (di), living room (li), home office (ho), master bedroom (bed), single bedroom (bes), and bathroom (bat).

Room:	Abbreviation:	Min. Width:	Max. Width:	Zone:
Vestibule	ve	3M	4M	z_entrance
Toilet	to	3M	4M	z_entrance
Kitchen	ki	2M	6M	z_semipublic
Dining Room	di	4M	6M	z_semipublic
Living Room	li	4M	7M	z_semipublic
Home Office	ho	4M	6M	z_semipublic
Double Bedroom	bed	5M	7M	z_private
Single Bedroom	bes	4M	6M	z_private
Bathroom	bat	3M	5M	z_private

Fig. 3. Nine possible types of rooms, their abbreviations, minimum and maximum width, and designated zones.

The next part of the grammar presents method for generating sequence of rooms inside zones. Each room is assigned to only one of three zones. The entrance zone incorporates a vestibule and toilet; the semipublic zone accommodates a kitchen, dining room, living room, or home office, while double bedrooms, single bedrooms, and bathrooms occur only in the private zone.

<z_entrance>	→	*<ve> <z_entrance>*
	→	*<to> <z_entrance>*
	→	*<ve>*
	→	*<to>*
<ve>	→	*ve*
<to>	→	*to*
<z_semipublic>	→	*<ki> <z_semipublic>*
	→	*<di> <z_semipublic>*
	→	* <z_semipublic>*
	→	*<ho> <z_semipublic>*
<ki>	→	*<ki>*
<di>	→	*<di>*
* *	→	* *
<ho>	→	*<ho>*
<z_private>	→	*<bed> <z_private>*
	→	*<bes> <z_private>*
	→	*<bat> <z_private>*
	→	*<bed>*
	→	*<bes>*
	→	*<bat>*
<bed>	→	*bed*
<bes>	→	*bes*
<bat>	→	*bat*

Derivation trees of language constructions in given grammar illustrate syntactic structure. Fig. 4 presents a part of a derivation tree of exemplary house, presented in Fig. 2. It covers generation of the sequence of rooms in the first bay (bay1) of the house.

Context-free grammar allows to generate all syntactically correct sequences of rooms in each bay based on the list of rooms indicated by the user (see Section 2.3 for more details). Additional restrictions have been introduced to eliminate undesirable solutions. Corners of the building we reserved for rooms requiring sun access; therefore, the placement of a toilet and dressing room in these corners was prevented. To allow the kitchen, dining room, and living room to form an open space, the placement of the kitchen between the dining room and the living room was restricted. Additionally, conditions verifying the proximity of rooms belonging to the same zone in two opposite bays of the building were introduced. These conditions prevent dividing zones by placing its rooms at opposite corners of the house.

From the set of generated sequences of rooms, the final solution is selected as the one that is identical or the closest to the sequence of rooms indicated by the user. The layout is drawn taking into account the selected sequence of rooms and their sizes indicated by the user. The final layout presented to the user is complemented by internal and external walls, windows, doors and exemplary furniture from the developed library of three-dimensional models. The generative design system using context-free grammar was implemented in Grasshopper—a parametric modeling tool running within the Rhinoceros 3D, using custom C# scripts.

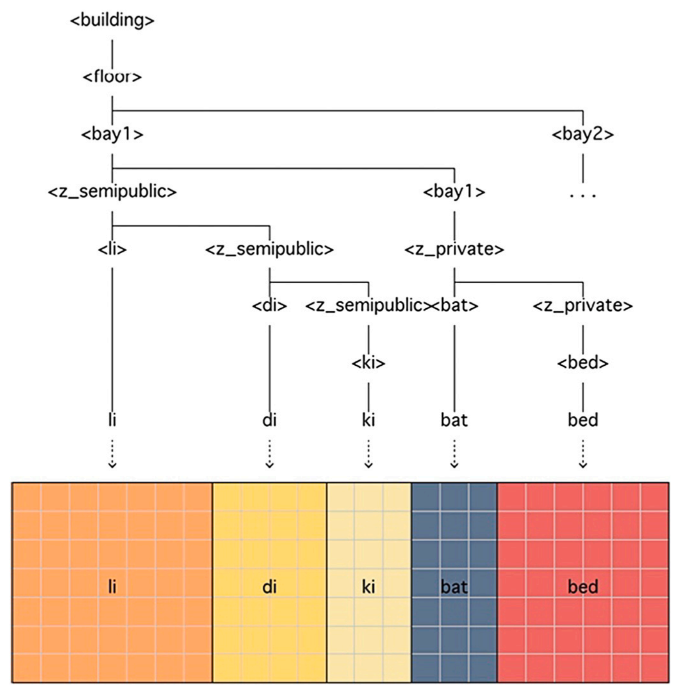

Fig. 4. Part of derivation tree in the developed context-free grammar. A first bay (bay1) of the house from Fig. 2.

2.3. User interface

A user interface was developed using the initial idea of shattering the building into smaller functional modules. Paper puzzles, used initially as a physical mockup to verify this idea, were developed twofold: 1. static physical representations of the modules were converted to parametric digital models, 2. direct interaction with the modules was transformed into interaction with markers representing each digital model. As a result, users interact with the system by modifying markers representing different rooms. The markers inform the generative system about its location and angle of rotation. By changing the position of the marker, the user indicates the expected location of a given room in the building structure; by rotating the marker, the user can change the size of the room. Additionally, rooms can be erased or added by removing or placing the corresponding markers in or out of the workspace. The user can control in which bay the corridor will be located by changing the position of the marker representing the vestibule.

Users have the opportunity to verify various design solutions in real-time by modifying the arrangement of the markers. Changing the arrangement of the markers informs the generative system about the expected order of the rooms in the building structure and their sizes. If the configured setting of markers does not meet the formalized design rules, the generative system searches for a design solution closest to the indicated by the user expected order of the rooms. Users are informed about the differences between the displayed solution and their input by lines connecting each room with the corresponding marker. The crossing of these lines indicates changes. The user can accept the generated design solution or further modify the arrangement of the markers.

The tool allows us to configure house designs in one of two configuration modes: M mode - modification of the initial design solution and S mode - independent configuration of a solution. Generated design solutions are displayed in the center of the workspace in the form of a perspective view of the building plan. A developed tool named HOPLA-Home Planner was tested with two different user interfaces: tangible user interface (Fig. 5) and multitouch screen interface (Fig. 6).

