

User-driven Configurable Architectural Assemblies

Towards artificial intelligence-embedded responsive environments

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The paper theoretically elaborates the idea of individual users' customisation activities to create and configure responsive spatial scenarios by means of reconfigurable interactive adaptive assemblies. It reflects Gordon Pask's concept of human and device interaction based on its unpredictable notion speculating a potential to be enhanced by artificial intelligence learning approach of an assembly linked with human activator's participative inputs. Such a link of artificial intelligence, human agency and interactive assembly capable to generate its own spatial configurations by itself and users' stimuli may lead to a new understanding of humans' role in the creation of spatial scenarios. The occupants take the prime role in the evolution of spatial conditions in this respect. The paper aims to position an interaction between the human agents and artificial devices as a participatory and responsive design act to facilitate creative potential of participants as unique individuals without pre-specified or pre-programmed goal set by the designer. Such an approach will pave a way towards true autonomy of responsive built environments, determined by an individual human agent and behaviour of the spatial assemblies to create authentic responsive built forms in a digital and physical space.

Keywords: *deployable systems, responsive assemblies, embedded intelligence, Learning-to-Design-and-Assembly method, Conversation Theory*

INTRODUCTION

The concepts of user-driven configurable assemblies to create customised spatial scenarios are starting to be prevalent again with applications of digital fabrication and automation methods for an assembly, employed in architecture in recent decades. Also the recent projects involving certain level of intelli-

gence of devices and building blocks with the ability to create spatial scenarios by themselves explore rule sets predefined by the designer. There are many customisation-related deployable systems, built and modified by users based on architect's proposed combinatorial system of configurations, such as concept of moving adaptive assemblies elaborated by

Bondin & Glynn (2014) or intelligent tensegrity self-assembly components by Hosmer & Tigas (2019). These two projects and a variety of deployable systems are reflected in the text below, in the State-of-the-art section. These systems use automation-enabled processes to discover spatial possibilities and locomotion of the building components to automatically assemble demanded configurations.

Contemporary built environments are facing many challenges, i.e. often changing spatial requirements, a necessity to be customised according to specific criteria (openness, closeness, flexible spatial arrangement) or spatial demands that cannot be predicted and that are addressed directly onsite. In addition, such a system should have capacities to be reconfigured physically and directly by end-users themselves. In response to their stimuli, the assembly may learn the unique demanded scenario defined by the end-user and offer an adequate response within a given conditions of environments.

Therefore, it is necessary to incorporate end-users' perspective into abilities of assemblies to be modified and changed in post-actuation processes of built environments and in an interactive way. Application of deployable architectural systems based on mechanisms and components driven by people's stimuli and embedded intelligence to meet their needs is a strategy where this intention can be achieved. The paper addresses a problem of mass-customisation and uniqueness of spatial scenarios considering users' spatial preferences. It theoretically outlines a method how to incorporate user's demands interactively and responsively, considering important relations between environment, built assemblies and people as end-users in a physical way. The mass-customisation as a process to meet people's needs and demands is an inevitable necessity in a current post-digital era, where the user plays a pivotal role in these activities. An architect's role within this context will mostly rely on a creation of initial rule-sets of an assembly and logic of spatial configurations based on combinatorics, with unpredictable results. An architect will serve here as an idea initia-

tor, mediator, activist and a creator. This idea meets Jean Prouvé's concept of being an architect, who, in fact, serves as a constructor (Wigley, 2017). This paper theoretically elaborates such an approach and outlines a possible route for further development of computational design-related and assembly strategies for intelligence-embedded spatial scenarios.

State-of-the-art in deployable systems

The advent of digital fabrication methods supported by processes-driven design strategies and scripting (Burry, 2011) opened broad opportunities to explore deployable systems in digital computational and physical models incorporating robotics and smart mechanisms and devices, such as in the CREASE project by Mesa et al. (2019). The idea of crowd-driven digital and physical participatory construction methods to address social engagement, customisation and open-ended spatial scenarios is addressed in Bondin & Glynn's project Morph (2014) as a starting point to deliver a physical prototype capable to interact with its environment. The Morph integrates interactive stimuli initiated by occupants where their role as end-users in the post-actuation processes of built scenarios is inevitable. This allows to outline a scope for participatory design strategies applicable directly on-site in infinite continuous design-to-assembly looping processes. The system is driven by end-users and capacities of assemblies themselves to responsively react to occupants' individual needs. Such an approach positively affects the public space and creates an important space for social engagement of end-users and visitors. Even though the system proposed does not integrate natural resources and materials used are not specifically environment-related, the system counts with the alternative sources of energy to drive the movement for adaptation.

