Large-scale Prototyping Utilising Technologies and Participation

On-demand and Crowd-driven Urban Scenarios

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The paper theorises and elaborates the idea of crowd-driven assemblies for flexible and adaptive constructions utilising automatic technologies and participatory activities within the context of twenty-first century cities. As economic and technological movements and shifts in society and cultures are present and ongoing, the building technology needs to incorporate human inputs following the aspects of customisation to build adaptive architectural and urban scenarios based on immediate decisions made according to local conditions or specific spatial demands. In particular, the paper focuses on large-scale prototyping for urban applications along with on-site interactions between humans and automatic building technologies to create on-demand spatial scenarios. It discusses the current precedents in research and practice and speculates future directions to be taken in creation, development or customisation of contemporary and future cities based on participatory and crowd-driven building activities. The main aim of this theoretical overview is to offer a more comprehensive understanding of the relations between technology and humans in the context of reactive and responsive built environments.

Keywords: *large-scale urban prototyping, on-site participation, human-machine interaction, intelligent cities, responsive cities, urban autopoiesis*

INTRODUCTION

The research outlines possible future directions in the field of large-scale prototyping practices for built environments. The methodological approach of this study mostly relies on the literature review, site visits, personal observations in fabrication laboratories, exhibition visits and conversations with selected experts. The information and data collected have been qualitatively evaluated based on an applicability and scalability of the building methods investigated. However, this research study also incorporates author's own speculative sketches to illustrate prospective strategies for the further deeper investigation in this field.

Automation and Adaptive systems for Mass-Customisation

This research study investigates potentials of intelligent automatic building technologies and robotics for customisation to become an integrated part of cities' building infrastructure within the context of adaptive and intelligent twenty-first century cities (Weinstock 2019). It introduces the idea of crowd-driven building strategies to be conducted on-site as a consequence of direct human-machine interactions in an immediate physical situation related to a specific design or building process. Current movements and practices in manufacturing and building industry operate with large and costly machinery and robotics. Sky Factories, Automatic Building Construction and Crane Systems or Contour Crafting systems (Hu et al. 2018) (Buš 2019) [4], are mostly pre-programmed and deliver built products and constructions in a strict and constrained top-down building processes. These are without any possibility of post-actuation of the built outcome for other specific customised or adaptive scenario and without deeper end-users' engagement. Apart from those, there are ambient robotics used as maintenance and service systems in post-building processes on-site (Bock and Linner 2015). Contemporary building strategies started to implement and test human-machine interaction systems, but none of them have been implemented and scaled-up in current building practices.

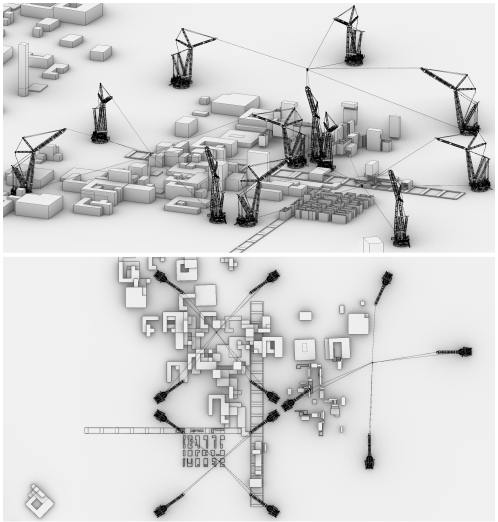
Political, Economic and Environmental Aspects

Pervasive technological advancements in manufacturing, automation, robotics and machine intelligence created unprecedented potentials to redefine wider political, economic and environmental context for the twenty-first century cities. In particular, digitisation and automation enable to significantly improve and simplify processes leading to reduced costs, delays and risks along with increased safety and overall productivity and efficiency. This opens new directions for democratisation of processes and not only at the design level, but during the construction phases and thereafter. The harnessing of automatic fabrication techniques and intelligence addressing elimination of material waste during the fabrication, will also decrease costs and will lead to more affordable solutions [2]. Direct involvement of users in all design, construction, assembly and post-assembly processes with their values, knowledge and inputs in participatory design and construction activities leads to a different model of building production, not necessarily following standard relationships based on a client-contractor-supplier with end-users' negotiations.