The tangible user interface uses physical markers in the form of wooden blocks with unique shapes. It operates on the InteracTable – an interactive table with a rear projector and a vision system developed by Jacek Markusiewicz in collaboration with the students of the Faculty of Architecture at Warsaw University of Technology [22]. Wooden blocks are tagged with engraved graphic symbols that enable their identification by the vision system. The vision system recognizes each block representing a specific room type, and information regarding its position and rotation is transferred to the generative system. While the generative system was implemented in Grasshopper 3D, the application enabling interaction with a tangible user interface was developed in Unity. This interface allows users to modify the design by affecting their sense of touch and spatial perception. The interface also poses some limitations, such as the need to place the physical markers in the workspace to allow for a modification of the design solution (in the M mode). To overcome some of these limitations, the interface was extended with a tablet that enabled the user to start and finish the configuration process, enter initial data, view detailed information about the project, and be informed about the lack of necessary rooms in the configured solution.

The tool was also integrated with an interactive table, which allowed the interaction through a multitouch screen (Fig. 6). Although this interface limited tactile experiences, it allowed the same scope of design participation as the previous version. Moreover, this interface did not require additional devices and the need to manually set the physical markers in the M mode configuration on a tabletop, as they were displayed.

2.4. Usability studies

Design alternatives generated by HOPLA-Home Planner were verified from architectural point of view, and the tool was tested during the whole development process. Design outcomes were assessed in relation to initial assumptions and manually designed floor plans during the design method development stage. After reaching the expected functionality, HOPLA-Home Planner usability tests were planned with non-expert users.

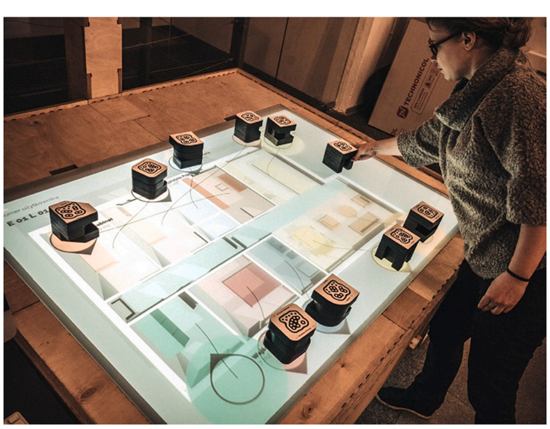

Fig. 5. Tangible user interface of the HOPLA-Home Planner participatory design tool, photo: Jacek Markusiewicz.

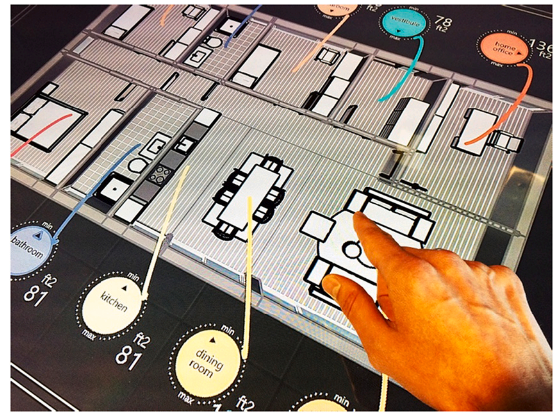

Fig. 6. HOPLA-Home Planner operating on a multitouch screen, photo: Krystian Kwieciński.

Three usability studies were planned: E01 – a preliminary study with architecture students, and two analogous studies, E02 and E03, with users not related to architectural design. E02 and E03 were planned as a public event where people could get information about the project, try the tool, and take part in the testing. Such a form allowed all interested people to participate in the study but constrained a priori estimation of the exact number of participants. It aimed at verifying the interest in computer-aided design participation. As suggested by several studies, the minimum number of participants of usability tests was set using general rule of "10 $\pm$ 2" [23] having in mind that a small number of users can lead to not all problems being detected [24]. Therefore, we planned to conduct as many user tests as possible in the allocated time. A protocol steps to conduct all three studies were developed and a questionnaire to collect participants feedback was prepared.

2.4.1. Study protocol steps

To verify the feasibility of the proposed method in supporting the participatory design process, usability tests were planned in the form of a design task to be performed by the research participants. The design task was to configure the spatial layout of a one-story single-family house for a family of 4 (2 + 2). The building was intended to be located on a plot with the context presented in the diagram (Fig. 7). The site is characterized by an access road from the east side and a rectangular plot adjacent to the access road with a shorter side. The building was placed perpendicular to the access road, with a longer elevation having both a southern and northern exposure.

Usability tests were planned to be performed in two modes. The participants of the M mode had to modify the preselected design solution, while the S mode participants had to configure the design solution from scratch independently.

The assignment of the participants to each mode was random. Participants were informed about the voluntary nature of their participation and the possibility of terminating it at any time. Each participant was given 15 min to finalize the design task. Feedback regarding the tool's usefulness and the proposed method was collected with an evaluation questionnaire that each participant completed at the end of the test.

2.4.2. Questionnaire

Developed questionnaire consisted of three parts. In the first part, participants' demographic data were collected like gender and age. This part also aimed to verify the participant's inclusion in the study. Therefore, they were asked if they were architects, students of architecture, or non-architects. A closed-ended question verifying

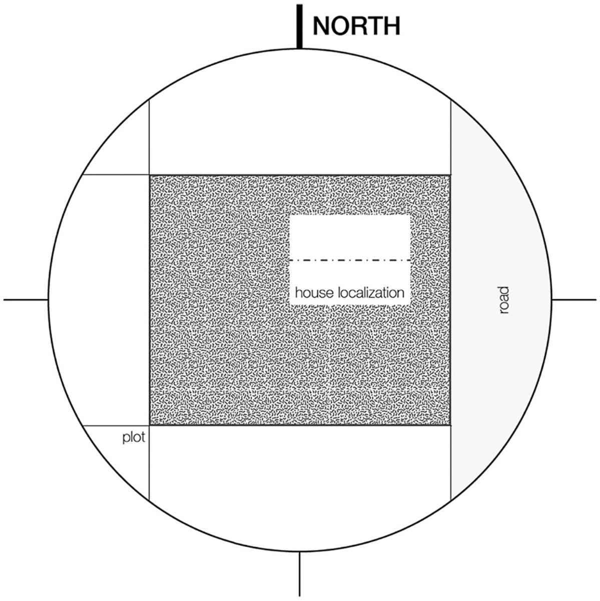

Fig. 7. Site plan scheme of the plot of the design task.

participants' previous experience designing/customizing houses was also included.

