RESPONSIVE MEGASTRUCTURES: GROWING FUTURE CITIES FOR GLOBAL CHALLENGES

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INTRODUCTION

In an era of rapid transformation and global uncertainties it is evident we need to forge new pathways for the design, delivery and sustainability of future cities.[1] In this paper, we propose a novel approach that aims to tackle such issues through our speculative design for a 'responsive megastructure', based on principles highlighted from our ongoing future visioning and prototyping research. We discuss the important role developing visions for future cities plays in seeking to address global challenges alongside how the development of a novel vision reveals and reframes key challenges in our prototyping research. By doing so, we define what a responsive megastructure might be and how it could be designed and fabricated to maximise its performative capacities and capabilities. The paper is structured into five sections. First, we provide a brief survey of past visions of megastructures to identify relevant key characteristics. Second, we then provide a definition of the criteria for our responsive megastructure. Third, we explain our design and fabrication approach for programming granular matter. Fourth, we present our vision for a responsive megastructure. Finally, we discuss the various benefits and challenges of this approach, prior to outlining several future research trajectories for this work. In doing so, we present a new vision for megastructures, where matter can be aggregated and scaled to grow future cities, that can embody the complexities of urban life in contexts around the world and respond to their situation and future challenges.

PAST FUTURES OF MEGASTRUCTURES

Future cities have long been dreamt up by a wide range of artists, architects, and designers.[2] As the impacts of industrialisation began to increasingly characterise urban landscapes around the world, these were reflected in visions of fast-paced future cities in the twentieth century and the technological thrust that drove many of these. Furthermore, as the complexity of urban life became apparent, the need and desire for architects and urban designers to respond to this situation led to a variety of attempts to envision future cities in spectacular ways.[3]

Through this impulse, the mid-twentieth century gave rise to the megastructure as physical embodiment of technological prowess to address the problems of urban populations.[4] For example, Kenzo Tange's 1960 vision for the *Plan of Tokyo* included a network of transport infrastructures, floating residential islands, and concentrated urban centres to alleviate development pressures within the existing city. It took growth processes of biological organisms as a metaphor for future cities to illustrate how they could share capabilities of reproduction and responsiveness to their environments.[5] By contrast, Paul Rudolph's scheme for the *Lower Manhattan Expressway* project in New York City, 1972, sought to drive a megastructure through existing urban fabric. Here, the megastructure was conceived as a dynamic unstoppable force that aimed to integrate transport infrastructure with higher levels of monorails and people movers.[6]

Of particular relevance to this paper are those megastructures formulated from the outset as reconfigurable and responsive to changing needs. An important figure in this development was the British architect Cedric Price whose work investigated how architecture might promote social change through its adaptiveness. Price's collaboration with theatre producer Joan Littlewood, *Fun Palace*, 1961-1976, sought to integrate concepts of social participation and improvisation with technological interchangeability to produce a highly responsive environment. Price conceived the project in terms of process, with a core design principle committed to indeterminacy, thereby embracing the nascent fields of cybernetics, computer technologies, and game theory.[7] The endless adaptability of Fun Palace was to be able to both anticipate and respond to a constantly evolving programme.

In a similar vein, *Plug-in City* by Peter Cook, 1964, proposed a megastructure as a network of reconfigurable clusters and replaceable units. Based on principles of flexibility and functionality as well as being in thrall to science fiction, Pop Art, and the mundane technologies of the era, Plug-in City depicted the future through its kit of parts approach.[8] The project represents a powerful vision, premised on its ability to accommodate and actively encourage changes borne by obsolescence, as typologies of building nodes, each with a different lifespan, would plug into the main 'craneway', itself designed to only last forty years. Such fascination with social experimentation notably cooled down following the peak oil crisis as various countercultures imploded or were absorbed into the mainstream.[9] Yet, parallel to this decline there was a steady rise in future visions driven by technology, buoyed by advancements in computational processing power and software applications during the last three decades of the twentieth century.