But what is the role of human presence in the world of ambiguity and technological shifts towards a post-digital society [3]? This technology allows people to immensely contribute to creations and improvements of build environments. This rises the question of the form of democratisation of ideas and, in consequence, it implies strategies where high-dimensional aspects and information delivered form a variety of sources will require a proper identification of trending ideas in a distributed decision-making (De Monchaux and Goldberg, 2016). Such an approach will lead to more obvious urban equability and will activate and empower urban communities. Following these ideas, it is necessary that architects need to address and promote those strategies within local environmental and political conditions.

Cities are in a constant evolution and behave as unstable non-fixed entities. As such, the importance of adaptability and their ability to flexibly react on unexpected demands among interacting human actors evokes a necessity for re-definition of the "smart city" paradigm towards collaborative human collective and machine intelligence. This will activate a direct responsive interaction between the technology and human agents enabling processes, decisions and scenarios creation based on multidimensional characteristics and diverse bottom-up collaborative activities. In that sense the city can be understood as an open platform where humans interact with technology delivering open-ended changing environment. Robots are no longer single-tasks

Figure 1
A speculative visualisation of the deployment of large-scale cranes in urban context. The cranes can serve as a supportive construction method for cable-driven automatic systems interconnected into an urban network.



building units in these processes. If we paraphrase Greg Lynn's idea of *architecture as a giant robot* (Lynn 2016), the city itself can behave like an automatic machine with an embedded intelligence considering *faster, safer, cheaper and environmentally better design-to-construction processes* (Sinclair 2017).

THEORETICAL OVERVIEW OF LARGE-SCALE CONSTRUCTION DELIVERIES

This section outlines examples of current practices and speculates possible directions to be taken further for large-scale construction deliveries.

Contemporary Practice

There are precedents in current architectural practices which started to reflect a necessity of customisation in a large-scale city context. Arup company and Mamou-Mani studio tested more flexible cable-driven robotics, such as the Polibot Code-builder in Sir John Soane's Museum in London [1][5] in order to implement adaptive building strategies using open-source technologies for the building industries, e.g. the high-rise DNA Blockchain Tower taking into account aspects of circular economy [6]. As such, the building can be remodelled and reconfigured following specific needs and demands reflecting changes in social and economic conditions.

Similarly, Diller Scofidio + Renfro and Rockwell Group's built The Shed in New York encompassing a large-scale movable construction which provides many spatial variations of flexible scenarios for urban visual and performative artistic activities (Davidson 2016). The *Supra.Studio* led by Lynn and Koerner at the UCLA explored a variety of concepts and scales [7] with students where movement of movable architectural components leads to reorientation of spaces [8]. A concept of novel strategy for building reconfiguration was introduced in Poustinchi's project *The Rising Rotating Space* [9]. In this project, the industrial robotic arm allows one to reconfigure different spatial scenarios in a real-time process based on a variety of motions and foldable constructions leading to customised architectural spaces.

Digital Fabrication Technologies - Cable Robots

Cable-driven systems as flexible automatic robotics adopted from different industries are currently being tested in various institutions and companies to deliver small-scale built outcomes efficiently, rapidly and without high costs for demanding automatic robotic machinery (Pott 2018), (Wu et al. 2018). They operate mostly with reconfiguration and manipulation of predefined components, additive printing processes or other assembly or stacking techniques.

Apart from these smaller-scale prototypes (Sousa et al. 2018), the cable-driven robots haven't been implemented in larger urban-scale in any built scenarios within specific urban conditions and contexts so far. The cable-driven robots deployed on a larger urban landscape can be harnessed into an interactive robotic network of collaborative end-effectors (Figure 1). However, this approach comes along with specific limitations in process logistics, payload, safety, precision and ability of the working end-effectors to deliver demanded scenario. The role of a human interacting with such a system on-site is problematic due to safety reasons.