The second part aimed at verifying the user's satisfaction with the tool and final design solution. This section included a closed-ended question asking if there was enough time to configure the design.

It also included 5-point Likert scale questions asking to evaluate satisfaction with listed configured project elements: configured house layout, configured division of the building into the entrance, semi-public and private zones, the position of the rooms in relation to the entrance to the plot, the position of the rooms to the cardinal directions, configured sizes of the rooms, configured room furnishings, configured building contour, placement of the building on the plot, matching of the configured project to the needs of the characterized family and matching the configured project to the characteristics of the plot. Since the developed tool verified the users' design decisions and, in response, generated room layouts, it was crucial to confirm if such workflow met the expectations. Therefore, participants were also asked to answer open questions regarding their satisfaction with the configured project solution and to report identified problems. Additionally, they were also asked: the closed-ended question, "do you think that tool such as HOPLA could help in searching and obtaining housing design solutions that fulfill expectations" and to assess the usefulness of such tools using a five-point Likert scale.

The last part aimed at gathering information on the expectations towards computer-aided participation in the design process. In this section, a closed-ended question was included to verify whether users are interested in customizing house designs independently or whether they would prefer to be assisted by an architect. Additionally, this part was intended to verify users' preferences regarding the desired functionalities and expected outcomes of house design configurators to compare them with what is currently offered to future home occupants by commercial online house configurators. Therefore, two ranking questions were included in the questionnaire. First asked to order from the least important to the most critical listed possible functionalities of such tools: site plan customization, building layout customization, building technologies selection, kitchen and wet rooms finishing material selection, kitchen and wet rooms appliance selection, other rooms finishing materials selection, furnishing selection, exterior finishing materials selection, facade customization, building form modification. Second, asked to order the importance of possible design customization outcomes: site plan, house floor plans, elevations and sections, visualization of the building, specification of the selected choices, estimated building costs, estimated maintenance cost, energy ranking, environmental ranking, and the possibility to order. The completed questionnaires, as well as the design solutions, were anonymized with a unique number.

2.4.3. E01 usability study

E01 usability study was planned as a preliminary study with architectural students at Warsaw University of Technology. This pilot study aimed to verify the proposed research method of testing the tool's usability with users. Although any interested student could take part in the study, we specifically invited first- and second-year students to participate in the study. Our goal was to conduct research among people with the least possible design experience, similar to what we would expect from non-expert users. The study, conducted on December 4–8, 2017, met with great interest among students. 44 students evaluated the usability of HOPLA-Home Planner equipped with a tangible user interface (Fig. 5).

2.4.4. E02 usability study

E02 was planned as the primary study with users not related to architectural design. The study was conducted on April 3–6, 2018 in the USA in the HUB building on the Pennsylvania State University campus during a research trip as part of the Fulbright Commission Scholarship. E02 was combined with the public presentation of the research, where everyone could get information about the project, try the tool, and if interested take part in the study. Results of the preliminary study (E01) showed limitations of the tangible user interface. To overcome them E02 study used a different interaction method – a multitouch interactive screen which offered the same scope of participation (see Section 2.3 for more information). 30 people evaluated the usability of HOPLA-Home Planner equipped with a multitouch screen interface (Fig. 6). The surveys revealed that people with professional architectural design skills were among the participants. As a result, the data corresponding to their participation was excluded from the analysis. Finally, data collected from 12 people in M mode (Fig. 8) and 13 people in S mode (Fig. 9) were analyzed.

2.4.5. E03 usability study

E03 was planned as an analogous study to E02 with users not related to architectural design. It aimed to analyze the impact of cultural differences on the perception of the functionality of digital tools to support the design participation of single-family houses. The study was conducted on September 8–9, 2018 during the Murator-Expo building fair in Warsaw, Poland. Fair participants could get information about the project, try the tool, and if interested take part in the study. Seventeen people evaluated the usability of HOPLA-Home Planner equipped with a multitouch screen interface (Fig. 6). In this study the surveys also revealed that people with professional architectural design skills were among the participants. Their data was also excluded from the analysis. Finally, data collected from 7 people in M mode (Fig. 10) and 8 people in S mode (Fig. 11) were analyzed.

3. Results

Preliminary study E01 met with great interest among students and as planed it attracted mostly people at the beginning of their studies. Almost half of the participants (48%) of the preliminary study E01 study were second-year students (Table 1) and 39% declared that they had not designed a single-family house before. All the participants completed the design task using HOPLA within 15 min. In the questionnaires 84% of participants stated that the time provided was sufficient. Tangible user interface allowed users to modify the design by affecting their sense of touch, but it poses some limitations. It had to be extended with a tablet that enabled the user to start and finish the configuration process, enter initial data, view detailed information about the project, and be

Fig. 8. Table of design solutions obtained by participants using a tool in M mode – modification of the design solution, during the E02 experiment.

informed about the lack of necessary rooms in the configured solution. Moreover, it requires to manually place the physical markers in the workspace to allow for a modification of the design solution (in the M mode).

Questionnaire answers allowed to analyze the participants' satisfaction with the configured design solution. 66% of E01 participants stated that they were satisfied or partly satisfied with their design solution. People who were not satisfied with the configured design justified their dissatisfaction with both individually made design decisions and the limitations imposed by the developed tool. Among the latter, the most frequently mentioned were the inability to change the corridor layout of the building, the inability to locate the room in the indicated place, insufficient range of room sizes or the inability to change the arrangement of the room. Despite the identified limitations 82% of participants stated that the proposed tool could be utilized by users without experience in architectural design. In the responses to the open questions, the users noticed that HOPLA enables the inclusion of a future user in the design process, which could foster cooperation between architects and their clients and the self-configuration of solutions by a nonprofessional.