From the mid-twentieth century the primary drivers for cities were industrialisation and globalisation, as urban development sought to maximise productivity via access to labour, resources and connectivity to markets. More recently, these drivers have been augmented and, in some contexts, replaced by those that emphasise people and their environment over profit.[10] As the manifold anthropogenic impacts of cities present major global challenges, it is clear we need new visions for future cities to respond accordingly. In order to open up the discourse concerning visions for future cities, in their analysis of such representations Dunn and Cureton propose three primary themes:

- Technological Futures - examines the optimism of those visions driven by technology and their dialogue with their expressions within science fiction.
- Social Futures - investigates the experimental and experiential visions for future cities led by an impulse to provide for a new society or create novel urban situations.
- Global Futures - takes account of those visions produced in response to the significant challenges of climate change and how we might enable collective life to be sustained.[11]

By placing emphasis on complementary types of futures, the value of this approach is that it enables different ideas and alternative pathways to be explored. We suggest that this presents an imperative for future cities to effectively bring together the technological, social, and global. We use speculative design to produce a vision for a responsive megastructure that seeks to achieve this in a manner that can be transferable and adaptable to a range of scales and contexts. In order to develop this proposition further, we next identify key criteria for such a vision.

IDENTIFYING CRITERIA FOR RESPONSIVE MEGASTRUCTURES

Past visions of megastructure highlight several key aspects that begin to inform how our responsive megastructure visualisations could extend their material resolution and responsiveness:

- Scalability - the use of space frame structures highlighted a scalable construction process based on modular units and universal interfaces between the material units. What assembly processes lead to scalable forms of manufacturing?
- Material interactions - the material units that make up the kit of parts were massive, heavy, inert and artificial. How can granular material units be interacted with to guide and grow structures that can respond in-situ?
- Resolution - the fixed dimensions and properties of individual material units dictated the resolution and types of responses the megastructures could produce. How can material units at granular resolutions enable a greater range of responses?

A major challenge evident in past megastructure visions concerns the scalability of their assembly process. Research at MIT's Self-Assembly Lab has illustrated material units can be programmed to assemble themselves by pre-designing the individual material units' geometries and their interfaces.[12] Thus, the fabrication system can: self-error correct without incorporating hardware/electronics[13]; self-reconfigure[14]; self-heal when broken apart; and generate structures not conceived within the design stage as the fabrication process is non-deterministic.[15] Furthermore, Tolley and Lipson demonstrate how modulating stimuli can begin to guide these material assembly processes.[16] This highlights the potential role modulating stimuli could play in programming matter at granular material resolutions.

By pre-designing individual units' geometries and fixing their material properties three main issues arise. First, the structures only generate reconfigurable geometric patterns that are recursive. Second, the resolution of the material units become fixed, which means local properties of the structure cannot be altered below the set dimensions of the individual units. Finally, the individual material units are materialised in advance and are artificial, meaning a surplus of parts could be generated. Alternatively, biological processes of fabrication are capable of materialising matter where and when it is needed. The ability to materialise matter on demand is particularly evident in bone remodelling via cellular activity[17] and in the meristematic zones of plants via cellular division (mitosis).[18] In the next section we set out the principles for such an approach for our responsive megastructure.

PRINCIPLES FOR A NOVEL DESIGN AND FABRICATION APPROACH

To explore the challenge of resolution and material interactions in regards to scalability as well as empirically grounding our vision for a responsive megastructure we present the design and fabrication approach developed through a series of iterative prototypes. Through our prototyping research, we aimed to increase the resolution of the material units and explore how they could be iteratively programmed to autonomously-assemble to:

1. Increase material capacities so multi-material responses are achieved with increasing sensitivities.
2. Develop the scalability of the assembly process by increasing material resolution.
3. Explore an approach for how granular matter can interact as part of large-scale architecture.
4. Understand how matter can be materialised when and where it is needed.