These building methods driven by a crowd and robots require non-traditional understanding how the built scenario is built and how can be rebuilt. Looking back to architectural history, there are many examples of open-ended architectural and urban scenarios utilising modules as either whole parts of the buildings or building blocks as discrete components (Retsin 2019). Such strategies lead to multi-scenario solutions for mass-customisation creating different spatial iterations. Harnessing digital fabrication and robotics along with *platforms* encompassing a *kit* of architectural *parts* will create a new kind of construction model for the future enabling end-users to constantly change the spatial characteristics of built scenarios (Hall 2019).

Waterfront Crane Systems

Industrial harbour stacking crane systems employed in industrial port areas in waterfront cities are fully or semi-automated systems, usually controlled by a small amount of operators (Manaugh 2019). The shipping cranes stack standardised industrial shipping containers creating never ending constant change of an industrial landscape. The cranes have building scale sizes and they are driven by an operator in an indirect way not being on-site through telepresence, using joystick and monitor. The access for humans into these port areas are strictly forbidden due to safety reasons. The interaction of humans with the automatic systems is not directly conducted on site where the crane systems are positioned.

This strategy for the automatic system operations can serve as a catalyst for participatory digital platforms linked with construction deliveries via cloud and these machines can be a part of Internet of Things delivering on-demand built and spatial scenarios (Figure 2). As such, the human contributions in these participatory platforms can be delivered fully digitally, then analysed, evaluated and stored for further learning processes by means of artificial intelligence methods. The data sets can serve as an input for an automatic generative approach to deliver next generation of future spatial scenarios driven by a crowd. Such a method for making a consensus among large amount of contributors can be supported by artificial intelligence-enabled evaluation strategies using a blockchain-based databases.

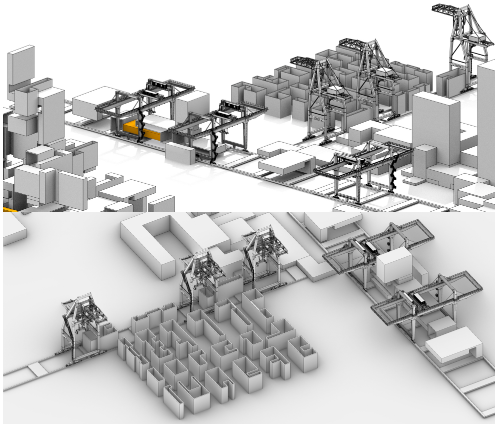


Figure 2
A speculative urban scenario adopting waterfront harbour crane systems to deliver customised modular elements embedded within the urban context. The cranes can serve as on-site fabrication and construction technologies as an integrated part of the Internet of Things.

FUTURE PERSPECTIVES

Perspectives of On-demand Cities

There is an abundance of projects created by architects and students from across the world, depicting a variety of more realistic, unrealistic, utopian, and dystopian visions of cities. The team of students from the TU Delft and IAAC Barcelona in cooperation with The Why Factory, led by W. Maas and tutored by A. Ravon (2016), developed speculative ideas for near and far future usage of robotics in urban contexts, examining the potentials and strategies for future cities and "*how existing and newly developed robotic systems will change the way we inhabit our urban environments*"[10].

All these systems, assembly models and techniques operate with or without specific direct human intervention on-site from the position of an end-user of adaptive architectural or urban space. The humans' involvement in participatory design and construction processes have not been taken into consideration in practice as the industry predominantly