Similarly, the ART system by Hosmer & Tigas (2019), explored the notion of artificial intelligence-embedded moving agency creating fully autonomous scenarios pre-defined by the designer in computational simulation models and small-scale

prototypes. Although these artificial intelligence-driven assemblies created unique scenarios, the implementation of original stimuli taken and learnt from end-users as occupants to meet their individual needs or requirements is problematic. An advanced electronic setup based on robotic actuators requires a specific experts' attention, probably unclear and peculiar to operate with by a lay person. This can be possibly achieved digitally, via user interface supported by the computational design framework. Both projects use the process of deployment for the main structural elements of the moving component. Although Hosmer & Tigas (2019) developed successful prototypes of intelligence-driven components, a certain level of technological complexity is present, which is a challenge how to overcome this level of complexity if dealing with real non-experts occupants.

The idea of deployable adaptive and flexible typologies for built environments is not new. Inventor Buckminster Fuller [1] and later architect Emilio Pérez Piñero applied these systems extensively into hierarchical spatial structures in a variety of projects (Escrig Pallares et al., 1996). Félix Escrig investigated Piñero's systems to be applied as contemporary architectural interventions (Borrego, 2016) enhancing Piñero's components. There are several examples proposed integrating deployable folding mechanisms, mostly driven by a human force and energy applied to modify the overall form of hinged and folding mechanisms capable of expanding and contracting without colliding with neighbouring components. Stadium constructions, theatres and roofs utilise mechanical joints and linear elements extensively. Architect Cedric Price investigated customisation and "kit-of-parts" approach in his housing projects [2], or integrated flexibility of spaces in his famous Fun Palace (Glynn, 2005) [3], addressing flexibility, mass-customisation and open-ended construction framework [4].

The structures integrating so called *auxetic* properties, such as KinetiX (Ou et al., 2018) or Hoberman's Sphere (Hoberman, 1990)[5] operate with sim-

ple mechanisms embedded into the structural system. As such, the system can be reshaped, expanded and changed in its size and in a physical profile based on a variety of transformative movements of its components, possibly aggregating as self-autonomous components, previously explored by Tibbits (2017). Overvelde et al. (2016) and Soft Robotic Matter Group investigates self-driven deployable systems either by using robotic actuators (Mesa et al., 2019) or gravitational, pulling or pushing forces to reshape the assembly of unit cells [6]. All these systems integrate capability of the component to be morphed and reshaped into a different state. The Morph tetrahedron also reflects Greg Lynn's ideas of a building which operates as a robot itself (Lynn, 2016), reacting on a specific demands and having a capacity to be reshaped and reconfigured according to spatial demands. However, this opens a question, whether current technological advancements in robotic industry and construction sector are capable to deal with such processes in real 1:1 scale, as all these kinetic assemblies are in a state of small-scale or medium-scale prototypes.

The intelligent discrete components, capable to learn from the inputs and users' profiles, may create flexible adaptive landscape or a spatial configuration within the existing building or a given urban public space creating a unique spatial "landscape", flexible, movable and topologically changeable, as argued by Stephen Gage (conversation with the author, December 11, 2019). In addition, the assembly may incorporate hierarchical structure of the assembly operating with different characteristics of the components and hierarchical complexity.

Reflection on Gordon Pask's Conversation Theory

Following the idea of customisation of public urban or architectural spaces with a deep social engagement of its occupants (Bondin & Glynn, 2014), this opens a broad range of new research possibilities how a public space can be perceived and what is the role of an end-user in post-actuation processes of

built environments. Gordon Pask's Conversation Theory (Haque, 2007) elaborates the aspects of interactivity between human and machine (i.e. a device), between two machines (devices) and between human agents themselves. Such a responsive communication creates unprecedented opportunities of human and robot interaction bringing artificial intelligence capable to learn from users' stimuli and response. This allows the device to create unique and unpredictable responses meeting each individual's inputs and needs, always ready to adapt to new conditions or purpose and produce a variety of spatial solutions to answer on different requirements. This is outside of the idea of typical participatory design, where there is always a need for a consensus between interested parties. Reflecting existing developed systems addressing a variety of spatial requirements and flexibility, it is necessary to claim that Pask's idea of being "*able to account for an explicitly human contribution*" would be essential to continue with the development of responsive building components for built environments for the 21st century. John Frazer and his team (Frazer, 1995) in his approach implemented this concept providing electronic devices for end-users' participation in the Self-builder Design Kit project.

