Versus Habitat

Multi-agent spatial negotiation for topology-aware, large scale architectural assemblages

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With the burst of automation in the AEC industry, modular design for collective living is having a reissue; as for industrial construction in the post WW2 era, the economies of a construction system trigger urban models, but an exploration of non-standard spatial models based on computational methods is still lacking. This research proposes a competition-based process for the design of large scale (urban) collective habitats as topology-aware architectural assemblages of spatial (as in including constructive elements + void) components. Two competing multi-agent systems negotiate spatial occupancy, leveraging the morphological computation capabilities of individual and combined components at increasing scales. Localized information stored in the environment by the agents is converted in architectural components, resulting in a multi-level spatial organization that transcends typical typological classification. Space syntax techniques are used to map the assemblage properties and support design inferences on spatial occupation such as potentially implementable functional programmes.

Keywords: *Multi-agent System, Automation, Assemblages, Stigmergy, Space Syntax.*

INTRODUCTION

With the rapid propagation of automation in the architectural, engineering and construction industry, modular design is having a new lease on life after its popularization in the modern period, when prefabrication and industrialization saw analogous development dynamics. Such was the attractive power of the economy of scale induced, that in some cases entire urban plans became a reflection of the construction technology logistics. That was the case, for instance, of the Zeilenbau, in which the room size, floor height, and buildings span were tied to the reach and payload of the crane, conveniently placed to work on two buildings at once and minimize its operations and relocation (de Graaf 2017). It is not too far-fetched to maintain, as de Graaf does, that "the crane is the architect of the new settlement", but the technology and its logistics cannot be separated from the culture of mechanical repetition and idealistic homogenization they thrived on. It takes a few decades for a manifestation of a distinctive use of the same technology in the realization of a unique spatial model for living, with Moshe Safdie's Habitat 67 (Safdie 1967). The demonstrative project for the Montreal Expo makes a singular statement in blurring the threshold between architecture and urban scale by means of combinatorial design of modular spatial units, claiming its slot in a thread that includes, among others, the work initiated by Team 10, Dutch Structuralism (with particular regard on the work of Piet Blom for his generative use of geometry (Palacios Labrador 2016), Ricardo Bofill's The City in the Space [1] and Yona Friedman's use of the

Flatwriter program for his Ville Spatiale (Rouillard 2018) [2]. These projects aimed at joining mass production and logistics with care for social relations of a community beyond mere housing, the concept of "unit", and the imposed stratification of the gridiron.

Automation is here defined as the condition by which action and abstraction are granularized in a network of distributed, adaptive relays through living bodies and non-living media (Bratton 2019). It intensifies further the shortcut between logistics and urban patterns, but while applications on building systems and design software are a reality (Delve [3], and Intelligent City [4] among many others), investigations on automation-induced spatial models and their implications at the threshold of architectural and urban are still very few; a notable example is the work of Lab-eds ([5] and Koehler 2017). Studying the implications of automation in architectural design begets a revisitation of modular and combinatorial design, introducing open-ended computational methods in place of mechanical reproduction. This research proposes a design strategy based on distributed decisions through communities of autonomous agents in competitive relationships, capable of generating architectural assemblages.

COMPETITION & CONTROL

Distributing decision implies the utilization of decentralized systems composed of autonomous agents: entities able to perceive and act in an environment (Russel and Norvig1994). Signal-based communication can be found in decentralized systems, natural or artificial, where intelligence and organizational patterns arise from local interactions between individuals of a community that follow few, simple rules, unaware of the global state of the system and devoid of top-down coordination. This phenomenon, defined as swarm intelligence (Beni and Wang, 1988), is instrumental in its capability to generate complexity from a low initial information cost. The possibility of swarm intelligence emerges from the design of control and communication in the system in order to achieve self-regulation (Wiener 1948), based on how agents store, exchange and manipulate information in the form of signals. Negative feedback processes are essential for self-regulating systems in order to maintain stability under changing conditions; this process, also called homeostasis, is particularly relevant for communal constructions, where circulation and inhabited spaces are interdependent but also in constant competition.

