GoDesign

A modular generative design framework for mass-customization and optimization in architectural design

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We present a modular generative design framework for design processes in the built environment that provides for the unification of participatory design and optimization to achieve mass-customization and evidence-based design. The paper articulates this framework mathematically as three meta procedures framing the typical design problems as multi-dimensional, multi-criteria, multi-actor, and multi-value decision-making problems: 1) space-planning, 2) configuring, and 3) shaping; structured as to the abstraction hierarchy of the chain of decisions in design processes. These formulations allow for applying various problem-solving approaches ranging from mathematical derivation & artificial intelligence to gamified play & score mechanisms and grammatical exploration. The paper presents a general schema of the framework; elaborates on the mathematical formulation of its meta procedures; presents a spectrum of approaches for navigating solution spaces; discusses the specifics of spatial simulations for ex-ante evaluation of design alternatives. The ultimate contribution of this paper is laying the foundation of comprehensive Spatial Decision Support Systems (SDSS) for built environment design processes.

Keywords: *Generative Design, Spatial Configuration, Serious Gaming, Mass Customization, Decision Problems*

INTRODUCTION

This paper presents a 'participatory generative design framework' emblematically called 'Go Design' after the game of Go. This framework is designed to enable Mass-Customization and application of Multi-Criteria Decision Analysis for supporting multi-actor decision-making processes such as those aimed at reaching consensus among stakeholders on goals and design requirements, objective decision-making processes such as finding the best configuration respective to environmental factors (e.g. light, energy), and finally subjective processes such as choosing styles, materials, and colors of the final structure. The focus of this paper is on the mathematical formulation of the spatial configuration problem, given exemplary inputs for user preferences to establish the generality of the framework as to different optimization/decision-making approaches and various participatory processes. Thus, the details of implementation and the participatory processes are beyond the scope of this paper. Effectively, the proposed framework reformulates architectural design as a chain of systematic decision-making problems in terms of given inputs and desired outputs rather than ad-hoc drawing and representation challenges.

We present a mathematical categorization and formulation of archetypical design problems, that provides for adequate utilization of a variety of computational methodologies. This categorization sets out a spectrum of decision-making problems ranging from the most abstract to the most concrete: 1) [space] planning in the context of Graph Theory, 2) configuring in the context of Algebraic Topology, and 3) shaping in the context of Computational Geometry. This categorization distinguishes the priorities of decision-making and specifies the widely-spoken notion of early-stage design decisions. By revisiting such typical architectural design problems from 'drawing' problems to 'decision' problems, they fall naturally within the purview of "The Sciences of the Artificial" (Simon, 2008), as defined by Herbert A. Simon. As such, this framework is a tribute to the initiative of several pioneers of computational design, namely the eloquent quest of Yona Fridman's "Towards a Scientific Architecture" (Friedman, 1980).

BACKGROUND

It has been argued that design and planning problems are "wicked problems"(Rittel, 1973); evading formulation, benchmarking, objective definitions of goals, etc. Inspired by (cf. (Voordijk, 2009)) we provide four lenses for revisiting such compound complexities by suggesting that the multi-dimensional and multi-criteria complexity of decision-making in design is attributable to the physical nature of the design task, while the multi-actor and multi-value complexities of decision-making are attributable to the concerning human factors in design (see Figure 1). Multi-dimensional complexity corresponds to the complex spatial (geometrical, topological, and graph-theoretical) relations that need to be orchestrated between spaces and elements. Multi-criteria complexity is concerned with balancing static and dynamic/operational qualities that a design is required to provide, such as light, solar energy, etc. The multi-actor complexities stem from the difference in the goals of stakeholders. Finally, the multi-value complexity originates from the uncertainties and ambiguities inherent to human perception and communication, which can be traced in self-contradictory preferences, bounded-rationality, miscommunication of goals, and individual-communal good dilemmas as discussed in Game Theory (q.v. (Cunningham, 2018)).

Given this decision-making approach, we naturally aim to structure the decisions to maximize the customizability for the actors while maintaining the explainability of the process. In doing so, we generalize this framework to incorporate an arbitrary number of spatial quality criteria, some of which might be related to human factors. In addition, we proffer a mechanism for integrating Multi-Criteria Decision Analysis (abbr. MCDA, q.v. (Ogrodnik, 2019) & (Huang, 2011)).

