

An aerial photograph of a forest floor, showing a dense carpet of ferns and several mushrooms. The scene is captured from a high angle, looking down into the woods. The lighting is soft, creating a range of green and brown tones. The ferns are in various stages of growth, and the mushrooms are scattered throughout the undergrowth.

DESIGN BEHAVIORS

Programming the material world
for Responsive Architecture

PHD DISSERTATION
ARETI MARKOPOULOU

Thesis Director: Dr. Eduard Bru i Bistuer
Thesis Co-Director: Dr. Manuel Gausa Navarro



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Responsive Architecture**

PHD DISSERTATION

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Programming the material world for Responsive Architecture

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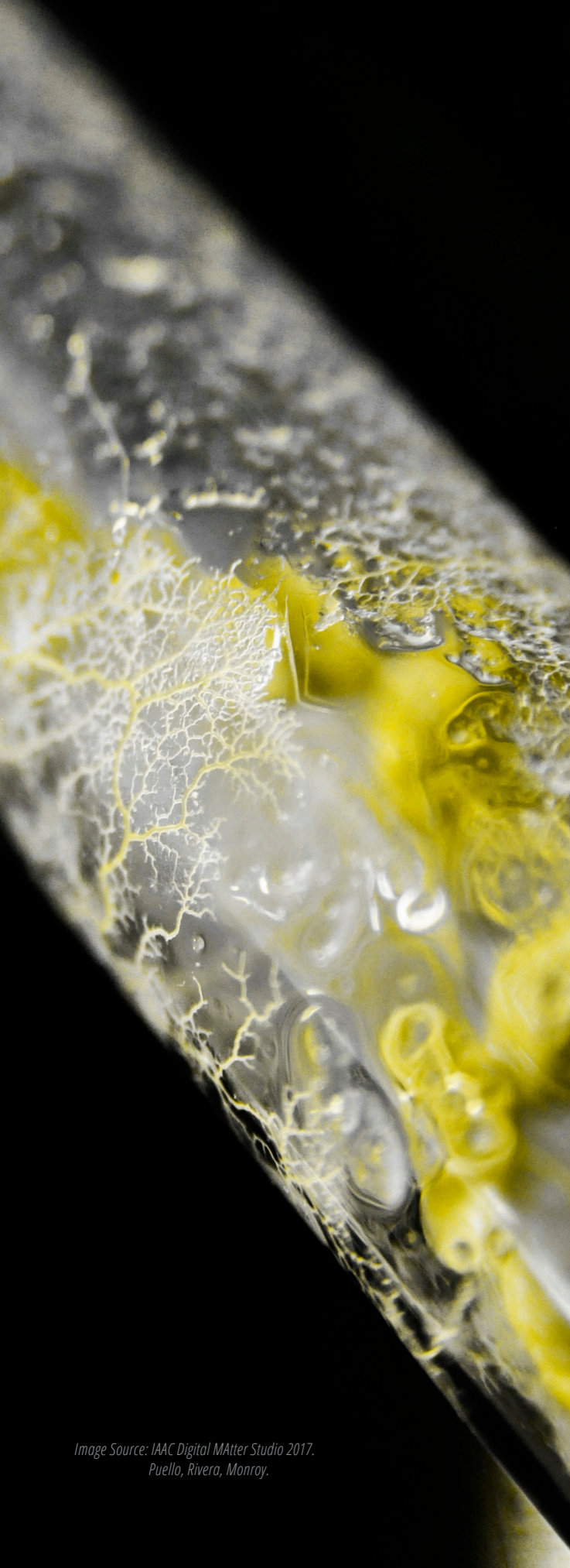
A special thank you to my good friend Angela Kouveli, since without her, I would have never arrived at IAAC, and therefore I would have never arrived at designing (or even thinking about designing) any behavior whatsoever.

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Without them, the spark would have never lighted a fire.

To Eleni. My mother



ABSTRACT

Image Source: IAAC Digital MAter Studio 2017.
Puella, Rivera, Monroy.

The advances of material science, coupled with computation and digital technologies, and applied to the architectural discipline have brought to life unprecedented possibilities for the design and making of responsive, collectively created and intelligent environments. Over the last two decades, research and applications of novel active materials, together with digital technologies such as Ubiquitous Computing, Human-Computer Interaction, and Artificial Intelligence, have introduced a model of **Materially Responsive Architecture** that presents unique possibilities for designing novel performances and behaviors in architectural space.

Beyond the use of mechanical systems, sensors, actuators or wires, often plugged into traditional materials to animate space, this dissertation proves that matter itself, can be the agent to achieve monitoring, reaction or adaptation with no need of any additional mechanics, electrical or motorized systems. Materials, therefore, become bits and information uniting with the digital world, while computational processes, such as algorithmic control, circular feedback, input or output, both drive and are driven by the morphogenetic capacities of matter, uniting, therefore, with the material world.

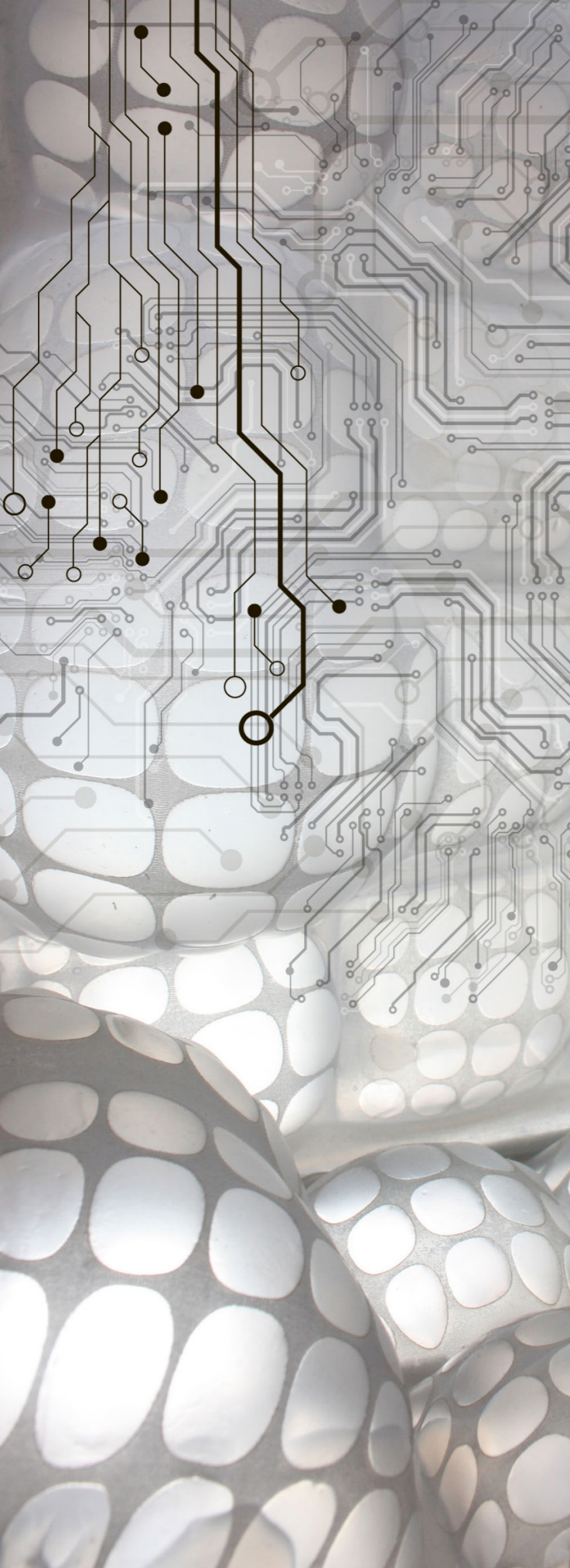
Through the applications and implications of *Materially Responsive Architecture* we are crossing a threshold in design where physicality follows and reveals information through time and through dynamic configurations. Design is not limited to a finalised form but rather associated to a performance, where the final formal outcome consists in a series of animated and organic topologies rather than static geometries and structures. This new paradigm, is referred to, in this thesis, as the **Design Behaviors** paradigm, and is characterized by unique exchanges and dialogues between users and the environment, facilitated by all human, material and computational intelligence.

Buildings, objects and spaces are able to reconfigure themselves, in both atomic and macro scale, to support environmental changes and users' needs, behavioral and occupational patterns. At the same time the *Design Behaviors* paradigm places not only **matter** and the **environment** at the center of design and morphogenesis, but also the **users**, that become active participants of their built environment and play the final creative role. This paradigm shift, boosts new relations between the built space and humans, or among inhabited space and human body and perception.

The new design paradigm is also a new cultural one, in which statics, repetition and Cartesian grids, traditionally related with safety, property and comfort, give way to motion, unpredictability and organic natural principles.

Materially Responsive Architecture and the *Design Behaviors* paradigm define uniquely enhanced "environments" and "ecologies" where human, nature, artifice and technology collectively and evolutionally co-exist **within a framework of increased consciousness and awareness.**

This thesis argues that, while there is no doubt that our future cities will consist in an extensive layer of distributed sensors, actuators and digital interfaces, they will also consist in an additional layer of novel materials, that are dynamic and soft, rather than rigid and hard, able to sense as sensors, actuate as motors, and be programmed as a software. The new materiality of our cities relies on the advances of material science, coupled with the cybernetic and computational power, and that can be actuated by the environment to change states (**Re-Active Matter**), can be controlled by the users to respond (**Co-Active Matter**), and eventually can be designed and programmed to learn and evolve as living organisms do (**Self-Active Matter**). The physical space of the city is, thus, the seamless intertwining of digital and material content, becoming an active agent in the dynamic relationship between the environment and humans.



FOREWORD

AUTHOR'S NOTES ON METHODOLOGY & DEVELOPMENT

The principle steps and methodology that this thesis follows, represent the actual gradual and practical steps that have been taken along the evolution of the “Digital Matter” Studio. Digital Matter is a design and research studio, led by the author, and developed in the Master in Advanced Architecture at the Institute for Advanced Architecture of Catalonia (IAAC), from 2013 to today.

The creation of this studio in 2013 was the response to rapid advancements of smart and responsive materials, and their applications in the fields of industrial design, medicine and engineering. The curiosity and research interest of the author led her to understand that smart materials could bring potential disruption in architectural design and its behavior.

Phase 1_Re-Active Matter

The Digital Matter research, initiated with a clear agenda and brief on how smart materials can be applied in architecture to achieve — what initially has been named by the author as, architectural ‘performance’. The first 2 years of the research (2013-2015) were entirely focused on the possibilities of these materials to replace existing mechanical systems. Taking into consideration their dynamic properties of responding to certain environmental stimuli, the focus of this first phase has been on achieving a passive architectural ‘performance’. The studies, analyses and outcomes of this phase represent what is today, in this thesis, referred to as *Re-Active Matter*: an architectural matter able to respond to environmental inputs and be in-sync with its environment.

Along the development of this first phase, a series of successful outcomes and possibilities have been achieved and discovered, while other failures and practical limitations have been faced. The limitations were mainly related with observing a lack of control on the systems, and, above all, with the absence of user-desire or needs integrated within their operations. At a moment of growing interest in bringing personalization, customized fabrication, open source or crowdsourced logics into design, Re-Active Matter, although a valid organic and sustainable vision for architecture, was still, totally disconnected from its major agents; the users and occupants of the architectural space. This observation led to a re-formulation in the methodology and brief used in the Digital Matter Studio until then.

Phase 2_Co-Active Matter

In 2015 and after two years of interesting projects and research outcomes, the methodology and the brief of the Studio were to shift, and opened to include in the architectural system, the parameter of user-desire and user-control. Aligned with the latest technologies in human-computer interaction that were emerging in this period - including user interfaces,

mobile apps or Virtual Reality devices - the Digital Matter Studio focused on developing prototypes and projects that explored how the passive systems of Re-Active Matter could be hacked or re-programmed to allow a more direct and fluid interaction with the continuously changing needs of the user. The projects and studies that emerged from this second phase of experimentation, represent what is today, in this thesis, referred to as *Co-Active Matter*: an architectural matter that responds to both its environment and to the personalized needs and desires of its users.

The outcome, combining the passive environmental response of smart materials with user interfaces, mobile apps, ubiquitous computing and eventually user-control, bring forth the possibilities also of designing with the people rather than simply designing for them. The projects and studies developed during this second phase, have the objective to combine the possibilities of smart materials with their potential to empower users to actively participate in the formation of their built environment and customize this according to their needs. Throughout this second phase, a series of new possibilities, limitations and questions have emerged:

What if there were a multitude of user that desired to control a space, given they cohabit them? Which user takes the final decision? Does the passive actuation prevail over the hybrid one, or how could the inherent properties of the material find resonance with the user's needs?

These, among other questions, led to a steady but essential redefinition of the agenda and brief of the Digital Matter Studio.

Phase 3_Self-Active Matter

It was not until 2017 that the parallel work of the author, (in the field of big data and smart cities, developed in the framework of the Master in City and Technology that she directs at IAAC), brought her to discover, and go deeper into, the technical details and operations of artificial intelligence, neural networks and evolutionary algorithms. Mainly applied in the field of big data, artificial intelligence uses vast amounts of data to train algorithms that are able (through these data) to identify patterns, learn from them and eventually predict the outcome of certain operations. Image recognition algorithms, for instance, are being trained with extensive amounts of visual inputs, fed to the system, until the system is able to recognize the patterns that recognise a car, a building or a person in a photograph. The understanding of how such technologies operate, brought the author to realize that their implementation was without a doubt the next significant step in Materially Responsive Architecture.

The combination of smart materials, big data and evolutionary algorithms through machine learning could, in fact, be the answer in most of the limitations previously faced; and this would become the brief of the third phase of the Digital Matter Studio. The outcome of projects and studies, currently still in progress, represent what is today, in this thesis, referred to as *Self-Active Matter*: architectural systems of smart materials that are able to respond in an autonomous way, combining all data from the environment, and the users' needs to determine the most optimum performance at a specific time and in a specific context.

It is at this exact moment in which the author realizes that the idea of 'performance' does not accurately define the coming architectural operation. Architectural systems that present consciousness or learning capacities are systems that resemble human nature, and therefore, are able to assume 'behaviors' rather than pure 'performance'.

Possibly - notwithstanding the necessity to consent developing further research as not all the answers have been given, or all the limitations faced -, Self-Active matter describes the ultra-latest development in this field. The lack of existing and limited references, showcases exactly the extension to which these efforts are, in fact, contemporary. Rather than a limitation, this lack of references is considered by the author as a positive gap that calls for further exploration and experimentation.

Throughout the process of development of the thesis, it became apparent that the aforementioned categories of Materially Responsive Architecture, prove to be closely linked with diverse design protocols and logics. These logics and protocols are studied in detail through this thesis, particularly in reference to different contemporary technological contexts. The conclusions of these emerging design logics, as well as their aesthetic qualities, is what this thesis, in conclusion, defines and refers to as the **Design Behaviors** paradigm.

After almost six years of research in the field of Materially Responsive Architecture, and although the current stage of this thesis is complete, the author reserves an intuition that soon, maybe sooner than expected, we can start to speak of a fourth shift, a fourth evolution and a new category of Matter, linked to the further development and combination of the miniaturization of machines, further innovation in material sciences and the evolution of Artificial Intelligence.

The author commits to continue working and sharing with both the academic, scientific and professional community, the outcomes of her continuous research.

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INTRODUCTION TO THE THESIS

Image Source: IAAC Creative Food Cycles, 2019.
Farinea, Elatab.

I. BACKGROUND

“Evolution now must include evolving environments which evolve man, so that he in turn can evolve more propitious environments in an ever quickening cycle”¹

Warren Brodey, 1967

Throughout the past centuries, we have been building in a search for stability. Our - artificial - architecture, made of stone, bricks concrete or metals, has been designed and materialized for stability and durability. These characteristics are those of an age where flows and interactions - metabolic cycles - are related to humans and other living organisms. Consequently, our design strategies have focused on the creation of finalized and static forms; a one-directional design that defines a closed architecture, fully determined prior to its occupancy, and that, more often than not, stands out as a protective rigid layer between the environment and occupants of the architectural form in itself.

Although several futuristic visions towards responsive and animated architecture did emerge already in the early 1900s, such as the work of Antonio Sant’Elia or Villemard, it was the rise of Cybernetics, in the 1940s, that marked a turning point, and provided the technological means, theories and detailed logics that powered futuristic visions of responsive architecture, within a unique cultural and technological context. The emergence cybernetics as a scientific discipline saw new ways of thinking and of interacting with built space, in particular the introduction of questions related to virtuality in architecture, data and feedback, and the unique interactive relationship between humans/living organisms and technology/machines. Flows and interactions, during this period, extend to include technology, machines and digital data, rather than only humans and living organisms. Furthermore, the ideas of cybernetics are given power also by the last two decades’ advancements in information technology — such as the Internet, the Internet of Things, Human-Computer Interaction and Ubiquitous Computing, becoming less theoretical and speculative, with the emergence of a series of built and experimental work.

¹ Warren Brodey, ‘The Design of Intelligent Environments: Soft Architecture’, Landscape 17, no. 1 (1967).