MULTI-AGENT SYSTEMS

For the purpose of capturing these dynamics in the design process, we define multiple agent systems interacting in the same environment, with the capacity to add building elements, fostering or hindering the process in search of an autonomous convergence to stability. The design of such systems, their parameters and post-assemblage evaluation of qualities are all instrumental for the architectural speculation.

The technical implementation is carried out in Rhinoceros+Grasshopper, writing bespoke algorithms inside custom C# components. Agents, geometrically defined as points, move in a voxelized space, interacting with other agents and obstacles with the typical steering behaviours defined by Reynolds (1987), and exchanging signals indirectly through stigmergic interaction (Jones, 2010): they can read and write information in the closest voxel cell, and compare the stored information with their internal state to perform decisions and actions.

The digital environment is set as a voxel space of cubical cells whose dimension R represents the system resolution, and nX, nY, nZ are the corresponding number of cells in each cartesian dimension; nZ also represents an equal number of layers. Signals produced by agents are stored in each cell in the form of 3D arrays (fields), decreasing their intensity over time at an established rate (evaporation) and propagating to neighbour cells (diffusion).

Agents can detect one or more signal types through a sensor array characterized by a radius and an angle (Jones, 2010; Figure 1); they move following the strongest signal detected, increasing their own released signal intensity by a small amount as they pass through a cell.

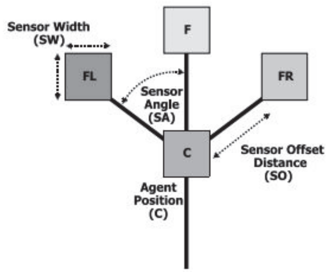


Figure 1
Jeff Jones (2010) sensor array setup

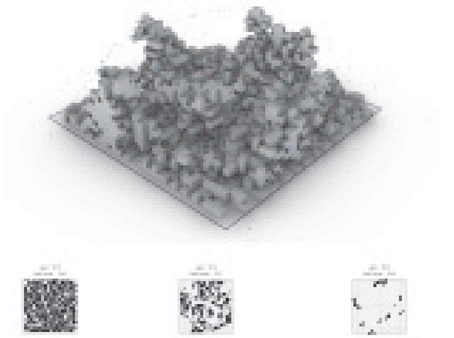


Figure 2
First assemblages with section at different levels (lower to higher)

An initial setup included two agent types: emitters and builders. Emitters act like environment explorers that foster the building process, following their own released signal in pure stigmergic fashion. Builders emit a different signal and follow both signal types, dropping a voxel-size building element where the detected emitter's signal intensity exceeds a designed threshold. The building process proceeds from the bottom up: elements can be deposited only on the base layer or on top of existing elements, and agents can reach an upper level only if they encounter a built element in the current layer. An analysis of respective agents' fields reveals overlapping paths.

The outputs, tested at several parameters ranges and values, are all akin to a scattered accumulation that heightens in rapidly decreasing density, with hardly detectable input-output causal patterns (Figure 2). Lack of feedback and simple voxel materialization results in unregulated growth with a limited spatial pattern expression; clearly, both building elements and agents' interactions require more sophistication.

To improve spatial assemblage beyond pure voxelization, building elements implementation leverage a combinatorial logic first introduced by Stiny (1980), where elementary blocks connect through coded faces according to grammar rules. Building elements are studied as parallelepipedal geometries, with an orientation plane, a direction vector, and connection planes (named handles) distributed on their faces: building elements connect with each other handle-to-handle using matrix transformations (plane orientation + rotation), defining a sender and a receiver role for "waiting to be placed" and "already placed" elements and their respective handles (Figure 3). A combination between two elements is coded in the form of a heuristic that includes two pairs of indices (sender and receiver elements' handles) and a rotation angle for the sender.