For these reasons we employed the mineral accretion process,[19] i.e. electrolysis of seawater, as the material platform across a series of prototypes.[20] The series highlighted several key principles for iteratively programming the matter of responsive megastructures, which we use to inform characteristics for our vision. First, creating scaffolds composed of physically separated cathodes can grow 2D shapes and 3D patterns and structures (Figure 1) from material units that autonomously assemble at highly granular resolutions i.e. molecular resolution, made possible by modulating localised parameters of stimuli.[21] Second, the mineral accretion process is a multi-material platform, enabling structures with variable material qualities to be manufactured, such as compressive strengths,[22] compositions, surface textures and densities.[23] Third, matter can be materialised when and where is it needed within our distributed cathode scaffolds by extracting material resources from the surrounding volume of water. Figure 2 illustrates matter being materialised away from the constraints of the pre-defined scaffold shape, which is possible as the material source surrounds the scaffolds. Finally, our prototypes reveal how highly granular units of matter can be iteratively programmed and interacted with by modulating parameters of stimuli, such as duration, magnitude, location, concentration, instead of pre-designing their properties. We term this approach 'tuneable environments.'

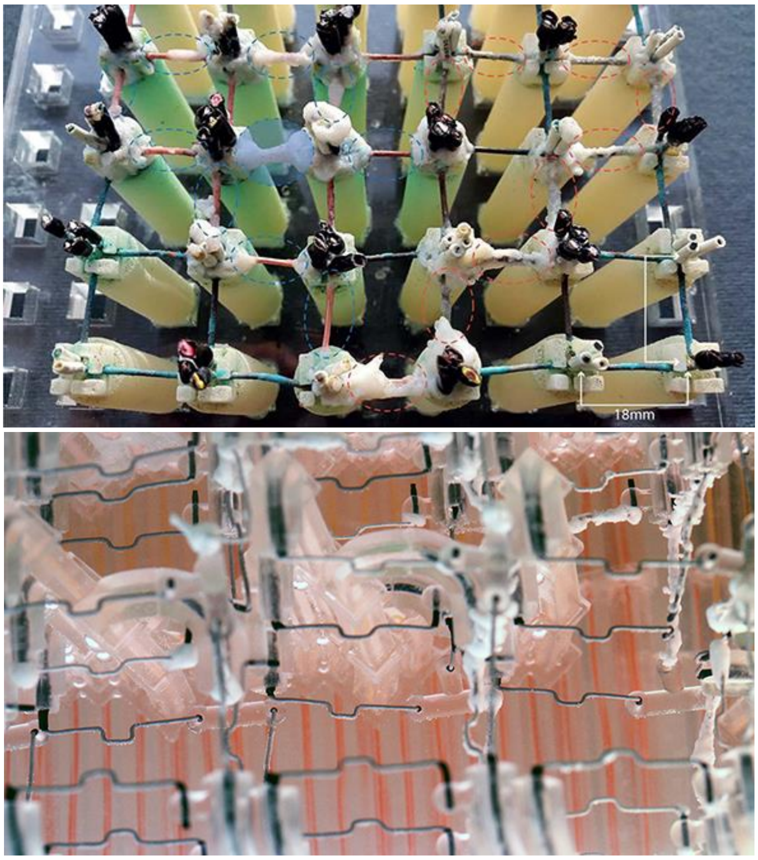

Figure 1. Upper image showing the growth of a 2D pixelated heart shape with various volumes of matter accreted. Lower image illustrates 3D shapes with various material properties.