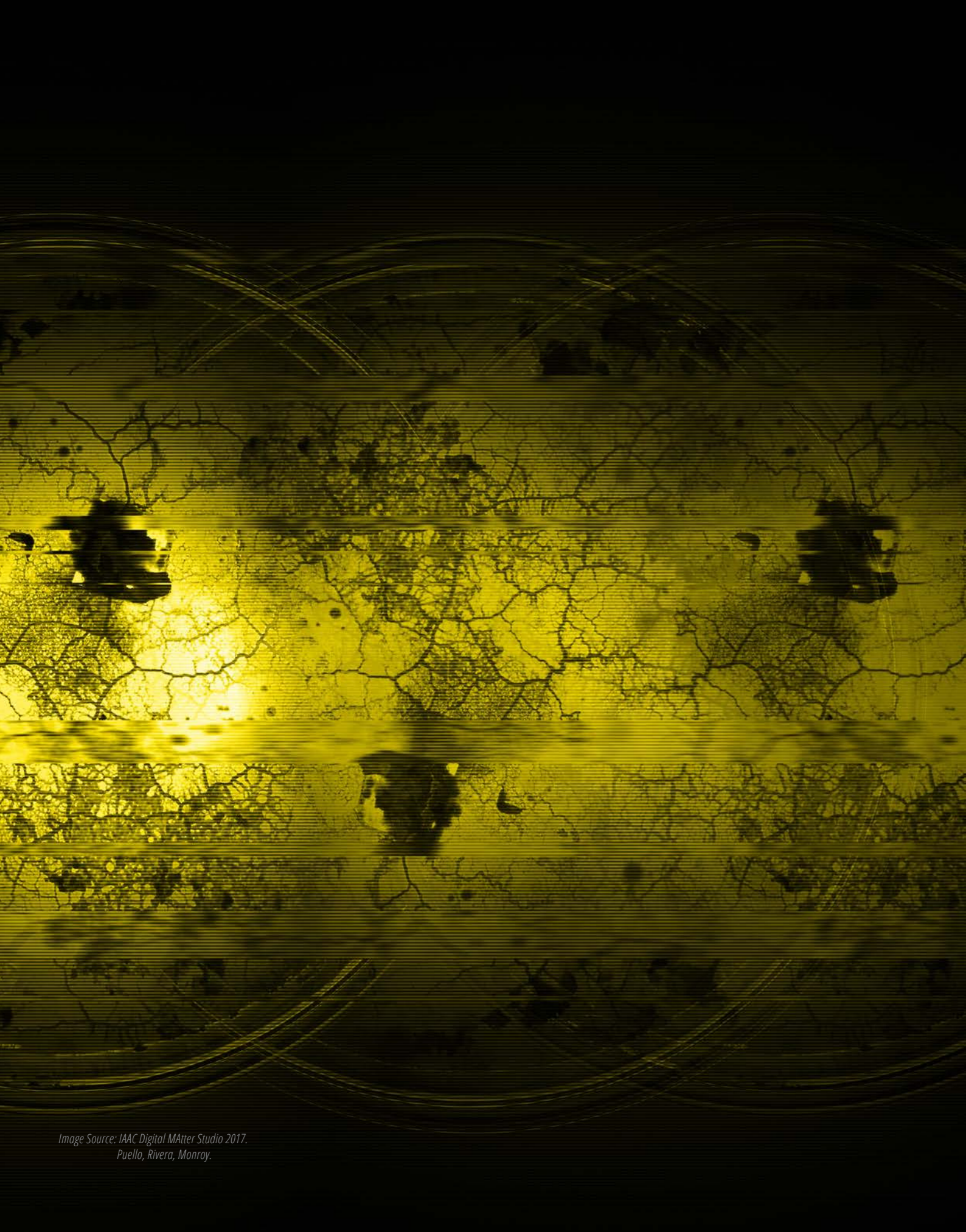


Image Source: IAAC Digital Matter Studio 2017.
Puella, Rivera, Monroy.

The principles and applications of Responsive Architecture from the 60s until late 90s, were mainly based on mechanized systems plugged into and activating traditional materials. However, with the advancements in material sciences over the past two decades (2000-2019), new potentials for Responsive Architecture emerge, in particular the introduction of novel active materials that have inherent dynamic properties, consolidated by their wide applications in different disciplines, such as aeronautics or medicine.

As a result, the first examples of architectural applications that integrate active materials in their structure and materiality, embedding performance, start to appear in the first decade of the 21st century. These approaches, which start to multiply in an accelerated way, introduce new notions and requests for a non-static matter that is able to actively sense, actuate or reprogram itself.

A new approach on **Materially Responsive Architecture**, combining responsiveness with active materials, is the result of such efforts, and for the first time, embracing matter as a dynamic and evolutionary agent becomes apparent as a crucial parameter that can affect and contribute to the behavior of Responsive Architecture.

The advances of material science, coupled with computation and digital technologies, and applied to the architectural discipline has brought to life unprecedented possibilities for the design, making and perception of non-static, adaptive and intelligent architecture. Over the last two decades, research and applications of novel active materials together with digital technologies such as Ubiquitous Computing, Human-Computer Interaction, User friendly Interfaces and Artificial Intelligence, have introduced the possibility of designing novel performances and behaviors in the architectural space that are embedded and integrated in both material nano-scale and in digital information.

The research presented in this thesis aims to prove that placing intelligent matter at the centre of contemporary architectural thinking and design, is the key agent for achieving integrated intelligence in the built space, and that *Materially Responsive Architecture* is a unique technologically-enhanced digital and physical design process that generates and represents a new paradigm of design in the discipline of architecture.

Beyond the use of mechanical systems, sensors, actuators or wires, often plugged into traditional materials to animate space, this dissertation proves that matter itself, can be the agent to achieve monitoring, reaction or adaptation with no need of any additional mechanics, electrical or motorized system.

Questions of how *Materially Responsive Architecture* affects design logics and architectural aesthetics are extensively analyzed in their potential and limitations as a new design paradigm, in which design is not limited to a finalised form but rather to a performance, and where the final formal outcome consists in a series of animated and organic topologies rather than static geometries and structures. This new paradigm, is referred to, in this thesis, as the **Design Behaviors** paradigm.

Today we are experiencing a radical shift in the perception of notions such as stability, privacy, autonomy, and property. We shift our actions from the digital to the physical world uncountable times per day. We turn on and off connected devices to access the news or navigate to our cities, we access mobile applications of shared vehicles instead of owning our own, we work from anywhere, we live in more than one city or home, thanks to the multiple possibilities of accessible and quick communication means between places and people.

This thesis argues that, while there is no doubt that our future cities will consist in an extensive layer of distributed sensors, actuators and digital interfaces to facilitate our hybrid physical and digital operations, they will also consist in an additional layer of novel materials, that are dynamic and soft, rather than rigid and hard, able to sense as sensors,

actuate as motors, and be programmed as a software. The new materiality of our cities relies on the advances from material science, coupled with the cybernetic and computational power, and that can be actuated by the environment to change states (**Re-Active Matter** [i]), can be controlled by the users to respond (**Co-Active Matter** [ii]), and eventually can be designed and programmed to learn and evolve as living organisms do (**Self-Active Matter** [iii]). The physical space of the city is, thus, the seamless intertwining of digital and material content, becoming an active agent in the dynamic relationship between the environment and humans.

II. HYPOTHESIS AND RESEARCH QUESTIONS

The search for *Materially Responsive Architecture*, an architecture that integrates in its elements active and smart materials in order to change with time, as well as adapting to a variety of parameters, is currently booming. With the objective of Design Behaviors (as the name of this thesis states), Materially Responsive Architecture is being experimented, applied and theorized in an accelerated way by architects, artists, architectural schools, as well as through a variety of diverse disciplines, including computer sciences, material sciences and philosophy. This infiltration, described in chapters 1 and 2, brings with it undeniable dynamics of innovation and transformation in architecture, both from the perspective designers, as well as those who inhabit the spaces. However, the variety of approaches on designing architectural behaviors through active matter, requires a clear indexation for a deeper understanding of their possibilities and limitations, as described on chapter 3. The emerging architectural systems that are able to respond, adapt, move or perform reveal new processes and logics for their design, while they additionally introduce new formal and performance language. This design logics paradigm shift, as well as its affect in the spatial aesthetic qualities are defined as the **Design Behaviors** paradigm, analyzed in depth in the fourth chapter.

Starting from these observations, and as the backbone of this thesis, the author poses the following three questions:

1. What categories and associated approaches can be identified and defined in contemporary work through the application of active and smart materials to achieve architectural and urban dynamic behaviors?
2. What kind of changes can programming materials bring to the discipline of architecture and especially, to its processes of design, the role of the designer and its aesthetic qualities?
3. To what extent can such changes be considered as the starting point of a new design paradigm, towards architectural and urban intelligence?

These questions are the central questions from which this thesis is developed, based

[i] In this thesis, Re-Active Matter refers to an architectural matter able to respond to environmental inputs and be in-sync with its environment. See Chapter 3.1. for the full development of this concept.

[ii] In this thesis, Co-Active Matter refers to an architectural matter that responds to both its environment and to the personalized needs and desires of its users. See Chapter 3.2. for the full development of this concept.

on the hypothesis that Materially Responsive Architecture is a disruptive technologically-enhanced design process that can generate and represent a new paradigm of design in the discipline of architecture. In this emerging paradigm, which introduces new design protocols, designers, users and environments are participants of unique exchanges and dialogues, facilitated by all human, material and computational intelligence. In support of this affirmation, the 4th chapter of this thesis presents a constellation of new design principles and spatial characteristics attributed to the Design Behaviors approach.

III. OBJECTIVES

The objectives of this research lie in three main goals. The first is oriented to generating a deeper analytical understanding of largely distributed approaches linked with the application of smart materials in architecture. This was developed through an indexing process, classifying these approaches, and defining a series of categories, within the context of Materially Responsive Architecture.

From this classification, the second objective emerges, highlighting the drivers of these categories, with the goal of understanding their possible future evolutions, taking into consideration the latest technological advancements in design, materials and computation. Finally, the research aims to rigorously formulate the impact of the present and future Materially Responsive Architecture in design logics, principles and aesthetics.

IV. RESEARCH METHODOLOGY

The research has been orchestrated following an analytical and experimental methodology, developed through a variety of international experiences of research and design in the context of Materially Responsive Architecture. The development of the research identifies three specific categories of Materially Responsive Architecture: Re-Active, Co-Active and Self-Active Matter. These are analyzed and described as well as evaluated through a series of case studies and experimental approaches. It is important to highlight that although this thesis seeks to theorize the current and future panorama of Materially Responsive Architecture, it is in its core driven by a highly experimental and prototype based approach, where built work, prototypes and mock-ups are developed for both a quantitative and qualitative analysis. The author herself, being the Academic Director of

[iii] In this thesis, Self-Active Matter refers to architectural systems of smart materials that are able to respond in an autonomous way, combining all data from the environment, and the users' needs to determine the most optimum performance at a specific time and in a specific context. See Chapter 3.3. for the full development of this concept.

a highly experimental research and educational institute, has been in the forefront of this experimental and making approach, and this thesis is specifically emerging from these learnings, failures and visions, developed in the last six years at the Digita Matter Studio of the Institute for Advanced Architecture of Catalonia.

Such an approach contributes to a better understanding of the possibilities and limitations of both technology and matter, as well as embracing these changes in architecture today that cannot be envisioned or theorized detached from other disciplines contributing to scientific innovation or from current environmental, social or economic challenges.

The results from both the quantitative and qualitative analysis of the case studies, as well as the study of technological advancements in other disciplines, has driven this thesis to catalogue Materially Responsive Architecture in 3 aforementioned categories of projects and approaches, whose behavior can be controlled by design, according to a variety of parameters (environment, user desire, vast digital data) and according to a variety of computational processes (user interfaces, Human-Computer Interaction and machine learning).

The first category of projects, identified as **Re-Active Matter** focuses on the ability of Materially Responsive Architecture to inherently respond to environmental changes and stimuli, without the need of any additional mechanical or electrical system for actuation.

The second category of projects, identified as **Co-Active Matter** focuses on novel collaborative design logics, driven by advancing technological means, such as User Interfaces or Human-Computer Interactions (HCI) that allow users to participate and drive the changes of their space in Materially Responsive Architecture.

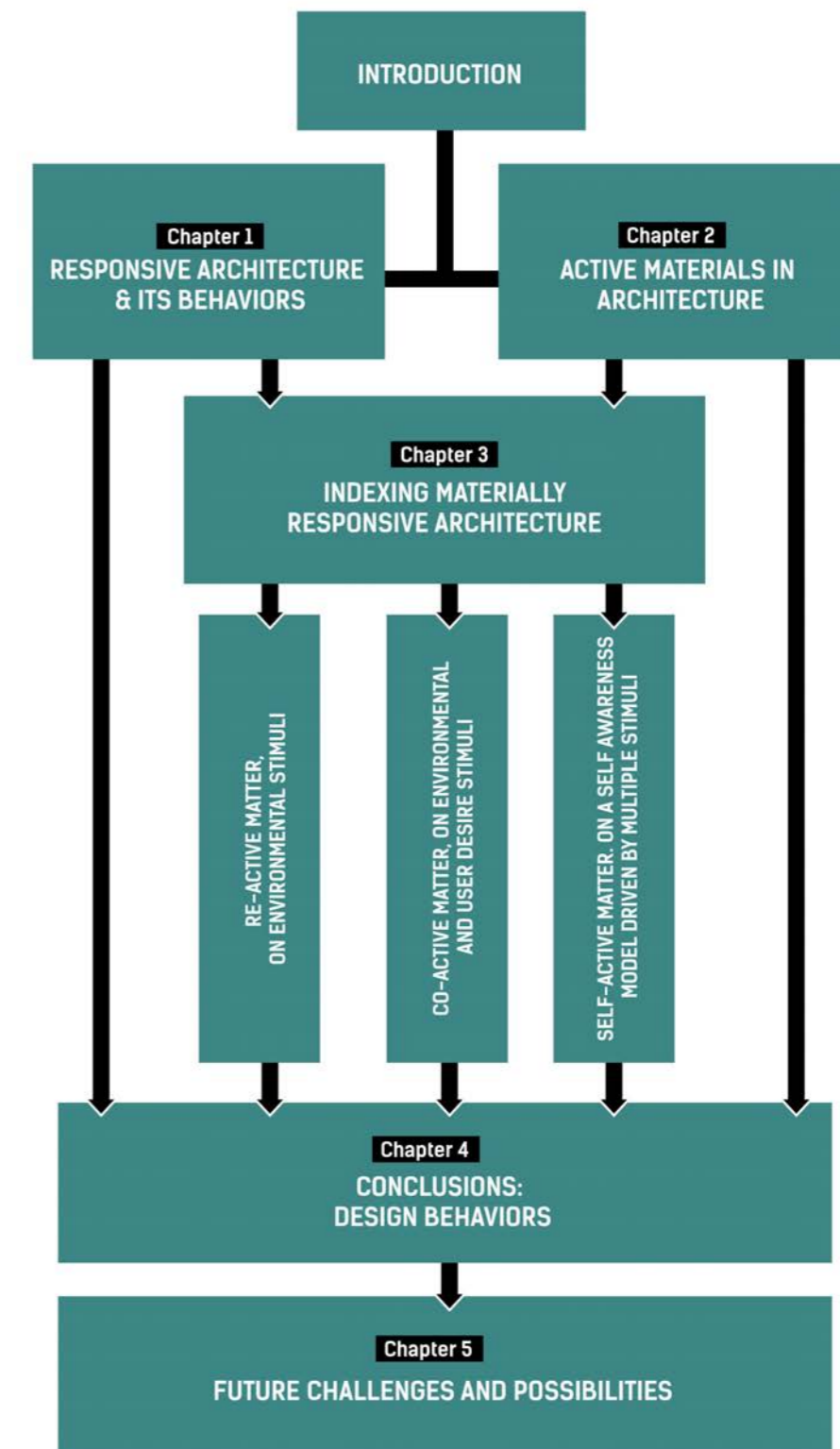
The third category of projects, identified as **Self-Active Matter** focuses on the design of Materially Responsive Architecture that is able to learn from both environmental data and user behaviors and evolve to predict balanced decisions for both agents. It introduces unique interactions of physical materials, environmental changes and user desires through evolutionary algorithms, computation and eventually, artificial intelligence.

V. RESEARCH OUTPUTS

The fourth chapter focuses on extrapolating and envisioning a more theoretical aspect of the effect of the mass use of such materially driven responsive architecture, through a series of design logics and aesthetic aspects that are driven from the performance of the built prototypes and are opening ways to a new architectural design and language.

These new models are described within a strong understanding that there are limitations on both technological, societal, and cultural aspects. Taking though, into consideration that we are at an era of accelerated technology, where adaptation and change is a norm, as well as that many of those extrapolations are already being built, the thesis concludes that once certain limitations are overcome, *Materially Responsive Architecture* could generate and represent a new paradigm of both design and human-space interaction in the discipline of architecture.

VI. RESEARCH PLAN



VII. SUMMARY OF PUBLICATIONS

The development of this thesis includes a series of publications, a selection of which, is listed below:

CONFERENCE PROCEEDINGS:

Next Generation Building Journal

A. Markopoulou, 'Design Behaviours, Programming Matter for Adaptive Architecture', *Next Generation Building, Info-Matter*, Amsterdam, Baltzer Science Publishers, 2016.

Whats the Matter, Materiality and Materialism at the age of Computation, ENHSA, EAAE

A. Markopoulou, A. Dubor, 'Digital Matter, Intelligent Constructions Systems for Responsive Buildings', *ENHSA, EAAE, Whats the Matter, Materiality and Materialism at the age of Computation*, Barcelona, Enhsa, 2014, pp. 188-209

Proceedings of Future Trajectories of Computation in Design, CAAD Futures 2017:

J. Won Jun et al, 'Remembrance: A Shape Changing Adaptive Structure', *CAAD Futures 2017, Future Trajectories of Computation in Design*, Istanbul, Publisher, 2017, pp. 180-199.

Proceedings of Symposium on Simulation for Architecture & Urban Design, SimAUD 2018:

A. Zervos et al, 'Graphene Embedded Composites for Thermal Performance Optimization of Traditional Construction Materials', *SimAUD, Simulation for Architecture & Urban Design*, TU Delft, 2018, pp. 101-107.

Proceedings of the 36th Conference on Computer Aided Architectural Design Futures (eCAADe)

N. El-Gewely et al, 'Programming Material Intelligence Using Food Waste Deposition to Trigger Automatic Three-Dimensional Formation Response in Bioplastics', *eCAADe, Complexity & Simplicity*, Oulou, 2016.

Design Modelling Symposium

A. Markopoulou et al, 'City Gaming and Participation' *Design Modelling Symposium, Humanizing Digital Reality*, Paris, Springer International Publishing, 2018.

Proceedings of the 35th Conference on Computer Aided Architectural Design Futures (eCAADe)

A.Chronis et al, 'Merging the Physical and Digital Layer of Public Space - The PobleJoc Installation Case Study' *eCAADe, ShoCK*, Lodz, 2018.