The majority of the participants in the E02 and E03 studies, aged 18–34, accounted for 88% and 80% of the people in the surveys conducted in the USA (E02) and Poland (E03), respectively (Table 1). The remainder of the participants were aged 35–49. Both studies involved more male than female, who in both cases accounted for 60% (Table 1). Answers to the questions about previous experience in designing houses showed that 36% (E02) and 27% (E03) of participants determined that they had previously designed a house (Table 1) and often referred to their previous experience in using the computer simulator "The Sims." Almost all statements of prior experience in designing houses were made

Fig. 9. Table of design solutions obtained by participants using a tool in S mode – self-configuration, during the E02 experiment.

Fig. 10. Table of design solutions obtained by participants using a tool in M mode – modification of the design solution, during the E03 experiment.

by participants aged 18–34. In contrast, only one participant over 35 in E02 indicated that he had previously designed a house.

All participants in both studies finished the given design task and configured their houses within the planned 15-min time. 92% (E02) and 93% (E03) of the participants stated that the time provided was sufficient. A detailed analysis showed that the median setup times for the E03 study and E02 study were approximately 7.5 min and <4 min, respectively.

The collected data allowed to compare all recorded participatory design processes by examining the number of configured rooms over the time of the configuration (Fig. 12). Graphs illustrate the basic difference between the configuration in M mode, where the user modifies initial design consisting of 10 rooms, and S mode, where the design has to be created from scratch. In the M mode, most participants maintained a similar number of markers on the table throughout the entire configuration, with the exception of the participant E2.L1.M.10 and E3.L1.M.06. In the first case user removed and add rooms multiple times verifying different solution. The second one is an example of the complete removal of the initial design and configuration of the solution from scratch, as in the configuration in the S mode. Graphs allow also to observe the difference in the rate of reaching the final number of rooms in the S mode. The steepness of the curve indicates the speed of configuration in reaching the final solution. The flat lines show the time when the number of rooms did not change, when participants could modify arrangements of rooms.

Questionnaire answers allowed us to analyze the participants' satisfaction with the listed elements of their designs. A comparison of the collected responses for E02 and E03 (Fig. 13) shows that participants tended to be very satisfied with their design solutions. The median rating of satisfaction with the majority of the elements of the solutions was 4 out of 5, where 5 means completely satisfied. The Krustal-Wallis test showed no statistically significant difference among the medians at the 95,0% confidence level (*P*-value = 0,956,952 for E02 and P-value = 0,548,812 for E03). These findings were confirmed by participants who additionally answered the open question, “Are you satisfied with the configured project solution and why?” In total 11 people (eight participants of the E02 study and three of the E03 study) answered that question. One E03 study participant reported that “single-direction house development prevented to obtain the desired shape of the house”. Others declared that they are satisfied with both the configured final solution and the possibility of self-configuration of the house provided by the tool.

In addition, participants were also asked to answer the open question, “Have you encountered any problems when configuring?” In total 24 participants (18 participants of the E02 study and six of the E03 study) answered that question. Six people declared they had no problems. The remaining 18 participants reported problems which can be grouped into three categories: problems related to the use of the proposed interface, dissatisfaction with the proposed room arrangement, dissatisfaction with the generated room layouts. In the first category participants reported difficulties in precisely resizing rooms. These functionalities were carried out by rotating the markers, which means that for some participants this activity was not precise enough. In the second category the inability to configure an island kitchen and the

Fig. 11. Table of design solutions obtained by participants using a tool in S mode – self-configuration, during the E03 experiment.

Table 1
Summary of data collected for studies E01, E02 and E03 from the first part of the questionnaire: year of study, age, gender, experience in home designing.

	Year of studies						Age			Gender		Have you designed a house before?	
	1	2	3	4	5	6	18–34	35–49	>50	Male	Female	Yes	No
E01	0	21	8	2	6	7	–	–	–	17	27	27	17
E02	–	–	–	–	–	–	22	3	0	15	10	9	16
E03	–	–	–	–	–	–	12	3	0	9	6	4	11

inability to locate the entrance door on the gable wall of the building were reported. The third category included the highest number of reported problems. Nine people (7 participants of the E02 study and two of the E03 study) did not like the fact that HOPLA did not allow them to configure solution they wanted, including: placing of the entrance between two bedrooms, separating the bedrooms into different parts of the building, separating the bathroom from the bedroom. All these comments resulted from grouping the rooms into zones, which limited the possibility of placing the room in a zone other than one's own.

Verification of the design solutions obtained by the participants made it possible to identify cases where the order of the rooms in the generated plan differed from the configured setting of the markers. The intersection of the lines connecting individual rooms with the corresponding markers informed the participants about the changes in the generated layout, and in the case of a final solution, it may indicate its inconsistency with the expected sequence of rooms. In the E02 study, we observed 11 final solutions that differed from the marker configuration, five obtained by participants using a tool in M mode – modification of the design solution (Fig. 8) and 6 when using the tool in S mode – self-configuration (Fig. 9). While in the E03 study, we observed just two final solutions that differed from the markers sequence all of them obtained by participants using a tool in M mode (Fig. 10) and none when using the tool in S mode (Fig. 11).

Despite that all of the participants of the E02 and E03 studies confirmed, "that tools such as HOPLA could help in searching and obtaining housing design solutions that fulfill expectations". Additionally, participants highly assessed the usefulness of digital tools in supporting the participatory design of houses. The medians of the collected ratings for the experiments conducted in the USA (E02) and in Poland (E03) were 5 (very useful) and 4, respectively. The Mann-Whitney W-test did not reveal a statistically significant difference between the medians at the 95,0% confidence level (*P*-value = 0,182,752).

