A PARTICIPATORY DESIGN GAME FOR THE MASS-CUSTOMIZATION OF BUILDING CONFIGURATIONS

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ABSTRACT

This paper conceptualizes a participatory design game as tool for the mass-customization of the configuration of Open Buildings. Based on existing literature, the text establishes that the prevalent design process is not equipped to deal with the complexities involved in architectural design. Instead, a mass-customization approach is proposed. Within this process, a design game plays a major role by allowing participants to test design decisions, negotiate with other stakeholders, and receive feedback, ultimately resulting in an agreed-upon configuration. The development of the design game itself is then further elaborate upon through design science research. The main steps of the development involve the definition of a modular coordination system, the translation of building elements into modular game components, the definition of possible game rules and an introduction into evaluation systems.

KEYWORDS: *mass-customization, configuration, design game, participation, open building*

1. INTRODUCTION

1.1 Background

Within the next ten years, between 0.4 to 1.2 million new homes are needed in the Netherlands (PBL, 2021). To meet this goal, the Dutch government is looking to densify urban areas, applying a 'compact city' strategy (Nabielek et al., 2012). Besides being a quantitative strategy, densification is also intended to result in qualitative improvements. New developments can be used as an opportunity to implement climate adaption measures, increase the support base for amenities, and improve accessibility, inclusivity, and the local economy (Nabielek et al., 2012; PBL, 2021).

Yet, this strategy introduces a huge task for the building industry. Densification is generally more expensive, subject to longer processes, and requires more deliberate design decisions than urban expansion (Nabielek et al., 2012). At the same time, the industry has to drastically reduce emissions and waste production. Thus, the building industry faces two conflicting problems: it needs to speed up production and lower costs, while at the same time implementing solutions that increase costs and lengthen processes.

One suggested approach to deal with these issues is Open Building. Open Building is a strategy for the transformation of the building industry, based on concepts developed by N. John Habraken and Stewart Brand. The main principle of open building is the introduction of distinct levels of environmental decision making, through the separation of building elements with different life cycles (Cuperus, 2001; Habraken & Teicher, 2000; Kendall & Teicher, 2002). On the building scale, a distinction is made between the common and long-lasting elements, named the *support,* and the elements specific to each unit, known as the *infill* (Kendall & Teicher, 2002). This distinction, originally defined by Habraken (1985), is strongly motivated by its potential for mass-customization. He argued that users should be able to customize their dwelling on the infill level through a system of interchangeable components. As such, Open Building is strongly related to *product modularity* (Halman et al., 2008; Rocha et al., 2015; Veenstra et al., 2006), which considers the use of a limited set of independent components, or modules, to create a variety of products (Gershenson et al., 2003). Authors name multiple potential benefits of mass-customization in the building industry. Pine (1993) mentions that modular mass-customizable systems benefit from both economy of scale, due to the reuse of components, and economy of scope, due to the similarity of the components. Similarly, Habraken (1985) argues that mass-customization is necessary for buildings to realize the full potential of prefabrication, as it allows for the reuse of elements without unwanted repetition of forms. Moreover, Rocha et al. (2015) links mass-customization to environmental and social sustainability, because it reduces waste and creates a sense of identity and ownership.

However, for the realization of a standardized mass-customizable building system some barriers need to be overcome. Mass-customization will involve users directly in the design and negotiation process, while assessment of real-estate development in the Netherlands identifies negotiation between stakeholders as a major bottleneck and cause of long turnaround times (Michielsen et al., 2019). In turn, long turn-around times may eliminate densification as a solution for housing shortages (Nabielek et al., 2012). A second issue, named in a survey of the Dutch building industry, is the lack of user knowledge of building-design and building-engineering (Halman et al., 2008).

1.2 Research goals and questions

In relation to the barriers described in the previous section, architect Yona Friedman argued for a new design process based on user-participation and mass-customization (Friedman, 1975). More recently, Azadi and Nourian (2021) defined a framework for mass-customization through generative design. In continuation of these, the research in this paper conceptualizes a participatory design game as a tool for the mass-customization of Open Buildings, using the following research questions:

Main question:

- *How to develop a serious game that allows for the customization of the configuration of open buildings, while ensuring technical feasibility and consensus between stakeholders?*

Sub-questions:

- *How to define a set of components that allow stakeholders to customize the configuration of an Open Building?*
- *How to develop a set of game rules based on spatial and technical criteria?*
- *How to give feedback on design decisions to promote technical feasibility and consensus among stakeholders?*

1.3 Methodology

The research consisted of two main parts. First, a framework was defined that introduces and supports the main concepts of the participatory design game. The framework was based on a literature review of existing theories on mass-customization processes, Open-Buidling principles, and participatory design games. Additionally, three cases of Open Building projects and three design games were studied (see Appendix 1 & 2). These cases were used as practical examples of the theories from the literature.

The method used for the second part was *design science research*. Design science research is used for the development of *artifacts* (March & Smith, 1995). Voordijk (2009) assesses that design science research can be used to develop multidisciplinary solutions for problems in the built environment. The *artifact* produced in this case is a concept for a participatory design game. Additional literature review is also used in this section to inform the game's design. The process and results from this stage of the research have produced some preliminary conclusions and serve as a foundation for the games' further development.

1.4 Scope

This research is multidisciplinary and combines elements from mainly the fields of architecture, building engineering, computational design, and game design. It also touches upon the use of games in the field of urban planning. The game concept produced in this research is part of a graduation project in the field of architecture and will be further developed in the remainder of the graduation process. However, as the design project within the graduation process considers a fictional development, the participatory design game cannot be tested in the real-life setting it is meant to be used in. Instead, it will be partially tested and implemented using scripting. Lastly, this research has been conducted focusing on the context of the Netherlands, meaning some elements of the study might not be applicable in other contexts.

2. Framework

2.1 Complexity of the architectural design process

The architectural design process involves dealing with compounding complexities, as formulated in Azadi and Nourian (2021), and illustrated in figure 1. Multi-dimensional complexities stem from the complex spatial relations between spaces and elements. Multi-criteria complexities relate to dealing with possibly counteracting qualities, for example views and privacy. Multi-actor complexities originate from the differing goals of stakeholders. Lastly, multi-value complexities are caused by inherent ambiguities in human perception and communication.

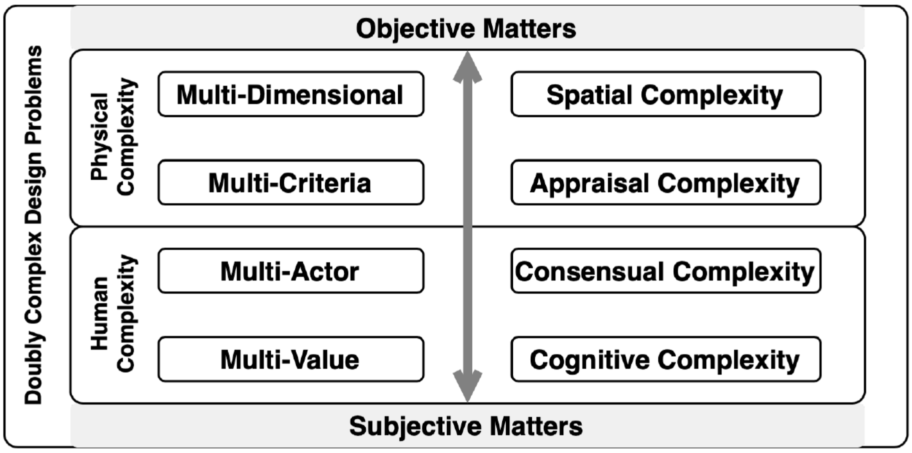

Figure 1: Complexities involved in design and planning (Source: Azadi & Nourian, 2021 p. 286).

Based on Friedman (1975), the currently prevalent architectural process is unequipped to deal with these complexities. Figure 2 shows the Friedman's description of the current process. The architect interprets the needs of many users and translates these into a design that the 'artisan' can construct. The architect cannot understand the needs of every user, so instead he designs for 'the fictitious average man'. As none of the users are this 'average man', none of them will be happy. Furthermore, the user is only able to experience the product and evaluate it once it is finished. The first of these two problems can be mainly attributed to the human complexities, which, as shown in figure 1 are multi-actor and multi-value. The second problem relates mostly to physical complexities.

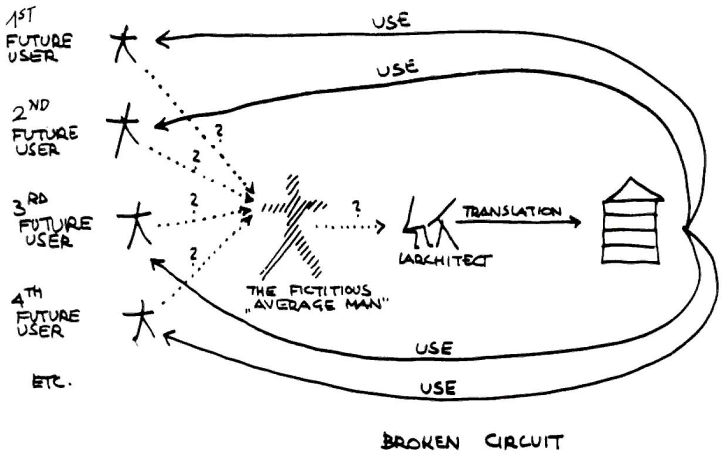

Figure 2: The architect's broken circuit (Source: Friedman, 1975, p. 5).