Fabricate

J. Laarman et al.(2014) 'Anti-Gravity Additive Manufacturing', *Fabricate: Negotiating Design and Making*, London, UCL Press, 2014.

Robotic Fabrication in Architecture, Art and Design,2018

A. Dubor et al, 'On-Site Robotics for Sustainable Construction', *Art and Design, Robotic Fabrication in Architecture*, Berlin, Springer, 2018, pp. 390-404.

Advances in Architectural Geometry 2016

A. Figliola et al, 'Digital Urban Orchard: robotic manufacturing of complex shape', *Advances in Architectural Geometry*, Zurich, 2016.

International Conference on Social Informatics

E. M. Daly, A. Markopoulou, D. Quercia, 'City Labs – Introduction', *Social Informatics*, Berlin, Springer, 2015, pp.3-4.

E-BOOKS:

Urban Next:

A. Markopoulou, *Living Breathing Skins*, Barcelona, Urban Next, 2018.
<https://urbannext.net/living-building-skins/>

Urban Next:

A. Markopoulou et al, *Designing Oneself with Artificial Senses*, Barcelona, Urban Next, 2018.
<https://urbannext.net/designing-oneself-with-artificial-senses/>

JOURNAL ARTICLES:

IAAC Bits

A. Markopoulou, 'Design Behaviors', *IAAC Bits Advanced Architecture Group Journal*, Black Ecologies, vol. I, number 9, 2019. <https://iaac.net/category/publications/iaac-bits/>

CHAPTER IN BOOKS:

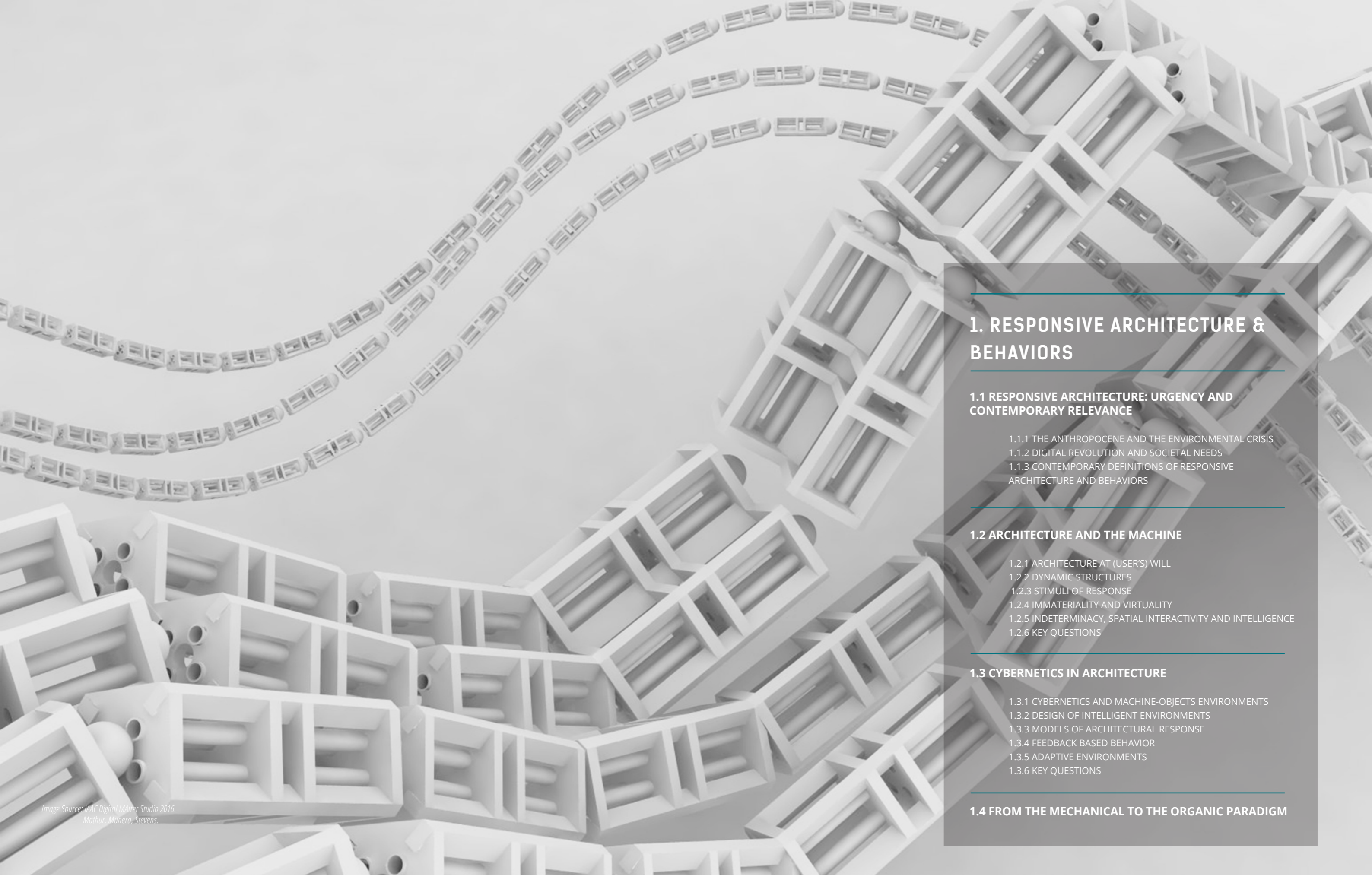
A. Markopoulou, 'In[form]ation', in M. Kretzer, L. Hovestadt (eds.), *ALIVE: Advancements in Adaptive Architecture*, Basel, Birkhauser, 2014.

A. Markopoulou, 'Alive, Forming vs performing', in M.Carta (ed.), Vol. 5: *R.E.D.S Rome ecological design symposium*, Trento, List, 2014.

A. Markopoulou, 'Smart City Project', In *A Smart Guide to Utopia, 111 Inspiring Ideas for a Better City*, Barcelona, Lecool, 2012, pp. 43-49.

A. Markopoulou, 'Post-Machinic Sense' (2012), in L. Cappelli (ed.), *City Sense-Shaping our Environment with real-time data*, Barcelona, Actar, 2012.

A. Markopoulou, 'Parametric Urbanism', in L. Cappelli (ed.), *Self Sufficient City_Envisioning the habitat of the future*, Barcelona, Actar, 2010.



1. RESPONSIVE ARCHITECTURE & BEHAVIORS

1.1 RESPONSIVE ARCHITECTURE: URGENCY AND CONTEMPORARY RELEVANCE

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1. RESPONSIVE ARCHITECTURE AND BEHAVIORS

Image Source: IAAC MAA02 2016
Lluisa Roth.

1.1

RESPONSIVE ARCHITECTURE: URGENCY AND CONTEMPORARY RELEVANCE

1.1.1 THE ANTHROPOCENE AND THE ENVIRONMENTAL CRISIS

What comes next for our buildings and cities, presented by data and numbers, is a future full of unseen challenges for our society. The urban population is predicted to surpass six billion people living in cities by 2045¹. United Nations data estimates that there will be 37 megacities by 2025, 100 million homeless people, and up to 1.6 billion people lacking adequate housing in the world². Urbanization fosters growth (cities are accountable for 70% of GDP³), creates opportunities for productivity opportunities, and improves quality of life, but at the same time our cities and our urban lifestyle are the major causes of air contamination, waste, and energy consumption.

Our human and construction impacts drive us to now experience a massive environmental crisis⁴. Increasing atmospheric carbon dioxide, extreme weather events, collapsing ecosystems, desertification, toxic pollution, sea level rise and blue sky extinction, are part of an extensive list, both protagonists and causes for the historic gathering and climate pact of 196 countries in the Paris Agreement on Climate Change reached at COP21⁵.

Efforts to label the expanded human impact in the planet, have created a scientific debate between geologists and environmentalists. Many environmental experts support evidence that suggests that we have entered into a new geological age, named the “Anthropocene” [1], that defines a human-influenced time period where the earth's system processes are highly altered by humans. Although, not all geologists agree, one can clearly identify the

¹ 'World Urbanization Prospects', *United Nations. Population Division*, [website], <https://population.un.org/wup/>, (accessed 10 September 2018).

² United Nations, *A World of Cities*, August 2014. http://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2014-2.pdf, (accessed September 2018).

³ 'UN Habitat', *Urban Themes: Economy*, [website], <https://unhabitat.org/urban-themes/economy/>, (accessed September 2018).

⁴ A. Markopoulou, 'Design Behaviors', *IAAC Bits Advanced Architecture Group Journal, Black Ecologies*, vol. I, number 9, 2019. <https://iaac.net/category/publications/iaac-bits/>

⁵ COP21 or CMP 11 is the United Nations Climate Change Conference held in 2015 in Paris. In this conference, a global agreement on the reduction of climate change, was signed by the representatives of 196 countries.

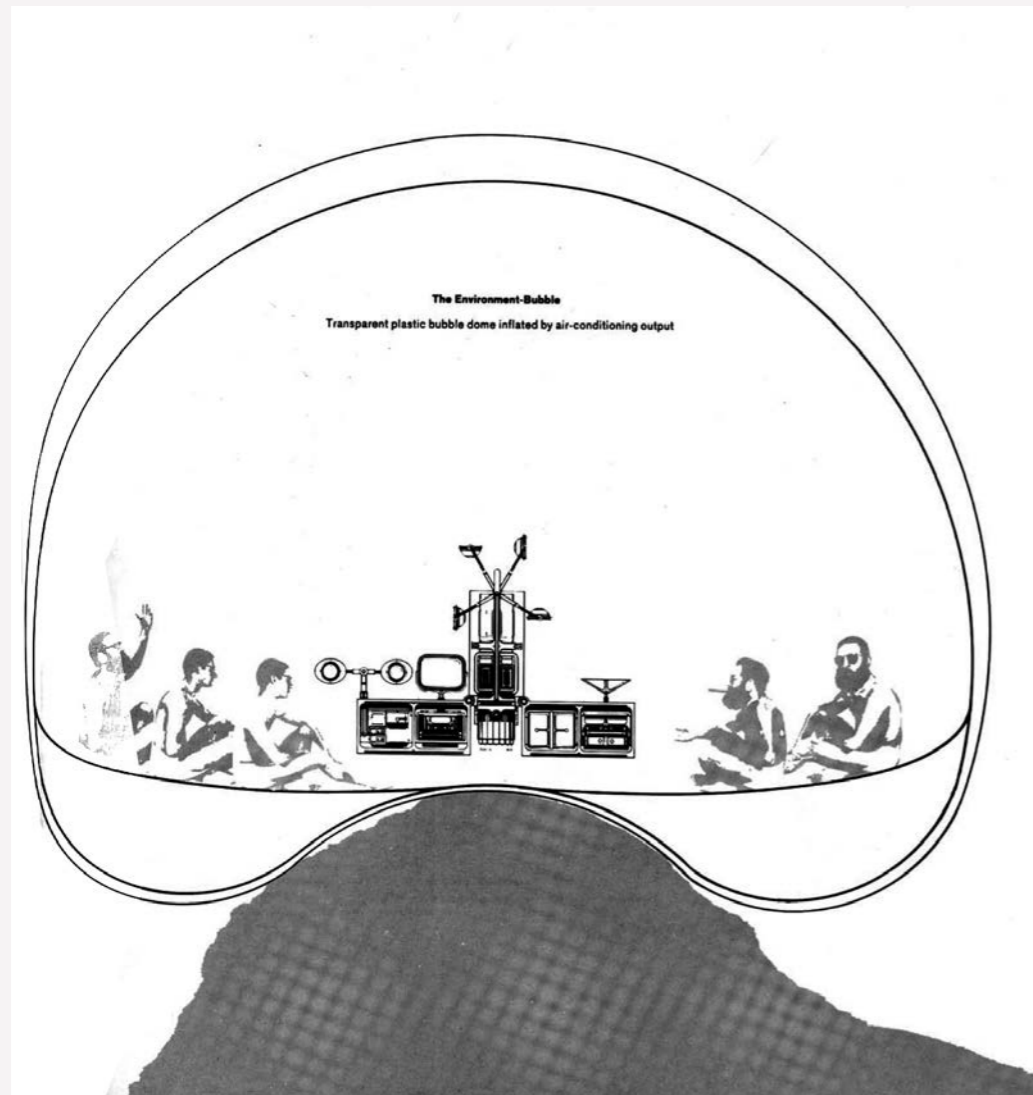


Figure 1.
François Dallegret, *The Environment-Bubble: Transparent Plastic Bubble Dome Inflated by Air-Conditioning output*.
Image Source: "A Home Is Not a House," Reyner Banham, *Art in America* (April 1965), Illustration by François Dallegret.

[i] The Anthropocene is distinguished as a new period either after or within the Holocene, the current epoch, which began approximately 10,000 years ago (about 8000 BC) with the end of the last glacial period. The term has been popularized by the atmospheric chemist and Nobel laureate Paul Crutzen in 2000, and it is being used by many environmentalists, although, it is not totally accepted by the geologists

[ii] LEED is a rating system for new construction developed by the U.S. Green Building Council (USGBC) in 2000.

[iii] The Green Building Initiative (GBI) was originally developed in Canada to assist the National Association of Homebuilders (NAHB) in promoting its Green Building Guidelines for Residential Structures. It has later expanded and became available for use in the U.S.

⁶ *Energy Performance of Buildings Directive, European Union Law, 2010*. https://eur-lex.europa.eu/legal-content/EN/ALL/;ELX_SESSIONID=FZMjThLLzfxmmMCQGp2Y1s2d3Tjwtd8QS3pqdkhXZbwqGwlgY9KN%212064651424?uri=CELEX:32010L0031 (accessed September 2018).

⁷ *Energy Performance of Buildings Directive, European Union Law, 2010*

⁸ *Energy Performance of Buildings Directive, European Union Law, 2010*

⁹ A. Markopoulou, 'Design Behaviors', 2019.

¹⁰ T. Jaskiewicz, 'Towards a methodology for complex adaptive interactive architecture', PhD Thesis, TU Delft, 2013.

¹¹ R. Banham, 'A Home Is not a House', *Art in America* 2, 1965, pp 109–118. Reprinted in W. Braham and J. Hale (eds.), *Rethinking Technology: A Reader in Architectural Theory*, London/New York, Routledge, 2007, pp159–166.

urgency for the environmental community to raise awareness about the multi-layered human impact on the planet.

More specifically, in the urban, architectural and building sectors today, we observe that our buildings are responsible for 40% of energy consumption and of 36% of CO₂ emissions into the atmosphere in Europe⁶, and similar numbers apply to the rest of the world. According to the Energy Performance of Buildings Directive, improving the energy efficiency of existing buildings and the introduction of energy related innovation in new constructions can not only have a positive impact on the environment and energetic consumption, but it can also generate other economic and social benefits too⁷.

The creation of "green" or "energy efficient" or "sustainable" building standards first appeared in the 1990s with the creation of the Building Research Establishment's Environmental Assessment Method (BREEAM), the first green building rating system in the U.K. The BREEAM has been followed by numerous similar building standards aiming at improving the environmental performance of buildings, such as the Leadership in Energy and Environmental Design (LEED [ii]) in 2000, or the Green Building Initiative [iii] (GBI) in 2005.

In a review of the European and global regulations and reports, keywords like "better performing buildings", "adaptive environments" and "climate adaptive buildings" are often interchangeable⁸ and one can observe the urgency for an alternative to the prevailing model buildings as static and based in linear consumption models. Of course, the principle of environmental adaptation in nature is an inherent property of organisms. Living organisms such as animals and plants always adapt to the environment, while in the case of humans, instead of adapting to, they mainly adapt the environment to their needs. In the context of buildings, as purely linear consuming and static organisms, it is of significant importance to understand that responsive architecture, presents a radically different model of operation. In this model, buildings operate as living entities, with embedded performance and intelligence to adapt not only to user's desires but additionally to environmental stimuli, the same behavior as found in living organisms⁹. Responsive Architecture presents potentials to reduce environmental impact, and requires revision of existing design and construction principles, as well as further implementation in the architecture and construction sector.

It is important though, to expand the definition of responsive architecture, beyond its embedded technology. In the search for reducing environmental impact, during the last two decades technologies of the Internet of Things and smart appliances have been proliferating in the building panorama. These technologies of architecture automation, as explained by Tomasz Jaskiewicz, by definition, require implementation of control systems that intermediately steer flexible building features, and that operate in connection to actuators and sensors¹⁰.

The question of Reyner Banham that opens his essay "A Home is Not a House" in 1965, is a direct warning to the loss of architectural existence, materiality, and identity driven by such automation. Although, the goal of Banham's theoretical paper is the creation of environmentally friendly mobile habitats that fit the needs of an increasingly nomad society, his vision presents architecture automation as the ultimate means for sustainable housing and questions the cultural importance of "home", reducing it to its environmental systems and electromechanical domestic services and functions (Figure 1). More specifically Banham asks: "when your house contains such a complex of piping, [...], wires, inlets, outlets, [...], hi-fi reverberators, antennae, conduits [...]- when it contains so many services that the hardware could stand up by itself without any assistance from the house, why have a house to hold it up?"¹¹.