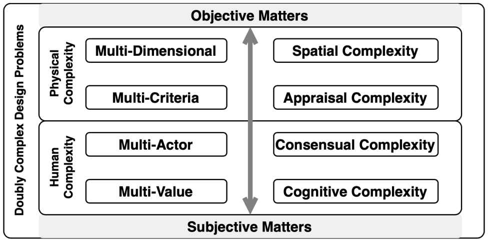

Figure 1
Variety of complexities involved

Explicitly discretizing the decision space facilitates analyzing the computational space and time complexity of procedures, enabling the simulation of spatial quality aspects related to accessibility, visibility, etc. Discretization of a design space not only facilitates the computational processes for providing play & score 'design games' (q.v. (Sanoff,1978) & (Bots, 2003)) but also inherently supports ultimate modularization of buildings as products, thus reducing the costs of production (q.v. (U|lrich,1995), (Salvador, 2002), (Salvador, 2007), and (Rocha, 2015)).

However, the mathematical formulation of design and planning problems is a challenge that precedes the use of computation and explainable Artificial Intelligence. A rigorous mathematical framework for design processes can create the methodical foundation necessary for developing Artificial Intelligence that can incorporate objective environmental factors and multi-actor user preferences in the process of design/planning. Within such frameworks, it is necessary to include a set of objectives for the design tasks that can describe the user preferences and environmental necessities, a model for spatial relations and qualities, and an assessment module that can assess the spatial relations and configurations based on the user preferences and environmental factors.

FRAMEWORK

We propose to organize the order and priority of design decision-making processes from abstract to concrete through three significant procedures: Planning, Configuring, and Shaping as a meta-level procedures with precise inputs, outputs, and problems. **Planning** is the first procedure in which stakeholders will collectively specify the relations and criteria of spaces. Planning involves multi-value, multi-actor, and multi-criteria complexities and aims to reach a graph theoretical description of spatial specifications, spatial relations, and collective design goals. **Configuring** is a procedure focused on generating a configuration of spaces from the specified criteria and relations in the previous step. Configuring is primarily concerned with the multi-dimensional and multi-criteria complexities and aims to explore different spatial configurations and represent them as graph mappings that describe 'discrete dimensionless [topological] design' (Steadman,1983). **Shaping** is the latest step that focuses on concretizing the geometry of the last procedure's topological design. Shaping involves multi-dimensional and multi-value complexities of design as it determines the aesthetic styling of design.

The precise formulation of the data structures passed between these procedures is crucial as they function as interfaces between the procedures. To ensure the modularity and generality of the framework, we propose a mathematical formulation of these data structures. The same logical transition from abstract to concrete that is present in the order of steps is also evident in the data structures passed between steps as they are formalized using different branches of mathematics from graph theory to topology to geometry.

Table 1
Meta-procedures in the proposed framework

Process	Product	Scope	Complexities
Planning	Network	Graph Theory	multi-value multi-actor multi-criteria
Configuring	Configuration	Algebraic Topology	multi-dimensional multi-criteria
Shaping	Shape	Geometry	multi-dimensional multi-value

Avoiding the black box approach and explicating the design process in utmost clarity to the actors fundamentally supports human participation. This vertical inclusion of stakeholders will enable them to customize the design not only to match their personal goals but also to adhere to the societal context that the design is situated in.

Generally, this framework utilizes feed-forward mechanisms in the micro-level when decisions are numerous, and they need objective adherence to preset spatial constraints and criteria, and feedback mechanisms at the macro-level when human insight is required in societal and cultural connotations of spatial constraints and criteria, or when subjective opinions are to be addressed in customization.

Framework: Planning

Ensuring actors' participation with customization capabilities requires strategies for targeting social, economic, and environmental sustainability goals. Formulating, communicating, and justifying such strategies and decisions for/together with multiple stakeholders is challenging from a scientific point of view, mainly due to the multi-actor and multi-value complexities. Overcoming this challenge requires including the inhabitants [and contextual stakehold-

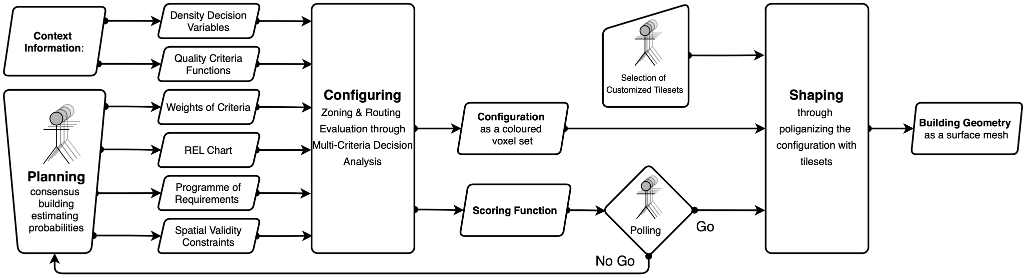

Figure 2
Main flowchart of the framework

ers] in the decision-making process (inclusion) as well as explaining and justifying the decisions (transparency). Thus, the planning phase frames an interactive approach for collaboratively setting out the spatial specifications and relations.