Participants also had the opportunity to post individual comments. 16 people took advantage of this opportunity. Two people expressed

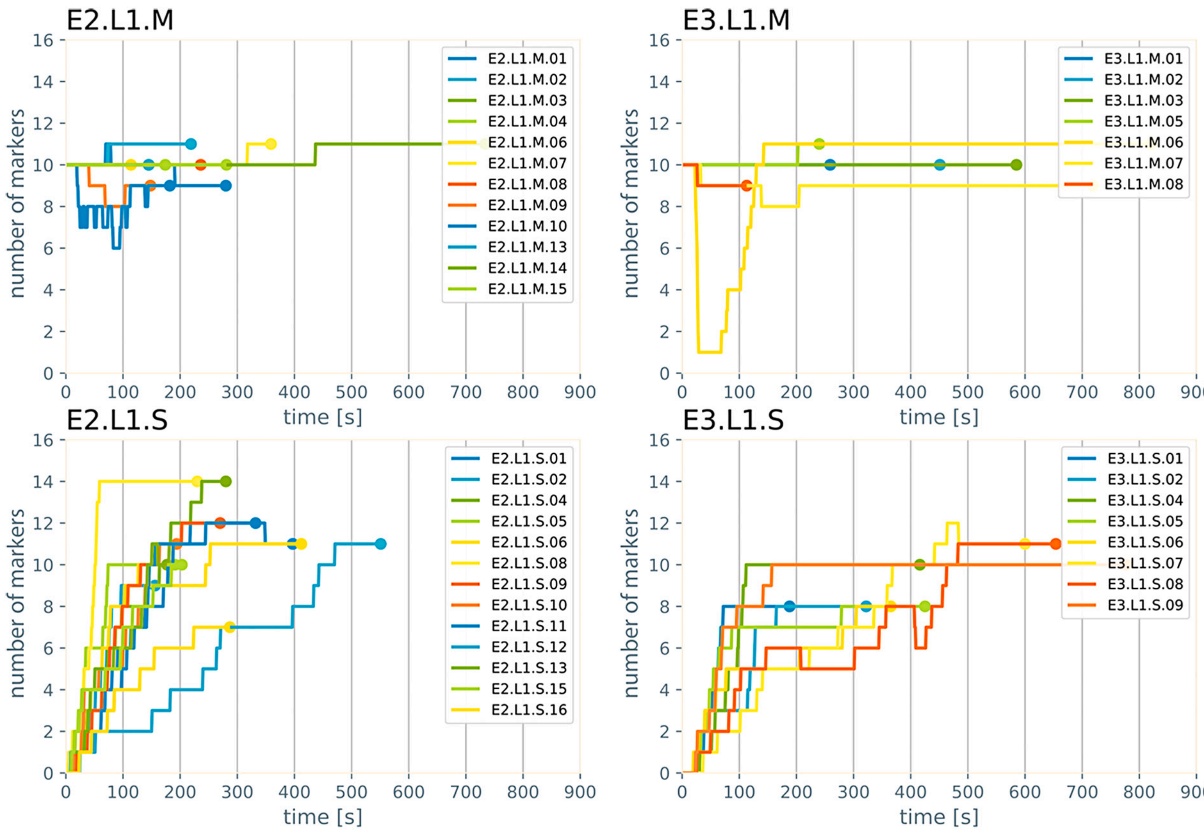

Fig. 12. Comparison of the number of displayed rooms during the configuration process. On the left, diagrams for an E02 study, on the right E03. At the top, are the diagrams for the configuration in the M mode, at the bottom in the S mode.

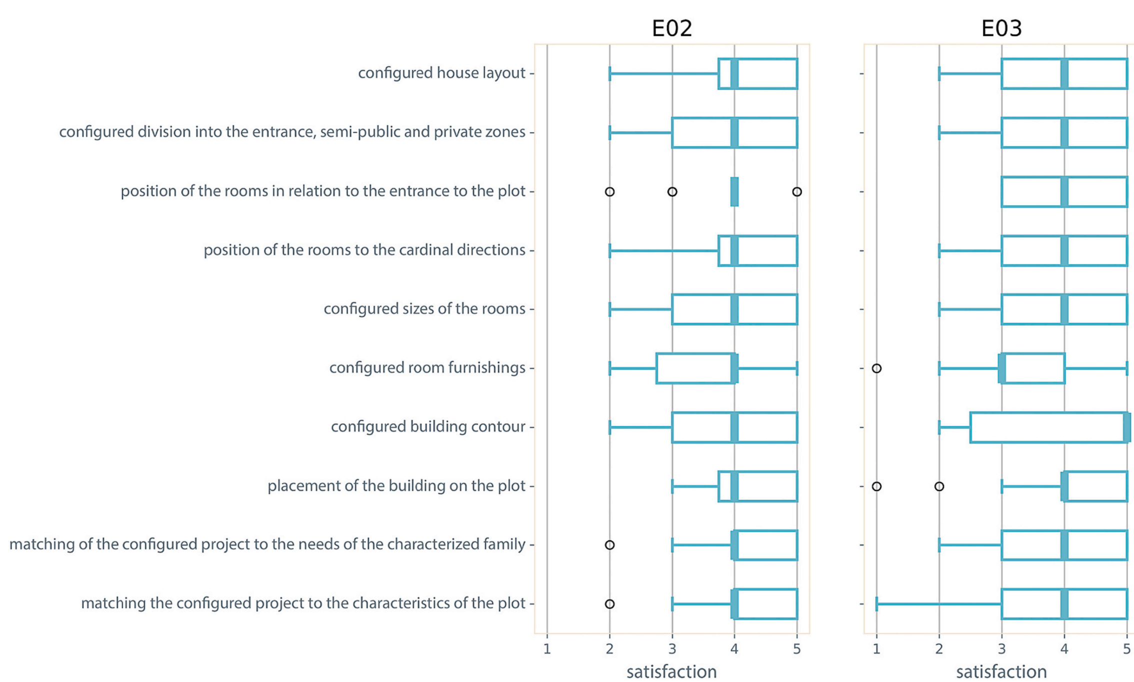

Fig. 13. Results of the survey. Box plots of satisfaction levels with the listed elements of the project [1-very dissatisfied, 5-very satisfied]. On the left is a summary of research conducted in the USA (E02); on the right is a summary of research conducted in Poland (E03).

their dissatisfaction that HOPLA did not allow them to configure the solution they wanted. Two people reported that they had previously played "The Sims". One of them compared HOPLA to "The Sims", claiming that the developed tool is "very intuitive" and that it implements new functionalities for creating buildings. More than half of the people praised the idea and implementation of the developed program. The participant with the number E02.L1.S.15 posted a comment illustrating the trust placed in computer technologies: "i have no problem using this technology for my future home because i place a lot of trust in technology daily and programs like this are being used to report my finances so why not my home?"

Questionnaire answers allowed us also to analyze users' expectations towards computer-aided participation in the design process. More than half of the participants of both experiments stated that they would prefer to configure the house using the computer tool on their own (56% and 67% for E02 and E03, respectively) rather than configure the house with assistance from a specialist (Fig. 14).