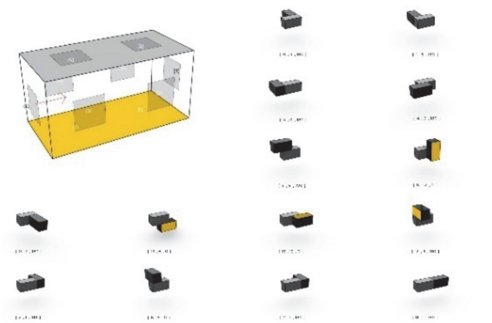


Figure 3
Elementary component with handles and some of its possible combinations

A combinatorial analysis of the heuristics generated by all possible handles permutation helps in designing connections and in making inferences about spatial qualities and architectural potential of each. Elements are deposited by building agents, with their direction vector resulting from the approximation of the agent's velocity to the nearest cartesian axis. Once deposited, they try to connect to the nearest available free handle choosing among the possible clash-free handles combination: distances between handles' centres are used to make a list of connectable couples in descending order. If the attachment is successful, the new element starts emitting a constant signal for the builder agents. Topological information about the connection is preserved on both elements involved: each element knows its neighbours and which handle connects them.

In order to achieve system scale self-regulation, competitive behaviour is introduced. In this evolved setup, emitters are discarded, builders move and deposit elements following their own signal intensity, and a third entity with a stabilization role is introduced to regulate the building process. This new kind of agent, defined competitor, has the same properties and communication capabilities as builders (except for element deposition), and its main function is to reduce the signal emitted by the latter, affecting the building process by modulating signal distribution. Deposited elements attract both builders and competitors, in order to trigger the interaction and feed the process (Figure 4). The multi-agent system manages three types of signals: every voxel or cell in the environment stores one value for each signal type, that all agent types can read and sort by importance, with system-wide criteria chosen from a set of 3 cases. The desired cell is selected among those detected, with a sorting process that is influenced by signal type order and relative ascending or descending signal values (Table 1). For example, in case A agents order cells searching the combination of the highest element signal value and lowest values of agents' signals.

Agents' direction consequently depends on the perceived signals value and the priority order chosen for the simulation.

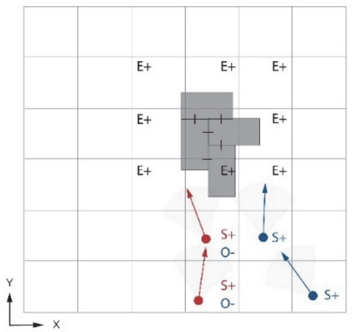


Figure 4
Scheme of agents' signals distribution where S = same type
O = other type
E = elements.

case A	case B	case C
E >	S >	S >
S <	O <	E >
O <	E >	O <

Table 1
Signal detection order cases for each agent type values where:
> descending
< ascending

Different ways of signal emission and vision capacity are explored in parallel with priority orders. Agents can release signals in the cell which are passing through (local emission) or its neighbours (diffused emission) and this applies also to signal alteration performed by competitors (Figure 5).

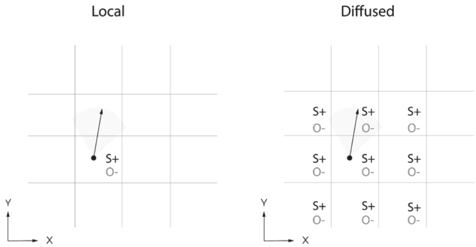
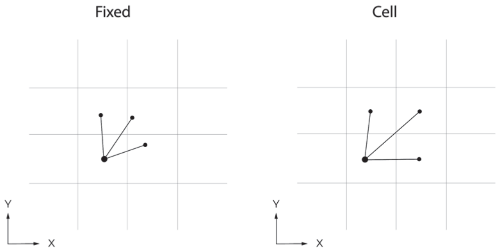


Figure 5
Local vs diffused signal emission and/or alteration

Vision capacity is explored by 2 variations in sensors definition where one is set as a star of 3 vectors with fixed angles of 33° degrees (fixed vision) while the other allows the agent to construct the star of sensors computing the distance vector between its position and every centre of the neighbouring cells (cell vision) within 90° degree apart from previous velocity (Figure 6). The system is then evaluated by testing the process with the combination of these variations in properties.