Table 2
Framework of Planning Procedure

Input	**Data Type**	**Input Name: Notes**
$\mathbf{c}$	$[c_k]_{m\times 1}$, $c_k \in \mathbb{N}$	List of indices of spatial quality criteria
$\mathbf{s}$	$[s_i]_{n\times 1}$, $s_i \in \mathbb{N}$	List of indices of spaces
Output	**Data Type**	**Output Name: Notes**
$\mathbf{P}$	List of Lists	static properties of spaces in terms of area, minimum ceiling height, label colour, space-specific local constraints (such as contiguity, [star] convexity, rectilinearity, single-layered vs multilayered, fixed locations, etc.) indexed w.r.t. an ordered set.
g_b	List, $b \in \{0, 1, \ldots, r\}$	List of global constraints to be staisified by the configurator such as adjacency, compactness/cohesion, rectilinearity, non-overlapping spaces, adjacency to fixed elements, reachability, etcetera.
$\mathbf{G}$	$[G_{i,j}]_{n\times n}$, $G_{i,j} \in [0, 1]$	desired closeness between s_i and s_j
$\mathbf{W}$	$[W_{i,k}]_{n\times m}$, $W_{i,k} \in [0, 1]$	weights of spatial criteria for spaces, such that $W_{i,k} \in [0, 1]$ shows the relative importance of criterion c_k for space s_i

Problem: Given the list of spaces $\mathbf{s}$ and spatial quality criteria $\mathbf{c}$, the actors are asked to reach a consensus on space properties $\mathbf{P}$, the desired closeness ratings $\mathbf{G}$, and spatial quality criteria's weights $\mathbf{W}$.

By abstracting and discretizing the design space, we mathematically formulate the planning phase as a multi-actor and multi-criteria decision-making problem. Within this formulation, the actors/stakeholders to negotiate, reach a consensus, and graph theoretical objects will represent the final decision. These objects consist of the relation of spaces with each other as a uni-partite graph and the relation of spaces with criteria as a bipartite graph. This phase's gamification provides for reaching consensus on the user-preferences (Bots, 2003) and provides transparent and inclusive decision-making processes for the planning phase.

Framework: Configuring

Given the contextual information, the main objective of configuring is to find a configuration as a colouring of a discretized design space (building envelope) that satisfies the local and global spatial validity constraints, the desired spatial relations, the spatial quality criteria, and their corresponding weights that have been determined in the planning phase. The resultant configuration will be represented by a graph mapping or graph colouring that assigns a colour/label to each of the envelope's volumetric cells. As such, configuring is formulated as a feed-forward process since the contextual information and spatial criteria are provided at the beginning of the phase. The buildable envelope can either be empty or contain already existing buildings.

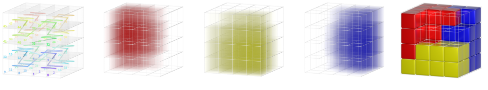
Z-Order indexing $\mathbf{X}[:, 0]$ $\mathbf{X}[:, 1]$ $\mathbf{X}[:, 2]$ *Configuration:* $\mathbf{X}'$

Figure 3
Z-Order Indexing of Voxels, Visualization of the density matrix, and Configuration

Within this procedure, contextual information layers correspond directly to the set of criteria in the planning procedure. The weights of importance given by the actors will indicate how the MCDA will evaluate the allocation of different voxels based on their value in the quality criteria functions. Within this framework, each information layer is a quantity that has a value in each position of discrete space. Thus it can be formalized as a field: f_k :$[0,1]^{o \times n} \mapsto [0,1]^o k \in \{0,1,\dot{s},m\}$ and thus they can be called spatial quality criteria functions. As such, we can distinguish two categories of quality criteria based on their computational nature: Firstly, Accessibility-Related Quality Criteria, which must be computed based on geodesics and geodesic distances on [approximate/discrete] 2D manifolds. Secondly, Visibility-Related Quality Criteria must be computed based on straight-lines of sight and Euclidean distances on [approximate/discrete] 3D manifolds (e.g., direct sunlight, sky view, noise, etcetera). It is important to note that field formulation of quality criteria allows for including any quality criteria function as long as they are computable.