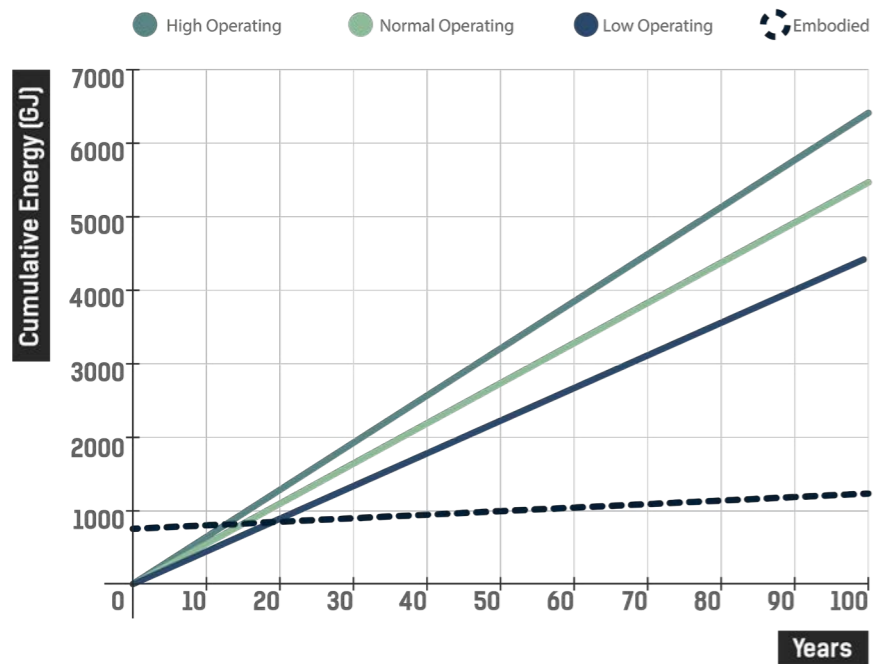


Figure 2.
 Research by CSIRO1 [iv] has found that the average house contains about 1,000GJ of energy embodied in the materials used in its construction. This is equivalent to about 15 years of normal operational energy use [v].
 Image Source: Adams, Connor and Ochsendorf 2006¹⁵ adapted by Geoff Milne and Chris Reardon

[iv] The Commonwealth Scientific and Industrial Research Organisation (CSIRO) is an independent Australian federal government agency responsible for scientific research.

[v] According to Milne and Reardon, until recently it was considered that the embodied energy content of a building was small compared to the energy used in operating the building over its life. This led to focus the efforts into reducing operating energy by improving the energy efficiency of the building envelope. Though, embodied energy can be the equivalent of many years of operational energy, which depends on the occupants. Embodied energy is not occupant dependent since the energy is built into the materials. For more information: G. Milne and C. Reardon, *Materials, Embodied Energy*, 2013. <http://www.yourhome.gov.au/materials/embodied-energy/>, (accessed July 2018)

¹² M. Kretzer, *Information Materials*, Berlin, Springer, 2017

¹³ C. Llatas, A model for quantifying construction waste in projects according to the European waste list, 2011, p 31. https://idus.us.es/xmlui/bitstream/handle/11441/65695/CWQuantificationModel_2011.pdf?sequence=1

¹⁴ C.S.Poon et al, *Quantifying the impact of Construction Waste Charging Scheme on construction waste management in Hong Kong*, 2013. https://www.researchgate.net/publication/50213299_A_model_for_quantifying_construction_waste_in_projects_according_to_the_European_waste_list

¹⁵ E. Adams, J. Connor, and J. Ochsendorf, *Embodied energy and operating energy for buildings: cumulative energy over time. Design for sustainability*, Cambridge, MIT Press, 2006. U.S. Energy Information Administration, *Annual Energy Outlook 2014*, 2014. [https://www.eia.gov/outlooks/aeo/pdf/0383\(2014\).pdf](https://www.eia.gov/outlooks/aeo/pdf/0383(2014).pdf)

¹⁷ S.L. Hsu, *Life cycle assessment of materials and construction in commercial structures: variability and limitations*, Master Thesis, Massachusetts Institute of Technology, 2010. Available from: <https://core.ac.uk/download/pdf/4425169.pdf>, (accessed October 2018).

¹⁸ O. Høibø, E. Hansen, and E. Nybakk, 'Building material preferences with a focus on wood in urban housing: durability and environmental impacts', *Canadian Journal of Forest Research*, 2015, p 45.

From the industrial revolution to today, such technologies of automation are mainly presented as systems of automation plugged in over traditional materials and existing building systems. Although, electric devices have dominated the field of building automation, the research work of contemporary architects such as Philip Beesley, Skylar Tibbits or Manuel Kretzer, among others, argue that other forms of sensing, control and actuation are also possible, through the focus on material response and with the introduction of "smart", "active", "functional" or "information materials"; a term Kretzer uses to describe the active and smart materials of which sensing, actuation and transformation are inherent properties, and which materials can be designed and applied in novel responsive architecture models¹².

A closer look at the impact of architectural materials in the environment, highlights the urgency of achieving built space behavior, performance and response not only through technological automation but additionally through rethinking which kind of architectural materials could be used. The building industry is one of the heaviest waste generators globally, with our construction or demolition waste (CDW) accounting for approximately 35% of all global waste¹³. More specifically CDW accounts for 70%, 50%, 44%, 36%, and 30% of the total waste in Spain, United Kingdom, Australia, Japan and Italy, respectively¹⁴.

Steel, concrete (cement) and plastic are the building materials that generally dominate the construction industry today. The cement industry, that heavily relies on coal and petroleum, is the most energy-intensive of all manufacturing industries¹⁶. The Embodied Energy (EE) of concrete is of 12.5MJ/kg EE, the EE of steel is of 10.5MJ/kg¹⁷ and the EE of plastics is of 10MJ/kg. The Embodied Energy of a material is defined by the energy consumed by all required processes, including manufacture, transport, installation or maintenance, in a building¹⁸. In a comparison with wood, of which the EE is of 2.00MJ/kg, the highly negative environmental impact of concrete and steel becomes more clear (Figure 2).

Within this context, and in relation to both the environmental crisis and material impacts, a number of interesting topics should be addressed:

- **Can the environmental crisis become the appropriate context for exploring novel possibilities towards adaptive building solutions that contribute to the energy hungry life and inhabitation style we lead?**
- **Can novel materials and technologies contribute to lowering buildings' energy consumption and environmental impact?**
- **Is a model of Responsive Architecture responding to the environment, one of the possible solutions to the urgent issue of low building performance and adaptability?**
- **How can architecture respond to growing population's needs and can it provide program optimization through adaptive spaces that are occupied differently according to time?**

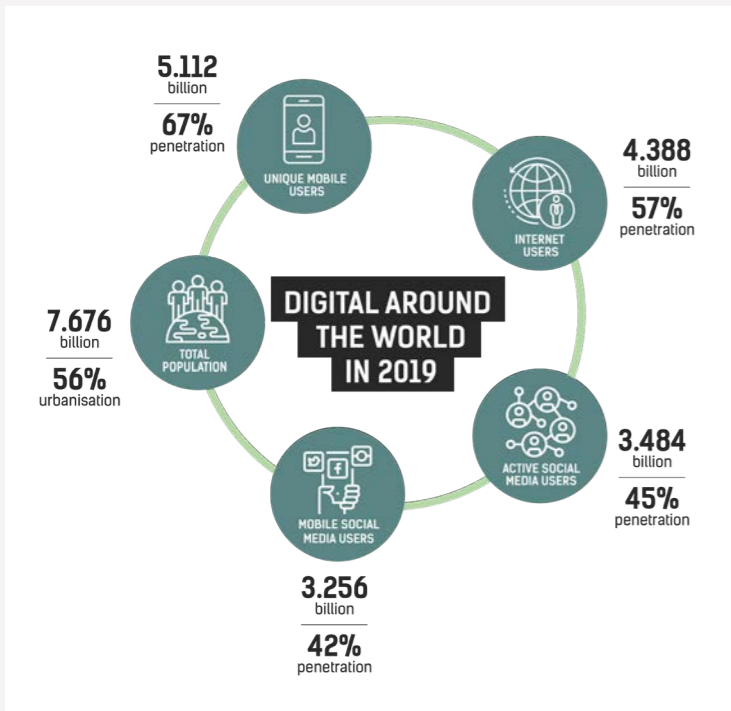


Figure 3. Number of digital services users in 2019. Diagram adapted by the Digital 2019 Reports. Adapted from Global Digital Overview, <https://datareportal.com/reports/digital-2019-global-digital-overview>

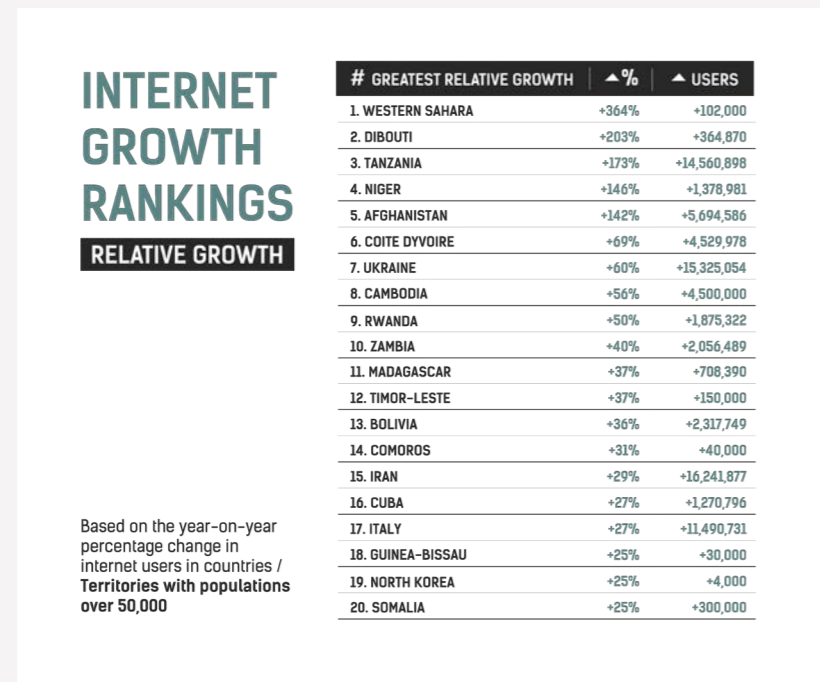


Figure 4. Top 20 countries with the highest relative growth in Internet Users in 2019. Diagram adapted by the Digital 2019 Reports. Adapted from Global Digital Overview, <https://datareportal.com/reports/digital-2019-global-digital-overview>

1.1.2 DIGITAL REVOLUTION AND SOCIETAL NEEDS

History indicates that any profound social change is in a circular feedback with a technological revolution, meaning that one is both fueling and being fueled by the other. With the revolution of the press we distributed information and knowledge. With the revolution of the steam engine we physically connected people with places and generated massive amounts of energy at will. With the revolution of the personal computer we digitally connected people to people and places, while with the Internet and the Internet of Things we democratized information and connected the physical with the digital world. Erik Brynjolfsson and Andrew McAfee, MIT professors and authors of the book “The Second Machine Age” consider that the Industrial revolution has brought the most profound changes in the history of our world. But they assert that the effects of Digital Revolution will be even greater:

“Computers and other digital advances are doing for mental power — the ability to use our brains to understand and shape our environments — what the steam engine and its descendants did for muscle power. They're allowing us to blow past previous limitations and taking us into new territory.”¹⁹

Digital Natives and Liquid Society

Digital technologies are becoming as transformational to society today, as has been the steam engine during the industrial revolution. According to Zygmunt Bauman, a Polish philosopher and sociologist, the digital age is aligned with a society of continuous change, temporariness, as well as fragility. He names this state of modern life as “liquid modernity” and argues that we are experiencing an age where the importance is not the final shape or state of somebody or something, but rather the process of a ‘forever becoming’, driven by principles of blurred limits and ‘undefined’ state and shape.

“[...] 'liquid modernity', is the growing conviction that change is the only permanence, and uncertainty the only certainty. A hundred years ago 'to be modern' meant to chase 'the final state of perfection' -- now it means an infinity of improvement, with no 'final state' in sight and none desired”²⁰

The digital revolution, brought together not only the possibilities of abundance in information, knowledge and connection but also the strong familiarization with accelerated and constant changes. Our needs and desires today (either physical or virtual) change following the accelerated rhythm and speed of bits and bytes, of the Internet. The Global Digital Overview of the Digital 2019 Reports showcase an average increase of internet users of more than one million users every day. An average of 57% of today's population is connected to the internet, with this number increasing day by day. (Figure 3). According to the same report there is a 9,1% annual increase in internet users and 10% of annual increase in mobile social media users. A detailed geographical chart connecting the increase of digital users with different countries in the world, showcase that developing countries are the ones ushering us into an internet revolution by rapidly increasing their users annually on rates that range from 25% to 360%. (Figure 4).

¹⁹ E. Brynjolfsson, A. McAfee, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, New York, W. W. Norton Company. 2016, first published January 2014.

²⁰ Z. Bauman, *Liquid Modernity*, Cambridge, Polity, 2000, pp.82.



Figure 5.
View of the world map of Fab Labs as of 2019.
Image Source: fablabs.io

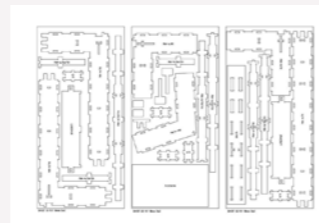
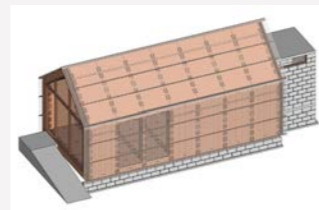


Figure 6.
Views of open source designs, axonometric, and fabrication plans of the WikiHouse project, an internet-based open source project for constructing sustainable and affordable housing.
Image Courtesy: WikiHouse

[vi] Instructables is a web based platform focusing on featuring do-it-yourself (DIY) projects that are uploaded by users. The content and projects include step by step visual and textual descriptions for allowing any user to make the project uploaded. The platform is based on crowdsourced collaboration, where community users collaborate to build projects together. A dedicated section of forum and discussion, empowers users to collaborate, comment, and share ideas on how to create new projects or revisit and evolve existing ones. For more info see: <https://www.instructables.com/>

[vii] Fab Labs are digitally fabrication laboratories located in different cities in the world, that share common equipment of fabrication machines such as 3d printers, laser cutters or CNC machines. The inventor of the idea of Fab Labs is Neil Gershenfeld, the Director of the Centre for Bits and Atoms (CBA) at the Massachusetts Institute of Technology (MIT) in Boston. Gershenfeld believes that the revolutions in digital fabrication machines can allow everyone to “make almost anything”. To support this idea he initiated the network of Fab Labs in order to empower people to have access to basic digital fabrication technologies and be able to produce big part of their ideas, designs or products they need. “Because all Fab Labs share common tools and processes, the program is building a global network, a distributed laboratory for research and invention”. Today, there are more than 1000 Fab Labs in the world. For more information see: Fab Foundation at <https://www.fabfoundation.org/> and <https://fablabs.io/labs/map>

[viii] WikiHouse is an internet-based house construction project. It is based on providing open-source customized designs for easily fabricated houses. Any user can choose a blueprint, download it and customize it to his/her needs, as well as share the model after customization. WikiHouse was initiated in 2011 by Alastair Parvin and Nick Ierodiaconou with the goal to democratize and simplify the construction of sustainable and self-fabricated houses. The goal is to be able to build houses quickly with a minimum cost related with raw materials and tools. For more info see: <https://wikihouse.cc/>

²¹ Bloomberg, *Rise of Gen Z Over Millennials*, 2019. <https://www.bloomberg.com/news/terminal/PDMAV0T25UKH>, (accessed February 2019)

²² T. Vardouli, ‘Who Designs? Technological Mediation in Participatory Design’, in D. Bihanic (ed.), *Empowering Users through Design*, Berlin, Springer, 2015, pp. 13-41

²³ D. Crow, *Left to Right: The Cultural Shift from Words to Pictures*, Lausanne, AVA Publishing, 2006

At the same time, a Bloomberg analysis based on United Nations data, showcases that in 2019, 32% percent of the global population is born after 2000 while 31.5% is born between 1980 and 2000. The first, called the Generation Z, have never known a non-digital world²¹, while the latter, called Generation Y have experienced the digital shift before the age of 20.

Within this context of an increasing digitally connected population, as well as its familiarization with constant change, a number of crucial questions for architecture emerge:

- **What kind of built space can accommodate the continuous changing needs of a digital native population? Can architectural space become dynamic to changes?**
- **What kind of novel mediums could connect the physical space with the digital content?**

Participatory Culture

The increasing digital connections and the rise of the Internet 2.0 boosted a highly participatory culture. The introduction of platforms such as “Wikipedia” or “YouTube”, allowed users to additionally produce and share content, becoming “producers”, rather than just “consumers” of content. As Vardouli writes when describing the views of the writer and Internet critique Nicholas Carr, “personal empowerment is currently the central theme of an almost universally accepted liberation mythology associated with information technologies”. She continues on referring to a number of names given by contemporary writers and thinkers to describe the effects on personal empowerment given by the internet and information technologies such as the “prosumer” by Toffler in 1989, the “designer-user” by Mackay in 2000, the “innovation user” by von Hippel and Katz in 2002, or the “maker” by Anderson in 2012²².

More and more people are becoming familiar with the idea of participating in the design and production of everything that surrounds them. Open source culture initially opened up music, and later on design and fabrication protocols, allowing everybody that is not an expert to be able to design and even participate in the production of most of the things they need. Following the “IKEA” model, today, we can assemble our furniture, following the model of digital platforms such as “Instructables” [vi] we can access, download or customize designs and following the “Fab Lab” [vii] network of digital fabrication laboratories, we can fabricate our own furniture or house (Figure 5).

With an accelerated generation eager to participate in everything that surrounds them, architecture will not stay unaffected. From open source design and fabrication of houses such as the WikiHouse [viii], to the interactive screens and appliances in our domestic environments, or the customized open plan of co-working spaces, people wish to be active participants with their buildings, their homes and their urban environments. (Figure 6).

Within this context a series of questions related with architecture emerge:

- **How can architecture integrate a variety of performances and experiences that allow users to customize them?**
- **Within a highly digital and participatory age, surrounded by digital natives, how can architecture respond to the users desires and needs?**

An increasing image-based culture

The introduction of the personal computer, the world wide web, the mobile telephone, the digital camera and social media are running in parallel with an increasingly image-based use of language²³. Media and visual content are present in every step of the daily lives of



Figure 7.
 Example of digital indoor navigation tool. View of mobile application for indoor navigation in the London Gatwick Airport. The system is based on the implementation of 2000 beacons (small Bluetooth radio transmitters) that can locate passenger position and provide instructions how to move towards their desired destination. The wayfinding tool, is supported by an augmented reality platform that helps the passenger visualize in physical space the indicated paths.
 Image Courtesy: PointrLabs
<http://www.inovateonthenet.net/news/article/uk%27s-gatwick-airport-installs-navigation-beacons-for-augmented-reality-wayfinding>

[ix] One of the three major conclusions of Brynjolfsson and McAfee about the digital age is that the transformations that they bring are and will be beneficial. They argue that digital technologies increase “consumption” of things that they are not necessarily material and tangible, such as information, knowledge, leisure or interaction. Without discarding other kind of risks, they assert that when such “consumables” are digitized they are subject to norms that they are defined by abundance rather than scarcity and, therefore, they can offer us more choices or freedom. Technology, in their opinion, could improve the physical world by expanding the digital one. For more see: E. Brynjolfsson, A. McAfee, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, New York, W. W. Norton Company, 2016, pp.10-12. First published January 2014.