The collected data on ordering from the least important to the most important 10 listed functionalities of house design configurators allowed us also to verify users' preferences regarding the desirable functionalities of such tools (Fig. 15). For the research conducted in the USA (E02), the Kruskal-Wallis test revealed a statistically significant difference among the rank medians of the listed customization possibilities at the 95,0% confidence level (*P*-value = 0,000072). Pairwise comparison between the average ranks of the listed customization possibilities using the Bonferroni procedure revealed a statistically significant difference at the 95,0% confidence level between "building layout customization" (median rank of 8 out of 10, where 10 indicates the most important) and all the other possibilities, except for "site plan customization," "building technologies selection" and "building form modification."

For the research conducted in Poland (E03), the Kruskal-Wallis test revealed a statistically significant difference among the rank medians (*P*-value = 0,000001). Pairwise comparison between the average ranks of the listed customization possibilities using the Bonferroni procedure revealed a statistically significant difference between "building layout customization" (median rank of 9 out of 10, where 10 indicates the most important) and "kitchen and wet rooms finishing material selection," "kitchen and wet rooms appliance selection," "furnishing selection," "exterior finishing materials selection" and "facade customization."

The results showed no significant impact of cultural differences on the perception of the functionality of digital tools to support the design participation of single-family houses. Participants in both the experiments conducted in the USA (E02) and Poland (E03) ranked "building layout customization" the highest. A comparison of medians using the Mann-Whitney W-test showed that there could be some significant difference (*P*-value = 0,0410248). However, after removing the outliers rank (rank 3 in E02), the test showed no statistically significant difference between the two medians (P-value = 0,0590178). Additionally, there was no significant difference between the E02 median and E03 median for the customization possibilities ranked the lowest. The analysis showed that the lowest ranks received "exterior finishing materials selection" (P-value = 0,735,932 for comparison between E02 median and E03 median), "kitchen and wet rooms finishing material selection" (*P*-value = 0,747,266), "kitchen and wet rooms appliance selection" (P-value = 0,884,028), "other rooms finishing materials selection" (P-value = 0,130,371), "furnishing selection" (P-value = 0,558,723) and "facade customization" (P-value = 0,183,943). These expectations are very different from what is offered to future home occupants by commercial online house configurators.

The data from the questions on ranking of the house design customization outcomes showed which are the most desired by the users. For participants in both experiments, the most critical feature of the tool is to provide information about the estimated building cost (Fig. 16). A comparison of medians of this feature using the Mann-Whitney W-test showed no statistically significant difference between the ranking of this feature by participants of the experiment conducted in Poland (E03) and that of the experiment conducted in the USA (E02) (P-value = 0,225,766).

4. Discussion

The conducted research showed the feasibility of the proposed method in supporting the participatory design process of single-family houses. The developed tool assists users in the design process and guarantees outcome correctness with formalized rules. The implemented generative procedure provides a large scope of design solutions and supports users by verifying their design decisions on layout configuration. In its current state of development, the tool does not allow visualization of the building from the outside or the inside. The users were shown the perspective view of the furnished house layout they configured by themselves.

The proposed configuration process allowed all participants in the experiment to obtain design solutions in <15 min. The usability tests showed that the majority of the tool users were satisfied with the final design solution they configured in a limited time. However, some users were dissatisfied with the tool which did not allow them to configure the solution they wanted and changed the specified order of rooms. The tool verified the sequence of rooms indicated by the user and when it did not meet the formalized design rules, it displayed the closest generated solution. It informed the user about the differences between the displayed solution and their input but did not explain the rationale behind that what may cause misunderstanding and dissatisfaction among some users.

Despite that, participants confirmed that tools such as HOPLA could aid users in searching for and obtaining design solutions that meet the expectations of future residents. It is worth noting that the usability test was based on the "free-ended" task. Participants' evaluation was based on their experience with the tool and design results that they had configured themselves. In addition, participants' design decisions did not involve any obligations. Configuring the solution did not require living in such a building. The necessity to make binding spatial decisions and the related financial obligations, occurring in the real case of building a house, may distort the obtained results. Therefore, the stated level of satisfaction with the tool and configured designs may not reflect willingness to build and live in such houses.

Although the research focused on the verification of the proposed method from the user's perspective, the design solutions obtained by the participants were also analyzed by the authors. All of them met the formal rules, but in some cases, the low design quality of the obtained solutions was observed. Some users did not take into account the compositional principles, such as the use of a repetitive module, rhythm of the room's sizes, alignment of adjacent rooms placed in different bays,

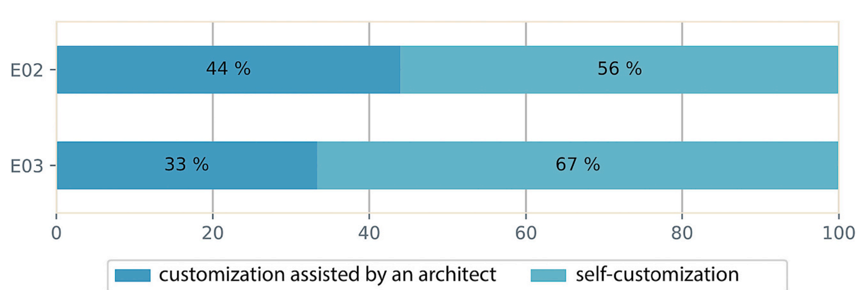

Fig. 14. Results of the survey. Answers to the question: when customizing a design of your own house, would you prefer to design it on your own using a tool similar to HOPLA or be assisted by an architect?