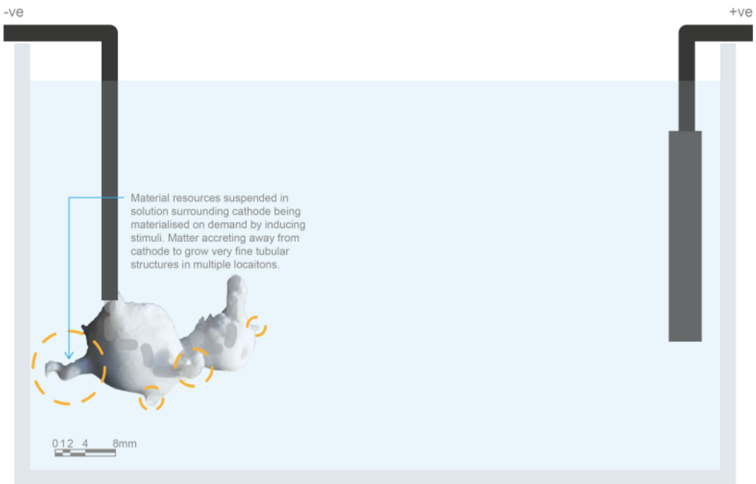

Figure 2. Illustrates how matter can be materialised away from scaffolds when surrounded by the material source as highlighted by the emergent tubular growth forms.

TOWARDS A RESPONSIVE MEGASTRUCTURE

We now present our vision for a responsive megastructure, which we deliberately chose to give expression to in a similar manner to past megastructure projects to aid its legibility. This decision is borne of the desire to better understand the implications of applying our approach at the scale of an urban region. We present these visualisations as a way to extend our inquiry and explore the potential of it as living-material system. Drawing inspiration from Constant's *New Babylon* project[24], 1959-1974, which was illustrated in a variety of contexts to demonstrate its relative impact, we situate our responsive megastructure within Paris, illustrated in Figure 3. It is intentionally located along the city's waterway network and main transport axis as we envision these could provide potential material sources as Figures 4 and 5 show. Specifically, the waterway network could supply abundant material resource to facilitate a materialisation process similar to the mineral accretion process. The major transport axis, meanwhile, could provide a carbon-based material source, extracted from the polluted air and transforming it into usable building materials.

Figure 3. Aerial render of existing Paris context.

Figure 4. Aerial render of responsive megastructure located in areas of Paris that generate materials that can be used materialise the structure and enable in-situ responses.

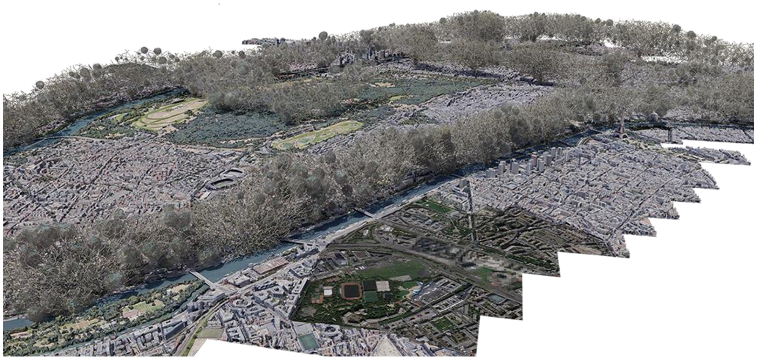

Figure 5. Visualisation illustrating the scale of the responsive megastructure relative to the existing Paris context.

Principles from our mineral accretion prototypes provide the rationale behind the world-building[25] for our speculative vision. Our prototypes highlight the ability to materialise small amounts of matter away from individual cathodes and on demand by modulating localised stimuli. This ability to generate matter on demand in relation to design associations resembles the process of mitosis (new matter being produced) within a plant's meristematic zones based on growth principles. However, new matter is materialised internally within the plant's 'skin', which acts as a flexible scaffold since it transports material resources, does not restrict the global and local shape changes of the plant during growth or a plant's position within 3D space. This highlights the significant impact scaffolds have on how responsive growth occurs in relation to geometric and material extent alongside the resolution of a structure. Our visualisations are informed by reflecting on these aspects and attempt to portray the requirements of a flexible scaffold.