Figure 6
Scheme of variations in vision capacity



Attractor areas (areas with constant element signal emission) are set in the environment at the base layer in order to start the deposition; these initial values can represent environmental factors for the system, derived from existing conditions or used as a design device. The environment resolution R is set to 10 meters and the deposited elements have dimensions of 5 x 5 x 10m; these values are chosen to balance spatial proportions in relation to the human body (close to the 11.80 x 5.30 x 3.50m of Habitat 67 units) with the modularity of the voxel space. Populations of agents are uneven, with a builder/competitor ratio of 2:3 in order to contain the building process. Agents start points are evenly distributed in relation to the attractor areas.

ASSEMBLAGE ANALYSIS

Graphs and maps are created to obtain a snapshot of the system's evolution in time and comprehend relationships between spatial distribution and agents' paths:

- building progression is plotted as the number of deposited elements over time;
- space occupancy is analysed through tomographic scans of the assemblage layers;
- a Built Factor (calculated by dividing the built space by the section area at each layer) is plotted against layer sequence, bottom to top;
- history of signal distributions for builders and competitors are represented as heat maps at a given time instant.

Multiple tests expose the tendencies of the assemblages depending on combinations of design parameters.

Priority orders

Signal detection order cases affect the prevalent direction of expansion, vertical or horizontal. Case A leads to wide horizontal and very dense assemblages in the first few layers, and vertical development is not achieved; a trend confirmed by the analysis of the Built Factor (BF) which starts at 0.7, and then steeply decreases to 0 moving up. On the other hand, B and C cases show a more balanced vertical expansion with a maximum value of BF near 0.6 and a less steep decreasing curve of the relative graph.

Emission

Variations in emission capacity directly affect deposition chances as diffused emission increases deposition chance for builders in a larger portion of the environment than local emission. Tests with diffused emission present an increase of almost 50% of built elements on average.

Vision

Vision capacities can be analyzed through agents' signal distribution displayed as heat maps. First layers are the most relevant, as agents tend to move on the base layer most of the time; for this reason heat maps represent a negative of the built assemblage. Cell vision produces path curves that closely respect the grid subdivision of the environment and, if coupled with local emission, assemblages tend to develop more linear and

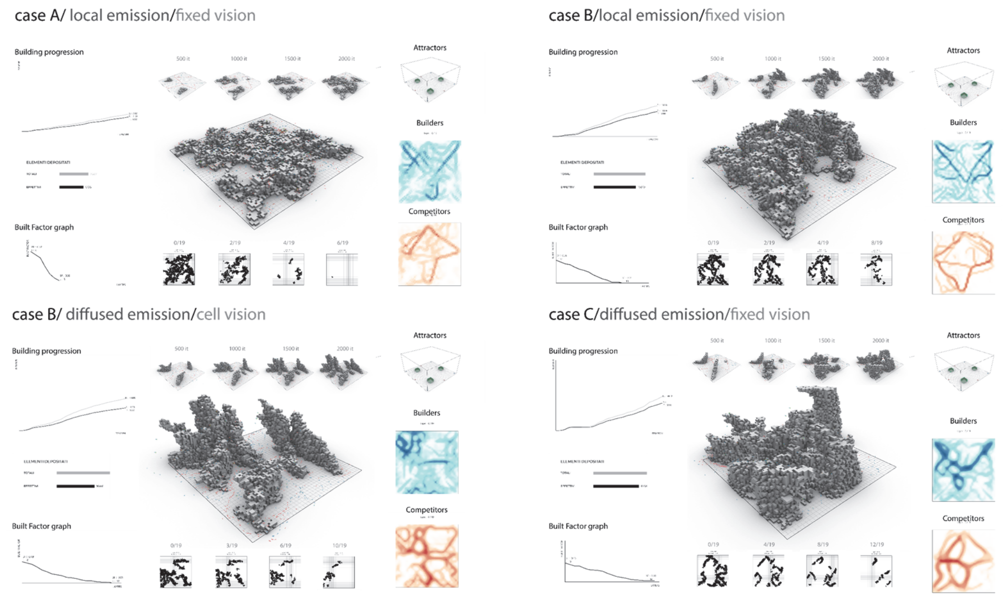


Figure 7
Test examples with graphs, heat maps and final assemblages.

orthogonal clusters. This tendency changes with fixed vision: critical paths (denser values) are sharper, clusters develop in multiple directions and in this case, system stabilization occurs faster (Figure 7). Space occupation is continuously negotiated with local interactions between agents, design inputs and contextual information.