Furthermore, as the configuring procedure is often iterative, fields can be categorized into three categories based on how they should be re-evaluated given an existing configuration: firstly the **Static** fields representing quantities that their value in space are entirely independent of the configuration, such as height, distance to the facade, etcetera; and secondly, the **Dynamic** fields representing quantities that theoretically can be evaluated in the absence of configuration, yet the configuration affects their evaluation (e.g., direct sunlight, sky view, etc.; and finally, the **Dynamic & Dependant** fields representing quantities that their evaluation is only possible when a configuration exists (e.g., closeness to the entrance, closeness to the lobby, etc.)

As indicated in Table 1, the configuring procedure does not include human complexities such as multi-actor and multi-value aspects. This ensures the generality of the framework and allows for both optimization and participatory decision-making formulations of such configuring procedures. However, given the typical challenges in formalizing societal, cultural, and other human-related criteria, an optimization formulation of this step could be excessively simplistic and reductionist. Thus, we advocate for a participatory decision-making formulation that allows for explorative approaches and utilization of various Multi-Criteria Decision Analysis methodologies.

Table 3
Framework of
Configuring
Procedure

Input	Data Type	Input Name: Notes
$\mathbf{v}$	$[v_l]_{o\times 1}$	Array of volumetric cells (voxels) that comprise the rasterized envelope.
$\mathbf{X}$	$[X_{l,i}]_{o\times n}$	Array of denisties of volumetric cells (voxels) indexed with l per space colour/lable indexed with i, optional input, necessary when working with an existing configuration.
f_k	$f_k :$ $[0,1]^{o\times n} \mapsto$ $[0,1]^o$ $k \in$ $\{0,1,\ldots,m\}$	Quality Criteria functions mapping the set of coloured density matrix $\mathbf{X}$ to a vector of evaluated criteria whose compoents are mapped in range of $[0,1]$; this mapping transforms objectives to unitless criteria that are individually understandable for the human actors.
$\mathbf{P}$	List of Lists	static properties of spaces
g_b	List, $b \in \{0,1,\ldots,r\}$	List of global constraints to be staisified by the configurator
$\mathbf{G}$	$[G_{i,j}]_{n\times n}$	desired closeness between s_i and s_j
$\mathbf{W}$	$[W_{i,k}]_{n\times m}$	weights of spatial criteria for spaces
Output	**Data Type**	**Output Name: Notes**
$\mathbf{X}$	$[X_{l,i}]_{o\times n}$	Matrix of denisties of volumetric cells (voxels) indexed with l per space colour/lable indexed with i; representing the configuration of spaces in the discrete (voxelated) design space. At the output, this matrix only contains discrete values from the set $\{0,1\}$.
$\mathbf{\Sigma}$	$[\Sigma_{i,k}]_{n\times m}$	The scoring function that aggregates the compliance of each configured space with respect to the set goals $\mathbf{P},\mathbf{G},\mathbf{W}$

Problem: Given the discrete envelope as a set of voxels $\mathbf{v}$, the quality criteria functions f_k, the space properties $\mathbf{P}$, the desired closeness ratings $\mathbf{G}$, and spatial quality criteria's weights $\mathbf{W}$, it is desired to find a configuration $\mathbf{X}$ satisfying the local constraints as listed in $\mathbf{P}$ and the global constraints g_b.

Nevertheless, the proposed procedure is so general that, if desired, it can frame the problem of configuring as a generalized Topology Optimization procedure similar to those exploited in structural design, mechanical engineering, and fluid dynamics. For this reason, the decision variable matrix $\mathbf{X}_{o\times n}$ can contain continuous density variables inside the configurator so that the functions remain differentiable and that the gradients required for the updating scheme of topology optimization algorithms can be computed. However, once the decision is taken and fixated at the front-end of the process, the continuous densities will be mapped to the set $\{0, 1\}$. Furthermore, as indicated in the main flowchart (Figure 2), this step's resultant configuration is subject to polling amongst actors to ensure the ultimate consistency with unquantifiable values and criteria.