First, the global form is based on creating a minimal surface volume along these material networks in which branching structures grow. This minimal surface envelope acts as a way to prevent uncontrolled growth that could be similar to issues with urban sprawl, including resultant drosscape.[26] Second, the structures resemble a branching network of roots or compartmentalised vein-like structures. We propose this acts as a flexible skin-like scaffold which is capable of growing with matter as it is generated. Third, for the materialisation of matter generated from liquid-based material resources the branching scaffolds would have to contain and transport material resource to where and when it is needed, ready for generating new, programmed matter. Finally, materialisation of matter has to be reversible to its original state. The use of state-changing materials could enable evolvable structures that are totally reversible[27] and still allow multi-responses at highly granular resolutions. As a result, large global and sensitive local responses could be achieved without the constant consumption of material resources. Instead, matter could be redistributed and reprogrammed to where it is needed most with minimal waste. In effect, this type of responsive megastructure would act as a living material eco-system by forming a material cycle that integrates with biological environments. These structures and processes would be capable of sharing resource when and where they are needed, potentially beyond the demands of an anthropocentric city and current material cultures. However, this also opens up new research challenges as we shall now discuss.

DISCUSSION

We conclude our paper by providing a critical evaluation of our vision for a responsive megastructure. Our speculative design and the visualisations developed to envision it has provided a valuable process through which we can reflect on, reframe and conceptualise key challenges raised through our prototypes. They provide a basis for reinvigorating ambitious architectural visions that were prevalent in countercultural movements evident between the late 1950s and early 1970s. Critically, our vision centres around the exploration of a design and fabrication approach that could enable a scalable and responsive architecture that is highly sensitive to external stimuli. We incorporate principles from our prototypes to illustrate how an assembly processes can be reimagined and how matter can be continually reprogrammed based on naturally occurring phenomena, such as stimuli, autonomous assembly and materialisation. Implementing these principles into an urban context to envision novel material interactions and a highly granular, multi-responsive architecture opens up new possibilities. One future trajectory points towards where architecture is capable of integrating with natural material cycles. This could address, perhaps even reverse, some of the anthropogenic impacts that cities produce due to the high demands they place on the environment based on current modes of assembly, which continually deplete and degrade natural resources. In addition, challenges of disassembly that currently exist within in the built environment due to aggregations of multiple materials could be tackled directly because the material make-up of our responsive megastructure can be iteratively reprogrammed at highly granular levels.

The speculative nature of our design necessarily raises questions that provide avenues for further research. First, determining the types of stimuli and how they are induced to create global, local and reversible responses within the overall megastructure will be crucial in shaping its ability to flourish in specific contexts. Second, there is a need for greater exploration into how non-linear associations can be created within a complex system and their interrelationships understood, so that it is possible to respond to competing interests from the social, global, and technological demands of urban life in a multi-scalar way. Third, being able to develop design strategies that can generate and reveal what a desirable response would be within a complex, multi-responsive system so material properties and current behaviours within cities co-evolve. Fourth, to create robust assembly processes that can prevent or reverse the hacking of the megastructure by those who could use stimuli to damage or exploit the materialisation of matter. Fifth, to examine suitable material platforms and processes that can lead to multi-material responses and interrelated, complex interactions that do not compromise unforeseen far future demands due to path dependencies including technological lock-in.

To conclude, it is our intention through developing a vision for a responsive megastructure to address the challenges of literally growing cities for the future. By drawing on our future visioning and prototyping research, we have sought to illustrate one way in which this might be achieved in practical terms. Despite the rigour of the underpinning laboratory work, we acknowledge the experimental approach of this inquiry. In this manner we have contributed our vision as a means of expressing the not-yet, since such imagery shapes our ideas of, and intentions towards, futures.[28] Through this example we have aimed to show that visions are powerful vehicles through which we can explore scenarios. Our ongoing work will delve deeper into the critical questions this raises including where cities can be located and where they cannot, what arrangements of density and settlement size are viable, and which materials will protect us and not further exacerbate environmental degradation.

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