2.2 Customization

To deal with the complexities in the architectural process, it is necessary to involve the user more directly. Friedman proposes the system shown in figure 3. In this system, the user picks from a finite repertoire of options created by the designer. The user receives feedback on their choice, the advantages, and disadvantages, of the chosen solution. When the user is satisfied with their choice, they communicate their choice from the repertoire to the 'artisan', who erects the building. The goal is to make the user entirely responsible for the process, as they suffer the consequences of the design choices. Furthermore, consequences of each design decision are communicated to all stakeholders, facilitating consensus building. While the architect and other experts seem absent in this process, their knowledge is embedded in the repertoire and the feedback the user receives.

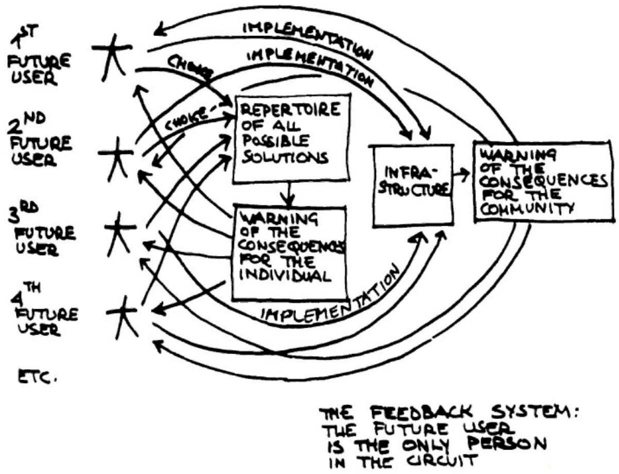

Figure 3: The feedback system (Source: Friedman, 1975, p. 8).

In (Azadi & Nourian, 2021) a different participatory process is proposed. Instead of users directly making design decisions, the design is generated with stakeholder input. In this case the traditional role of the architect is replaced by a generative design process that operates using mathematically formulated inputs. Consensus building happens during the formulation of inputs in the 'Planning' stage and as a feedback loop during the evaluation or 'Polling' stage. Both this and Friedman's proposal show that participation can mitigate the human complexity in the architectural process, as it negates ambiguous communication between the user and designer and facilitates consensus building.

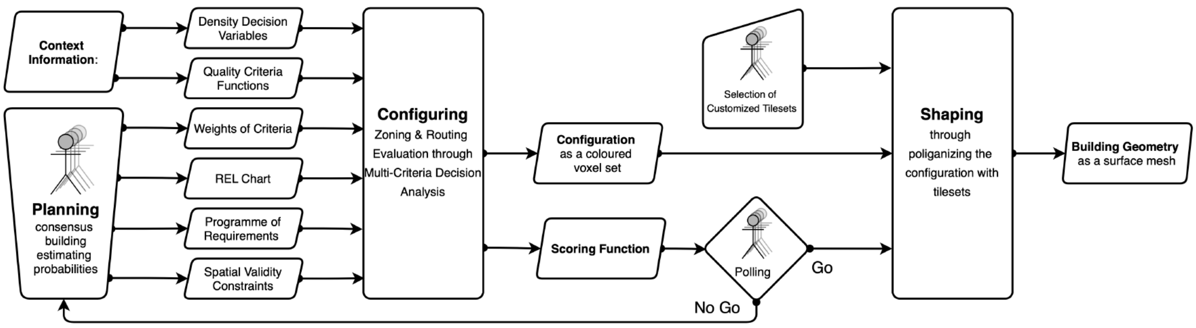

Figure 4: Flowchart of a modular generative design framework for mass-customization and optimization in architectural design (Source: Azadi & Nourian, 2021, p. 288).

2.3 Simulation

As prescribed in section 2.2, stakeholders require feedback on design choices made in the customization process. To give feedback to stakeholders, a simulation of the resulting design is needed. Figure 5 shows Friedman's (1975) idea for the 'Flatwriter'. The Flatwriter can be used to design an apartment using the predetermined set of elements from a repertoire. It also knows the consequences of each possible configuration, and as shown in figure 5, will warn the user of these consequences. Furthermore, the Flatwriter can determine whether a user's choices interfere with any qualities of other apartments, such as light. The other stakeholders can use this information to decide if the effects of the designing user's choices are acceptable.

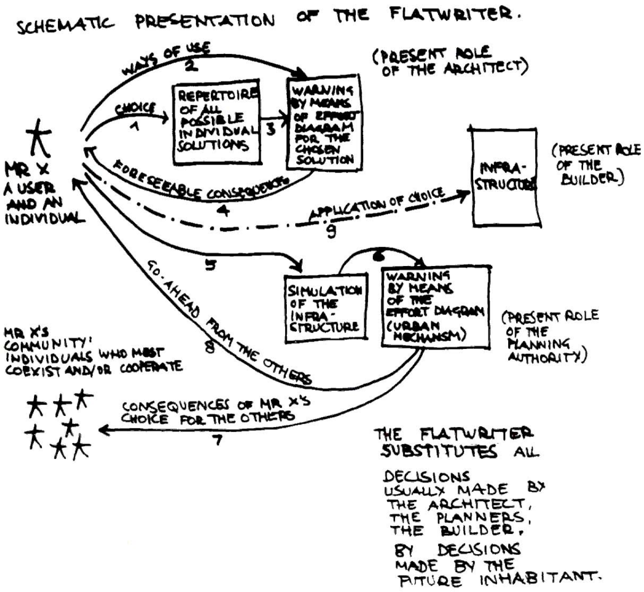

Figure 5: The Flatwriter (Source: Friedman, 1975, p. 54)

In the generative design process defined by Azadi and Nourian (2021), simulation takes place in the 'Configuration' phase. The objective of this phase is to find a configuration that satisfies the inputs defined by stakeholders in the 'Planning' phase, as shown in figure 4. The validity of configurations is computed using multi-criteria decision analyses. Once a valid configuration is found, it is subject to a polling phase to ensure it also satisfies unquantifiable criteria.

In both processes, simulating solutions before they are realized allows stakeholders to ensure they satisfy certain criteria regarding physical qualities of the design. Thus, simulation of the design lessens the effect of the physical complexities present in the design process.

2.4 Open building and product modularity

Open building enables user involvement in the design process by discretizing levels of decision making. As described in Kendall and Teicher (2002), the three main levels are the urban level, the support level, and the infill level. Each level should be designed as to not interfere with design decisions on the lower levels. The support, or base building, level contains common building components, so that the infill level can be customized. As noted in Kendall and Teicher (2002) and discerned from the studied cases (see Appendix 1), the main elements of the support layer are the load-bearing structure, the mechanical and conveyance systems, and the shared entrances. In practice it resembles a vertical-real estate that can be parcellated. This is especially evident in the example of Object One by architecture firm Space&Matter (see Appendix 1).

The infill level contains all dwelling specific elements and can be customized. Habraken (1985) described this level to be made up of a system of premanufactured and interchangeable elements, similar to Friedman's (1975) repertoire of possibilities. Such a system is essentially a form of product modularity. Rocha et al. (2015) defines that mass-customization concerns the creation of product variants as a result of different module combinations. For modules to be interchangeable, they need to have the same interface standard. Thus, reducing the number of interfaces through standardization is a key element in mass-customization. In contrast, Kendall and Teicher (2002) observe that most Open Building projects use project specific infill components. Likewise, while the case Superlofts (see Appendix 1) uses its infill system for multiple projects, the cases do not suggest an adoption of standardized infill systems on a larger scale.

2.5 Spatial configuration

Hillier (2007) argues that the process of architectural design is fundamentally a process of configuration, and that the configuration has the biggest impact on how a building is formed and performs. Hillier defines configuration as the dependence of the relation between spaces on their relationship with other spaces. Similarly, Rocha et al. (2015) describe buildings a mix of physical components and spatial voids. Out of these, the spatial voids provide the primary function of buildings, which is providing space for human activity. The physical elements are in service of the spatial voids, as their function is to create the spatial voids and to make sure people can comfortably carry out activities in these voids. Therefore, the most significant aspect of a building to be customized is its spatial configuration.

Moreover, Rocha et al. (2015) assert that the interfaces between building modules are primarily characterized by spatial and geometric interactions, meaning interfaces need to be properly positioned and have an appropriate shape. For example, doorways need to be positioned as a connection between two spaces, on floor level and be large enough for a person to pass through. Structural elements depend on their location and geometry to properly transfer loads. In conclusion, when customizing a building, users should be able to configure a group of spatial modules while adhering to a system of spatial and geometrical coordination.

2.6 Design game

The participatory design and feedback process needed for mass-customization can be implemented in a design game. Games can simulate real situations and allow participants to experiment within an abstracted version of a complex problem (Sanoff, 2000; Tan, 2017). Yap-Yaşa (see Appendix 2, case 1) used game rules to allow non-experts to negotiate with specialists in the design of urban blocks, while maintaining certain quality criteria. Levelling the playing field between parties resulted in configurations that successfully integrated different stakeholder preferences and complex social dynamics. Constraints, limiting the amount of solutions, can be implemented through rule systems and methods of procedure (Sanoff, 2000). The game Townscaper (see Appendix 2, case 3) generates complex configurations using simple inputs, a set of rules and a limited set of elements. Finally, games can give feedback on design decisions through a scoring system, or through the game as a representation of the design. Block'hood features an abstract simulation of urban systems (see Appendix 2, case 2). The game evaluates the balance of different resources. When design errors cause an imbalance in resources, the player is warned through the user-interface. If the player does not respond appropriately, modules relying on a missing recourse will deteriorate. In short, participatory design games can use components and rules to simulate a design process. During the play process, stakeholders can experiment, negotiate, receive feedback, and reach consensus.