Architecture capable to learn from its occupants just as occupants can learn from architecture may bring relevant cultural and spatial solutions to cover intelligence-based built scenarios based on simple interactions to create more complex results, beneficial for inhabitants themselves. Thus, a "conversation" between human and artificial components can emerge, between an individual, an environment and a building device, not pre-programmed or pre-defined for a finite state, but always ready to be re-configured in a flexible way and bringing "*novel responses in unpredictable and novel situations*" (Haque, 2007). This enables occupants to share performative and environmental characteristics to construct unique and tailored habitable spatial scenarios.

PROSPECTIVE FUTURE SCENARIOS

In the 21st century-built environments a user-centred approach needs to be taken in the design and post-actuation processes to fulfil uncertain users' demands. Immediate environmental properties as well as unique individual requirements are needed to be considered during the design, configuration and assembly processes, where the user plays the main role in assembly and post-assembly activities. As such, the assembly process equals the design process with a constantly reiterated feedback loop. The artificial intelligence will certainly help in these activities, however, not as a main driver, but as an additional ability of the building component to be morphed and re-assembled informed by a specific user profile meeting his or her demands. The idea of flexible *auxetic* properties of the building components might serve as an initial strategy employing mechanics driven by manual, natural or mechanical forces, enhanced with the capability to learn from predefined states, from the users' inputs and deliver customised scenarios, proposing specific situation-related states. The mutual intelligent interaction, as argued by Gordon Pask, will yield appropriate scenarios bringing new spatial qualities, responding to previously learnt states of the building components, capable to interact between themselves, humans and within a given environment.

In fact, this design problem of customisation brings also the question of precision and technical and computational requirements. Is the building component a machine? Or a digital (virtual) post-machine? There is always a tension between anthropocentric and digitally driven "technocratic" approach and there is no right or wrong direction for further move.

Learning-to-Design-and-Assembly Method

The research proposes a new method called "Learning-to-Design-and-Assembly" (LTDA) for users' participation to create spatial scenarios that may evolve and be changed in time. For that reason, a novel type of spatial typologies as user-driven as-

Figure 1
The definition of configurable cell units, developed by Overvelde et al. (2016). This paper investigates configurable units of the extruded cube to generate a variety of spatial assemblies for urban tower blocks utilising evolutionary generation method.

Figure 2
Auxetic behaviour of the structure. The structure has the capacity to expand into a different spatial state. Each component is adjustable and configurable.

semblies are being developed to enable users to construct unique and tailored habitable spatial scenarios. The LTDA method will incorporate artificial intelligence-supported learning process and decisions in mutual interactions between humans and building components capable to be morphed, components between themselves and building components interacting with the given environment.

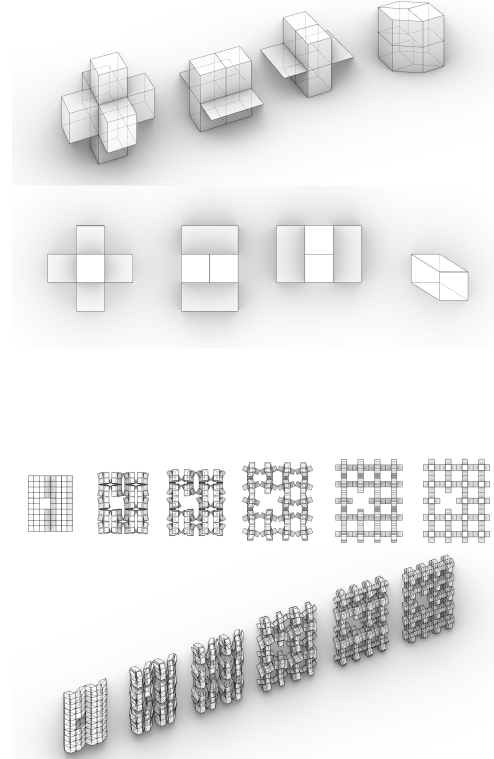
There are two core features of the proposed user-driven assemblies, which the LTDA method will operate with: a physical kit-of-components based on auxetic principles for morphing and reconfiguration of an assembly integrating manual, auto-matic or semi-automatic operation; and, artificial intelligence-enabled logic and integration based on self-generation of interactive spatial configurations and following unique user profiles. As such, the LTDA method follows the specific users' individual requirements and properties, which are educed from the users' behavioural patterns and their habits. These are self-generated and condensed in a spatial scenario, physically present in situ. The LTDA method will allow users to physically participate on a construction and configuration of spatial scenarios delivery, often as a result of improvisation and collective or individual decisions made.