A generic formulation of such configuring procedures is proposed in Table 3. Such configuring procedures can be implemented as a **Configurator** (industrially known as Configure, Price & Quote systems, q.v. (Jordan, 2020)) as a Decision-Support System that is capable of facilitating Play & Score processes, which can be possibly multi-player or single-player. To assess the different aspects of the resultant configuration, we propose a set of MCDA aggregators capable of reporting the quality of a configuration concerning the set of spaces, the set of criteria, the set of actors, or one single score for the configuration as a whole.

Framework: Shaping

In the shaping procedure, the previous step's configuration will be polygonized to create the geometrical representation of the configuration. Two main approaches can be distinguished in such procedures: discrete & continuous. In the discrete approach, a tileset is used to specify the geometry, which inherently facilitates modular construction. In the continuous approach, a level set is generated based on the difference in the voxel colors. The continuous approach offers a more robust process though it limits the customizability of the architecture of the resultant mesh. In its utmost generality, however, the continuous approach can significantly increase manufacturing costs -only if continuous density variables are to be permitted. It must be noted that given a voxelated domain and discrete densities from the set $\{0, 1\}$ even a continuous iso-surface will be a mesh that can be post rationalized as a modular surface. The discrete approach, on the other hand, allows the actors to customize the tilesets and consequently personalize the final design; while still benefiting from the economy of scale in that they will be using a set of few tiles (to be precise, between 8 to 256 tile geometries, irrespective of their other attributes). This entails that the whole building is not only customizable to a high level of detail, it is also going to be affordable because of the possibility of mass-production of such tiles as construction components.

Table 4
Framework of
Shaping Procedure

Input	**Data Type**	**Input Name: Notes**
$\mathbf{v}$	$[v_l]_{o \times 1}$	Array of voxels
$\mathbf{X}$	$[X_{l,i}]_{o \times n}$	Matrix of denisties of volumetric cells (voxels) indexed with l per space colour/lable indexed with i; representing the configuration of spaces in the discrete (voxelated) design space.
Output	**Data Type**	**Output Name: Notes**
$\mathbf{M}$	Surface Mesh	A surface mesh representing the geometry of the configuration, whose attributes may include indicies referring to the materials of choice, codes for the construction details, etcetera.
Problem: Given the configuration $\mathbf{X}$ on an array of voxels $\mathbf{v}$, it is desired to find the mesh that interior-exterior bounds the spatial regions in the configuration		

METHODOLOGY

The same way a structured collection of techniques is referred to as a technology, a structured collection of methods is referred to as a methodology. As indicated earlier, each of the three procedures focuses on different aspects of the design process and has different complexities. In this section, we elaborate on the suitable methods for each procedure. In the following section, we present a spectrum of methods from domains ranging from the digital game industry and Procedural Content Generation (a.k.a. Scene Synthesis) to Engineering Optimization methods and Artificial Intelligence, all of which can be utilized within our proposed framework.

Methodology: Planning

An exemplary mathematical definition of a multi-actor game for reaching consensus on the user preferences on shared/communal spaces based on abstractions of Game Theory and Graph Theory is proposed by (Bai, 2020). This can be extended by the opinion pooling method suggested by (Batty,2013)or consensus Building suggested by (Sanoff,2000) to model different decision factors and their dynamics with Network Models.

Methodology: Configuration

As indicated in Configuring Framework Section the configuring phase provides a problem formulation that allows for applying a spectrum of existing methods such as Engineering Optimization, MCDA, and gamification. However, the feed-forward nature of such procedures requires a new category of simulation and approximate evaluation tools capable of taking highly abstract inputs.

Starting from the most automated (and yet explainable) approach, this formulation provides the structure for application of Topology Optimization (TO) (Bendsoe, 2013) as the configuration is represented by a discrete density matrix **X**, and a reciprocal analogous of the strain energy (compliance) in a conventional TO is the spatial quality criteria functions f (see Table 3). This formulation is thus suitable for gradient-based mathematical programming. The caveat here is that in this framework we formulate the quality criteria as benefits to be maximized for better human understanding as it is common in RL framework which they formulate as rewards, however in TO approach it is more common to formulate objective functions as cost to be minimized.

