HOPLA

Interfacing Automation for Mass-customization

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HOPLA (Home Planner) is a computer-aided design system aimed at simplifying customization of house design. It merges aspects of user-centered computer-aided design with machine-centered computerized design, as defined by Negroponte in *The Architecture Machine*. The tool was developed to fulfill mass-customization principles without compromising mass production efficiency and to support users' participation in design processes to help them formulate expectations and search for design solutions. We describe the details of the system development and its possible use in the process of mass-customization and participatory design of single-family houses. The system consists of two core elements: an algorithm based on a generic grammar responsible for generating design solutions in relation to user input, and a Tangible User Interface allowing users to introduce data and to control the process in an intuitive way. The main challenge in developing the system was to synchronize the freedom of user's design decisions with the rigor of machine's verification process.

Keywords: mass-customization, participatory design, tangible user interface, house design, generative design

INTRODUCTION

Generative methods simplify the process of architectural design in response to parameters defined by architects and clients. These methods allow us to find multiple solutions to a problem, but choosing the solution that best meets defined criteria is challenging. The challenge becomes even bigger when dealing with ill-defined problems that may occur in the process of designing a single-family house. Can we program algorithms so that they generate design solutions that reflect the needs of their future inhabitants? Is it possible to quantify such needs? What if the future inhabitants are not fully aware of their needs? How can we - as architects - give these inhabitants a possibility to browse and understand different design options?

One approach that tries to respond to all these questions would be to make an extensive list of parameters that characterize future dwellers along with their needs and then associate these parameters with a form-generating algorithm. This approach assumes, however, that we can represent all the information required to generate a design solution in a numerical form and that we can develop a procedure generating answers that are always correct. Another way, not necessarily computerized and tradi-
tionally used by many architects, would be to involve future inhabitants in a process, in which the architect presents her proposal and iteratively adjusts it based on the clients’ feedback. This approach appears to be more appropriate if the design task is at risk of being ill-defined, as in case of designing a house for people who do not know exactly their housing needs. The iterative process it involves does not have to be based exclusively on objective criteria but it can also be affected by subjective criteria expressed by individual clients. The threat in this method is that the architect can provide an undesired solution at the very beginning so that too much focus is put on modifying this solution towards the desired outcome.

**Participatory design**

Participatory design has a long tradition in architecture. It emerged in the 60s of the 20th century in different places around the world as a reaction to impersonality and monotony of mass-produced housing. John Habraken in the Netherlands (Habraken 1961), Lucien Kroll in Belgium (Hofmann 2014), Walter Segal in Great Britain (Blundell 2005), Oskar and Zofia Hansen in Poland (Hansen 2005) or Christopher Alexander (Alexander 1969) are architects who noticed the importance of involving future users in design processes. Already at that time, many architects imagined that such approach could be partly automated. Alexander, Hirshen, Ishikawa, Coffin, and Angel, while working on El Proyecto Experimental de Vivienda, proposed a step-by-step description of what they called the combinational process (Alexander 1969). About the same time, many researchers started developing ideas of how computers could support automatic generation of houses (Mitchel 1974, Stiny & Mitchell 1978) and design participation (Cross & Maver 1973, Wrona 1981). Research in that area was fueled by the advancement of computer technologies and the emergence of the concept of mass-customization introduced by Davis (1987) and later developed by Pine (1999). The works of Duarte (2001), Benros and Duarte (2009), Huang and Krawczyk (2006), Niemeijer (2011), Sprecher and Friedman (2013), Khalili-Araghi and Kolarevic (2016) show how mass-customization can be merged with house design and how computer systems can support it.

In this paper, we present HOPLA (Home Planner): a computer-aided design system aimed at streamlining customization of single-family house designs by actively involving users in a computer-aided participatory design process. We describe details of the proposed system that consists of a generative procedure, which automatizes the production of design solutions, and a Tangible User Interface, which allows users to introduce data and to control the process in an intuitive way.

