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Keywords (separated by '-')	Human-centered design - Housing - Cloud computing - Generative design - Co-creation

Author Proof

Human-Centered Design and Co-design Methodologies for Mass Customization in Housing: A Case Study Using Cloud Computing Applications

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Abstract. This research paper presents Turing: an innovative tool that approaches mass-housing design and demonstrates how cloud computing and generative design can be conjointly used via an accessible web-based application to achieve a high level of user input and co-design integration. The technologies implemented are a Grasshopper *cloud* application with Rhino.Compute, linked to a web server and using Three.js as a visualisation engine on a website. AQ1

This work explores the design, industrial and commercial opportunities of co-designed, platform-based processes for customisable collective residential developments through generative design and cloud computing from a human-centred perspective. AQ2

The findings of this research explore an user integration approach in mass customisation using web tools. This paper also investigates the potential of generative design and cloud computing by examining how residential models can be co-designed by architects, developers, manufacturers and users through a novel workflow.

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1 Non-standard Mass Housing and End-User Engagement

The advent of the Internet, digital production techniques as well as changing markets have induced businesses to increasingly turn their attention towards the end customer and adapt product and services. In the Architecture field these technologies have nurtured non-standard explorations and Architects have been focused on formal experimentation as opposed to prioritising the end user [2]. Housing specifically, and mass housing in

A.-L. Andersen et al. (Eds.): CARV 2021, LNME, pp. 1–9, 2022.
https://doi.org/10.1007/978-3-030-90700-6_109

particular, is still today characterised by lack of innovation, conventional design, where traditional workflows and building techniques are still employed [1, 8].

Despite promising contemporary ways of reconsidering the design and construction industry (BIM or MMC, for example), the exchange of knowledge and information within the design process is still today very much fragmented. In particular, the involvement of end-users is still very limited, however, a big unexplored opportunity [5].

This work takes a stance towards the capabilities of digital technologies to improve residential design approaches from a human-centered perspective where the customer - not only the industry - is at the center of focus [6]. A prototype tool (artifact) has been developed to allow computational methods to enhance customisation of housing design as well as the relationship between designers and potential users of the tool, these being homebuyers, developers and manufacturers.

The prototype tool has been called Turing, named after Alan Turing to emphasise the importance of computation in society. This paper presents some initial developments, testing and conclusions of this tool.

2 Literature Findings and Objectives

This piece of research takes an exploratory and innovative approach to the unexploited implementation of a human-centered use of computational methodologies in housing design and supply chain, trying to bridge the gap of user co-creation between designers, developers and homebuilders [9]. The current study tackles the following unexplored research opportunities with regards to mass customisation:

1. The housing industry currently acknowledges the business benefits of end-users' engagement because it would increase their value added [4];
2. There is a condition to be improved: innovation in manufacturing processes [1];
3. There is an unexplored opportunity in digitalisation of human-input processes [5];
4. There is a gap in the application of mass customisation as a business strategy in the homebuilding industry and computational tools can play a key role in that [7].

Even though the potential benefits of a client focused approach are widely accepted by the industry, the lack of customer-centrism in the supply chain is notable as there are structural, technological and organisational issues that hinder its deployment [1]. As the literature findings show, these opportunities are at present unexploited.

Besides this, there is scarce research stemming from practical propositions as much of the existing research on mass customisation in housing is related to case studies, planning activities and strategies. The main objective of this research is to bring together the unexplored opportunities in housing design and fill the existing gap between homebuyers and developers by means of an artifact development and testing [6].

The purpose of the proposed computational tool is to plan, assess and automate the plot analysis, feasibility studies, and basic development metrics of collective housing modular schemes from the plot selection input. The end goal of this tool is to raise the engagement, accessibility and personalisation of future mass-housing schemes by exploring novel methods of engagement and co-creation through computational methods.

Conceived as a digital platform, Turing aims to act as a mediator between seemingly disparate and opposing parties in the housing delivery process: end user, developer and manufacturer. With the help of computational design methods, including generative design, search algorithms and machine learning, this tool aims to achieve a satisficing position in terms of design quality, real estate metrics and construction feasibility.

3 The Turing Application

The Turing application addresses the problem of user co-creation and participation in the design process (co-design) through a cloud-computing generative design, web-based software. It generates design options at feasibility study stage for high-level residential master planning with a novel approach that involves user engagement in the decision-making process through the use of interactive, responsive and accessible web- based choices and visualisations.

Turing's purpose is to provide the user with a fast and reliable feasibility test engine accompanied with comprehensible metrics and a set of design input options for the problem of residential planning in a selected site, according to a series of user-defined and local regulation constraints.