Computational strategy

An initial computational framework is proposed to accommodate a strategy for the LTDA method implementation, consisting of following steps:

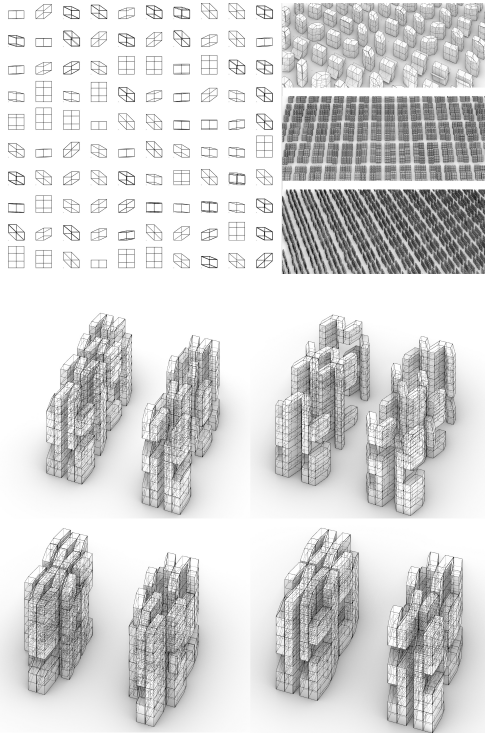
- component definition of configurable parts utilising auxetic principles of an assembly;
- a set of initial spatial configurations definition by the designer in the computational model;
- data mining process based on users' submissions via online interface (this process is temporarily substituted by evolutionary generation method for the purpose of this paper);

- data set integration and deep learning implementation for spatial assemblies delivery.



The concept of spatially configurable assemblies incorporates cell units capable to transform and morph to a variety of states, implementing the principle of *auxetic* expandable structures. The shape of the unit had been previously investigated by Overvelde et al. (2016), analysing the extruded cube unit cell and its state variations (Figure 1). For the purpose of this paper, this cubical cell unit and its configurable states were taken for further testing and analysis of possible configurable assemblies, envisaging an urban scale of units for configurable urban tower blocks (Figure

2). Therefore, spatial configurations are created either by the set of components or the component unit itself creates the spatial scenario, depending of the component's and scenario's scale, scenario definition, spatial demands and component's ability to be deployed or morphed.



Hosmer & Tigas (2019) developed a computational framework utilising deep learning methods with ML agents implemented in the UNITY game engine to deliver spatial geometrical scenarios [7]. The process of learning which ML agents accommodate uses the Google TensorFlow platform running on GPUs for massive deep learning processes from predefined datasets [8]. Such datasets can be delivered from end-users in the first instance and the system can learn from these preferred solutions to artificially

generate novel spatial solutions. However, this paper does not present the utilisation of current machine learning methods for the spatial scenarios delivery, as this will be tested in the next phase of the research. For the purpose of this paper, the first initial generations of possible spatial solutions were tested utilising the evolutionary generation method based on the Wallacei tool [9]. This method was utilised to generate big amount of data, instead of users' data mining. These can prospectively mimic and substitute the users' preferred scenarios and can be used for further deep learning implementation in the future research (Figure 3).

The evolutionary method delivered a population size consisting of 5000 solutions in 100 generations of configurable assemblies and meeting the particular volume size and dimensions of the configurable unit as a design objective. Each spatial solution operates with a different or similar state of each particular unit (Figure 3), creating unique tower assemblies (Figure 4 and 5).