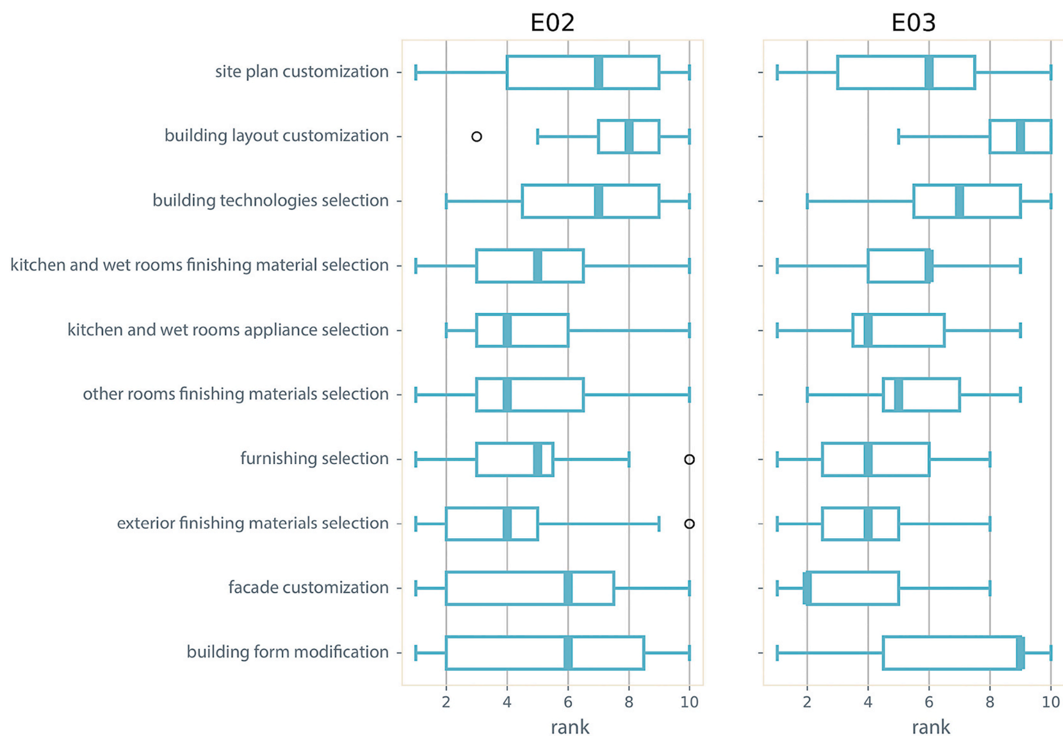

Fig. 15. Results of the survey. Box plots of ranks of house design customization possibilities [1-less important, 10-most important]. On the left is a summary of research conducted in the USA (E02); on the right is a summary of research conducted in Poland (E03).

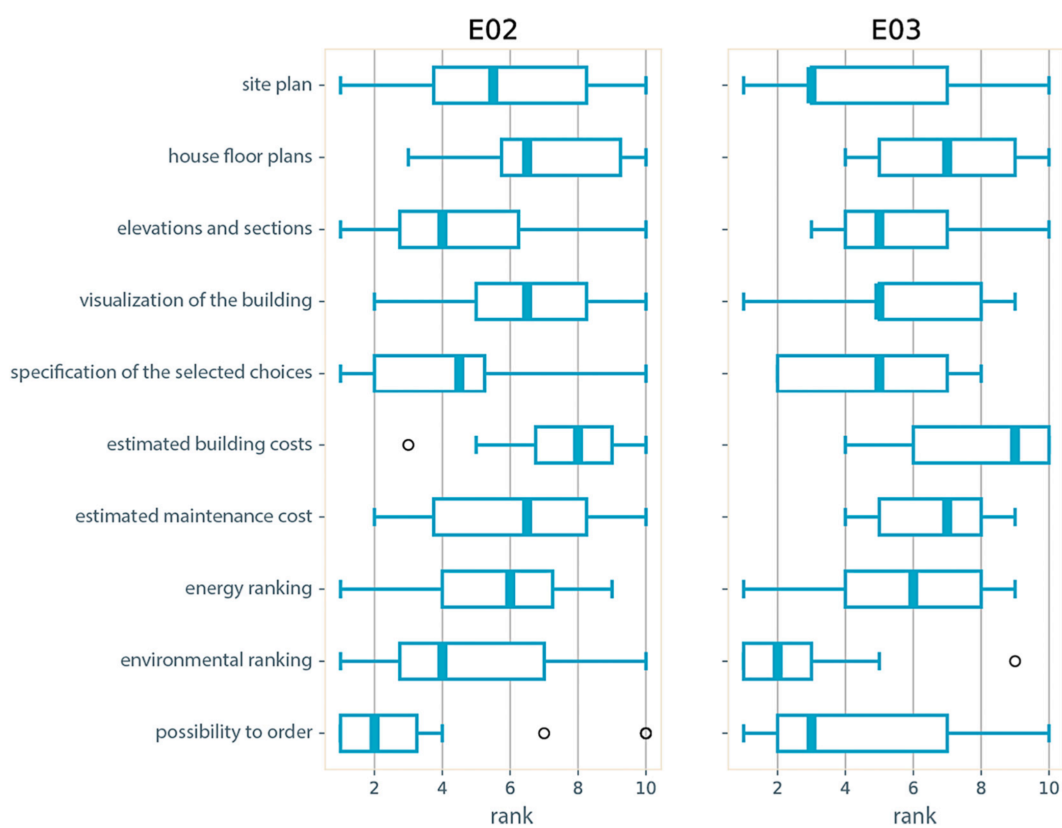

Fig. 16. Results of the survey. Box plots of ranks of house design customization outcomes [1-less important, 10-most important]. On the left is a summary of research conducted in the USA (E02); on the right is a summary of research conducted in Poland (E03).

or simplification of the external contour. Most of these features could be enforced by implementing additional design rules, however, such an approach would limit the flexibility of the system and reduce the number of possible design solutions. It is worth noting that the improvement of the quality of designs can be achieved both by further limiting the design possibilities but also by supporting the use of the tool by an architect who could additionally provide expert advice. Nevertheless, computer tools such as HOPLA, in comparison to the traditional participatory design process, can shorten the time needed to obtain the design solution while increasing the number of design iterations and verified alternatives.

The research results did not reveal a significant impact of cultural differences on the expectations of non-expert users towards computer-assisted participatory design of single-family houses but did show that these expectations are different from what is currently offered on the market. While the most important feature in the customization of houses for participants in both experiments (E02 and E03) was the possibility of modifying house layouts, the lowest ranks received furnishing selection and interior, and exterior finishing materials selection, which are currently mainly offered to them on the construction market. As the data comes from the force ranking task, it does not mean that the possibility of modifying the finishing materials is not important for the participants, but it is less expected than the possibility of modifying the house layouts. The usability studies confirmed the hypothesis that one of the most critical aspects of the house design process for non-expert users is the possibility of customizing the layout of a building. Research also showed that users' expectations of the possible outcomes of configuration were similar among participants in Poland (E03) and in the USA (E02) studies, where information about building cost was ranked first.