The tool is designed to help the user navigate through what has been called a solution space (see Sect. 4) and to produce fast high-level feasibility study variations for a specific site. The application has been developed by Labit Analytics, Labit Group's in-house R&D+i team in London and Madrid.

3.1 Initial ideas and Sketching

Firstly, a series of ideas and a comparative analysis of state-of-the-art methods currently on the market (e.g. testfit.io, hypar.io, spacemakerai.com and archistar.ai) were compiled in an online Miro board, as an accessible environment for review (see Fig. 1).

While we note that the aforementioned existing design tools are well-developed and user-friendly modelling environments with refined visualisation, the extent to which they engage with the end-user and their specific input as a part of the design process is limited, especially with housing projects at stake. One may note that the majority of existing computational tools (especially when bespoke) are problem-oriented pieces of software, helping clients to address specific modelling and drawing tasks as well as geometric challenges. These include a wide range of applications from real estate assessment to parking design or modelling through a Design for Manufacture and Assembly (DfMA) approach. The functionalities of such tools are either an extension or simplification of commercial CAD and CAM software packages with a much more user-friendly interface and sophisticated automations.

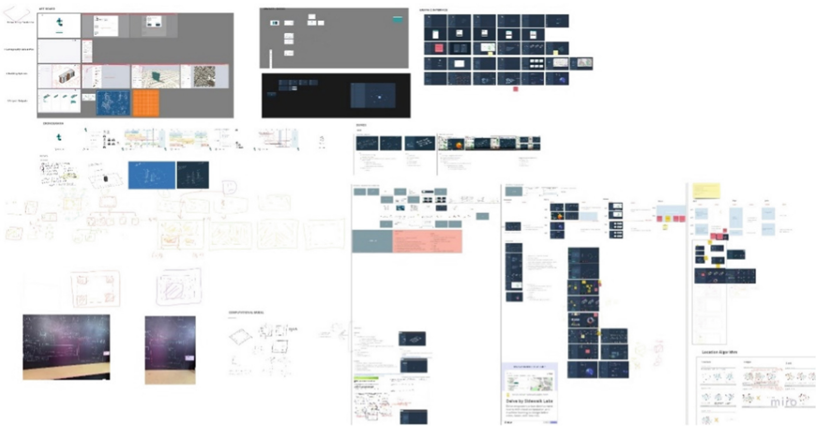

Fig. 1. Screenshot of Turing's Miro Board, used for application development and reviews. This figure illustrates the collaborative process through which the team developed the presented tool from conception to more operational phases and prototyping (image by the authors).

In most cases, current commercial tools are extremely accurate and effective in resolving a given task. However, the involvement of the end user as an active party in the design process is limited. Often, the user is required to generate inputs, control the progress, and assess the final results until a satisfactory outcome is reached. Unless the user has an adequate level of technical knowledge, such tools are not easily customisable, or indeed comprehensible to a general customer (e.g. a homebuyer). Turing aims to address this gap in usability and transparency, aiding the user through the decision-making process by providing them with a solution space that they can navigate through.

We conceived the idea of solution space as a way for users to be directly involved in the design process, becoming a co-author with the algorithm. We want to replace the usual linear organisation of work (user input, machine computes, user checks, machine recomputes, user stops the process) with a more collaborative approach where the user and the algorithm are co-designers in a continuous looping process.

Therefore, Turing's distinctive value lies in providing a solution space and assisting the user in the selection of a potential desired option by means of an accessible and user-friendly platform in a step-by-step procedure. Not only does Turing quickly visualize the design solutions, but it also shows the metrics associated to each option, making the process more customisable and comprehensible at each step of the process.

With these ideas in mind, a series of low-fidelity prototypes through sketches were uploaded for discussion amongst the design and development team on the Miro board (see Fig. 2). The key initial premise of the project was the need to prioritise simplicity, user experience, accessibility and customisation, therefore, a web, cloud-computing environment was the starting point. This decision influenced later development of the tool, including the need to develop not only a website from scratch but also the associated algorithm that would produce the solution space, leaving aside other potential development avenues such as a desktop CAD package plug-in. The development steered towards a parametric heuristics algorithmic approach, which was more suitable for computing times and cloud-computing capabilities at the time when the application was developed, as opposed to other, more computationally expensive options, such as the use of genetic algorithms, which would have been more feasible on a desktop package.

Within this framework, a high-fidelity digital prototype was developed by Labit Analytics UX/UI team using Adobe XD which was also refined through design iterations, sketches and meetings using the Miro board. This prototype showed the different application steps through a set of pages which were exported to a local html file that mocked-up the controls and interactivity of the future platform. This prototype also showed a refined front-end and branding design with the controls on the left-hand side and the visualization window to the right-hand side of the pages (see Fig. 3).