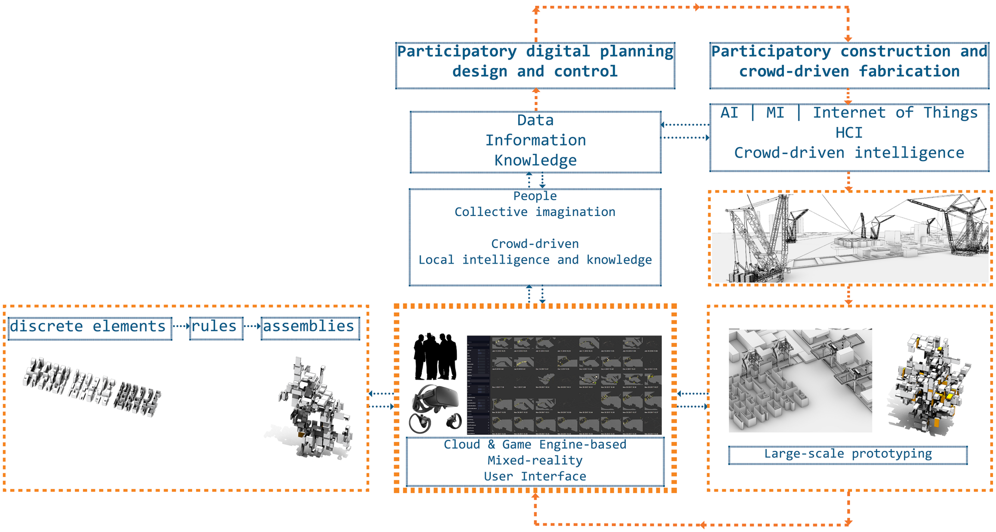


Figure 3
Diagram of the proposed crowd-driven design and fabrication process encompassing artificial intelligence-enabled interface.

operates itself as an independent sector based on designer-client-contractor relationships. Currently, with the advent of intelligent machines that are able to learn, artificial intelligence technologies, and supporting user interfaces for a variety of purposes, this traditional view is vanishing as the boundaries of industries are blurred as become trans-disciplinary. In this context, future end-users of architectural and urban spaces will be able to customise the built scenarios utilising technological devices and interfaces (Sanchez 2019). But what is the exact role of the citizen as an end-user in the age of robotics and automation in the context of cities in the twenty-first century? Does the dynamic machines' intelligence and contextual awareness lead to new spatial typologies?

The Role of Citizens in Participation and Human & Machine Interaction

Utilising the *Design-to-Robotic-Production method and assembly* (D2RP&A) and incorporating interaction scenarios between humans and robots and human-machine cooperation, Chiang et al. (2018) tries to define a better position of humans in the building processes: " *Main consideration is that production and operation of buildings will be in the future robotised and identifying which skills sets are better acquired and executed by humans while others by machines is key to developing interaction scenarios between humans and robots*". However, the construction process itself cannot be considered as one building or an assembly process before the construction is built and finished. Considering shifting economies and specific time-independent demands for using of spaces, the post-assembly customisation processes require end-users' participation and interaction. As the diagram shows on the Figure 3, the design-to-construction process is in a never-ending loop, where final construction assembly informs the interface with the new content, the interface can learn from it and from the contributor's previous or future inputs and deliver next generation of spatial possibilities following changes in spatial demands or requirements (Figure 3). This approach creates constant interactive process, accessible for different parties or contributors via cloud. Such a cloud environment can be supported by additional augmented and virtual reality methods to illustrate the demanded scenario on-site in an augmented or in a virtual space.

Hypothesis for Deeper Investigation

By reflecting above mentioned precedents, large-scale construction and post-construction methods based on a customisation and post-assemblies driven by a crowd, the overall research hypothesis can be defined as follows:

- Crowd-driven assembly processes supported by flexible automatic or semi-automatic construction methods will lead to highly adaptive architectural and urban scenarios;
- The construction deliveries based on multi-agent components (e.g. cable-driven systems harnessed into a network of end-effectors, swarming robotic units, self-assembly systems, soft robotics or customisation of harbour crane systems) for larger-scale scenarios will lead to constantly changing and adaptive notion and morphology of cities in the future (Figure 4);
- The citizens as end-users of built environments are becoming a crucial part in the processes of customisation operating with users' interfaces to drive and control automatic building technologies or dealing with pre-cut elements delivered on-site.