**Human-Computer Interaction**

Negroponte in Being Digital (1996) criticizes contemporary advancements in human-computer interaction that are based on a mouse and a keyboard - especially in the context of architectural design. He also claims, however, that there is no such thing as a perfect interface. What Negroponte defends is a multimodal approach to interacting with machines - a one that would allow users to transmit the same information in many ways using multiple senses and channels - by speaking, pointing, touching. Li and Teng (2017) point out major drawbacks of contemporary CAAD tools. Excessive mathematical precision limits flexibility at early design stages and the use of WIMP interfaces (windows, icons, menus, pointer) makes design tools less capable of comprehensively representing physical 3D objects.

It is hard to imagine designing a house using a traditional WIMP interface that consists of labels, tables, sliders, dropdown lists, and buttons, especially if a user is a non-professional involved in a participative process. It is true that a lot of information that shapes a future house can be defined with numerical data, but what is missing is an interface that enables the user to shape her house without defining this data directly. Such an interface should be intuitive and engaging. While interacting with it, the user should be aware of the effects her actions have on the
final outcome, so that she can verify the final results, make informed decisions and visualize them.

Quoting Li and Teng, design is an act of seeing, thinking, and making, which involves eyes, brain, and hands. Visualization is about more than just an image: it is about finding a balance between sensations, activities, and concepts. Evans in his book The Projective Cast (2000) notes that sight is not the only sense responsible for spatial perception. Already in the 18th century, it was considered insufficient to perceive the third dimension without the assistance of touch. We think that multisensory (or multimodal) integration is substantial for humans to understand their environment, take actions and respond to stimuli. Implementing touch in experimental interfaces may be a crucial step towards a fully immersive interaction with a machine.

One of the means of human-computer interaction that can complement traditional WIMP approach is Tangible User Interfaces (TUI), i.e. environments in which the user interacts with the machine by manipulating physical objects. These objects are understood not only by the machine but also by humans (e.g. as abstract or figurative representations of other objects).

Research conducted by Kim and Maher reveals that TUIs positively change designers’ spatial cognition, and then these affect the design processes by increasing designers’ problem-finding behaviors. (Maher and Kim 2006) Tangible User Interfaces may also be a chance to eliminate the false dichotomy between input devices (such as the keyboard and mouse) and graphical output devices (monitors, projection, head-mounted displays). (Ullmer and Ishii 2001).

The Sayre Glove developed in 1977 by Daniel J. Sandin and Thomas Defanti at the Electronic Visualization Laboratory and based on the idea of Richard Sayre is believed to be the first tangible device enabling human-computer interaction. [1] Other important examples of design interfaces that take advantage of the sense of touch include: Universal Constructor by J. Frazer 1981 (Fielding-Piper 2002), Geometry Defining Processors from MERL 1989 [2] and more recently the works developed at MIT Tangible Media Group, such as URP, Triangles, inSide or Physical Telepresence. Ishii et al. (2012) propose to try merging the tangible and the digital seamlessly, what would result in what they call Radical Atoms.

**METHODOLOGY, PROTOTYPE, AND WORKFLOW**

For the purpose of this research, we developed a computer tool facilitating the participation of future inhabitants in the process of designing a house. The tool had to provide solutions that meet various users expectations, support evaluation of the designs in relation to subjective criteria of individual users and allow for flexible modification of results. At the same time, the tool had to eliminate incorrect solutions and propose alternatives. We followed a concept of computer-aided participatory design (Kwiecinski et al. 2017) composed of 3 elements: design system, digital communication medium, and participatory design process. Similarly, HOPLA also consists of three elements: a generative design system responsible for generating solutions in relation to user input, a digital communication medium allowing users to tangibly interact with the design system and a participatory design process inviting people to actively take part in shaping their houses.

**Generative Design System**

The generative design system that we implemented is based on shape grammar developed during previous research (Kwiecinski et al. 2016). We implemented grammar rules using attribute grammars as proposed by Homenda and Kwiecinski (2016) for controlling house layout customization.