This first high-fidelity prototype was tested and validated not only through internal sessions but also in a series of Labit's business development meetings with potential clients which were received positively and proved the potential future interest in such a tool. Data and feedback from these meetings have been collected in the form of questionnaires to inform the next stages of the development.

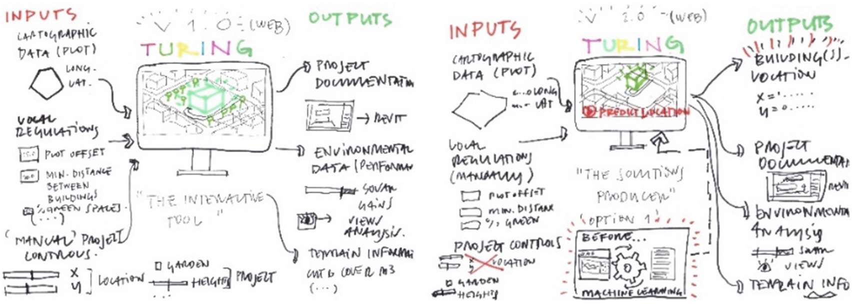

Fig. 2. Turing's low-fidelity prototypes (sketches by MVC) during the conceptual phase.

3.2 Prototyping with Grasshopper and Web-Based Visualisation

Whilst the digital prototype was being developed, tested and validated, research on potential development platforms and approaches was carried out. The cloud computing application Rhino.Compute was selected because of its easiness of set up, linkage with Rhino's Grasshopper software and connection via JSON files with a web interface, which was developed in Three.js. This solution would also allow for an almost real-time update between the Grasshopper algorithm and the web visualisation environment. Rhino.Compute AppServer is a very recent application (launched at the end of 2019) developed by Robert McNeel & Associates to embed cloud computing capabilities in the algorithmic design software Grasshopper. Rhino.Compute can run Grasshopper applications from the cloud and read and write data from web servers. For communication and visualisation purposes, Three.js – a library based on Javascript – was used to produce the graphic environment that links with Rhino.Compute through JSON format. Three.js was chosen for its speed, drawing quality and extensive documentation.

The development was carried out combining the back-end development through the Rhino.Compute server and Grasshopper computational algorithm as well as the front-end web design and space solution visualization. The tool currently has the following structure, which integrates the three aforementioned layers (Grasshopper, Rhino.Compute, Three.js/website visualisation) with the user input:

– User management and login (from Labit Group's server database).
– Site Selection or plot upload (in CAD format): plot geometry input.
– Site regulations user input: plot offset, maximum height and development area.
– Building module definition: number of floors (maximum and minimum), number of blocks (maximum and minimum) and site development potential threshold.
– Solution Space Display and Navigation, where an array of potential solutions along with their metrics are displayed. A plan diagram as well as associated metrics of development potential, GFA, free area, number of blocks and heights is displayed for each option which is generated through the bespoke Grasshopper solution space algorithm (see Sect. 4). The solution space visualization and top summary graph is responsive and the options metrics are displayed in an annotated coordinates graph.
– Selected Solution Display: the user can select one option to be displayed in more detail with a 3D visualisation and enhanced metrics.

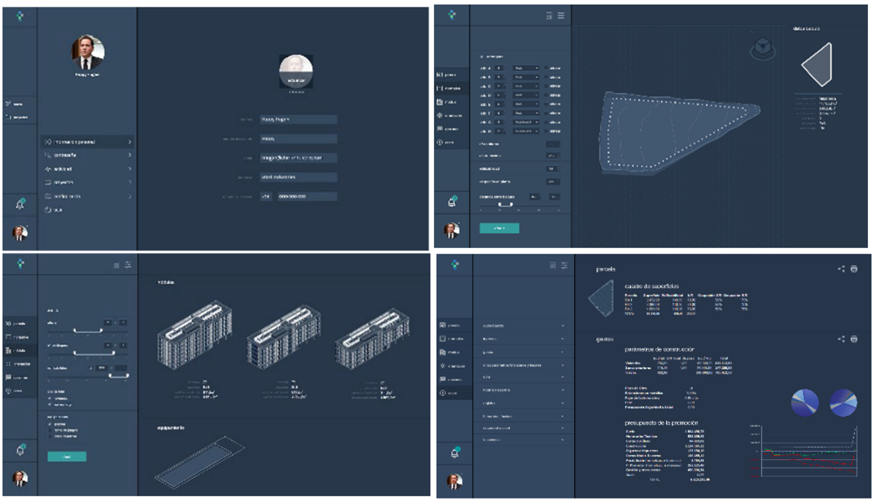

Fig. 3. Screenshots of Turing's high-fidelity prototype. From left to right and top to bottom: login page, site regulations input, module definition and cost calculation and data visualisation.