²⁴ G. Debord, *The Society of Spectacle*, Las Vegas, Rebel Press, 1973. (first edition published in French in 1967 by Buchet-Chastel)

²⁵ J. Baudrillard, *The Mirror of Production*, Telos Press, 1975. https://monoskop.org/images/b/ba/Baudrillard_Jean_The_Mirror_of_Production_1975.pdf

²⁶ A. Markopoulou, ‘Design for the Flux’, in Willy Muller (ed.), *Urban Science*, Barcelona, Institute for Advanced Architecture of Catalonia Publisher, 2018

²⁷ A. Haw, C. Ratti, ‘Living Bits and Bricks’, *The Architectural Review*, 2012. <https://www.architectural-review.com/essays/viewpoints/living-bits-and-bricks/8629380.article> (accessed December 2018)

a vast majority of people. From expressing feelings through images and emoticons, to diaries based on social media photos and web based image libraries such as "Pinterest, the increasingly visual nature of our culture is mainly immediate and public. Many believe that the “Society of the Spectacle” presented in 1967 by Guy Debord, one of the key theorists in Situationist theory, had already foreseen our image-saturated and mediated society of the digital and social media age. For Debord modern society has lost its authentic social life since "all that once was directly lived has become mere representation" and the “being has declined into having, and having into merely appearing”. The Spectacle in his Society highlights the social life under capitalism, where audiences choose “commodity” instead of vital interaction²⁴. For Jean Baudrillard, on the other hand, that has been highly influenced by Debort and the Situationists, the audiences become passive viewers since the “real” is being replaced with “virtual” or simulated events, and the spectacle replaces "real life" entirely with technology²⁵.

Revisited today, the views of Debord or Baudrillard might be extremely relevant but not necessarily a clear representation of today's age of digital interaction. The spectacle and image of today, is not limited in social media and a pure representation or a “commodity”, but it rather expands to present an unprecedented merge of bits (digital) and atoms (physical) where audiences and users have unique control over creating personalized experiences. Technologies of Augmented and Mixed realities or technologically enhanced user interfaces present a new role for audiences, where participation is fundamental and where everyone can be a producer of content²⁶. Nevertheless, media and images become such crucial parts of our society today, which is why architecture needs yet to acquire new and variable formal identities, allowing audiences to actively participate.

Within this context an interesting question for architecture arises:

- **Which are the new aesthetic and design qualities of an architecture system that allows users to participate in it?**

The influence digital technology has had on the way we communicate, move, share, or behave is unprecedented. In order to highlight the accelerated progress of digital age Haw and Ratti argue upon laws of mathematics and physics:

“Kryder’s Law predicts doubling of digital storage at double the speed, and Butters’ Law of Photonics suggests a doubling of fibre-optic bandwidth even faster...In an age of powerful new systems and radically emancipated social relations, architecture – the persistent and unavoidable nexus and mediator between people and technology – lies at the heart of future change: its epitome (not just host) with the capacity to embody the opportunities of this accelerated manmade evolution”²⁷.

Our way of life is becoming increasingly digitally driven, and so is our architecture. We use computation to deliver work tasks, to communicate with our peers, to navigate to the urban environment and, eventually, to take decisions (Figure 7). For the first time in human history, the infrastructure of our needs acquires a new layer, a virtual one, operating in vast datasets, promising “abundance”, “variety of choice” and “freedom” [ix].

Within a context of increasing digitization, social participation and rapid urbanization, architecture, as the vital connector of humans, environment and technology, cannot remain unchanged. Similar to the essential changes that occurred as an effect of the industrial revolution, the architecture of the current digital age evolves to become a natural nexus between bits (digital world) and atoms (physical world).

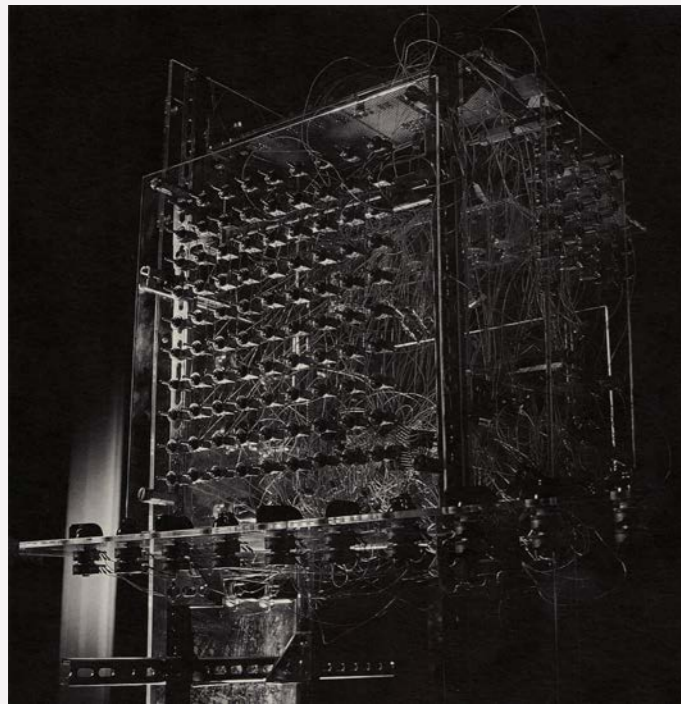


Figure 8.
Experimental Neural Network Computer: Miles Dobson, 1991
 "Neural Network computers are intended to be more closely analogous to the human brain than conventional serial computers. The function of neurons is simulated by components which are arranged in a network: several inputs represent synaptic connections which cause the neurone to learn to fire when a particular threshold signal level is received. This model was constructed so that the logical structure, the switching of the network and the adjustment of the threshold levels could all be seen and understood". (Frazer, 1995, description text for the image)
 Image Source: J. Frazer J. *An Evolutionary Architecture*, London, Architectural Association Publications, 1995, Section 1, pp. 26.



Figure 9.
"Universal Constructor", AA Diploma 11 Unit students, 1990, with Gordon Pask and Julia Frazer.
 Image Source: J. Frazer, J. "Computing without computers", *Architectural Design* 75(2), 2005, pp. 41

[x] See Chapter Section 1.2 *Architecture and the Machine* and 1.3 *Cybernetics and Architecture*

[xi] The Institute for Advanced Architecture of Catalonia (IAAC) is a centre for research, education, production and outreach, with the mission of envisioning the future habitat of our society and building it in the present. For more info see: <https://iaac.net/iaac/about/>.

[xii] MIT's Center for Bits and Atoms is an interdisciplinary initiative exploring the boundary between computer science and physical science. CBA studies how to turn data into things, and things into data. It manages facilities, runs research programs, supervises students, works with sponsors, creates startups, and does public outreach. For more info see: <http://cba.mit.edu/about/index.html>.

[xiii] Directed by Prof. ir. Kas Oosterhuis and managed by Dr.-Ing. Henriette Bier and Dr. Nimish Bioria, Hyperbody focuses on employing and advancing techniques and methods for designing, building, and operating Non-Standard and Interactive Architecture. For more info see: <http://www.hyperbody.nl/about/what/>.

²⁸ J. Frazer, *An Evolutionary Architecture*, London, Architectural Association Publications, 1995.

²⁹ V. Guallart, L. Cantarella, *The Media House Project*, Barcelona, Actar, 2004

³⁰ V. Guallart, L. Cantarella, *The Media House Project*

³¹ C. Kievid and K. Oosterhuis, 'Muscle NSA: a basis for a true paradigm shift in architecture', *Hyperbody Archives*, 2003. <http://www.hyperbody.nl/research/projects/muscle-nsa/>, (accessed September 2018).

³² K. Oosterhuis and I. Lénárd, 'Vers une architecture -é-motive', in Frédéric Migayrou (ed), *Architectures non standard*, Paris, Editions du Centre Pompidou. 2003

1.1.3 CONTEMPORARY DEFINITIONS OF RESPONSIVE ARCHITECTURE AND BEHAVIORS

As we will analyze in the next sections of this chapter, Responsive Architecture ideas have been initiated since the 1940s, highly influenced by Cybernetics, as well as theories of complexity and systems [x]. These ideas, were increasingly present till mid 70s, when a big gap on further development and thinking is observed. Since the 1990s, though, many of the responsive architecture visions are not only revisited but they also become less speculative with the emergence of built prototypes.

The shift towards built prototypes, was powered by the advancements of the Internet, as well as the advancements of wireless computer technologies that gave birth to the Internet of Things (IoT) and Ubiquitous Computing. John Frazer was the most important instigator of transforming the ideas of the 60s into built prototypes. He had further evolved the work of Gordon Pask and the ideas of evolution in architecture in his book "An Evolutionary Architecture"²⁸. The book introduced ideas of natural ecosystem lessons, as well as artificial intelligence with a specific focus on neural networks and evolutionary algorithms, including a series of built prototypes developed by himself together with Gordon Pask and the students of the Architectural Association from 1989 to 1996 (Figure 8 and 9).

In parallel, other academic and research centres such as the MIT, TUDelft, and the IAAC started to develop experimental built work in large scale, combining emerging technologies with the visions of responsive architecture. In 2001, IAAC [xi], a highly experimental architectural school, joined forces with the Centre for Bits and Atoms [xii], a department at the MIT working on the Internet of Things, to build the Media House project²⁹. The Media House was conceived as a "house that is a computer" instead of a "house that has a computer" and presented "the structure of the house as a network", by integrating technologies of IoT within the structure of the prototype³⁰. Through real time data the house was able to respond to the users behaviors and needs, and making use of media projections and sounds (Figure 10).

In 2003, the Hyperbody [xiii] research group of TU Delft developed and built the "Muscle", a building that is able to reconfigure itself "physically and mentally", introducing into a built prototype the ideas of an "emotional relationship between the house, its occupiers and the elements"³¹ that had been previously developed by Kas Oosterhuis in the E-motive House³².

From 2003 onwards, when different technologies (such as the Internet, the Internet of Things, Ubiquitous computing, user interfaces, artificial intelligence or smart materials), further advanced and became more accessible, we can observe a new significant group of contemporary architects and researchers that deal with the fluid environments of an information era as the appropriate context for re-exploring novel possibilities for responsive architecture through experimental prototypes and pilot projects.

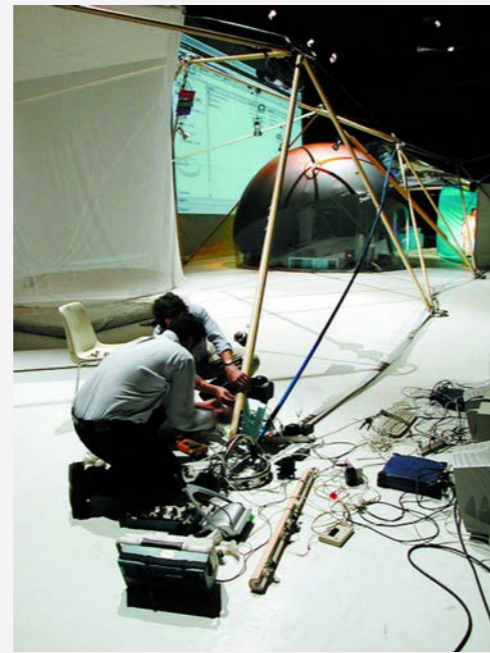
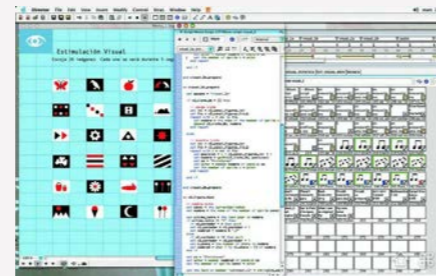


Figure 10.
 Top Left and Right: Structure of the Media House with embedded internet.
 Bottom Left: View of the Installation.
 Bottom Right: Media Interface screen for user's input in activating the house with media.
 Image Source: V. Guallart V., L. Cantarella, *The Media House Project*, Barcelona, Actar, 2004



[xiv] Kinetic architecture has been initially introduced by William Zuk and Roger H. Clark in 1970 when they published the book "Kinetic Architecture".

³³ K. Oosterhuis, *E-motive Architecture*, Rotterdam, 010 Publishers, 2002

³⁴ B. Kolarevic, A. Malkawi, *Performative Architecture, Beyond Instrumentality*, London, Spon Press, 2005

³⁵ B. Leupen, R. Heijne, J. van Zwol, *Time Based Architecture*, Rotterdam, 010 Publishers, 2005, pp12-15

³⁶ U. Haque, 'Architecture, Interaction, Systems', *AU: Arquitetura & Urbanismo*, no. 149, 2006.

³⁷ M. Fox and M. Kemp, *Interactive Architecture*, New York, Princeton Architectural Press, 2009.

³⁸ M. Fox, 'Bio-Robotic Architecture', B. Kolarevic and V. Parlac (eds), *Building Dynamics: Exploring Architecture of Change*, 2011, p164

³⁹ M. Hensel and A. Menges, *Morpho-Ecologies: Towards Heterogeneous Space In Architecture Design*, London, AA Publications, 2007

⁴⁰ A. Menges, 'Material Computation - Higher Integration in Morphogenetic Design', *Architectural Design*, Vol. 82, No. 2, 2012

⁴¹ R. Armstrong, 'How protocells can make 'Stuff' much more interesting', *AD Archt Design*, No. 81, pp. 68-77.

⁴² R. Armstrong, *Vibrant Architecture, Matter as a CoDesigner of Living Structures*, Warsaw, Sciendo, 2015. <https://www.degruyter.com/view/product/448453>, (accessed July 2018)

⁴³ R. Armstrong, *Soft Living Architecture, An Alternative View of Bio-informed Practice*, London, Bloomsbury Visual Arts, 2018

⁴⁴ P. Beesley, K. Omar, *Situated Technologies Pamphlets 4: Responsive Architecture, Performing Instruments*, New York: The Architectural League, 2009, pp.16-19

⁴⁵ M. Addington, DL. Schodek, *Smart materials and new technologies for the architecture and design professions*, Oxford, Architectural Press, 2005, pp. 16-19.

The definitions and the principles of performance in the contemporary approaches of responsive architecture vary. As previously mentioned, Kas Oosterhuis, focuses on the "**e-motive architecture**" that is based on the notion that buildings feed on, process and transmit information, while the individual building elements "behave like birds in a swarm"³³. Branco Kolarevic introduces "**performative architecture**" to describe an emerging approach to architecture in which building performance (especially environmental) is a guiding design principle³⁴. Bernard Leupen highlights the importance of time as a design parameter and introduced the term "time-based" in architecture, a concept derived from video and film-art. Leupen believes "**time-based architecture**" could allow for hybrid buildings, "part permanent, part changeable" as an answer to accelerated societal changes, and questions the practise of designing "slow moving objects/buildings"³⁵.

Delving into more detail of how the technology protocols work in responsive architecture, Usman Haque focused on the importance of "multiple feedback loops" as a "conversational" tool between users and environment³⁶. Similarly, Michael Fox, who initially focused on "**kinetic architecture**" [xiv] as founder of the Kinetic Design group at MIT in 1998, later on, in 2009 together with Miles Kemp published the "Interactive Architecture" book, highlighting a responsive architecture that is based on feedback loops and evolution opening ways to a biological paradigm versus a machine one³⁷. Following the principle of a biological paradigm, Fox also introduces "**bio-robotic architecture**" merging autonomous robots that could be both sensors and actuators with feedback loop systems of interaction³⁸.

The biological or biomimetic paradigm, is also followed by the work of Michael Hensel and Achim Menges that introduce the idea of "**morphoecologic architecture**" (Figure 11). Morpho-ecologies is a new proposed framework for architectural design concerned with issues of higher-level functionality and performance capacity, that provides specific material and energetic interventions in the physical environment³⁹. A few years later, Menges would add to that concept by redefining material performance and develop a series of built prototypes that explore the concept of responsive architecture based on the responsive capacity of the material itself⁴⁰. Rachel Armstrong's work, is the most representative of a group of architects and biologists that merge biological organisms with architecture introducing ideas of "**synthetic architecture**"⁴¹, "vibrant architecture"⁴² and "**soft living architecture**"⁴³.

In an effort to discuss the humanistic and theoretical side of the new architectural performance, Beesley and Kahn introduce "**responsive architecture**" that goes "beyond instrumentality". They focus on the potential of contemporary environments to "care," and on the "expansion of the power of architecture" on its inhabitants, introducing concepts of empathy and emotion⁴⁴.

Finally, a group of researchers and architects focus on responsive architecture through the implementation of next generation, smart and programmable materials. Addington and Schodek with the goal of thinking about architecture "as a network of transient environments" argue that architecture has seen relatively little technological and material change since the 19th century, and urge architects to integrate in their responsive design smart and active materials that are capable of creating change at the scale of their property⁴⁵. The director of the MIT Self Assembly Lab, Skylar Tibbits, foresees responsive design through the use of "**self assembly**" and "programmable materials". His work is focused on programming materials to change shape or behavior, to transform or to reconfigure themselves so that we have more adaptive, and responsive products⁴⁶. Similarly Manuel Kretzer highlights the possibility of an "**alive architecture**" and a new softness through the use of "information materials", which are active and smart, and which do not only "carry and visualize information but are also based on information, being artificially created from pure intellect"⁴⁷.