2.6 Mass-customization process

Using the arguments and concepts presented in the preceding sections as a basis, a proposal for a mass-customization process for Open Buildings using a participatory design game is presented in figure 6. First, context and project specific information and a standardized modular building system are integrated into the design of the game. In the play process, stakeholders use the game pieces, representing spatial units, to customize the spatial configuration of the building on the game board, representing the infill. Game rules are used to simulate real-life dynamics between stakeholders and to ensure the result fits technical constraints. After a validity check, the configuration is evaluated. Participants, now informed by the evaluation, decide whether to make changes to the design. If not, the final configuration is translated into a complete design.

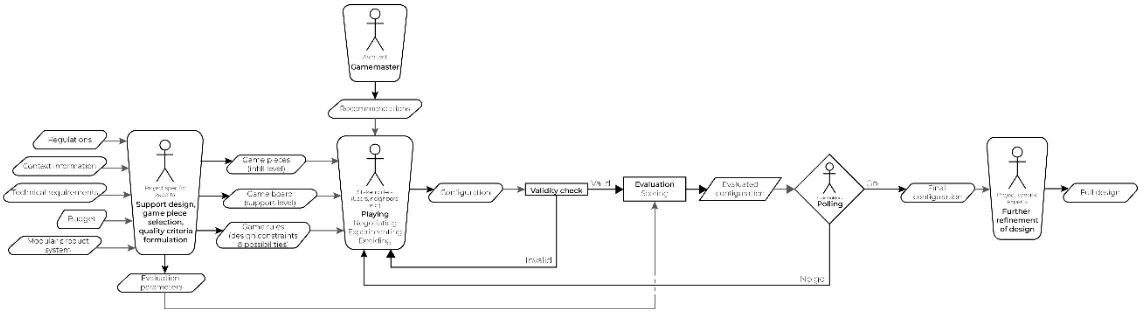

Figure 6: Design process for mass-customized buildings based on the use of a participatory design game (see Appendix 3 for a larger version).

3. CONCEPTUALIZATION

The following sections present the conceptualization of a participatory design game, elaborating on the process in figure 6. For accessibility, the game was designed to be played with physical components. However, it could also be adapted to a digital format. Moreover, the game master should translate the results of physical play sessions to a digital format, enabling the evaluation process to utilize the computational power of a computer.

3.1 Modular coordination system

The first step for the design game was to define a modular coordination system, or a system of dimension. As described in section 2.5, spatial and geometrical standardization of components is required for them to fit together and be interchangeable. Furthermore, a modular coordination system discretizes the design space, which facilitates the use of computational processes for evaluation. To accommodate human activity, the system of dimensions needs to be based on ergonomics. Two major precedents for a standardized dimension system for building design are traditional Japanese housing (Engel & Locher, 2020), and the 'Modulor' by Le Corbusier (Ostwald, 2001).

The system of dimensions used for the design game was defined through a series of steps (see Appendix 7). Most information regarding dimensions was gathered from Neufert and Neufert (2012) and Haak (1980). An expanded elaboration on dimensions used as input in the process can be found in Appendix 6. The requirements for the design of staircases were the main input for the first step (see Appendix 6.1). As noted in (Haak, 1980), stairs are the building component with the closest relation to human dimensions. Additional inputs were related to horizontal accessibility requirements: the minimum dimensions of corridors, hidden corridors, and doorways (see Appendix 6.3). Structural elements were also considered, by reserving a minimum of $35cm$ of the grid dimension, resulting in a tartan grid. Lastly, the possibility of using the dimensions of LEGO-bricks was investigated (see Appendix 6.4). Designing the game components to be compatible with LEGO increases the accessibility and flexibility of the game, because missing components can be replaced with LEGO pieces. The first step resulted in eight sets of dimensions, as shown in table 1.

Table 1: Initial dimensions and first selection

Number	**Rise (cm)**	**Thread (cm)**	**Step modulus = 2R+T (cm)**	**Pitch (°)**	**Mini voxel (cm)**	**Grid dimension (cm)**	**Fits LEGO? (Yes/No)**

1	18.0	27.0	63	33.69	9.0	162	No
2	16.2	27.0	59.4	30.96	5.4	162	Yes
3	17.5	28.0	63	32.01	3.5	168	No
4	16.8	28.0	61.6	30.96	5.6	168	Yes
5	17.5	29.0	64	31.10	5.4	174	No
6	17.4	29.0	63.8	30.96	5.8	174	Yes
7	17.5	30.0	65	30.26	2.5	180	No
8	18.0	30.0	66	30.96	6.0	180	Yes

A selection of three sets of dimensions was made from the initial eight: set one, six, and eight. The first set was selected because it had the largest mini-voxel size, which is the largest common divider of the rise and the thread, and the base dimension used for construction elements. Additionally, it fit the commonly used rule of a step modulus between $63cm$ and $65cm$ (see Appendix 6.1). The sixth set was chosen because it fit both the rule of the step modulus and LEGO dimensions. The eight set was picked mainly because of its grid-dimension of 180cm, which is divisible by all integers up to six. Moreover, it can be divided in exactly three hidden corridors.

In the second step, the three sets of dimensions were tested through the design of a staircase as found in a stairwell, as shown in figure 7. This eliminated set one, as it was the only one of the three which couldn't fit the stairwell and the reserved space for structural elements within six grid units. From the remaining two sets, set eight was chosen because of the simplicity of its numbers and the lack of discernible advantages of set six.

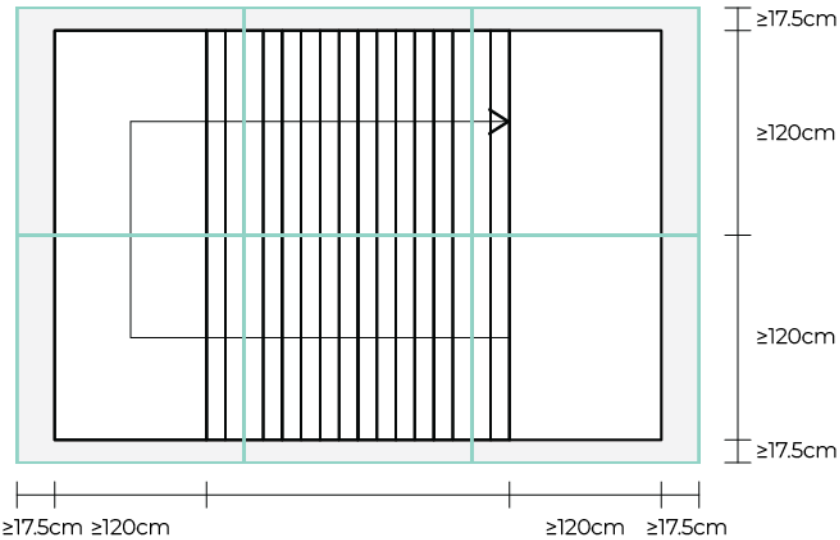

Figure 7: Minimum dimensions of stairwell

In the third step, the configuration of a studio apartment was used as toy problem to test and investigate ways to improve the spatial efficiency of the dimensioning system. The challenge in this problem is to use a set of spatial units to create the smallest independent dwelling while adhering to spatial requirements of functions and ensuring the access to those functions. The studio apartment had to consist of the following spatial units:

- A kitchen containing at minimum: a sink, a cooker with space for two pans, a refrigerator, and a counter space of 90cm in width.
- A bathroom containing at minimum: a washbasin, a toilet and a shower.
- A seating area containing at minimum: a sofa and TV cabinet.
- A sleeping space containing at minimum: a single-person bed and a wardrobe.

The result is shown in figure 8. The figure also a second attempt using a halved grid unit of $90cm$. While the second attempt required 20% less space to house the minimum activities, the smaller grid was too small to accommodate doorways or a person in a single unit. Thus, the decision was made instead to use the $180cm$ grid unit and introduce the possibility of merging spatial modules (see section 3.3). The final system of dimensions can be found in Appendix 8.

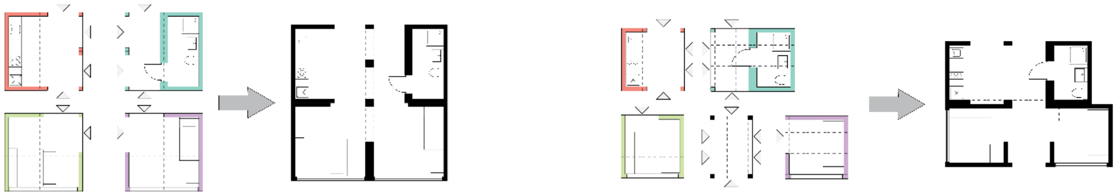

Figure 8: Results of the studio configuration problem, based on a grid of 180cm (left) and 90cm (right).

3.2 Game components

The components of the game consist of placeable modules and a game board. The modules are abstracted representations of spatial units with an associated function. They can be used by the players to generate spatial configurations and relate to the infill level of Open Building. The modules are divided into three categories: circulation (stairs, corridors), services (kitchens, bathrooms), and rooms (bedrooms, living rooms). All modules are based on the defined dimension system with a grid unit of 180cm. Service and room modules are generally 3 voxels, which is 324cm, tall. The number of grid units service and room modules occupy was determined by creating room layouts with appliances and furniture, as shown in figure 9. Dimensions of furniture were based on Neufert and Neufert (2012) and Haak (1980). The module in figure 9 is a medium-sized bathroom module. It can accommodate a shower, washbasin, toilet, and a laundry machine. Modules are also dimensioned to accommodate hidden corridors required to access activities, and if necessary, landings required as space for doors. Figure 9 also shows the access points of the module. Modules can be spatially connected by placing at least one access point next to an access point of another module.