Furthermore, given the spatial validity constraints g_b, a family of Combinatorial Optimization methods is also applicable similar to the approach of (Hua, 2019), and(Peng, 2016) which apply Integer Programming in multiple scales to layout and routing problems in discrete spaces; or as in (Wu, 2018) which applies Mixed-Integer Quadratic Programming(MIQP) to discrete interior design problems. Also, Reinforcement Learning (RL) methods are compatible with this formulation since we can define the configuring procedure as a Markov Decision Process (MDP) given that **X** represents the state space, spatial constraints can be embedded in the definition of agents' actions, and spatial quality criteria function f can provide the rewards for the learning agents. An example of such application is "Academy Spatial Agents" (Veloso, 2020) where spatial agents utilize DDQN to make decisions in a discrete space.

Moreover, the search process can be gamified to establish a play & score environment as well. Within such an approach, grammatical itemization can be used as the generative mechanism of playing (as applied in [ref. removed for annonymity]) and MCDA methods (as reviewed in (Huang, 2011) for scoring the configuration alternatives. Finally, there are also potentials for hybrid approaches such as combining a Multi-Agent System (q.v. (Veloso, 2018)) approach with local MCDA evaluators that guide their decisions about configuration in a discrete environment ([ref. removed for anonymity]).

Methodology: Shaping

As stated in Shaping Framework Section, polygonization of the configuration can be performed through a continuous or discrete approach. An exciting example of the continuous approach is the Marching Cubes algorithm applied in (Nourian, 2014). The discrete approach can be deterministic as proposed by (Savov, 2020) where geometric tiles are placed if a particular combination is present in the configuration, or they can follow a stochastic approach such as Wave Function Collapse Algorithm in which the tile selection for each location is modelled as a probability function that changes based on the selection of tiles in the neighbouring locations (Gumin, 2021). There have also been efforts to combine these approaches and generalize from a regular grid to nonregular grids. (Stalberg, 2015)

APPLICATION & RESULTS

The 'Go Design' framework has been partially implemented in the form of an open-source python package named topoGenesis to maximize its accessibility and reproducibility. We have developed a python library called topoGenesis (Azadi, 2020) The proposed workflow and this tool-set have been applied in educational design studios at TU Delft. In the BSc Spatial Computing design studio, students are asked to develop systems that allow future inhabitants to customize the configuration while satisfying environmental constraints such as direct sunlight, sky view factor, noise, etc. (see Figure 4). Their site is located in Agniesebuurt near the central station of Rotterdam. Students were asked to design a mixed-use complex in a specified parcel. They were instructed to identify future inhabitants and develop a gamified process for the planning phase to specify the inhabitants' preferences as to the aforementioned spatial quality criteria. Next, students were instructed to utilize a Multi-Agent System in the configuring process; embed spatial constraints in the agents' behaviors to avoid complex mathematical formulation of the constraints; utilize MCDA to aggregate each voxel's total value concerning different spatial quality criteria functions; and finally, synthesize a configuration based on the relative advantage of allocating each space to a particular voxel [1].

In the MSc EARTHY design studio (Nourian, 2020) the framework has been utilized for temporary accommodation of displaced communities in Al Zaatari Refugee Camp in Jordan. Students were asked to develop systems/games that allow inhabitants to customize the configuration of their collective habitats while satisfying structural and low-tech constructability constraints of adobe buildings. Their system is required to produce assembly plans of a set of modules to construct the buildings (see Figure 5) Students have developed combinatorial games for exploring configurations as modular permutations. In this project, students have taken a participatory grammatical approach to provide maximum control over the configuration for the future inhabitants [2],[3].

In the EARTHY studio, as the structural constraints are the main feasibility constraints of the design process, successful projects have adopted a modular approach based on different structural elements (e.g. dome, vault, arch, etc) as the basis of their configuration system. With this approach, they not only managed to gamify the decision-making process for inhabitants but also eliminated the need for post-design structural analysis of the structures to increase the independence of the inhabitants in configuring and constructing the buildings [2],[3]. On the other hand, in the Spatial Computing studio, the structural constraints were not as limiting as in the case of EARTHY. Thus successful projects focused more on spatial quality criteria such as day-