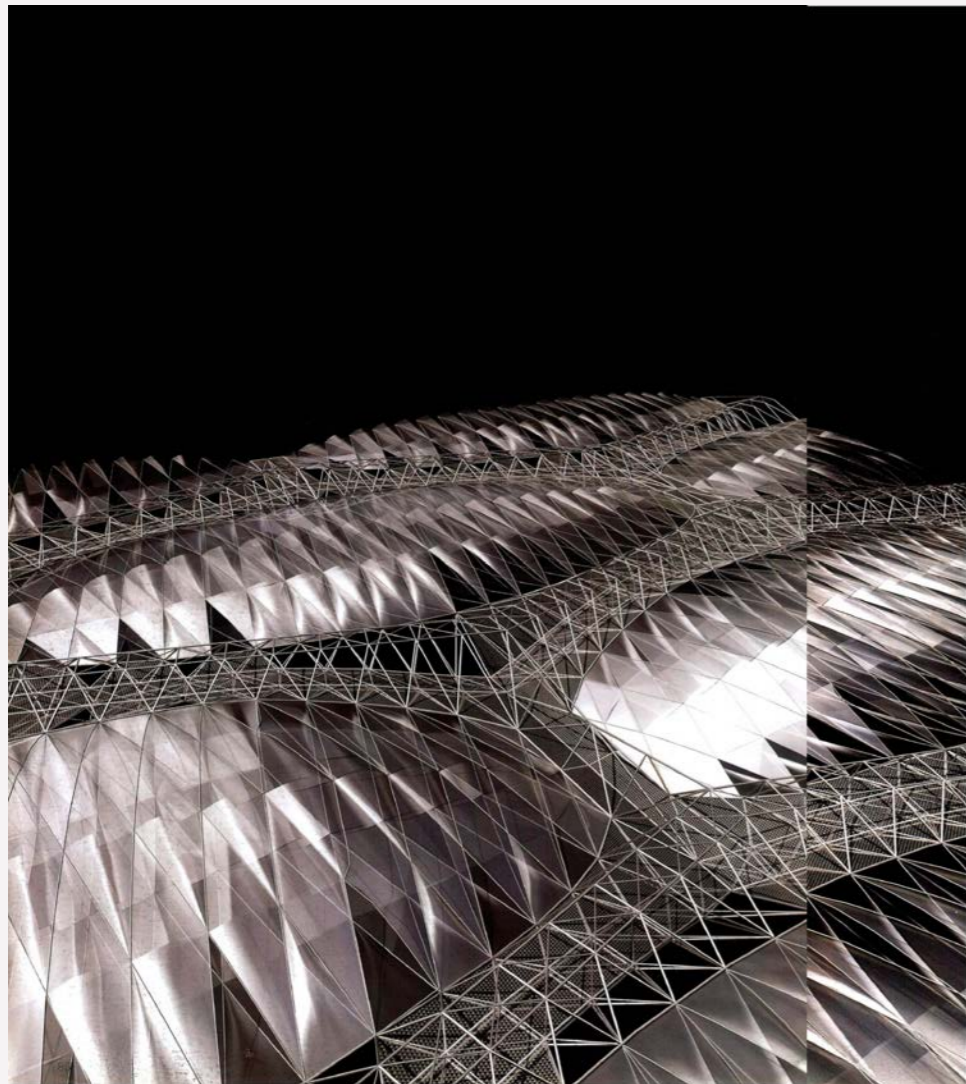


Figure 11.
Morpho-ecologic principles in form finding processes where surface components are formed based on structural and orientation parameters of the seams, as well as based on the type of the surface material.
 Image Source: A. Menges, *Morpho-Ecologies: Approaching Complex Environments*, *Architectural Design*, Vol. 74, No. 3, 2004, pp. 80-89.

As we observe, there is a wide variety of approaches that leads to a variety of design and construction logics for responsive architecture.

The reasons for working towards the materialization of a responsive architecture can be clustered in three categories:

- a. **the challenges related with the environmental crisis and the necessary symbiosis of architecture with its environment,**
- b. **the necessity of participatory design processes and the inclusion of users and citizens in the creation of the spaces they inhabit and**
- c. **the continuous changing needs and cultural shift based on technologies that consequently affect the way we inhabit spaces.**

This thesis recognizes that such variety of approaches and the design logics attached to them, makes it difficult to develop a coherent framework that could be useful to designers and architects that wish to further implement the principles of responsive architecture. At the same time, taking into consideration the material impact of our construction that we studied earlier in this chapter [xv], as well as the advancements of the material science in the last two decades [xvi], this thesis highlights the importance of Materially Responsive Architecture and proposes an index of the different categories of design and performance within the scope of active materials applied to built space.

[xv] See Chapter Section 1.1.1 *The Anthropocene and the Environmental Crisis*

[xvi] See Chapter 2. *Active materials in Architecture*

⁴⁶ S. Tibbits, '4D Printing: multi-material shape change', Bob Sheil (ed.), *Architectural Design*, vol. 84, no. 1, 2014

⁴⁷ M. Kretzer, *Information Materials*, Berlin, Springer, 2017, p. 16

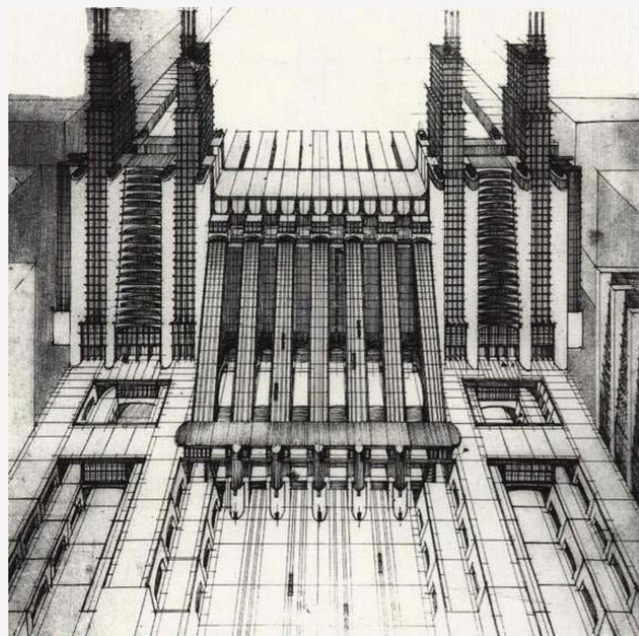
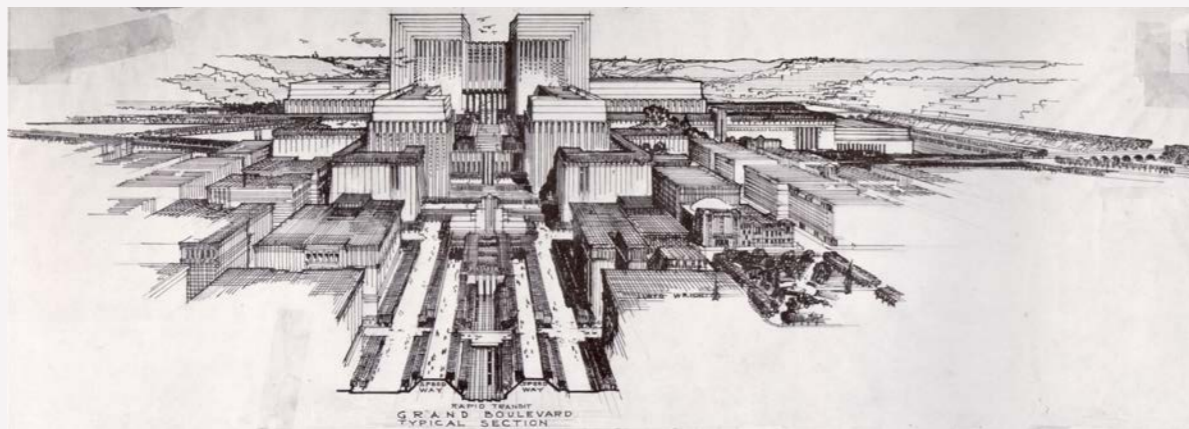


Figure 1.
Selection of drawing from Sant'Elia New City (Città Nuova) (1914) drawing series that were featuring the Futuristic City that later became the futuristic architecture. The image shows a futuristic train station and airport using new aesthetic design language and materials, 1913.

Left Image Courtesy: Digital library of the The "Sant'Elia project" at the Pinacoteca Civica,
<http://eng.antoniosantelia.org/>
Bottom Image Source: Amin Y., T.Dunkan,
<https://cpb-us-e1.wpmucdn.com/blogs.uoregon.edu/dist/6/11803/files/2015/10/Tyler-Amin-case-study-1yfhfju.pdf>



[i] In relation to the prevailing architectural styles of his time towards technological advancements and urban challenges Sant'Elia comments that "the kaleidoscopic appearance and disappearance of forms, the self-multiplication of machinery, the daily growth of needs generated by rapid communication, the concentration of populations, hygiene and a hundred other phenomena of modern life do not faze these self-styled renewers of architecture" (Sant'Elia, 1914).

¹ A. Sant'Elia, 'Futurist Architecture', *Futurism: An Anthology*, New Haven, Yale University Press, 2009, p. 200.

² A. Sant'Elia, 'Manifesto of Futurist Architecture (11 July 1914)', U. Apollonio(ed.), *Futurist manifestos*, London, Thames and Hudson, 1973. The "Manifesto of Futurist Architecture" of Antonio Sant'Elia was originally published in Lacerba in July 1914. It was the expanded version of Sant'Elia's earlier 'Messaggio, published in Nuove Tendenze in May 1914.

1.2

ARCHITECTURE AND THE MACHINE

"We must invent and rebuild our Futurist city like an immense and tumultuous shipyard, active, mobile, and everywhere dynamic, and the Futurist house like a gigantic machine...Just as the ancients drew their inspiration from natural elements, we - materially and spiritually artificial - must find our inspiration in the new mechanical world we have created, and our architecture must be its most beautiful expression, its most complete synthesis, its most effective integration"

Antonio Sant'Elia¹, 1916

Throughout the history of architecture, built environments have always been in close connection with technological advancements. The invention of the wheel, steam engine, automobile or the elevator and the computer, have been to architects a stimuli on envisioning how technologies can affect the way buildings and cities look, operate, and interact with the users and the environment. For many of these architects, the technological advancements have been a powerful tool to question not only traditional architectural aesthetics and functions but also environmental, political or cultural aspects of their times.

Antonio Sant'Elia, an Italian architect and the writer of Futurist Architecture Manifesto² of 1914, was inspired by technological innovations of grain elevators, power plants, and airplane hangars to develop a series of drawings featuring future trains penetrating buildings, external elevators that climb building's facades or high-rise minimalistic buildings that opposed to current building regulations (Figure 1). His visions expressed in the drawings, were a direct response to the need of city's expansion as well as to the hygienic challenges of Rome towards epidemics. He didn't stop there, though. His visionary proposals, as well as his written manifesto, radically questioned the traditional materiality of buildings as well as the cultural connection with the Baroque, Gothic and Neoclassicism style [i] of his time, expressed by straight lines and abundant decorations highly disconnected from structural or functional necessities. In his Futurist Architecture Manifesto, we clearly observe the desire to bring a new order, aesthetics and automated operations to the built environment through the use of technologies and new materials.

The written document asks from architecture to be motivated by "perfection of machine technology and the scientific use of materials" while it introduces aesthetic ideas that question stability and rigidity stating that "we have, in fact, lost our sense of the monumental, the ponderous, the static; we have enriched our sensibilities with a taste for the light, the practical, the ephemeral and the swift." He drives the attention of architects

to the use and exploration of new materials, that include reinforced concrete and steel but also explore "...cardboard, textile fibers and any substitutes for wood, stone and brick that allow a maximum elasticity and lightness". He, therefore, introduces the idea of **ephemerality and plasticity** and urges for the constant renovation of urban environments since "buildings will last less time than we will and each generation will have to build its own cities". Sant'Elia promoted that within our artificial materiality and spirituality we shall drive constructive inspiration in "the utterly new mechanical world we have created" and urged architects to "invent and reconstruct the Futurist city on the model of an immense and tumultuous shipyard, every part agile, mobile and dynamic; and the Futurist house must be like a gigantic machine" **that responds to people's enriched sensibility of the light, the ephemeral and the dynamic.**

Although Antonio Sant'Elia did not manage to actually build his high-flown visions, he has inspired architects such as Le Corbusier with his ideal functional and organized city, as well as playwrights such as the *Metropolis by Fritz Lang* (1927), a cinematography piece set in a dystopian future where social classes reflect the city's structure, and where city's shapes and materials are directly influenced by Sant'Elia's drawings.

Sant'Elia's manifesto was by no doubt futuristic and revolutionary for its time. Though, interpreting it today, one can claim that much of his written words were slightly contradictory with his spatial visions and applications. Although, for instance he speaks about ephemerality, dynamism and elastic architecture, his drawings reveal durable, static and rigid structures. The dynamic aspect of a space that reacts to people's sensibilities and needs for ephemeral or "light and swift" spaces only remains in the limited aspect of passing from stone to concrete and steel, or the introduction of high speed infrastructures that connect people with other people and places. This happens because Sant'Elia's vision, was deeply connected with the Machine paradigm driven by industrialization and infrastructural automation, the same paradigm that characterized the following Modern movement in architecture and the principles of "Machine for Living In" of Le Corbusier, the leading architectural figure of the modern movement in architecture³.

The decades that followed Sant' Elia's visions and the modern movement, introduced a series of novel ideas in relation to **responsive inhabitation** of architecture and cities. Le Corbusier, in his manifesto in 1924 introduces the concept of the open plan, driven by columns instead of structural walls, allowing thus, space to host different functions with different subdivision requirements. Such solution emerged from the acceptance that **static, closed plans are not efficient** and do not respond to the changing needs of programs. It is therefore, imperative to introduce new design and construction methods that allow buildings functions to change over time. Although such an approach which is highly present in the modern movement, supports the idea of architecture that can respond to different possible functions, it is finally driven by a result of fixed programmatic decisions and static configurations of spaces. Furthermore, such approach of flexibility gives no attention or control to the changing needs and desires of its inhabitants. Finally, the modern movement introduces the new materials of its time (concrete and steel) as a means to achieve open and flexible plans, but without exploring the relation of the change occurring with the same properties of the material systems.

³ Le Corbusier, *Toward an Architecture*, Los Angeles, Getty Publications, 2007 (first edition in French in 1923)

1.2.1 ARCHITECTURE AT (USER'S) WILL

During the post second world war period of 1950s and 60s, a new generation of projects started to arise that were relating to, but also questioning of modern views and connections of architecture and the machine. This period is characterized on the one hand by the accelerated technological advancements - especially the introduction of cybernetics (as is later explained in detail [ii]), and on the other hand, by unique social risk contexts related to post war conditions, and lack of diversity due to mass produced prefabricated housing modules.

During this period, the modernistic principle of open plan, extended from the building to the urban scale, can be found in the work of Yona Friedman and his post-war *Mobile Architecture Manifesto*⁴ (1958) presented in the Congrès International d'Architecture Moderne in Dubrovnik. Presenting principles such as architecture should be "mobile and shape the neighborhood" or, "buildings must be skeletons that are refillable at will"⁵, Friedman questions the modernist principle of the multiple but static configurations of space, as well as the **hierarchy of decision making** of such configurations. He, for the first time, proposes the design of an infrastructural framework in which the interior is directly manipulated and finally formed by the users and inhabitants.

In his *Spatial City* [iii], a framework of a modular grid truss is his proposal for a structure erected from the ground, with an open interior plan that can be finally decided, formed and continuously modified by users. Friedman introduces for the first time the idea of customized "dwelling decided by occupant" and **an architecture finally built and formed by users**, both principles that are totally absent from Sant' Elia's or Le Corbusier's vision of machinic, flexible and dynamic space. Similarly to the modern approach, though, Friedman's materiality and built structure, either made by concrete or steel, remains static and rigid, and do not respond or is not affected by any change occurring in the interior.

[ii] See Chapter Section 1.3 *Cybernetics in Architecture*

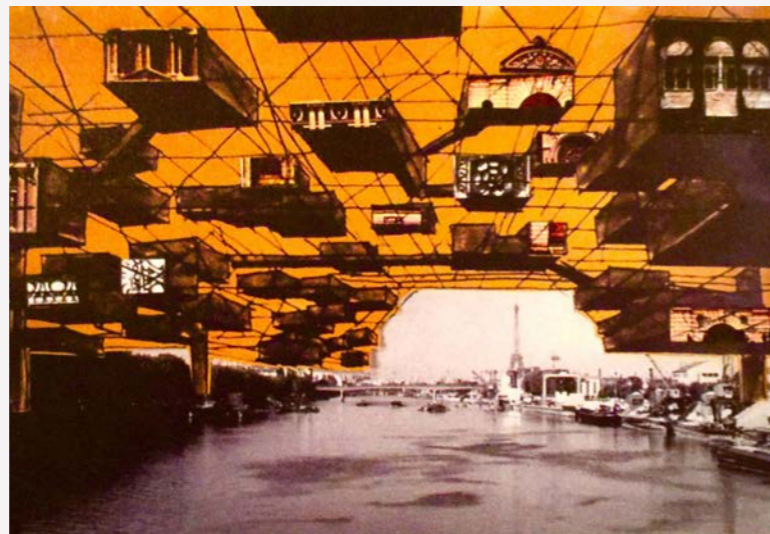
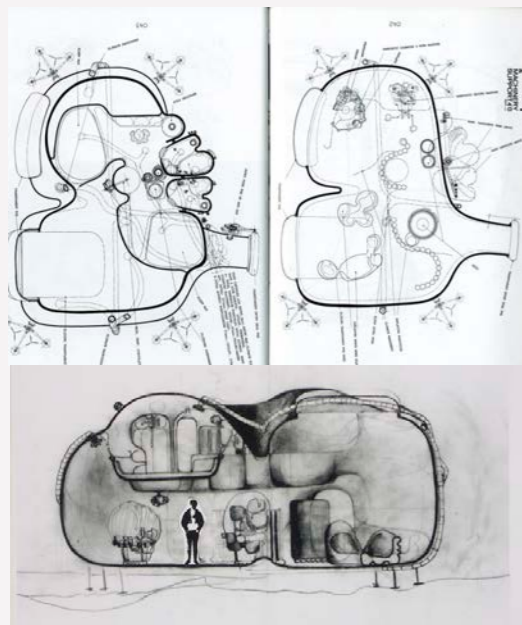
[iii] *Spatial City* by Yona Friedman is a speculative city proposal of 1958-59, seeking to respond to the critical issue of housing shortage in France.