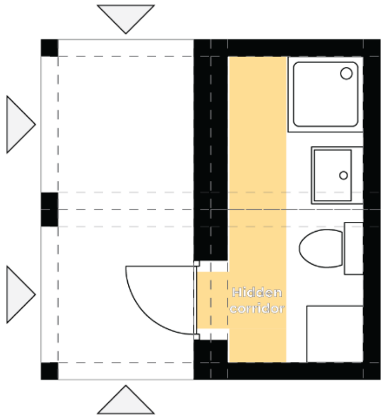

Figure 9: Plan view of medium sized bathroom module.

An example of a physical game piece is shown in figure 10. The pieces are compatible with LEGO-bricks. This allows players to use LEGO-bricks to replace missing pieces or to add pieces during the play process. Furthermore, the pieces have been designed with pressure-based structures, to make them easily 3d-printable. The arches represent possible access points. It is important to note they are just a representation of a spatial module, meaning they do not represent the architectural style of the building that results from the total process. Each type of module also has a card with associated information (see Appendix 9). This card informs players of the modules' properties, any requirements for the modules' placement and recommendations for certain criteria.

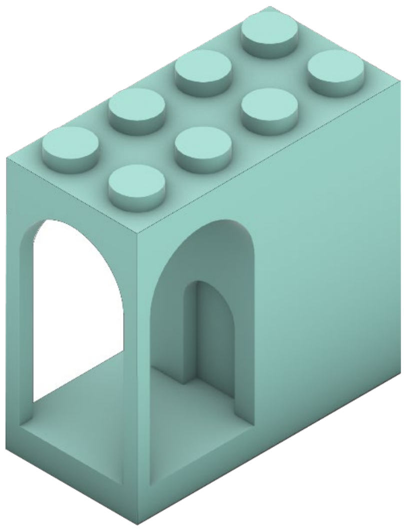

Figure 10: Physical piece of a small bathroom.

The game board represents the support level of Open Building. An example of a game board is shown in figure 11. It is divided into grid units and contains indicators for the location of elements from the support level, in this case the load-bearing structure, the building core and a shaft. During the play process, players have to place modules on the board in a way that properly integrates the support elements. The studied open building cases (see Appendix 1) demonstrate how the design of the support layer of Open Buildings has a major effect on the customization possibilities of users. In Molenvliet, the load-bearing structure is divided into single-storey layers. Consequently, possible locations vertical connections between spaces are pre-determined within the support, while in the case of Superlofts, users have some agency over the location of stairs within their dwelling. In short, the design of the game board will have a large impact on the options players have for placement of game pieces, and in turn for the customization of the building's spatial configuration.

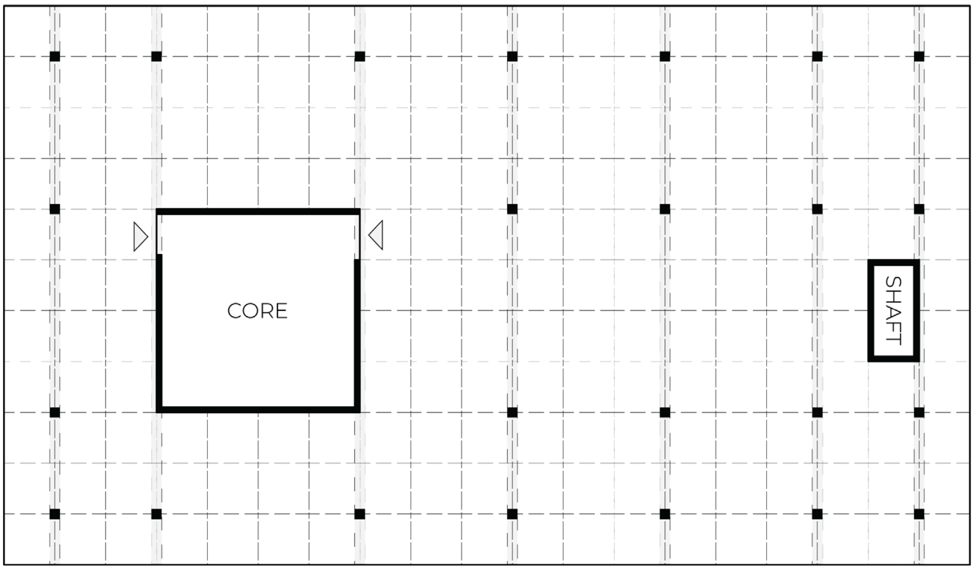

Figure 11: Plan representation of a game board.

3.3 Game rules

The game's rules describe the play process and can restrict or mandate player actions. The exact play process still needs to be defined, but some examples of rules that have been defined so far are:

- Every module needs to be spatially connected to at least one other module.
- Every module needs to be spatially connected to a building entrance.
- Bathrooms and kitchens need to be placed next to a shaft.

Essentially, the games' rules can be used to ensure validity of the configurations, regarding accessibility of spaces and technical requirements. Furthermore, to improve the spatial efficiency of the dimensioning system, modules containing excess space may be merged with other modules. Figure 12 shows two modules with excess hidden corridors in adjoining grid units. Merging these units results in the module on the right. This move is not possible with physical game pieces, which means the merged game piece would have to added as an additional module. Another option is to use LEGO bricks to represent the new module, as the physical pieces are specifically for LEGO bricks to replace missing pieces.

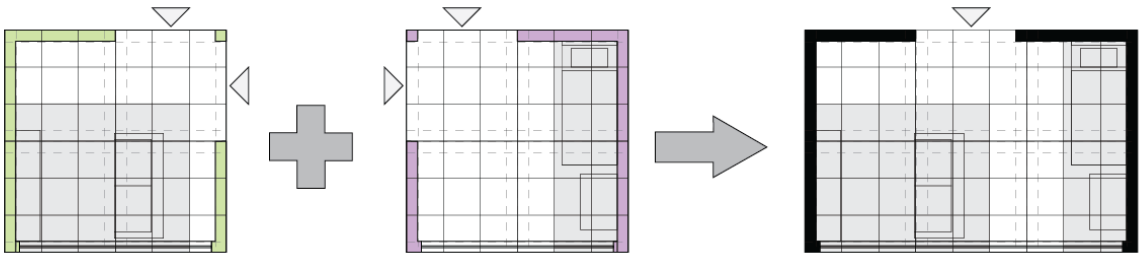

Figure 12: Diagram showing the merging of two modules

3.4 Evaluation systems

As described in section 2, a design process based on mass-customization requires that users receive feedback on their design decisions. The evaluation systems will score the configuration resulting from the play process on certain quality criteria. Some criteria are relevant for the complete configuration, others only for the location of single modules, and some for both. Examples of criteria are the amount of direct sunlight a module receives, view factor, module orientation, level of privacy, and accessibility. In (Nourian, 2016), architectural configuration is defined as graph of nodes representing spaces and links representing immediate spatial connections. This representation allows configurations to be analysed and can, for example, be used to predict how they will perform regarding certain social aspects. Friedman (1975) uses this representation for the communication and evaluation of user's design choices. The depth of a node representing a private space relating to a public node can for example indicate the level of privacy. The exact definition and development of evaluation systems, however, contains some of the same complexities as the current design process (see section 2.1). The weight of criteria, for example, will likely be different for each person, relating multi-actor complexities. As such, stakeholders will also need to be able to influence the application of evaluation criteria.

5. Conclusion

The main objective of this research was to conceptualize a participatory design game for the mass-customization of Open Buildings. The framework established in the first section establishes the need for user-customization in the design process. The separation of the support level and the infill level as dictated by Open Building, lends itself to the mass-customization through a standardized modular product system, wherein the user can customize the building by configuring standardized spatial modules. As the knowledge of users is seen as a barrier for the realization of mass-customizable systems, a participatory design game could function as an essential simulation, by embedding the knowledge of experts in game components, rules, and evaluation procedures. This game could be used by stakeholders to test design options, negotiate with other stakeholders, receive feedback, and finally reach consensus on a configuration.

The design game based on this framework is still in development. In particular, the second and third sub-questions defined at the start of the research require further elaboration. So far, a modular coordination system has been defined which is a foundational element for the design and interface of the game's components. It ensures the modules designed for the design game fit some requirements for ergonomics and accessibility. However, especially as this dimensioning system is meant to be used for all building elements, it requires further testing. The distinction between infill and support as in open building has been translated to a distinction between modules placed by the players and a pre-defined game board, essentially mimicking the levels proposed in Open Building. The definition of the game's play process is still in an early stage, as is the development of evaluation systems. The goal is to further develop the design game by partially implementing it in a design project using scripting. Different sets of parameters will be used to act as the differing preferences of stakeholders.

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Appendix

1. Open building cases

OPEN BUILDING CASE 1

NAME: MOLENVLIET
ARCHITECT: FRANS VAN DER WERF
YEAR: 1977
LOCATION: PAPENDRECHT, THE NETHERLANDS

Picture of Molenvliet from a parking street, photographer unkown, from: http://www.vdwerf.nl/molenvliet.html

DESCRIPTION

Molenvliet is a residential development in Papendrecht designed by Dutch architect Frans van der Werf and completed in 1978. The single- and two-floor dwellings are situated around courtyards. Each dwelling has its entrance on one courtyard and an outdoor space on another.