ARCHITECTURAL TRANSLATION

The assemblage provides additional contextual information for the definition of architectural properties and part-to-whole relationships. Deposited elements in the raw assemblage also double as data storage: they store the builder signal value at the moment of deposition, while handles, other than storing topological information about their connection, compute and store the mean value of connected elements signals.

The result is a context-aware topological network of granular information deriving from the agent interaction that can be used to define architectural qualities of spatial units according to their local, regional and global contextualization. Architectural partitions are divided into three categories to qualify their relative position in the assemblage as: internal, external, and horizontal (Figure 8). Handles' connection awareness is used to place partitions coherently with their categories: a vertical connection (XZ or YZ plane) belongs to an internal partition, a horizontal one to the homologue cases, and the remaining are external.

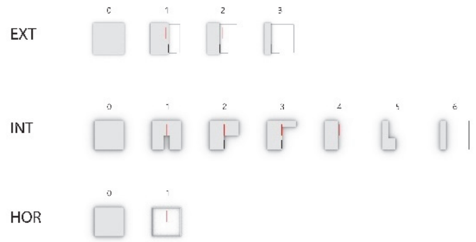


Figure 8
Architectural partitions

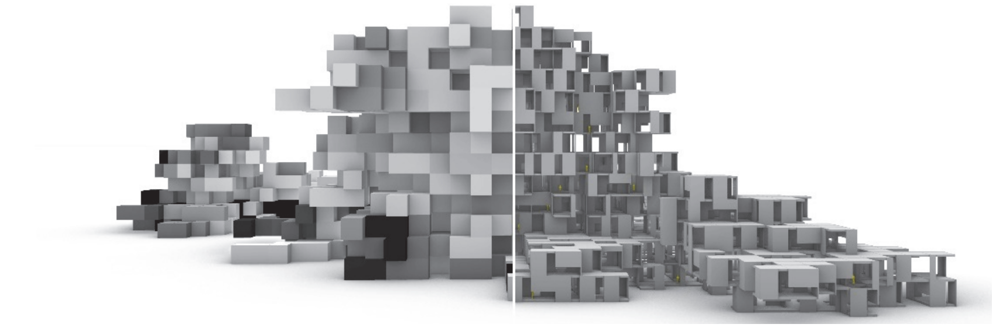


Figure 9
Assemblage, before and after translation

They are set with a permeability value proportional to the respective handle-stored value (Figure 9); given a remapping ratio $\mathrm{Mr} = \mathrm{MaxHandleValue}/\mathrm{nPartitions}$, each partition is assigned a weight $\mathrm{W} = \mathrm{HandleValue}/\mathrm{Mr}$.

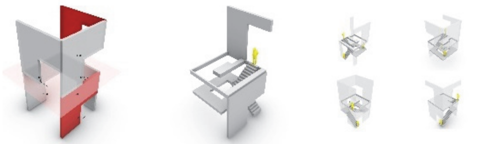


Figure 10
Vertical connections: generation and tests

Topological connectivity does not necessarily coincide with physical communication and circulation possibility between spaces; a group of elements whose spaces are physically connected and visitable form a cluster; partition distribution may fraction the assemblage in several clusters.

Planar horizontal connections between clusters are defined but the global topology study needs also vertical links. Stairs are generated to connect partitions with the highest W between consecutive layers (Figure 10). If a clash occurs, the horizontal partition is closed and accessible paths are created connecting other permeable partitions.