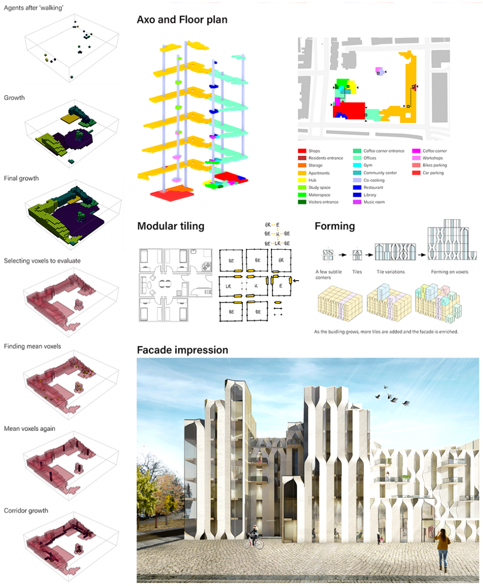

Figure 4
Examples of application of GoDesign framework in student projects: BSc [1]

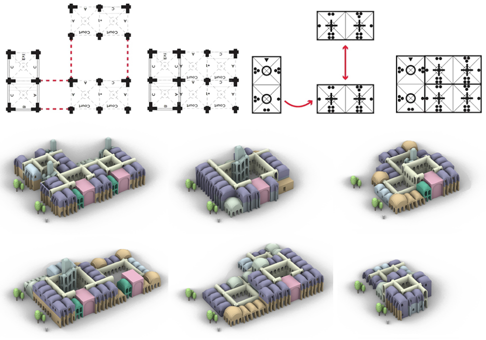

Figure 5
Examples of application of GoDesign framework in student projects: MSc [2][3]

light, accessibility, visibility, noise, etc., and developed a gamified decision support system that allows the stakeholders to set their preferences and see the effect of their preferences on the design. [1]

CONCLUSION & DISCUSSION

Generality

As the primary feature of this framework is to offer a **general formulation** of the design problem that does not only provide the structure required for the application of optimization and AI methods but also makes the design process more transparent by providing interfaces for participants to be part of the design process, inject their preferences and customize the design. This is particularly important as it provides for argumentation on spatial decisions in an evidence-based approach. As a result, spatial decisions can be traced back to the context conditions, quality criteria, and stakeholder preferences. Also, the framework in general, and the planning phase in particular, can support various forms of multi-actor decision-making mechanisms (participatory design) to ensure customization of the design in various steps. Beyond the decision-making perspective, this framework structures the design space as a countable set of solutions while maintaining topological and geometrical diversity.

Furthermore, the configuring meta-procedure offers a generalized formulation of quality criteria functions that encompasses any criteria that could be expressible as a function of space (field). Besides, the modularity of these quality critera functions allows for including an arbitray set of multiple criteria. Similiarly, various types of local and global spatial validity constraints can be included in such proecdures.

The combined implementation of configuring and shaping meta-procedures is compatible with both modular and integral construction techniques. Finally, the inherent process-modularity of the framework provides for partially adopting it or combining it with other frameworks.

Limitations

As explained in the Framework Section, this framework mathematically prioritizes abstract decisions over concrete ones. This prioritization structures the solution space and facilitates the formalization of objectives and constraints in the process. Consequently, specific solutions will be harder to reach. Mainly, designs that are geometrically simpler but topologically complicated are less likely to be generated. Furthermore, the mathematical nature of the framework requires the quantifiability of spatial criteria prior to their integration in the framework. However, there are ongoing research projects to assess its potentials in integrating non-quantifiable quality criteria such as the heritage value of attributes of existing structures in case of renovation projects.

Future Work

Primarily, this framework provides a foundation for the mathematical formulation of spatial quality criteria f and spatial constraints g. As the built environment is present in many aspects of human life, it influences and is influenced by many physical and societal aspects of human life. Consequently, a spectrum of different qualities needs to be modeled, formalized and added to the system. As such, the mainline of future work within this framework will be about developing various specialized evaluation procedures.

The configuring procedure provides the potential for applying MCDA and optimization methods, a couple of examples of which have been mentioned in the manuscript. However, there is yet much more room for exploring the applicability and suitability of a wide range of compatible methods for solving benchmarked problems. This is particularly important in order to situate the framework in the AEC industry, thus further investigation into the compatibility of the framework with existing conventional workflows is required to consolidate more test cases.

Finally, this framework offers an explicit formulation of spatial design problems that is compatible with many modern Machine Learning methods, not only for automating decision making by means of Generative Adversarial Networks (GANs), Deep Q-Networks (DQN), etc, but also, more importantly, for growing a body of evidence-based knowledge of 'quality' and its complex relations to our design decisions.