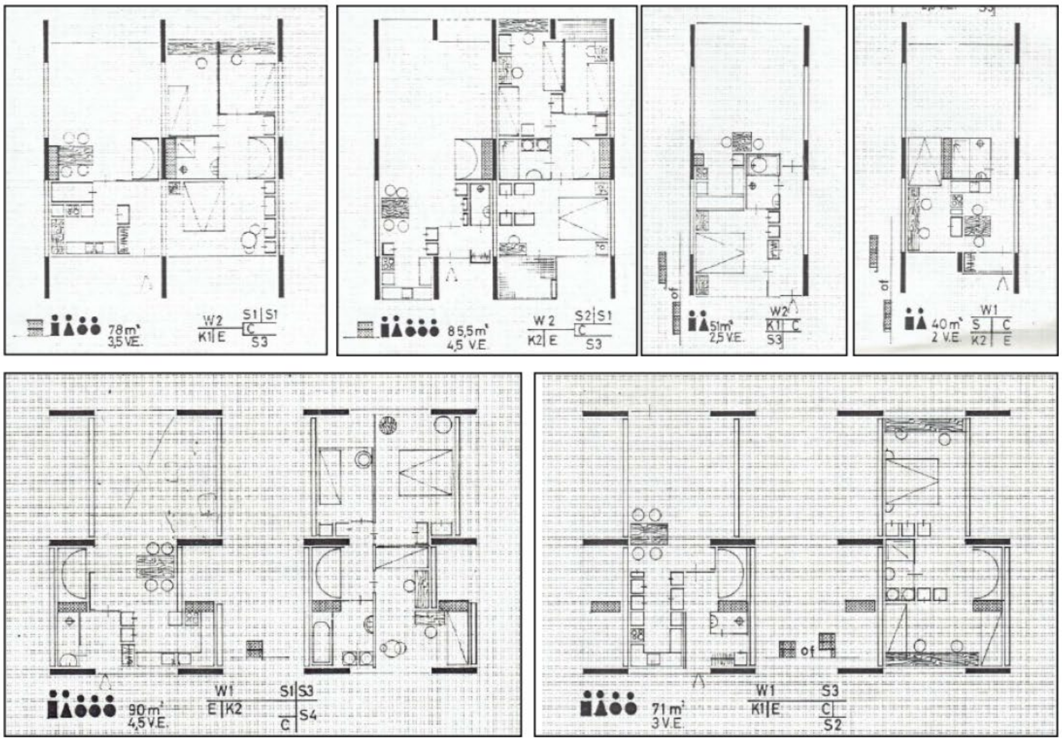
SUPPORT

The support level of Molenvliet consist of five regular and two exceptional components. The regular elements are the piers, floor slabs with openings, pitched roofs, galleries and shafts. The exceptional components are staircases and vides. The piers combine a longitudinal and transverse structure, allowing units to extend in both directions. The openings between the piers are closed with non-load-bearing materials, opening the option for future re-allocation of units. Galleries were chosen as access points, decreasing the number of stairs needed and removing the need for new stairs when new entrances are added. Shafts were designed to connect installations in four directions. The result of these design decisions is that the allocation of dwellings and other functions could be done almost freely, resulting in 67 different forms. Dwellings can be as small as 50m2 but also larger than 90m2.

Floor plan of bare support (left) and floor plan after parcellation and infill (right), by Frans van der Werf, from: Kendall and Teicher, 2002, p. 94

INFILL

The infill of the buildings included the interior walls, kitchens, bathrooms, windows, doors, and also the façade. Inhabitants were able to design the infill of their homes together with the architect. The façade was made of a family of prefabricated elements. The design of each façade depended on the adjacent function on the interior, mostly due to daylight requirements, but also to exhibit the variety of configurations.



Studies of infills of dwellings with the transverse support structure (top row) and the longtitudinal support structure (bottom row), by Frans van der Werf, from: http://www.vdwerf.nl/molenvliet.html

SOURCE(S)

Kendall, S., & Teicher, J. (2002). Residential open building. Spon.
Molenvliet on Frans van der Werf's website. Retrieved 29 May 2022 from http://www.vdwerf.nl/molenvliet.html

OPEN BUILDING CASE 2

NAME: SUPERLOFTS
ARCHITECT(S): MARC KOEHLER ARCHITECTS
YEAR: 2016 ONWARDS
LOCATION: VARIOUS, THE NETHERLANDS

Diagrams of superloft configurations and systems, by Marc Koehler Architects, from: https://superlofts.co/

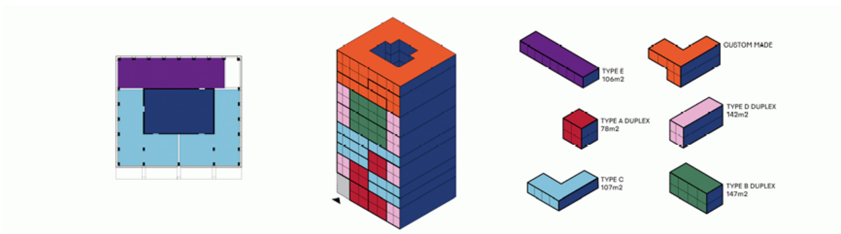


Diagram of loft forms and sizes in Superlofts Hoorn, by Marc Koehler Architects, 2018, from: https://superlofts.co/project/holenkwatier-hoorn/

DESCRIPTION

Superlofts is a framework for flexible design and development by Marc Koehler Architects. It was initially conceptualized during the development of an apartment building in Amsterdam in 2016 and has since been expanded upon. Besides a set of architectural and building-technical principles, it is also a framework for co-creation and co-ownership

SUPPORT

The support layer of the Superloft is a casco of modules of 5m to 6m tall and up to 18m deep, which can then be subdivided into multiple dwellings. A mezzanine suspended from the ceiling is used to expand floor area. Multiple shafts were added to each unit to provide flexibility in the spatial configuration, in particular of kitchens and bathrooms. As of May 2022, all realized Superloft projects use a concrete load-bearing system, but a system based on CLT is under development. Furthermore, the core has been moved to the façade to allow for a larger combination of loft-types.

INFILL

The main components of the infill, or user-customizable, level of Superlofts, are the interior wall, a possible mezzanine floor, the kitchen and bathroom, and the façade. The design of the cores allows for some freedom in the location of kitchens and bathrooms. The façade is made from a modular prefabricated aluminium system that can be adapted to the demands of the user. Lastly, a major goal of the design of the infill was to allow inhabitants to personalise their dwelling according changing needs.

SOURCE(S)

Marc Koehler Architects. (2016). Superlofts Houthavens. Retrieved 29 May 2022 from https://marckoehler.com/project/superlofts-houthavens/
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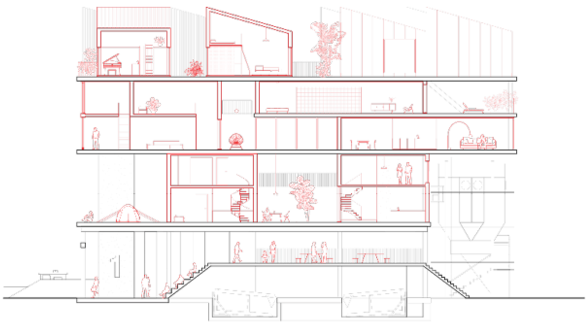
OPEN BUILDING CASE 3

NAME: OBJECT ONE
ARCHITECT(S): SPACE&MATTER
YEAR: 2017
LOCATION: LOOKING FOR A LOCATION

Render of Object One, by Space&Matter, 2017, from: https://www.spaceandmatter.nl/work/object-one



Section of Object One, by Space&Matter, 2017, from: https://www.spaceandmatter.nl/work/object-one

DESCRIPTION

Originally designed by Space&Matter for a competition in Deventer in 2017, Object One is a multi-residential building, consisting of a stack of parcels that can accommodate different residences. Each plot has a 'passport' with rules that make sure the whole remains unified in spite of differences between each dwelling.

SUPPORT

The support level, dubbed the 'Smartframe', is made up of the load-bearing structure, shared access to each level of the structure, and connections to the municipal grids. The load-bearing structure consists of concrete slabs, columns and crossbeams. The height of the levels of the structure varies, creating spaces for single- and two-storey units. Units with sloping roofs are placed on the top level of the structure.

INFILL

Within the support layer, future users can choose from three types of plots: single-layer, two-layer, and single-layer with a sloped roof. They are allowed to realise their own home within their plot, with their own architect, with some limitations as described in the 'plot-passport'. Alternatively, buyers can choose from a predesigned set of units, which are delivered casco with a customizable interior.

SOURCE(S)

Space&Matter. (2017). Object One: A multi-residential building designed to change. Retrieved 29 May 2022 from https://www.spaceandmatter.nl/work/object-one

2. Design game cases

GAME CASE 1

NAME: YAP-YAŞA
YEAR: 2010
CREATOR: EKIM TAN

Yap-Yaşa play process, from: Tan, 2017, pg. 231

Final design drawing of Yap-Yaşa outcome, from: Tan, 2017. pg. 242

DESCRIPTION

Yap-Yaşa was an experimental participatory game for the design of city blocks in the urban transformation of Istanbul. It was part of a series of urban planning games developed for a research project by Tan (2017). The aim of this game was to investigate the potential of gaming to allow non-designers to negotiate with professionals.

The game space consisted of a generic version of Istanbul's city blocks. This block had to be populated with a densified version of Istanbul's existing self-organized and self-built neighborhood typology. The hypothesis was that this urban block could accommodate both the renewal demands of Turkey's Housing Administration and developers, and the existing social and economic networks of residents.