4 Solution Space Generation Algorithm

Turing tackles the problem of the geometric test-fit of a specific number of same-sized rectangular blocks (the module) in a contained polygon (the plot). The solution space generation algorithm is based on heuristics and follows the Less Flexibility First Approach [11]. Turing's solution space generation algorithm also uses the geometric notion of the Collision Free Region (CFR), based on existing cutting algorithms [3], to define the space in which the modules can be placed. As well as in other packing algorithms, Turing's complexity is a NP problem [10], however, it differs from any other studied packing algorithms in the sense that it is not a spatial optimisation problem but a design one, whose solution depends not only on numbers but also on user preferences.

A heuristic method was chosen due to the computational limitations of a cloud-based platform as well as for user engagement reasons. Turing's space solution is defined by user-input parameters, as opposed to deterministically by the algorithm. Splitting the process in a series of decisions (step-by-step process), similar to human behaviour, would engage the user in the decision process more than with other methods, such as genetic algorithms, whereby the solutions generation relies on the algorithm itself.

A series of variations are created from the Less Flexibility First Approach in which firstly the corners of the plot, secondly the edges and finally the void remainder space are tested as a Collision-Free Region (CFR) left by the blocks already positioned. The algorithm places each block sequentially searching the most favourable position amongst the corners, edges and empty space of the Collision Free Region. Favourability is defined by the algorithm as the most isolated corner (as an average distance), being either a point in the edge or a point in the void space, with regards to previously positioned blocks. Starting from the plot polygon, in each iteration, the CFR is redefined as the resulting polygonal region from the previous step's CFR and the intersecting offset of the previously placed block within a pre-defined minimum distance threshold.

The solutions are generated by testing random variations of the minimum and maximum distance threshold between blocks and rotation angles when locating them on the edges and the CFR void space, and are ordered from resulting metrics (see Fig. 4).

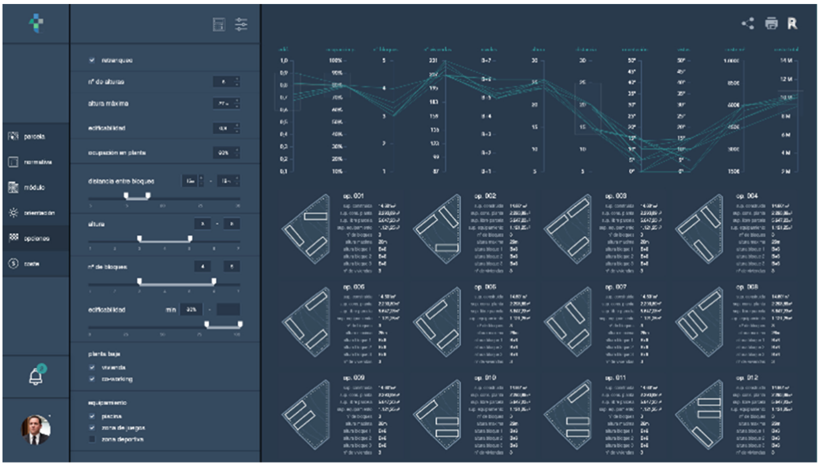

Fig. 4. Solution space visualisation.

5 Conclusions: Towards a Human-Centred Approach

This research investigates a high-level novel human-centred approach to housing design, development and manufacturing through digitalisation of user input processes. The first prototype here presented investigates ways in which a user-centric approach to computational design technologies can be integrated within a customer co-design choice methodology in the collective housing supply chain.

This work tries to bring together three main unexplored opportunities in mass customisation in the housing design industry: lack of end-user engagement, large space for innovation and automation in the supply chain and lack of agility and flexibility in the organisational aspects of the current business models [7].

With this paper, we present the first version of the Turing application to a concrete design and construction problem (in its feasibility study stage, based on a real projects). As a first prototype, Turing has been quite successful in helping users (designers and end users as sample groups) to visualise their own input in the design process and illustrate the impact of their contribution in each step. The limitations of this work lie on its application to a larger user population and a wider range of possible user types, as well as on the workflow, especially the part regarding the user's input. In future versions of Turing, the authors would like to explore more effective ways to include users' feedback into the development of the tool itself. In fact, the tool currently does not fully involve users in complex design decisions, such as accessibility, building adjacencies, topography or urban conditions that for a designer might be intuitively evident.

Finally, while in the case study shown here the authors focused on residential market stakeholders (designers, developers and contractors), future versions of Turing will be applied to different fields, including logistics, urban planning (smart planning, City Information Modeling), smart pre-fabrication and robotic-aided construction.

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