At present, this hypothesis remains open, however, as it has been observed from the past precedents and current tendencies, it is possible to estimate the prospective directions how the technologies and users' engagement will shape the future progress in construction and customisation of cities, mainly as follows:

- Employment of cable-driven systems as scalable and flexible construction deliveries. They can create a network of end-effectors covering larger areas, driven by humans and following time-independent requirements and always ready to function. As such, they require supportive constructions as a part of the building infrastructure;
- Smaller-scale robotics (aerial robots, ground agents, semi-assembly or self assembly robots) can create highly adaptable and flexible scenarios following demands for changes and customisation requirements and driven by a crowd through cloud-based and mixed-reality user interfaces, e.g. utilising game engines;
- Harbour crane systems can be adopted as construction deliveries in large-scale urban applications, especially in waterfront cities interacting with people through off-site operations; and
- Citizens can be directly involved in building processes by incorporating pre-cut elements assembled manually, semi or fully automatically in different scales. This brings and opens further questions related to humans' safety and their presence on-site.

Limitations of the Concept

The growing abstraction of outlined design and construction processes and methods can be challenging. Such a participatory-design and construction methods can be applied as an extension of BIM-cloud related design and planning strategies where access to the cloud is not only for engineers and experts, but also for much wider public, citizens and stakeholders. This may complicate the entire design-to-construction process and requires high demands for the computational power and complex programming strategies to provide a robust digital eco-system within one collaborative platform.

However, if we consider a need of adaptability of urban scenarios in time, such a method can incorporate the bottom-up needs, learn from them and can offer solutions in one multi-computational accessible environment linked with on-site construc-

Figure 4
Customisation and adoption of existing harbour crane systems for larger construction deliveries: a vision of the application for the future urban scenario in Tanjong Pagar waterfront in the city of Singapore.

tion deliveries, driven by an artificial intelligence-enabled system. The limitation of such a method lies in a complex and extensive urban logistics between machines, human participants and processes in the background. However, the artificial intelligence methods to collect, control, analyse, learn, generate and deliver scenarios will help in these processes immensely.

DISCUSSION

The paper outlines the possible directions for the customisation of architectural and urban scenarios and opens questions for further discussions and re-evaluation of the building strategies in the era of robotics and computation. It is rather an overview of potentials, or possibilities for future deep investigation. The scope of the article covers a variety of directions, but it is necessary to outline this topic from a wider perspective first as an initial framework to be discussed and investigated further. The article emphasises the aspect of customisation and how this can be achieved with the support of technologies. The illustrated example uses a modular approach to be taken as an initial direction for further investigation. As Diller claims in Davidson (2016), there might be a potential of intelligent architecture with embedded intelligence that can learn from the environment and *its wisdom can grow in time*. However, the human touch in this context of emerging technologies is inevitable. The artificial intelligence is certainly not a general answer on the question how to solve many urban issues, as claimed by Tom Verebes in conversation with the author in March 27, 2018. The answer is hidden in humans' decisions.

The article explores the aspects of on-site construction methods using selected technologies only. In particular, it envisages large-scale cable-driven systems for urban automation and takes the inspiration of processes-driven approach for construction from the shipping port areas in waterfront cities. There is an immense potential in a combination of off-site and on-site construction approaches whereas process-driven off-site systems expanding their "essence" towards on-site deployment, leading to an increased construction efficiency. In addition, there is a growing market with the Internet of Things solutions for the construction sector as well as container-based modular construction systems where non-traditional building methods will benefit from these with the support of digital technologies. However, there will be still an intensive necessity for a precise coordination of delivery processes and building logistics in the age of automation and digitisation as a part of the fourth industrial revolution.

ACKNOWLEDGEMENT

The theoretical part of this research has been supported by the Richard Rogers Fellowship awarded by the Harvard University Graduate School of Design and conducted during the author's residency in London in 2018. Selected figures in this article are based on the Tanjong Pagar 2080+ competition entry project developed at the Chair of Information Architecture, Swiss Federal Institute of Technology (ETH) in Zurich for the Responsive City competition in 2018 organised by the Institute for Advanced Architecture of Catalonia, Barcelona. Competition entry credits: Peter Buš, Lukas Treyer, Chang-Mei Chih, Ayça Tartar and Jin Li.

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