The game consisted of two types of rules, organizational rules and design rules. The organizational rules established the play-process. To properly simulate the dynamics behind Istanbul's urban renewal, a set of roles were introduced. These roles were modeled to reflect real powers and agencies and dictated the moves players could make. Furthermore, exchanging roles, or role-playing, was investigated as a way for stakeholders to understand each other's point of view. Design rules were introduced to mitigate the knowledge gap between professional and non-professional players. These rules ensured the configurations resulting from the play-process would adhere to certain qualities, such as limited building height and a certain amount of open space at ground level. In other words, these rules would protect less-informed players from certain design choices being made, either by themselves, or by professional players taking advantage of a difference in knowledge between players.

The play-process itself consisted of configuring urban blocks by placing stacks of 4 units on a grid, with each unit taking 1x2 grid spaces and one height level. Each unit could also be individually rotated around a screw that connected the units in the stacks, which facilitated more detailed designs and additional negotiation. The game was played in two sessions by three different groups. In the first session the Turkish Housing Association held most of the power, as only the player with this role was allowed to place housing units. In this session none of the groups were able to reach consensus without breaking the game's rules. In the second session all players could place at least some units. Additionally, in this session players also role-played as a different stakeholder. In this sessions players were able to reach consensus and come up with a design that satisfied all participants.

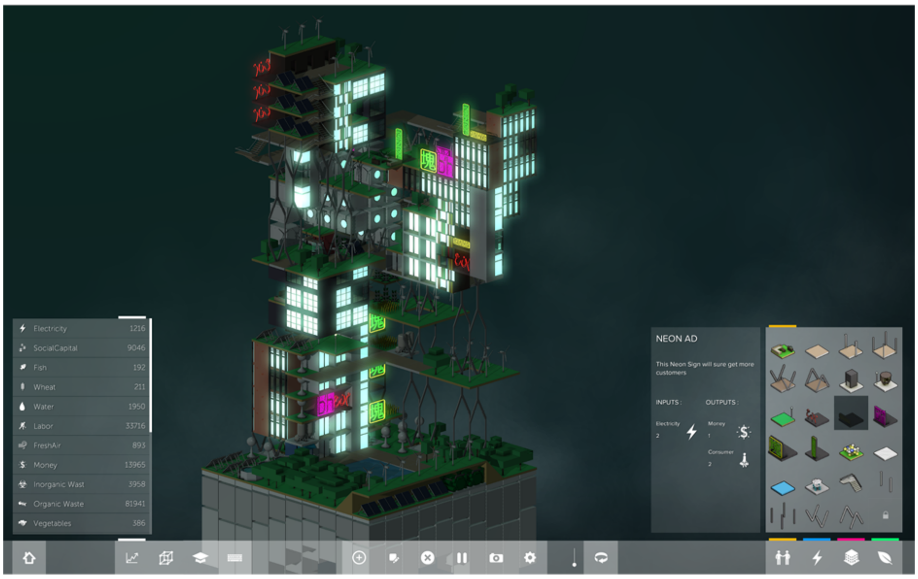
Using this game uninformed users were able to customize their housing and neighborhood in negotiation with other stakeholders. With some basic rules, different urban blocks could be configured while fulfilling the same requirements in density and open space on ground level. Further rules for the configuration would emerge from user preferences, negotiation and power dynamics within the groups. Another important conclusion is that without the ability for all players to take part in the design process the likelihood of consensus being reached is minimal, as shown by the differing results of the two sessions.

SOURCE(S)

Tan, E. (2017). *Negotiation and Design for the Self-Organizing City: Gaming as a method for Urban Design.* [Delft Technical University]. Delft.

GAME CASE 2

NAME: BLOCK'HOOD
YEAR: 2017
CREATOR: PLETHORA PROJECT



Screenshot of Block'hood, showing a player-designed neighborhood and the user-interface. The feedback on resources is displayed on the left, a library of blocks with information on each blocks is displayed on the right. By Plethora project, 2017, from: https://www.plethora-project.com/blockhood

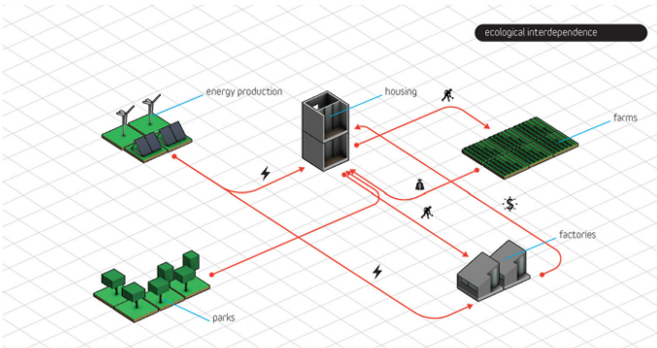


Diagram showing the resource interdependence of some blocks, by Plethora Project, 2017, from: https://www.plethora-project.com/blockhood

DESCRIPTION

The developers of Block'hood describe it as a neighborhood-building simulator that allows players to explore the diversity and ecosystems of cities. It is an example of a game in which players can use game pieces to customize an environment that simulates and gives feedback on real-life systems, but on an abstracted level. The players can configure a predominantly vertically stacked neighborhood by choosing from a library of blocks. Different blocks use and produce different resources. Some blocks can house inhabitants, including animals. The user-interface shows the amount of resources each block uses and produces, the total amount of each resource produced by the neighborhood, and the surplus of deficit of each resource. A resource deficit will cause blocks that use the particular resource to deteriorate, eventually leading to the blocks' collapse. In short, Block'hood allows players to experiment with designing an environment, and gives feedback on their choices.

SOURCE(S)

STEAM. (2017). Block'hood. Retrieved 27 May 2022 from https://store.steampowered.com/app/416210/Blockhood/
Plethora Project. Block'Hood. Retrieved 27 May 2022 from https://www.plethora-project.com/blockhood

GAME CASE 3

NAME: TOWNSCAPER
YEAR: 2021
CREATOR: OSKAR STÅLBERG

Examples of towns created in Townscaper, from: https://www.townscapergame.com/

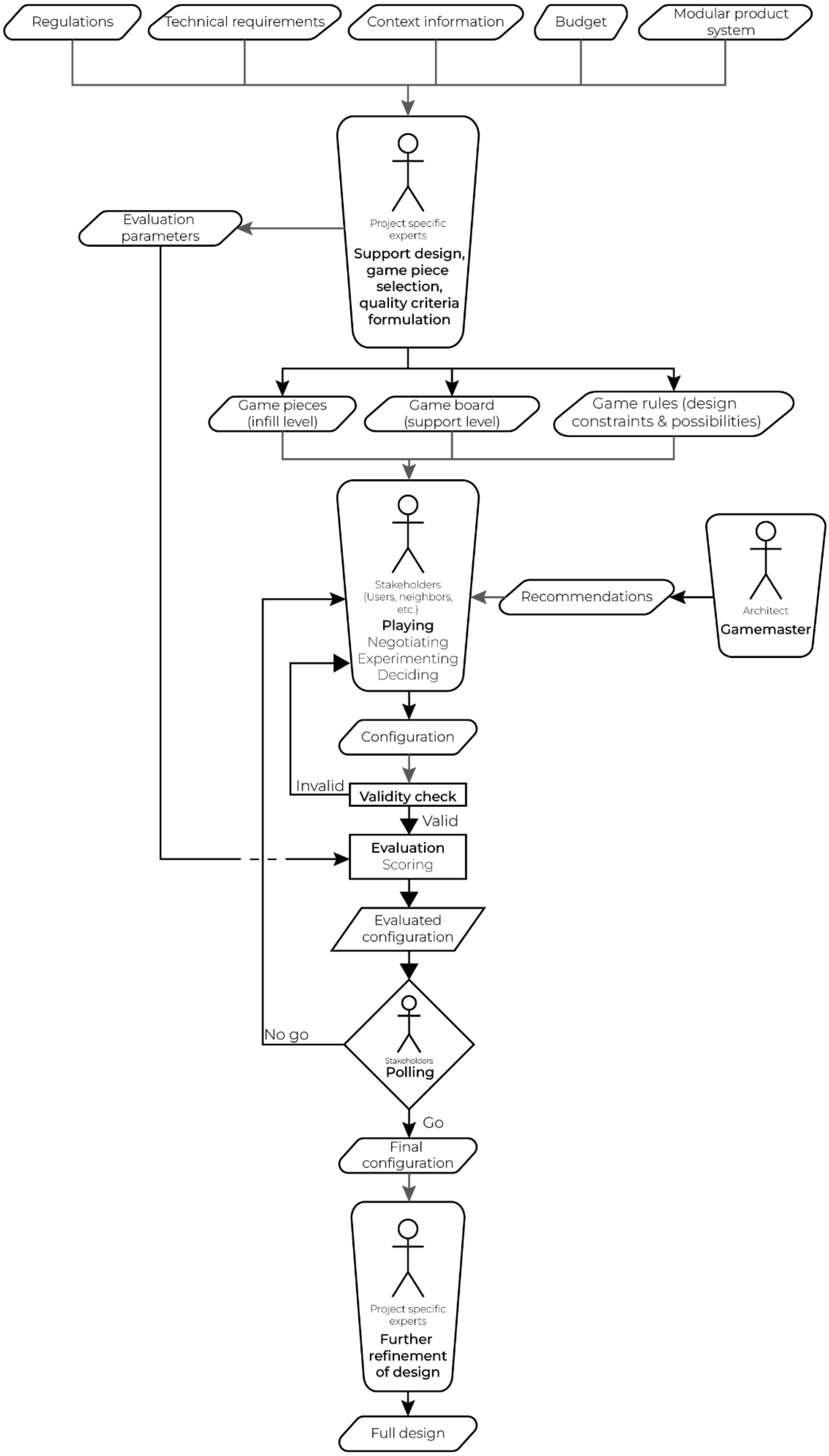
DESCRIPTION

Townscaper is a game that allows players to design an island town using only two inputs. It is an example of how rule-based design can generate complex configurations. Players select a color and click on a location in a grid, after which the game generates a building bases on a set of rules. The element placed in a grid slot is selected from a library using a wave function collapse algorithm, which selects elements based on surrounding elements. Players have crowd-sourced a list of rules and library of resulting elements.