DISCUSSION

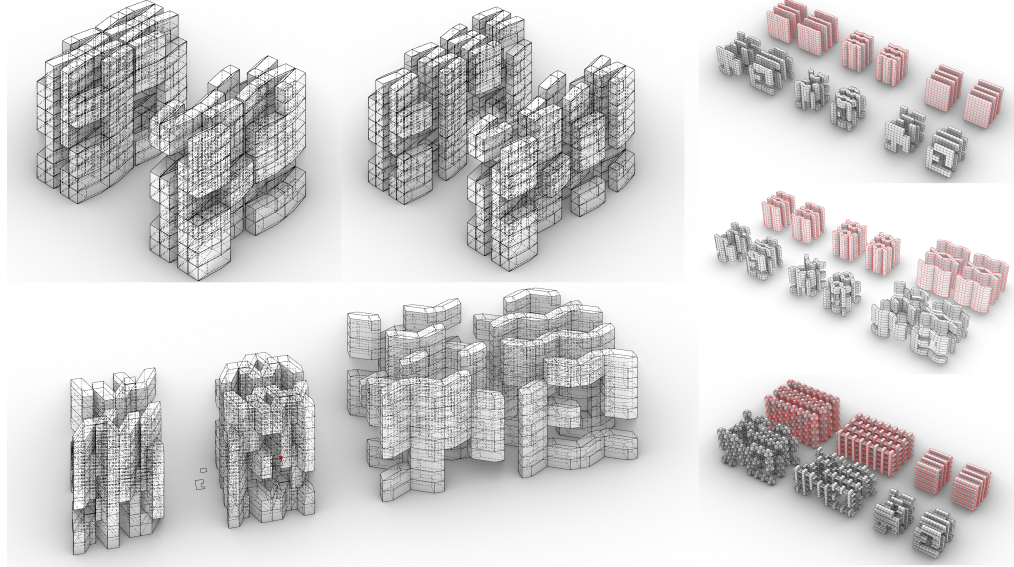
Several deployable and self-assembly systems were described and reflected, such as the Morph Tetrahedron to discuss aspects and criteria for customisation, social engagement of users and environmental responsiveness. Further, the artificial intelligence-driven tensegrity assembly system (ART) was discussed in the scope of customisation and the notion of learning approach of the automated or semi-automated assembly processes, pointing out a necessity to integrate end-users' role in the Learning-to-design-and-assembly method of the building process.

The test of the behaviour of auxetic principles of the structure was conducted computationally to understand the behavioural characteristics of the simple units in the computational model and to deliver generations of possible spatial scenarios which mimic the datasets, prospectively submitted by end-users (Figure 3). Next stage of the research will utilise these datasets to test the deep learning

Figure 3
Generation of the configurable units as components for tower assemblies.

Figure 4
The spatial assembly of configurable units utilising auxetic properties of the structure. The structure behaves as spatial origami.

Figure 5
Spatial assemblies
generated by
evolutionary
algorithm to meet
volumetric
objectives (size,
dimensions) and
integrating auxetic
principles of an
assembly.



method running on the TensorFlow platform to deliver artificially-generated spatial assemblies, incorporating specific spatial features.

Utilising auxetic characteristic of the structure to be expanded or morphed according to applied forces and external sources of energy, the assembly systems will be able to integrate more diverse scenarios into several subsystems under one emergent structure without any loss of notion or expression of the architectural quality and integrity. This will deliver open-ended collaborative and sharing platforms operating with several levels of responsiveness allowing design participation on-site. In that regard, the research can follow these directions further, concentrating on user-driven assembly processes, operating with discrete intelligent components responding to users' demands more comprehensively.

But how to achieve this integration encompassing technological advancements in computation and artificial intelligence? To address mass-customisation in physical built environments, the new forms of

"Learning-to-design-and-assembly" building procedures need to be applied instead of standard and usual designer-client-contractor relationships. The new modes of sharing economies might offer alternative solutions for participation, planning, design and construction, where the emphasis is given on the activation of users themselves with their values, knowledge and skills. On the other hand, the intelligent building components have to offer appropriate response meeting end-users' demands and following spatial, economical, aesthetic, and, sustainability-related criteria for the construction and assembly. Architects, as constructors and activators in these processes play a crucial role as they navigate, inform, supervise and promote these intentions, helping the users to orient them in the process.

The first step towards achieving this integration and pursuing these intentions can start with less technocratic solutions. Components may involve auxetic principles, material memory and can be based on simple moving forces, applied by the users

themselves. Several intelligence-enabled states of the building components and degrees of an assembly may yield a variety of spatial outcomes. The components delivered on-site as participatory constructions and assembled by users in semi-automatic or fully automatic processes may learn their own new spatial states in a continuous and open-ended feedback looping process. However, a comprehensive research in this field still needs to be conducted to fully embrace new potentials of built and responsive environments for the 21st century in the era of uncertainties.

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