The system operates on a list of 9 possible room types (vestibule, toilet, kitchen, dining room, living room, home office, master bedroom, single bedroom, and bathroom), out of which each may be used multiple times. Each room’s dimensions are multiples of the base module of 60 centimeters. Possible rooms’ widths and depths are presented in Ta-
Table 1. Each room was assigned to one of three zones (Table 1): the entrance zone (z_entrance), the semi-public zone (z_semipublic) and the private zone (z_private). Assigning rooms to zones corresponds to their degree of privacy, as proposed by Christopher Alexander in Pattern 127 - Intimacy Gradient (Alexander 1977). This allows to group the rooms and it prevents mixing of different zones. Each room can be placed in either of two house bays: north or south. The accuracy of placing the rooms in the building is being controlled by the grammar rules.

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

For the purpose of this research, we modified initial shape grammar rules to form a generic grammar, defined by Benros et al. (2014) as a formalism that allows the design of diverse solutions, unlike a typical grammar which focuses on a specific design language. The decision had a double motive. First, we wanted to include different site conditions scenarios resulting in different places of the vestibule in the structure of the house. Second, we wanted to increase the level of user's influence on the generated solutions. Since we knew that we were going to use an interac-

Table 2
Non-contextual grammar rules
tive table, this selection offered us more possibilities for user involvement in the house design process. We decided to allow users to specify not only type and size of the rooms but also their preferred location. We also wanted to use this system in the future for testing different rule sets by verifying design outcomes and users feedback. The implemented rules of the non-contextual grammar are presented in Table 2.

The grammar rules allow placing each room in the vicinity of any other room from the same zone and they allow adding each zone in the vicinity of any other zone. The rules were designed to allow high flexibility in configuring the floor plan so that we could analyze users’ design decisions in that aspect. A few conditions were added to eliminate undesirable solutions. Apart from constraining possible locations of each room by defining acceptable adjacencies (inclusion in a zone), we also constrained the relative position of some rooms to the resulting building boundary by specifying whether a room can be placed in a corner. In that respect, the toilet was prevented from being placed in the corner of the building as this location was reserved for rooms that may require more sun access. In order to allow kitchen, dining room and living room to form an open space, kitchen could not be placed between the dining room and the living room. An additional constraint was introduced to ensure that a zone is connected when rooms belonging to that zone are distributed in different bays of the house. This condition prevents dividing a zone by placing its rooms at opposite corners of the house.

We abandoned an initial idea to limit the plan to a rectangular shape. This decision was based on preliminary studies, during which we realized that rectangular floor plan often made it impossible to find a correct design solution.

The final solution is calculated taking into account - apart from the grammar rules - data defined by the user: a list of desired rooms, their sizes within given limits and their preferred location. Additionally, we developed a three-dimensional library of models for different types of rooms. The resulting layout is automatically complemented with interior and exterior walls, windows, doors, and sample furniture.

**Tangible communication medium**

In HOPLA users control the design process using a custom TUI called InteracTable and a set of fiducial markers that represent the rooms. InteracTable is an affordable TUI designed by Jacek Markusiewicz in collaboration with the students of the Faculty of Architecture at Warsaw University of Technology: Jakub Andrzejewski, Damian Lachtara, and Kacper Karpiński. It is a structure with a translucent glass panel as the tabletop, a rear projector below it, and a camera placed above to track markers that are handled by the user. (see figure 1) The system marks the continuation of the research described by Markusiewicz and Kręźlik. (2017).

The markers are physical wooden blocks differentiated by shape and each equipped with a unique image that is optimized for computer vision recognition. Each marker is recognized by the system as a representation of a specific room type. By changing positions of the blocks, the user specifies locations rooms they represent, while areas of these rooms are changed by rotating the blocks. All the necessary information - such as room name or its size - is displayed on the tabletop next to the marker. The information is color-coded to further facilitate function recognition. After placing the marker on the interactive table, the application recognizes the type of the room and displays its name, its area and a circle filled with a color representing the room’s type. The size of the circle is proportional to the area of the room and a black arrowhead informs the user about the rotation angle of the marker.

The user can also control other aspects of the project using the markers. The positions of the bays of the house are defined by changing positions of the corner markers: the upper-leftmost marker for the north bay and lower-rightmost marker for the south bay. The user can control the location of the corridor by changing the position of the marker representing
the vestibule.