SOURCE(S)

Townscaper offical website. Raw Fury. Retrieved 28 May 2022 from https://www.townscapergame.com/
Townscaping - Looking At How Things Generate. (2020, 7 May 2021). Retrieved 28 May 2022 from https://steamcommunitycom/sharedfiles/filedetails/?id=2155305102filedetails/?id=2155305102

3. Proposed design process diagram



6. Considerations for dimensioning system

6.1 Stairs

Rules for staircase dimensions can be divided into two types. Regulations are rules as defined in law by governments. These allow for broader ranges than other the other type of rules. These rules are best practices or recommendations related to ergonomics.

Dutch regulations (Bouwbesluit, 2012):

	Residential stairs	**Other programs**
Minimum width	80cm	80cm
Minimum clear height above stairs	230cm	210cm
Minimum thread	22cm	18.5cm
Maximum rise	18.8cm	21cm
Maximum total height	400cm	400cm

Furthermore, according to Dutch regulations, the top thread of a staircase has to connect to a landing of at least:

$$Stair\ width \cdot 80cm$$

Also, if the staircase is designated to more than 600m^2 occupiable space, it needs to be at least 1,2m wide for safe evacuation.

A commonly used rule for the design of stairs, often ascribed to French architect Francois Blondel's book Cours d'Architecture from 1675, is:

$$\text{Minimum: } 2R + 1T = 60cm$$

$$\text{Maximum: } 2R + 1T = 65cm$$

Here R is the rise of each step, and T is the thread. The resulting number is based on the stride length of a person.

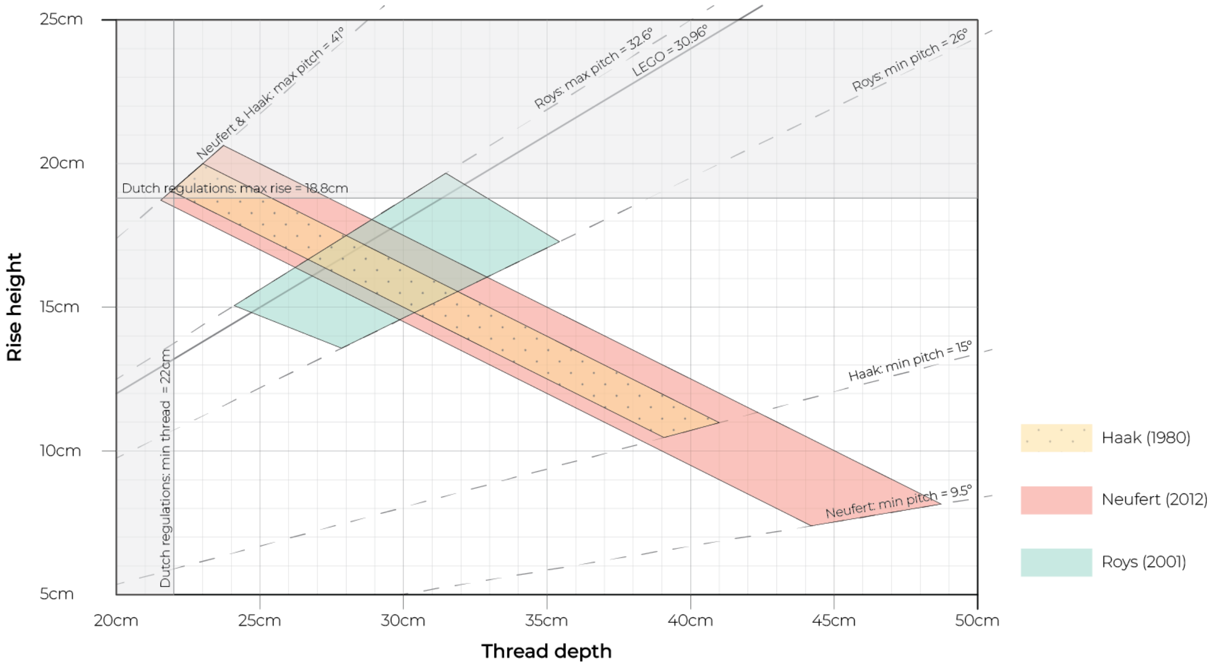
Other sources can be found with different ranges for the same formula:

- Neufert and Neufert (2012): $2R + 1T = 59\ to\ 65cm$
- Haak (1980): $2R + 1T = 60\ to\ 63cm$
- Roys (2001): $2R + 1T = 55\ to\ 70cm$

These sources also describe different ranges for a staircase's pitch:

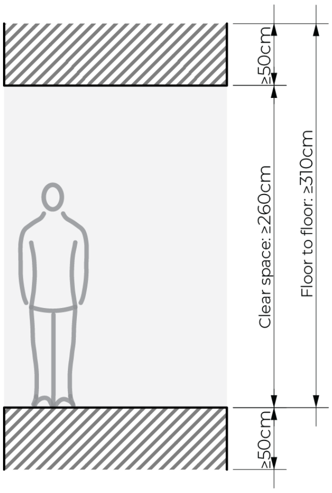
- Neufert and Neufert (2012) recommends between 9.5° and approximately 41°
- Haak (1980) recommends between 15° and 41°
- Roys (2001) recommends a different maximum pitch for private and public staircases. A range for all staircases would be between 26° and approximately 32°

All possible stair pitches, and rise and thread combinations for each source have been collected in the following figure:



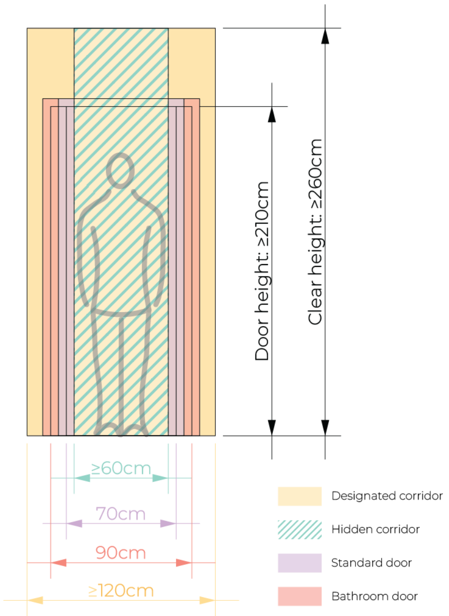
6.2 Storey height

Storey height needs to be considered for three reasons. Firstly, the clear height above each floor needs to be tall enough to comfortably move around in. Secondly, storey height relates to staircase dimensions, as staircases need to clear a storey in a positive integer number of steps. Lastly, storey height equals the height of the smallest spatial unit. Dutch law requires a clear height above the floor level of $2.6m$. The same minimum is recommended by Haak (1980). In addition to the clear height, the dimensions of services and floor structures need to be taken into account. Thus, a minimum storey height of $3.1m$ was used for this research.



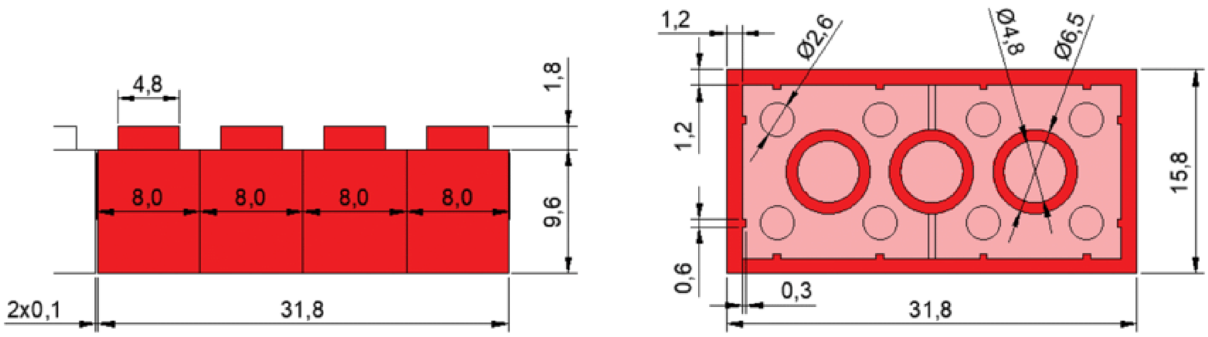
6.3 Horizontal circulation

Horizontal circulation spaces are required for movement between spaces and activities on the horizontal plane. *Designated corridors* are distinct spaces exclusively for movement from and to other spaces. As they are used for the access to dwellings, they are often shared and need to accommodate two people passing each other. Dutch law requires these spaces to be at least 120cm wide for safe evacuation (Bouwbesluit, 2012). Haak (1980) also recommends a minimum of $120cm$ width for two people to pass each other, while Neufert and Neufert (2012) recommends $130cm$. *Hidden corridors* are the spaces required within a room for people to move between and access activities. In simpler words, it is the space required for people to move between pieces of furniture. Haak (1980) and Neufert and Neufert (2012) don't explicitly define a dimension, but they generally recommend a minimum width of $60cm$. Lastly, doorways are the transitions between spaces. Neufert and Neufert (2012) prescribes a width of $90cm$ for standard doors and $70cm$ for bathroom doors.