The distributive pattern of partitions and their permeability generates a spatial structure that doesn't coincide with a breakdown in deposited elements: the variety of dimensions, proportions and connectivity of spaces in the assemblages exceed the properties of the individual components that make them. The understanding of the outcome in architectural terms (functional, performative, experiential, etc.) requires an analysis that cannot be performed before this phase.

SPATIAL ANALYSIS

A true three-dimensional analysis can be implemented, but it is hard to use as a design tool, mainly for the limitation of human perception: the third dimension is reconstructed in the brain through a series of images, with limits to the manageable complexity of its conceptualization. For this reason, bidimensional plans of clusters are used to create graphs and maps in order to extrapolate significant data to perceive quantities and qualities of the generated space (Figure 11).

Topology

Connections between units represent a type and degree of relationship and are useful to display topological properties of the assemblage. Units centers are nodes of the graph built connecting every space which has a at least a permeable partition with W > 0. Node valence V is represented with proportional radius dots.

Frequency

To determine the focal point of each cluster, the nodes crossing frequency is calculated on the

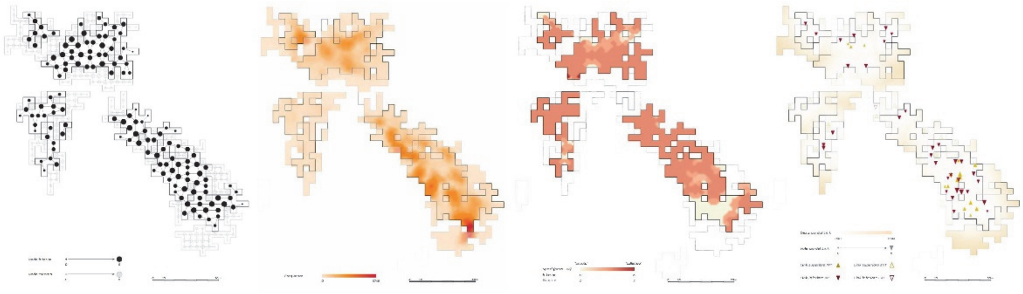


Figure 11
Spatial analysis maps: Topology, Frequencies, Distribution and Links

topologic graph using the A* algorithm, computing the shortest walk from each node to any other node in the cluster and counting how many paths pass through it. A heat map is built with a gradient intensity distribution.

Distribution
Functions in the scope of this research are not assigned to individual units a priori but depend on the achieved spatial structure and connectivity. A distribution analysis of partitions can help in identifying an initial quality of generated assemblages. Partitions can be understood as indicators of the private or public vocation of spaces: the higher the weight W, the higher the permeability and openness of an area, hence its potential as a public space; lower values characterize more isolated spaces. This correspondence is not a sentence, but a tool to map opportunities and potential functional programmes in the assemblage spaces.

Links
Vertical links between clusters must be also displayed to best comprehend the assemblage spatial communication and organization. For every link, the valence of related units in higher or lower layers is extracted and then used to map the connectivity degree of these focal points. Another heat map is generated to show the distance to vertical links from every point of the plan.

Space syntax
Space can be divided into components and analysed as a network of possible choices based on perception and visibility. This concept is the foundation of Space Syntax techniques first explored by Benedikt (1979) with the geometric definition of Isovist and then developed by Hillier and Hanson (1984) with the urban and architectural analysis of spaces introducing visibility relations defined by graphs. Every point in a discretized space can be related to others by plotting visibility connections (lines) and identifying common visible points. Turner et al. (2001) define and expand the definition of Isovists using graphs and their vertices to determine parameters for the analysis of visibility fields (Neighbourhood size of a vertex) and variation of visibility in space (Clustering coefficient$_i$). These mutations of space qualities, directly affect the decisional process of individuals in finding ways of navigation in space (Figure 12).