⁴Y. Friedman, *Mobile Architecture: 10 principles of spatial urbanism*, 1959. http://www.yonafriedman.nl/?page_id=351, (accessed February 2019)

⁵Y. Friedman, *Manifesto Architecture Mobile*, 1956. <http://www.yonafriedman.nl>, (accessed February 2019)



Figure 2.
 Left: *Instant City Airships, Visit to a Small Town* by Peter Cook, 1970.
 Image Courtesy: Archigram
 Bottom Left: *Plan of Living Pod*
 Image Copyright: David Greene, 1966
 Bottom Right: *Image of Spatial City proposal* of Yona Friedman, 1959.
 Image Source: Digital library of Yona Friedman's website: <http://www.yonafriedman.nl>, last accessed February, 2019



1.2.2 DYNAMIC STRUCTURES & STIMULI OF RESPONSE

A few years later, Archigram, a visionary group that Friedman also joined, started publishing a series of novel ideas on "machinic" architecture. In proposals such as "Plug-in City" (1964), "Instant City" (1968), or "LivingPod" (1966), the entire architectural structures are affected by, and produce change, either by moving in different locations or being aggregated and deployed in different configurations (Figure 2). The "Plug-In City", for instance, proposes a hypothetical city as a central megastructure in which modular residential units are plugged in, and which is able to grow in units and size according to the needs during time. The suggested city (megastucture) is being configured and takes shape by movable elements aggregated by giant cranes. Similarly, David Green in his proposal of "Living Pod" for Archigram, intends to **reject permanence** in the house brief creating a nomadic dwelling that seeks participating in a mobile world. " With apologies to the master, the house is an appliance for carrying with you, the city is a machine for plugging into", writes Green in his description for the project⁶.

The previous seen static structures hosting a flexible interior and program, are here **being radically explored as themselves being dynamic, flexible or mobile**. These visions, highly driven by social and economic challenges of the time, they are additionally influenced by the latest for the age, technological advancements. In their proposal, Archigram clearly introduces the use of both mechanical, engineering and media technologies such as automated machines, robots, projected audiovisuals and space technologies.

As Steiner describes, "the work prepared by Archigram introduces the transition from the industrial to the digital era", or one can claim to the post digital era since "from the analogies of infrastructural and bodily conduits to bubble skins, biomorphic podes and reflexive systems, the unity of technology and biology combined topological form with a biological paradigm"⁷. Buildings and space were not seen anymore, as a purely artificial static entity, but rather **as a space that presents principles of operation that resemble human or alive organisms behavior**.

It is interesting, though, to observe that, although much of this architectural work is conceived as the visions of technologically driven living environments that are able to move or respond as biological organisms do, the input of response is always attributed to one agent, which is usually the users. We observe the absence of diverse and collective inputs coming from other sources, such as environmental and material inputs, as well as the absence of inputs coming from the learning and evolving behavior of the living organism (mobile architecture) itself.

⁶ P. Cook, Archigram, Princeton, Princeton Architectural Press, Revised Edition, 1999

⁷ H. A. Steiner, *Beyond Archigram: The Structure of Circulation*, London, Routledge, 2013, pp 238, 240

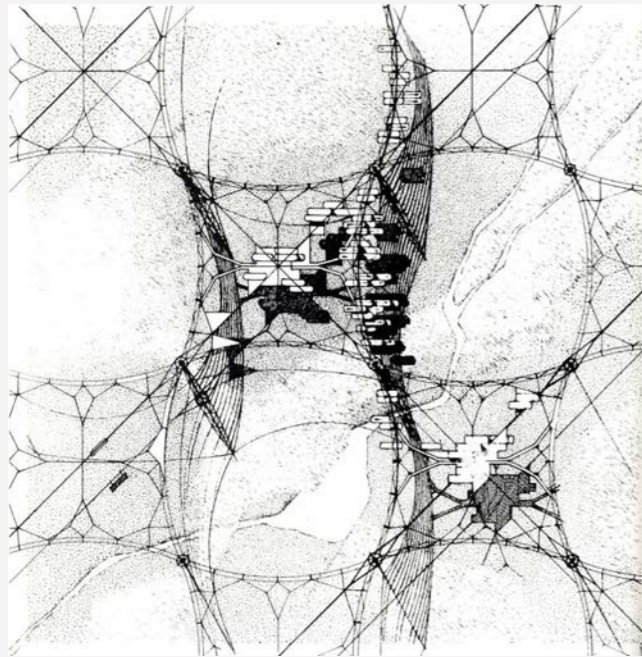
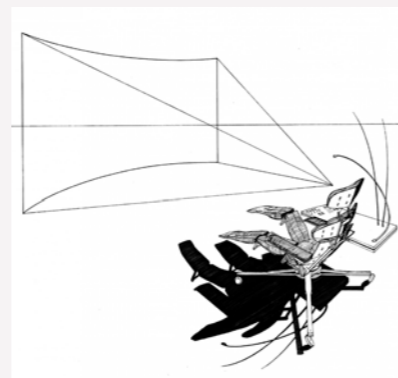
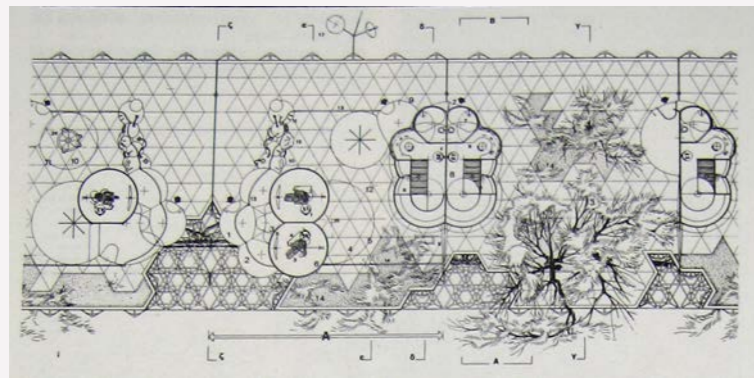


Figure 3.
Drawing of Takes Zenetos on the spider infrastructural web and the individual pods at the "Electronic Urbanism and the City of the Future", 1974.
Image Source: Takis Ch. Zenetos, 1926–1977 (Architecture in Greece Editions, Athens 1978)



[iv] In 1977, Reyner Banham in an architectural review of Centre Pompidou, noted the influence of Price work for the design of the centre by writing that "the concept of a stack of clear floors that can be adapted to a variety of cultural and recreational functions seems to recall the . . . Fun Palace of Cedric Price and Joan Littlewood, even if the project was never as radical as the floorless Fun Palace, or as casually innovative as Price's Inter-Action Centre." (Reyner Banham, "Centre Pompidou," *Architectural Review* 161 (May 1977): 270–94)

⁸L. Kallipolliti, 'Cloud Colonies: Electronic Urbanism and Takes Zenetos' City of the Future in the 1960s', *102nd ACSA Annual Meeting Conference, Globalizing Architecture, Flows and Disruptions*, 102nd ACSA Annual Meeting Conference, 2014, pp 678-685

⁹T. Zenetos, 'Town Planning and Electronics', *Architecture in Greece*, no. 8, 1974, p 125.

¹⁰S. M. Hobart and W. S. Colleges, 'The Fun Palace: Cedric Price's experiment in architecture and technology', *Technoetic Arts: A Journal of Speculative Research*, vol. 3, no 2, Bristol, Intellect Ltd, 2005

1.2.3 IMMATERIALITY AND VIRTUALITY

During 1952 and 1962, greek architect and cybernetician Takes Zenetos in his "Electronic Urbanism and the City of the Future" presents a radically different vision of responsive architecture and cities. Rather than a city that adapts to fulfill human desires and needs, the Electronic urbanism responds to adaptation on environmental and ecological risks. His suspended and detached from the ground city, is supported in "wire spider web" forms, that create closed protected environments and controlled microclimates. Individual pod containers are attached to the infrastructural web field, not as shelters for the inhabitant, but mainly as prosthetics to the inhabitants body. Zenetos, imagines that the technology is not just embedded into materials and structures but mainly **in the human mind**, which is able to control and change the environment by signals of communication that require no movement.

The City of the Future of Zenetos (Figure 3) introduces details of the "posture chair" as a body prosthetic where the human body virtually experiences all aspects of human life in atrophy⁸. In this sense, Zenetos is the first to introduce the notion of holistic virtuality and of an immaterial model of architecture and cities. The dynamic aspects and the adaptability of that model are not any more part of the mechanical infrastructure of the built space as seen in the previous models, but are driven by and only exist in the human mind and senses. Zenetos writes in his closing statement for Electronic Urbanism: "Conventional robots, along with the intelligent machines of A. C. Clarke, will be completely useless, because technological developments in the immaterial fields will proceed at a much faster pace and will be more effective than what we usually expect them to be."⁹

1.2.4 INDETERMINACY, SPATIAL INTERACTIVITY AND INTELLIGENCE

The most influential architect in responsive architecture, is by no doubt Cedric Price. The "Fun Palace", that started in 1962 as a collaboration between Cedric Price and avant-garde theater producer Joan Littlewood is conceived as a "socially interactive machine highly adaptable to the shifting cultural and social conditions of its time and place". Highly reprogrammable, the Fun Palace was able to be reconfigured by the users desires to create leisure, education or event performance. Price thought of the Fun Palace in terms of process, as events in time rather than objects in space, and "embraced indeterminacy as a core design principle"¹⁰. The project, that later in 1976 inspired the design of Centre Pompidou in Paris [iv], showcased pivoting escalators and moveable wall panels that would

permit endless variation and flexibility. The significant novelty in the project is related to the notion of spatial interactivity and intelligence. The project team, in collaboration with Gordon Pask, a pioneer of cybernetics of this time, envisioned and described a technology implemented in the Fun Palace that could directly monitor the patterns of use and desire, thus allowing the building to reprogram and control itself based on these patterns. For the first time, we observe the intention of creating **spaces with embedded intelligence and awareness**. As Jaskiewicz describes it, “user activities would be monitored and future behaviour and organisation of space would autonomously try to adjust to previously acquired knowledge about user preferences in connection to specific situations, ultimately leading to creation of space that interacts with rather than being controlled by its users”¹¹.

This exact principle of autonomous behavior emerging through learning by distinct data and stimuli, is the basis of artificial intelligence in computer science, which is why both “Fun Palace” and the “Generator Project” developed few years later with architect John Frazer, can be considered the first early investigations into artificially intelligent architecture. Price is proposing a new dialogue between users and physical space using technology as a mediator for this dialogue. He perceives responsive architecture as a living system starting on the basis of automation but evolving into an organism that can learn, remember, suggest and actuate. Although Price’s novel projects, can be considered the first attempts to design architectural behaviors through vast data and a variety of stimuli, the technology for actuating space mutations is **still based on traditional mechanical systems and materials** such as cranes, escalators and steel formworks.

1.2.5 KEY QUESTIONS

Friedman, Archigram, Price or Zenetos have inspired and have been inspired by similar projects booming in the same period, such as the work of Situationists [v] (1957), the New Babylon of Constant Nieuwenhuis (1955-60)¹² and the work of Metabolists [vi] in Japan (1958), all questioning a rather static architecture and plan, proposing buildings and cities that operate as machines and respond and adapt to environmental, cultural and societal needs. The projects and movements mentioned in this chapter, are emerging in the international architectural scene and are the most significant selection of an extensive list highlighting the need of architecture to respond to functions, environment, society and users in a more dynamic way. Although, it is not in the objective of the current thesis to describe in detail all the aforementioned initiatives, it is important for its development to highlight the following observations:

[v] According to the Situationists, the benign professionalism of architecture and design had led to a sterilization of the world that threatened to wipe out any sense of spontaneity or playfulness. They experimented with “the construction of situations” allowing individuals to pursue their own, primitive desires. From Simon Sadler, *Situationist City*, Cambridge, MIT Press, 1998.

[vi] Metabolism was a post-war Japanese architectural movement that fused ideas about architectural megastructures with those of organic biological growth. Their designs included vast cities that floated on the oceans and plug-in capsule towers such as the Nagakin Capsule tower in Tokyo built in 1972.

- **Matter:** All of the projects and initiatives above, introduce the notion of responsive architecture towards a programmatic change or a formal change but, they exclusively imagine the mentioned response through flexible construction systems that use traditional and existing static materials (truss, steel, inflatable membranes), or the absence of material and the introduction of the virtual as in the case of Zenetos. Furthermore, the actuating technology presented in all cases is limited to mechanical actuations including heavy motors, robots or pneumatic and hydraulic systems.

Within this observation, the current thesis seeks to introduce the question:

- **Can the material advancements of today enhance the behavior of response, presenting a new Materially Responsive Architecture model?**
- **Can novel materials become integrated actuators following a soft-organic, rather than a heavy-mechanical, paradigm of response?**

- Types of Stimuli:

Within the history of responsive architecture visions, we can clearly identify two distinct stimuli that activate response for space adaptation and reconfiguration. The first stimuli, prevailing in the work of Friedman or Archigram, is the stimuli of the user’s desire and need. The second (additional to the user’s desire) stimuli, introduced especially in the work of Zenetos is the stimuli of the environment, including temperature, humidity or oxygen levels. Finally, in the work of Price, we identify the intention of a more complex system, where stimuli is not linearly connected just with one agent, but the technology enables the system to internally generate new stimuli, by the capacity of learning from behavioral agent’s patterns and predicting user’s desires or environmental and context specificities.

Within this observation, the current thesis seeks to introduce the question:

- **Which materials and technologies in contemporary responsive architecture practice can be used to respond to the different stimuli for actuation in an holistic way?**

- Computational Intelligence and Multiple Inputs:

None of the above projects present an holistic vision of responsive architecture, where all inputs of environment, user desires, material performance, as well as the physical space mutation, are in a constant dialogue and feedback.

None of the above seek to create spaces that are truly intelligent, meaning spaces that they are not just actuated by mechanical inputs and outputs, but they acquire intelligence by learning through training [vii], the same process found in humans and living organisms.

Within this observation, the current thesis seeks to respond to the question:

- **Can computation and artificial intelligence technologies coupled with active materials contribute in an holistic vision of responsive architecture?**

While Sant’Elia or modernist visions have emerged from advancements in materials such as concrete or steel and advancements in engineering including the elevator, Cedric Price’s, Zenetos’ or Archigram’s visions have been driven by the advancements in computation and cybernetics that were thriving since the 1950s. Moreover, the development of Cedric Price’s projects brought together both architects and cybernetics and introduced unique multidisciplinary collaborations for the future of designing architectural behaviors.

[vii] The origins as well as the contemporary ideas of embedded intelligence, learning and training of objects/buildings are further described in the Chapter Sections 1.3 *Cybernetics and Architecture* and 3.3 *Self Active Matter: On a Self-Awareness model driven by multiple stimuli*

¹¹ T. Jaskiewicz, ‘Towards a methodology for complex adaptive interactive architecture’, PhD Thesis, TU Delft, 2013

¹² M. Wigley, *Constant’s New Babylon: The Hyper-architecture of Desire*, Rotterdam, 010 Publishers, 1998.

1.3

CYBERNETICS IN ARCHITECTURE

1.3.1 CYBERNETICS AND MACHINE/OBJECTS ENVIRONMENTS

The term Cybernetics was coined by Norbert Wiener in his book “Cybernetics” in 1948, defining it as “the scientific study of control and communication in the animal and the machine.”¹ Its focus is how anything (digital, mechanical or biological) processes information, reacts to information, and changes or can be changed to better accomplish the first two tasks². Cybernetics treats not things but ways of behaving. It is applicable when **the analyzed system generates change in its environment and that change is reflected in the system in a manner that leads to a system change**. This continuous dialogue between environment, object/subject and change, as well as the feedback among them, is considered the most crucial aspect of system behavior when we explore Responsive Architecture, as this thesis does.

Although the term of cybernetics has been given by Wiener, its principles and foundations lay in the previously published paper “Behavior, Purpose and Teleology”³ by Wiener together with Rosenblueth and Bigelow in 1943. In this paper, the authors categorize and create an hierarchy of the behaviors of a system according to whether this behavior can be predicted or not, and if the behavior has a purpose or not. Besides the definition of the different behaviors, the authors for the first time introduce the term “**feedback**” in **the relation of machine/object and environment**, describing a continuous dialogue among them, by exchanging information on their state and therefore adjust their behaviors based on the learning from that state (Figure 1). This notion of collective and embedded intelligence, influenced much of the architectural visions of this time, as described in the previous chapter, and became the foundation for the innovative work of Cedric Price.