6.4 LEGO

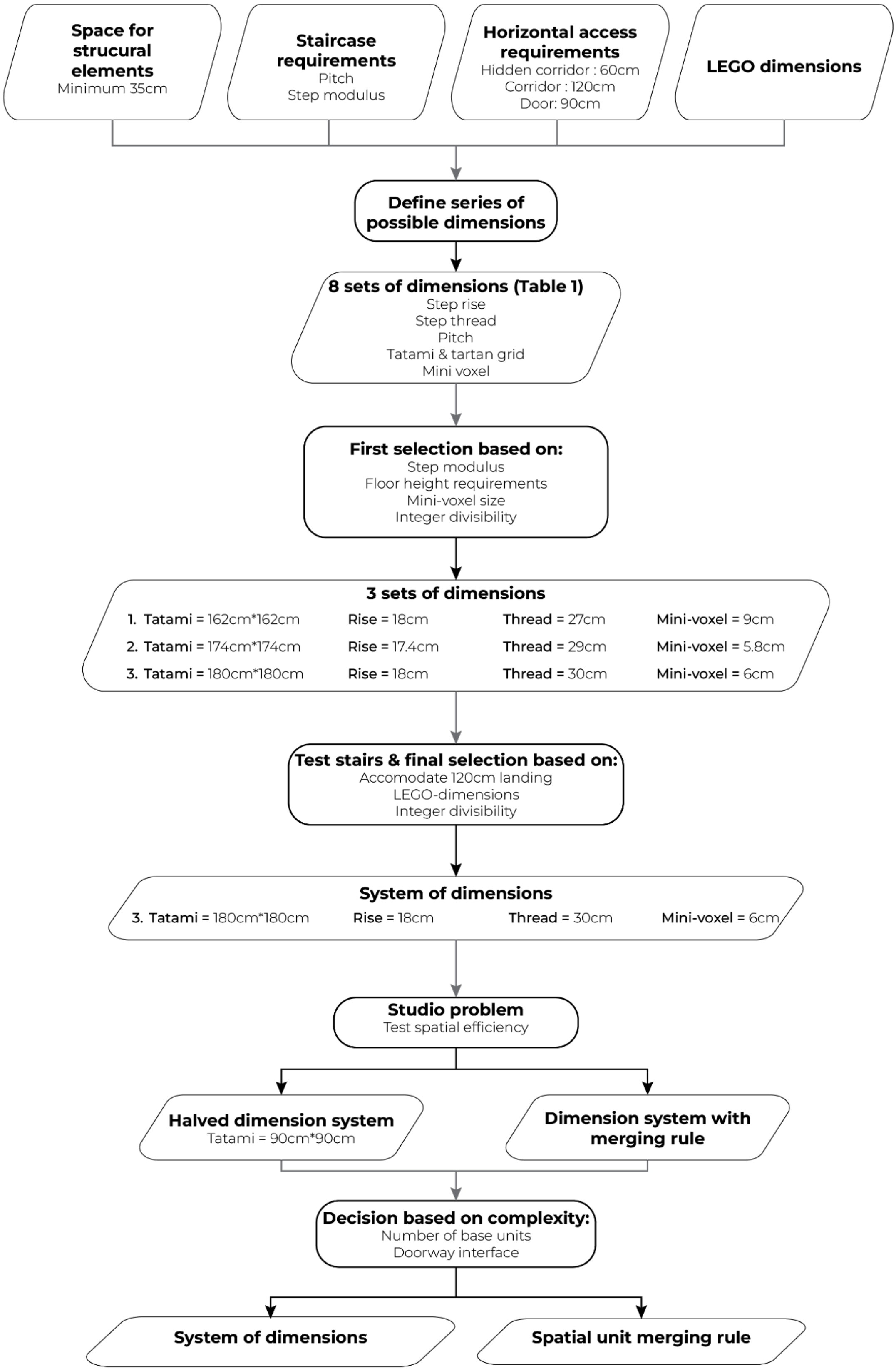
The LEGO bricks of $2 * 2$ studs are based on a height of $9.6mm$ and a width of $16mm$. Thus, LEGO bricks have a pitch of 30.96°.



Basic dimensions of LEGO toy bricks, by Calliau, R. (Source: Lemes, 2019).

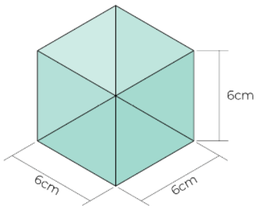
6.5 Studio apartment

7. Diagram of steps leading to the system of dimensions



8. System of dimensions

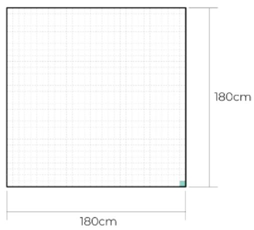
SYSTEM OF DIMENSIONS



Mini voxel

X = 6cm Y = 6cm Z = 6cm

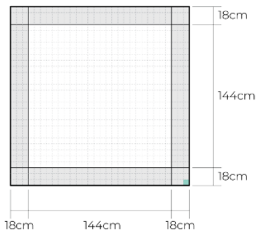
Base unit for building components.



Tatami

X = 180cm Y = 180cm

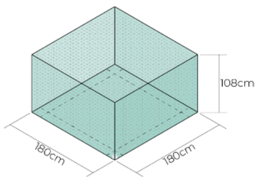
Base two-dimensional unit for room dimensions.



Tartan grid unit

X= 144cm+2 * 18cm Y = 144cm+2 * 18cm

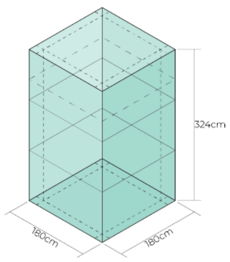
Tatami unit with 18cm on all sides reserved for structural elements.



Voxel

X = 180cm Y = 180cm Z = 108cm

Base three-dimensional unit. Accomodates six steps of a staircase.



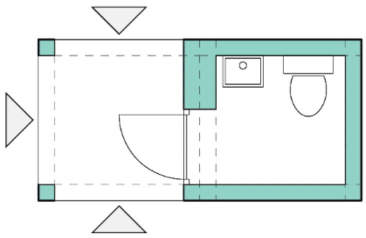
Base spatial unit

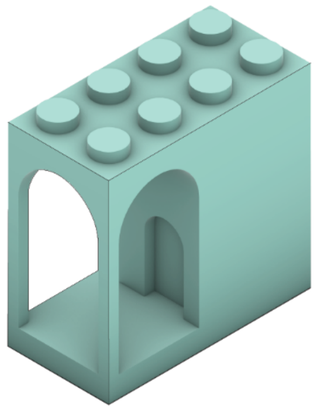
X = 180cm Y = 180cm Z = 324cm

Base three-dimensional unit for room dimensions. Contains a minimum 260cm tall clear space and a maximum 64cm tall space for floor structure and installations.

9. Game piece card example

BATHROOM | SIZE: **S** M L





POSSIBLE DOORWAYS

Category:		Services
Cost:		Number of game coins
Voxels: 2 * 1 * 3	**Grid spaces:** 2	**Dimensions:** 180cm * 360cm * 324cm
Voxels (L * W * H):		2 * 1 * 3
Grid spaces:		2
Real dimensions:		180cm * 360cm * 324cm
Concurrent users:		1
Furniture and appliences:		Toilet Washbasin
Placement requirement:		Next to shaft
Accessibility recommendation:		High
Privacy recommendation:		High
Daylight recommendation:		Not necessary
View recommendation:		Not necessary
Other notes:		

10. Traditional Japanese Housing

As described by Engel and Locher (2020), a major precedent for an architecture based on standardized dimensions is the traditional Japanese house. The base unit for tradition Japanese residential architecture is the *ken*, which was originally based on the structural centre-to-centre distance, and thus based on structural limitations. All other building measurements are derived from the *ken*. As mentioned in Engel and Locher (2020): "*In fact, everything that is a component of, or contributive to, the erection of a Japanese house is standardized"* (p. 37). This level of standardization allowed craftsmen to prefabricate building components. Damaged components could also be easily replaced. Furthermore, Engel states that construction standards were common knowledge to the point that everyone could be their own architect, similar to John Habraken's vision for open buildings.

However, the measures of the traditional Japanese house are not fully consistent. Firstly, two sets of dimensions exist, with a different *ken.* These two systems also result in their own deviations, which, as assessed by Engel and Locher (2020), stem from the discrepancy between centre-to-centre distance and clear distance between structural elements. In *kyo-ma* method the size of the *ken* is based on the size of the *tatami*, the traditional Japanese floor mat, and as a result determined the clear distance between columns. In turn, when two smaller rooms are placed next to a bigger room, the latter's floor requires additional infill. The *inaka* method's *ken* determined the centre-to-centre column distance. In this system different sizes of tatami are required . As Engel mentions, these inconsistencies can be easily solved when a building is constructed using handicraft but are a problem in a standardized industrial system. Consequently, the introduction of a modular coordination system that incorporates standards for both the clear distance between structural elements and the centre-to-centre distance is required.