The obtained results indicate the demand for tools that enable non-experts to engage in computer-assisted participatory design of single-family houses. Research unveiled the willingness of users to participate in the design process and their desire to use computer tools. In particular, HOPLA aroused greater interest in testing it among younger people, while no persons over 50 decided to participate in the research. Therefore, computer-aided design participation might currently support middle-aged users but exclude older users.

Releasing to the general public computer tools that support participatory design can trigger the willingness among non-expert users to actively participate in the design process. The study showed that among people aged 18–35, there is a belief of having experience in designing houses, which was often justified by the earlier use of the simulation game "The Sims." This finding may signal the impact of perceiving house design through the prism of experience gained while using computer programs that simulate this process. Use of such tools may have an impact on the perception of the architects and the professional design of houses by the generation that is entering or will soon enter the age of building a house.

The software supporting the participation of nonprofessional users in the house design process requires ensuring the correctness of the obtained design solutions and the possibility of their realization. A guarantee of the correctness of the designs presented by the computer tool can be ensured by:

- limiting the design possibilities to predefined solutions,
- using procedures that generate solutions,
- using procedures that verify users' decisions,
- supporting the use of the tool with a specialist.

Limiting the design possibilities to predefined solutions requires a priori anticipation of possible variants of the design. This method significantly increases the workload, requiring checking of all possible design variations, which might cause substantial limitations of the design modification scope.

Implementing generative procedures can significantly increase the scope of possible design solutions but requires algorithmizing the design process and formulating design rules. Such a solution might also constrain the participation of the user in the design process, giving them the possibility of accepting the presented solution, choosing from several presented proposals, or modifying the solution by changing the provided parameters.

The use of verifying procedures allows to increase the scope of users' participation in the design process and to change its character, enabling the recipients to configure them on their own. While increasing the flexibility of the tool can increase users' satisfaction by permitting them to fulfill their expectations, it is more challenging for the developers of the design system to guarantee the quality of design outcomes and compliance with desired design principles.

Support from a specialist in using the tool by non-expert can limit the necessity to implement algorithmic procedures that verify the correctness of the obtained solutions. In this case, the expert can provide ongoing verification of the quality of the obtained design solutions. The presence of a designer can support the user in obtaining design solutions and in gaining professional and technical advice on various design aspects. The development of digital tools that support design participation allows architects to define the framework for cooperation with clients and the range of possible solutions. Implementation of such tools in design practice may allow for shortening the time of the design process and related costs while maintaining direct contact with the client.

The use of computer software supporting participatory design involving the user and designer can be beneficial for both parties. However, in light of the results of this research, it may discourage users who are interested in the complete autonomous configuration of designs. More than half of the participants in both experiments (E02 and E03) stated that they would prefer to configure a design solution themselves using a computer tool rather than being additionally assisted by a specialist. The preference expressed by the participants to configure the design on their own without an architect should be further investigated. It is unclear whether this tendency is due to the users' willingness to create on their own or the lack of perception of architects as an essential and valuable part of the process.

Further research should focus on understanding non-experts' motivation to participate in the design process, their perception of the role of architects in the design process, and the feasibility of implementing computer-aided participation for single-family house design in architectural practice.

5. Conclusions

The 21st century brought to the market radical postulates for enablement of computer support for non-expert users in the design of residential spaces, what has been researched and foreseen by the Negroponte team. The IT revolution increased access to design software but also misled people who embraced the possibility of designing homes on their own. Non-expert users have wide access to design tools that do not guarantee that projects can be built. The popularization of personal computers with Internet access introduced companies to the possibility of selling customized goods at a distance. Companies offering home designs started to implement mass customization strategies; however, the need to ensure the correctness of possible outcomes limited the scope of customization. Restraining house layout modifications and focusing users' attention on the selection of finishing materials suggests that current online services are a natural evolution of pattern books. Research in the field of generative design revealed both the potential of the method for guaranteeing the correctness of outcomes with formalized rules and the challenges in users' participation and direct interaction with a design.

In this paper, a method was presented for computer-aided participation in single-family house design, which allows flexible configuration of house layout, along with the results of its verification through usability studies of the developed HOPLA-Home Planner tool with non-expert users. The study proposed integration of a generative design system with an interactive user interface. A generative system based on context-free grammar is employed to produce syntactically correct solutions and verify user design decisions indicated via an interface.

The usability studies of HOPLA showed that

- in comparison to the traditional participatory design process, the method allows to shorten the time needed to find an appropriate solution while increasing the number of design iterations
- the tool allows unprofessional users to obtain a design solution within a limited time, but it does not meet the expectations of all the users
- the generative system guaranteed the syntactic correctness of the house plans, but the flexibility offered to users posed a challenge to architectural quality of the obtained designs
- among non-expert users, there is a demand for tools enabling computer-supported participatory design of single-family houses especially allowing autonomous configuration
- among users aged 18–35, there is a belief that they have experience in designing houses, which is often justified by their use of simulation games, such as "The Sims"
- the most essential feature in the customization of houses is the possibility of modifying their layouts
- furnishing selection and interior, and exterior finishing materials selection received the lowest ranks of importance
- users highly expect to be provided information about building costs.

This research showed demand from non-expert users for interactive generative systems supporting participatory house design. The challenge, however, is to ensure the correctness and quality of the design results while at the same time offering the flexibility of the system to meet a wide range of expectations. The findings revealed that increasing the scope of users' participation in the design process can increase their satisfaction, but it may also challenge guaranteeing the design quality of the outcomes. Limiting the design possibilities offered by the tool can improve the quality of obtained solutions, but at the same time, it constrains the scope of possible design outcomes. Therefore, constraining configuration possibilities may result in an increased ratio of users whose expectations will not be met.

An additional identified method of guaranteeing the correctness and quality of solutions is to involve an expert in the configuration process. An interactive generative system supporting participatory house design can benefit both the user and the designer. However, implementing this strategy in the design practice should be further investigated. Future research should verify both the revealed demand for autonomous configuration of house designs by non-expert users and the interest of architects in employing participatory design in house design and supporting it with interactive generative systems.

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.

Data availability

Data will be made available on request.

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