REFERENCES

Azadi, S and Nourian, P 2020, *topoGenesis*, Zenodo, DOI: 10.5281/zenodo.4006514

Bai, N, Azadi, S, Nourian, P and Roders, AP 2020 'Decision-Making as a Social Choice Game', *eCAADe 2020*, Berlin, p. 16

Batty, M 2013, *The New Science of Cities*, MIT Press

Bendsoe, MP and Sigmund, O 2013, *Topology optimization: theory, methods, and applications*, Springer Science \& Business Media

Bots, PWG and Hermans, LM 2003 'Developing 'playable metagames' for participatory stakeholder analysis', *34th Conference of the International Simulation and Gaming Association (ISAGA)*, pp. 647-657

Cunningham, S and Hermans, L 2018, *Actor and Strategy Models: Practical Applications and Step-wise Approaches*, John Wiley \& Sons, Inc., Hoboken, NJ, USA

Friedman, Y 1980, *Toward a Scientific Architecture | The MIT Press*, MIT Press

Hua, H, Hovestadt, L, Tang, P and Li, B 2019, 'Integer Programming for Urban Design', *European Journal of Operational Research*, 274(3), pp. 1125-1137

Huang, IB, Keisler, J and Linkov, I 2011, 'Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends', *Science of The Total Environment*, 409(19), pp. 3578-3594

Jordan, M, Auth, G, Jokisch, O and Kühl, JU 2020, 'Knowledge-based systems for the Configure Price Quote (CPQ) process – A case study in the IT solution business', *Online Journal of Applied Knowledge Management*, 8(2), pp. 17-30

Nourian, P, Azadi, S and Hoogenboom, H 2020, 'EARTHY: Computational Generative Design for Earth and Masonry Architecture', *BOUT RUMOER: Periodical for the Building Technologist*, 74, pp. 47-53

Ogrodnik, K 2019, 'Multi-Criteria Analysis of Design Solutions in Architecture and Engineering: Review of Applications and a Case Study', *Buildings*, 9(12), p. 244

Peng, CH, Yang, YL, Bao, F, Fink, D, Yan, DM, Wonka, P and Mitra, NJ 2016, 'Computational Network Design from Functional Specifications', *ACM Transactions on Graphics*, 35(4), pp. 1-12

Rittel, HWJ and Webber, MM 1973, 'Dilemmas in a General Theory of Planning', *Policy Sciences*, 4, p. 15

Rocha, C, Formoso, C and Tzortzopoulos, P 2015, 'Adopting Product Modularity in House Building to Support Mass Customisation', *Sustainability*, 7, pp. 4919-4937

Salvador, F 2007, 'Toward a Product System Modularity Construct: Literature Review and Reconceptualization', *IEEE Transactions on Engineering Management*, 54(2), pp. 219-240

Salvador, F, Forza, C and Rungtusanatham, M 2002, 'Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions', *Journal of Operations Management*, 20(5), pp. 549-575

Sanoff, H 1978, *Design Games*, Create Space Independent Publishing Platform

Savov, A, Winkler, R and Tessmann, O 2019 'Encoding Architectural Designs as Iso-surface Tilesets for Participatory Sculpting of Massing Models', *Design Modelling Symposium Berlin 2019*, pp. 199-213

Simon, HA 2008, *The Sciences of the Artificial*, MIT Press, Cambridge, Mass.

Steadman, P 1983, *Architectural Morphology: An Introduction to the Geometry of Building Plans*, Pion

Stålberg, O 2016, 'Voxel House: Breaking Down the Voxel House Demo by Oskar Stålberg', *Vertex*, 3 , pp. 170-176

Ulrich, K 1995, 'The role of product architecture in the manufacturing firm', *Research Policy*, 24(3), pp. 419-440

Veloso, P and Krishnamurti, R 2020, 'An Academy of Spatial Agents', *eCAADe 2020*, -, p. 10

Veloso, P, Rhee, J and Krishnamurti, R 2008, 'Multi-Agent Space Planning', *International Conference on Computer Aided Architectural Design Futures*, 18, p. 24

Voordijk, H 2009, 'Construction management and economics: the epistemology of a multidisciplinary design science', *Construction Management and Economics*, 27(8), pp. 713-720

Wu, W, Fan, L, Liu, L and Wonka, P 2018, 'MIQP-Based Layout Design for Building Interiors', *Computer Graphics Forum*, 37(2), p. 11

[1] https://github.com/Pirouz-Nourian/Spatial_Computing_Design_Studio20

[2] https://github.com/Pirouz-Nourian/earthy_20

[3] https://github.com/Pirouz-Nourian/earthy_19