The customized design solutions are displayed in the center of the interactive table in form of a plan. The rooms are rendered with furniture inside and their floors are color-coded in relation to their function. In order to facilitate the identification of a room with its marker, the application displays a curve connecting the position of the marker and the center point of the room on the plan. This curve signals possible differences between the user-indicated marker location and the design solution proposed by the system.

At first, we assumed that the entire configuration process would be controlled using only the physical markers. However, while working on the tool, we noticed that not all information can be introduced using such interaction. We expanded the interface by adding a tablet with a dedicated application. It was paired with the TUI so that users can use it to begin and finish the configuration process, introduce initial data, browse detailed information on the project, and verify important information on the configuration they are working on. This information includes a list of suggested rooms that need to be incorporated in the final design. The application displays current area of each room and the total area of the building. If any of the required rooms are missing, the application displays it in red, whereas if there are any rooms included by the user but not required by the system, it displays them in green.

All calculations are performed by a Grasshopper3d definition, while the applications enabling interaction for both InteracTable and the tablet was developed in Unity.

**Participatory design process**

In order to start the configuration process, the user needs to provide initial information using the tablet. Based on this information, the software suggests a list of rooms which should be incorporated into the design solution. In the next stage, the user can decide whether she prefers to configure the building her-
A user interactively configuring design solution.

Figure 2

self from a scratch or to modify a suggested project. In both modes, users are asked to place the physical markers on the interactive table in order to express their expectations regarding the design of the house. The system collects data on the size of every room and its preferred location and analyses it. If the proposed arrangement does not fulfill formalized design rules, the system searches for a new configuration: a one that both fulfills all the grammar rules and resembles the one proposed by the user to the greatest extent. Such calculated solution is being displayed on the interactive table along with additional information supporting users informed decision.

If not satisfied, the user can modify positions of the physical markers and have another solution presented by the tool in relation to the specified modifications. As the resulting configuration of the house does not necessarily correspond to the configuration of the markers (due to the system’s verification process), the application displays a connection between the physical position of the marker and the center of the room that it represents. This way, the user is informed about all the changes the system makes and can react accordingly. The user can either accept the proposed design solution or keep searching for the one that is fully consistent with expressed expectations. Figure 2 shows the process of interacting with the system while figure 3 presents several configuration results.
RESULTS, CONCLUSIONS, AND FUTURE WORK
During this research, we developed a computer tool facilitating users participation in designing houses. HOPLA consists of three elements: a generative desig system, a digital communication medium and a participatory design process. The tool provides solutions to various users expectations expressed through a TUI. Users interact with HOPLA using physical markers that represent different functions of the spaces in the house. They specify the functional program of the house, the area of each room and the rooms' preferred location in the structure of the building. The algorithm based on attribute grammar verifies provided information with specified grammar rules and generates a design solution. HOPLA is able to provide a solution even if the specification provided by the user is not fulfilling formalized grammar rules. It allows its users to confront their design wishes with a generated outcome in real time. In

Figure 3
Exemplary houses floor plans configured using HOPLA.
the process, users can also formulate requirements if they are not explicitly defined. This way, HOPLA engages users’ participation in the design process of their future house and supports them in searching for the desired design solution.

In the next stages, we are planning to validate usability of HOPLA. Usability tests will verify users’ satisfaction with the design tool as well as with generated design outcomes. We want to use the system as a research tool for verifying the concept of the computer-supported participatory design process of single-family houses. We plan to review whether a tool like that can support mass customization of house designs in relation to users’ needs. In that respect, we want to verify implemented grammar rules and modify them if needed.

We believe that similar tools can shift the problem of meeting complex users’ expectations from ill-defined to goal-oriented. Such transition can be beneficial for both architects, who would gain detailed information regarding wishes of their clients in short time, and the clients themselves, who express their wishes in a more informed way. We think that HOPLA can support direct conversation between architect and their client, but it can also facilitate indirect conversation on a distance. We hope that based on our research other architects develop their own tools allowing active participation of their clients. We also hope that such approach might democratize design by extending the scope of people who have access to architectural design processes.

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