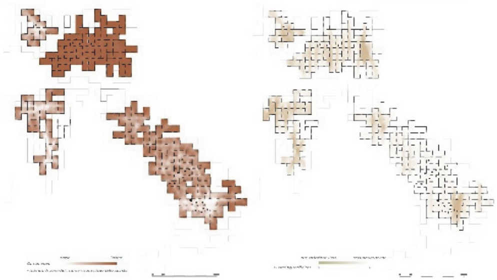


Figure 12
Space syntax analysis maps : neighbourhood size and clustering coefficient

In our case study, the Grasshopper plugin PlanBee [6] helps in performing clusters' plans voxelization and calculation of desired space syntax parameters. The Neighbourhood size map shows the amplitude of visual fields computed in every point of the map and it's directly related to isovists areas. The Clustering coefficient helps finding focal decisional points in the assemblage by defining a gradient of visual changes.

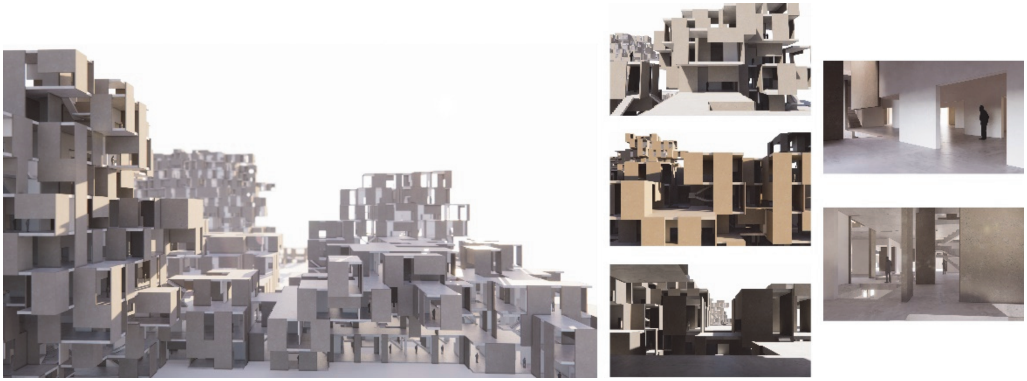


Figure 13
Renders of a large scale assemblages

CONCLUSIONS

This research showed a method to implement automation logic in architectural design as distributed decisions through multi-agent systems in competitive relation for the generation of large-scale architectural spatial assemblages for collective living, leveraging space-syntax techniques to analyse the variety of an open-ended combinatorial system.

The system evolves through signal exchange and competitive feedback among communities of agents, triggering a continuous negotiation for space occupancy until equilibrium is reached. The pivotal point of the research lies in the introduction of a counter-variable to provide regulation and stability to an otherwise indefinite and limitless growth process.

While prefabrication-based construction logistics is implied for its automation potential, the research in its current status remains agnostic with respect to the material and construction system of the building components, concentrating its attention on the relational and organizational features of the spaces constructed by the components organization. The open-ended combination of elementary components, modulated by the signal exchanges of the competitive process, engenders spaces whose qualities exceed those of the individual elements. This emergent behaviour proves to be the most interesting and challenging aspect of the research: the potential for the rapid and large-scale design of habitable spaces is clear, but control over the process and functional mapping of the outcomes is still entangled.

Postponement of functional mapping grants broader design freedom, an emancipation from the distributed modularity of the precedents, and the possibility to discuss function purely on the basis of topological structure and spatial affordances [7]. The price to pay is that qualities take centre stage, and their quantitative assessment over a large number of possibilities requires, other than extensive (and intrinsically partial) analysis, comparison and classification methods for high-dimensional data. This adds to the typical problem common to procedural generative methods (overabundant production, a jungle of results), the incompleteness of describing qualia with quanta – in other words, which and how many quantitative factors can capture or reveal certain qualities.

Enhanced analysis and classification tools powered by machine learning techniques like dimensionality reduction or Pix-to-Pix translation (Chaillou, 2019) from a database of semantically segmented functional plans might reduce the effort on the human side, but the dilemma remains: whether to shape technology over an existing spatio-functional paradigm or explore its undisclosed potential to explore different models and provide alternative proposals or objects for discussion.

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