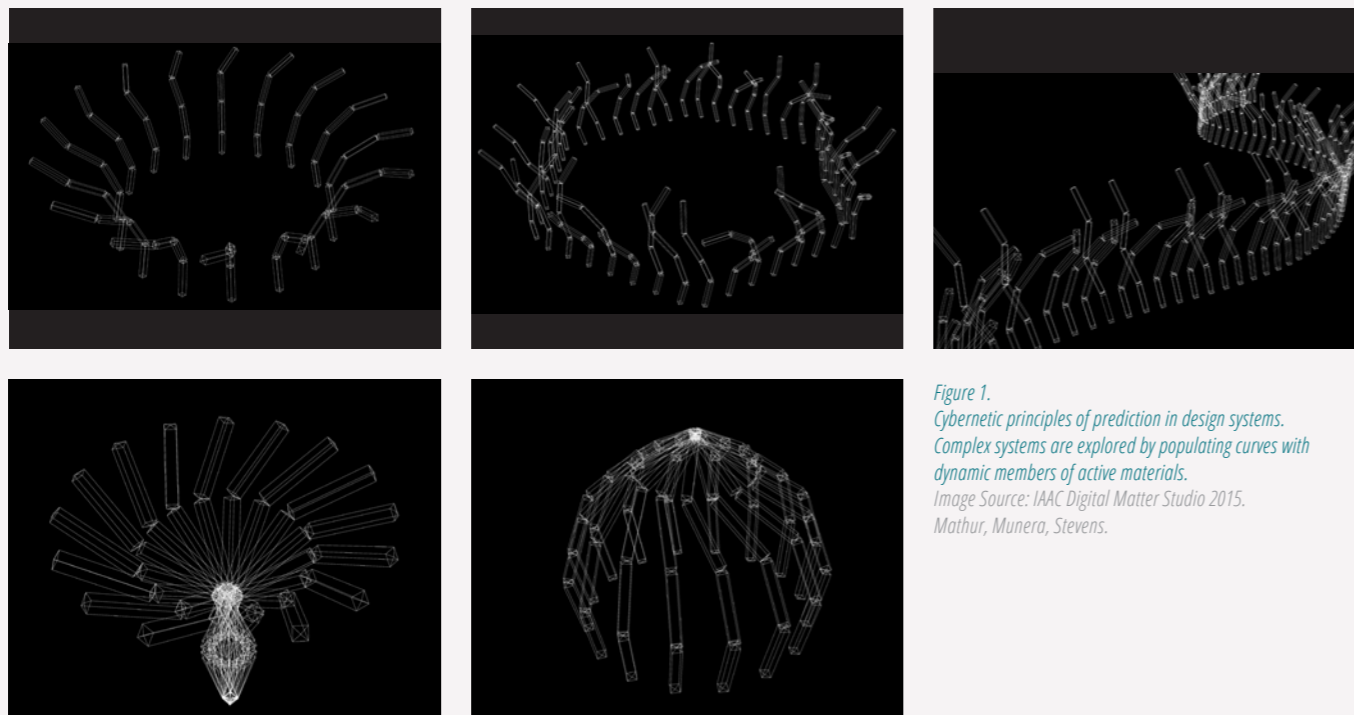


Figure 1.
Cybernetic principles of prediction in design systems.
Complex systems are explored by populating curves with
dynamic members of active materials.
Image Source: IAAC Digital Matter Studio 2015.
Mathur, Munera, Stevens.

¹ N. Wiener, *Cybernetics, or the Control and Communication in the Animal and the Machine*, Cambridge, MIT Press, 1985. (First published in 1948). https://uberty.org/wp-content/uploads/2015/07/Norbert_Wiener_Cybernetics.pdf

² K. Kevin, *Out of control: The new biology of machines, social systems and the economic world*, Boston, Addison-Wesley, 1994.

³ A. Rosenblueth, N. Wiener, and J. Bigelow, ‘Behavior, Purpose and Teleology’, *Philosophy of Science*, vol. 10, no. 1, 1943, pp. 18–24.

1.3.2 DESIGN OF INTELLIGENT ENVIRONMENTS

Following the advances in cybernetics and the new thinking in the dynamic relation to object and environment, in 1967, the architect Warren Brodey publishes a rather revolutionary essay called “Soft Architecture – The Design of Intelligent Environments”⁴, where for the first time the previous notions of dynamism, flexibility, ephemerality and swift in architecture, acquire a rather wider significance. Brodey describes as “intelligent environment”, one that goes beyond automation, and that operates in similar logics as self-organizing systems found in living organisms.

The environment described by Brodey is highly adaptive, and it is in a continuous interaction with the users that inhabit it. The environment’s behavioral changes are affected by the users, but this change also affects back the behavior of the users [i]. This interaction, by no means refers to formal language and aesthetics as in the Sant’Elia’s paradigm, but rather to a more sophisticated self-organizing system that presents evolutionary behaviors, similar to the built space of Cedric Price’s visions.

Highly affected by the exploration of cybernetics, Brodey claimed that current automation paradigms in physical space were restricting to the “limited human behaviors that the machines can accept as meaningful control”, and therefore, we need to consider that **machines should become more intelligent by being taught, in the same way as the humans become intelligent**. Such steps, could enhance human-environment evolution and he states that “evolution now must include evolving environments which evolve man, so that he in turn can evolve more propitious environments in an ever quickening cycle”.

[i] Warren Brodey defines an “evolutionary” system as a system that can form new “purposes”.

⁴ W. Brodey, ‘The design of intelligent environments: Soft architecture’, *Landscape*, 1967, pp. 8–12.

1.3.3 MODELS OF ARCHITECTURAL RESPONSE

An important number of architects and cyberneticists during the 60s and 70s have explored the applications of cybernetics in architecture, either by written articles or by different physical experiments. Andrew Rabeneck in 1969, highlighted the fact that building technologies were “inherently inflexible” and urged for using cybernetics in order to achieve flexibility in architecture. He supported the capacity of cybernetics to **“couple automation with predictive technologies”**⁵.

While Rabeneck and Brodey call for a responsive architecture model that is based on automated changes through prediction, Charles Eastman and Yona Friedman in the “Design Participation” conference of the Design Research Society in 1971, present two models of architectural changes that are directly manipulated by users. Friedman’s model is a centralized model of feedback loop, albeit Eastman’s model is a fully distributed one⁶. Whereas both models are based on prescribing an “objective,” “unintentional” mediation by users, Nicholas Negroponte’s⁷ proposal at the same conference, presented a different attitude. As Vardouli explains in her effort of identifying the different models in relation to the user, “opposite to Friedman who mechanized the human intermediary, Negroponte aspired to humanize the machine; opposite to Eastman who imagined the environment as a responsive servant of human activity, he envisioned **a co-evolving partner**”⁸.

Essentially, Negroponte’s proposal portrayed the users as active subjects whose decisions in changing architecture are shaped through embodied engagements with the technological environment itself. In his two published books, that followed the Conference, Negroponte will introduce the idea of “computer-aided participatory design”⁹, or a “design amplifier”, as well as the necessity of introducing artificial intelligence in buildings¹⁰.

⁵ A. Rabeneck, ‘Cybermation: A Useful Dream’, *Architectural Design*, 1969.

⁶ T. Jaskiewicz, ‘Towards a methodology for complex adaptive interactive architecture’, PhD Thesis, TU Delft, 2013, p 35.

⁷ N. Negroponte, ‘Aspects of living in an architecture machine’, in N. Cross (ed.), *Design participation: proceedings of the Design Research Society’s conference*, London, Academy Editions, 1972.

⁸ T. Vardouli, ‘Who Designs? Technological Mediation in Participatory Design’, in D. Bihanic (ed.), *Empowering Users through Design*, Berlin, Springer, 2015, pp. 13–41

⁹ N. Negroponte, *The Architecture Machine: Toward a More Human Environment*, Cambridge, The MIT Press, 1973.

¹⁰ N. Negroponte, *Soft Architecture Machines*, Cambridge, The MIT Press, 1976.

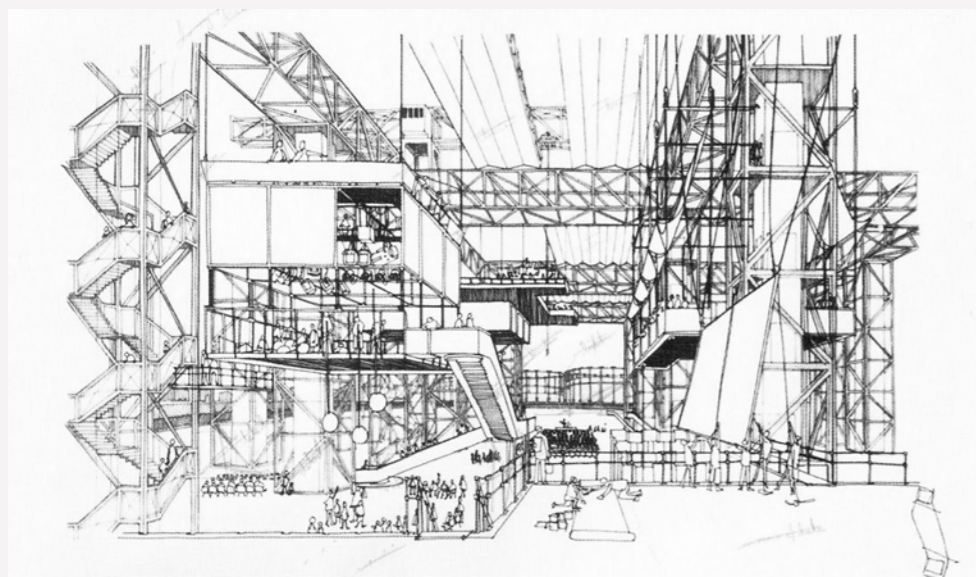


Figure 2.
Image of Cedric Price's drawing of the interior of the Fun Palace, circa 1965.
Image Source: S. Mathews, "The Fun Palace as Virtual Architecture Cedric Price and the Practices of Indeterminacy", *Journal of Architectural Education*, pp. 39-48^a 2006 ACSA in *Center for Architecture and Situated Technologies*.

[ii] Gordon Pask defines in his paper 'The Architectural Relevance of Cybernetics' as "descriptive", the taxonomy of building methods that architecture responds to, and as "prescriptive, the preparation of plans that architecture uses.

¹¹ G. Pask, 'The Architectural Relevance of Cybernetics', London, *Architectural Design*, September issue No 7/6, John Wiley & Sons Ltd, 1969, pp 494-6.

¹² G. Pask, *Conversation Theory: applications in Education and Epistemology*, Amsterdam, New York, Elsevier, 1976.

¹³ S. M. Hobart and W. S. Colleges, "The Fun Palace: Cedric Price's experiment in architecture and technology", *Technoetic Arts: A Journal of Speculative Research*, vol. 3, no. 2, Bristol, Intellect Ltd, 2005.

¹⁴ G. Pask, 'The Architectural Relevance of Cybernetics', London, *Architectural Design*, September issue No 7/6, John Wiley & Sons Ltd, 1969, pp 494-6.

¹⁵ J. H. Frazer, "The cybernetics of architecture: a tribute to the contribution of Gordon Pask, *Kybernetes*, vol. 30 Issue: 5/6, 2001, pp. 641-651.

¹⁶ G. Pask, 'The Architectural Relevance of Cybernetics', London, *Architectural Design*, September issue No 7/6, John Wiley & Sons Ltd, 1969, pp 494-6.

¹⁷ G. Pask, 'The Architectural Relevance of Cybernetics', pp 494-6.

1.3.4 FEEDBACK BASED BEHAVIOR AND EVOLUTION

The most known connection, though, between feedback based behavior among users and the built environment, has been presented by Gordon Pask, the most influential cyberneticist in the realm of responsive architecture. Pask regarded cybernetics not as a unilateral system of one-way reactivity, but as **a two way 'conversation' between entities**¹¹. In 1976, he developed his "conversation theory"¹² describing the technical aspect of how the exchange of information and feedback among object and environment can lead to the creation of knowledge that will allow both the environment and the object to alter their behavior.

To Pask, cybernetics held a particular promise for architecture and design, which he saw as essentially interactive systems of human interaction. Actually, in 1963, Pask joined the Fun Palace team in order to describe and integrate the cybernetics requirements for the project (Figure 2). He gradually shifted the focus of the Fun Palace towards cybernetics, since, as Mathews describes, the latest advances in cybernetic technology appeared to hold endless promise as a means of reconciling 'bricks and mortar' with the multivalent and ever changing functions and programmes of the Fun Palace¹³. Pask's work and writings that was focused on the comprehension of architecture as a compilation of active systems, in contrast to the perception of a building as simply a static material object¹⁴, placed him at the higher level of influence for responsive architecture today. As John Frazer, the architect that worked with Gordon Pask in the last decade of his life indicates¹⁵, Pask's "contributed to an increasingly environmentally responsive architectural theory that may lead to a more humane and ecologically conscious environment".

One of the most important for this thesis Pask's studies, is the study of the architect's role in design. He claims that architectural designs should have rules for evolution built into them if their growth is to be healthy rather than cancerous. "In other words, **a responsible architect must be concerned with evolutionary properties**; he cannot merely stand back and observe evolution as something that happens to his structures.¹⁶ Pask considers cybernetics as a tool for the architect to achieve the integration of evolution, since cybernetics have an "appreciable predictive power"¹⁷ that can add to the rather limited characteristics of architecture that is only descriptive and prescriptive by doing little to predict or explain. [ii]

In one of his footnotes of the "The Architectural Relevance of Cybernetics' paper, Pask touches the crucial for this thesis, **aspect of the material response**. He explains that cybernetics, although had the power to predict in architecture through simulations and artificial intelligence computers, it actually does not take into consideration any alterations related to biochemistry or the molecular scale of biology and matter. Referring to the work of Warren Brodey and his group at the environmental ecology laboratory at the MIT, Pask highlights the importance of active matter, that is able to return messages to the

computer, reprogram itself to acquire mechanical stability and actively look for signs of human beings around it. He explains the importance of a dialogue between computers, matter and humans within a “malleable and adaptive” environment. He also highlights that one important stage of architectural design, in the context of a reactive and adaptive environment, is the architect's choice of the basic environmental materials, since this way **the architect determines what properties will be relevant in the man-environment dialogue**. The matter he describes is enhanced with “tactile or visual sensors” [iii]. Pask has clearly foreseen the need of a novel matter within the new dialogue of responsive architecture, and one could claim that the evolution of the matter he describes is what today we know as active and smart materials, meaning materials that can change properties and that have embedded capacities of sensing and actuation.

1.3.5 KEY QUESTIONS

From the mid 70s to the 90s there has been a big gap on further development and thinking around the cybernetics and architecture. In the 90s, though, John Frazer, had further evolved the work of Gordon Pask and the ideas of evolution in architecture in his book “An Evolutionary Architecture”¹⁸. The book introduced ideas of artificial intelligence with specific focus on neural networks and evolutionary algorithms, as well as included a series of built prototypes developed by John Frazer, Gordon Pask and the students of the Architectural Association during the 90s.

The raise of cybernetics in the late 60s and mid 70s has provided the theoretical technological background for the development of novel architectural visions, where **architecture is not static and rigid, but rather flexible, adaptive and responsive to user needs as well as to cultural and environmental conditions**. None of such architectural visions could operate in the absence of cybernetic technology. Furthermore, for the first time in the history of architecture, **notions of intelligence and self-awareness are attributed to built space**, including the required technological descriptions and means for such embedded intelligence to be implemented.

Cybernetics provided the technological means, the theories and the detailed logics to power futuristic visions of responsive architecture within a unique cultural and technological context; on the one hand post war massive dwelling constructions and cold-war politics, and on the other, the blooming of information thinking driven by general systems theory. Cybernetics not only contributed giving birth to ideas of responsive architecture, but also bringing them closer to reality, as well as introducing a series of computer-based logics and terminologies to describe and define the architectural behaviors and their design. Moreover, beyond any technological empowerment, the scientific discipline of cybernetics suggested new ways of thinking of and interacting with built space. Introduction of questions related with virtuality in architecture, data and feedback, and the unique

[iii] At the ‘The Architectural Relevance of Cybernetics’, in one of his footnote related to the “appreciable predictive power” of cybernetics, Pask writes: “The impact of cybernetics upon architecture is considerable just because the theory does have much more predictive power than pure architecture had. Cybernetics did relatively little to alter the shape of biochemistry for instance, because although these concepts are bound up with everything from enzyme organisation to molecular biology, the discipline of biochemistry already had a predictive and explanatory theory of its own”. For more see: G. Pask, ‘The Architectural Relevance of Cybernetics’, pp 494-6.

interactive relationship of humans/organisms and technology/ machines are the central predecessors of our current digital age and culture.

Although, the architectural behavior during the 60s and until late 90s, is mainly achieved through sensors, computers, machines and mechanized systems, initial questions and visions on active and dynamic materials already start to appear in both the architectural and cybernetic world. Whereas the questions were not explored deeply enough to embrace a new material ecology, the notions and requests for a living and humanizing machine as described by Nicholas Negroponte, or the need of a matter able to actively sense human beings around it and reprogram itself described by Gordon Pask, are the first signs of a responsive architectural thinking that **embraces matter as an important aspect of the human-environment-technology dialogue**.

Finally, as detailed above, beyond any technology or materiality the key aspect to highlight, is that responsive architecture has been initially introduced as the potential solution to face social participation as well as cultural and environmental risks of the current society. As we have seen along the current chapter, these issues are still extremely relevant today. Moreover, further current advancements in computation and material sciences, already influence a wide group of disciplines, which seek to integrate responsive performances in objects (product design), vehicles (transport engineering) or bodies (wearable and fashion design). Architecture, slow and steady, starts to integrate such learnings, expanding the material and computational possibilities in both design and construction of our built environment.

¹⁸ John Frazer, *An Evolutionary Architecture*, London, Architectural Association Publications, 1995.

1.4

FROM THE MECHANICAL TO THE ORGANIC PARADIGM

“A biological paradigm requires more than just understanding pragmatic and performance-based technologies; aesthetic, conceptual and philosophical issues relating to the humans and global environment must also be taken into consideration”

Michael Fox¹, 2011

As described in the current chapter², the environmental impact of construction materials and processes, the cultural shifts towards the reevaluation of permanence and property in an accelerated digital society, as well as the increasing culture of participation, are some of the most important current aspects that urge for architectural solutions that are not only responsive and dynamic but also subject to changes that occur through a collaborative manner.

These novel cultural shifts require **a paradigm that goes beyond pure automation**, integrating aspects of collaboration, collective intelligence and evolution. Such an integration resembles a more organic and biological paradigm where all nodes of the responsive systems are highly interconnected and dependent. As a variety of people have highlighted, in order to enhance such paradigm, a new focus towards redefining the materiality involved in responsive systems is required.

Fox and Kemp argue that whereas until the 90s, the focus was to optimize a controlled performance of responsive architecture through computational information and processing, our contemporary culture of the 21st century begins to signal a shift from a mechanical paradigm of adaptation to a biological paradigm. The prevalence of the organic paradigm, they argue, begins to alter our conception and comprehension of our environment, and consequently, “the conceptual model that

we apply in order to design in our environment is also altered”³.

The organic paradigm, which is driven by biology and nature, is not new. In 1969, biomedical engineer Otto Schmitt defined “biomimetics” as a scientific approach that studies methods, designs and processes in nature, with the goal to imitate them in human made solutions and environments⁴. Within the field of responsive architecture, many have explored and are exploring the idea of biomimetics in architecture, since as Gruber and Jeronimidis argue, “using biology’s categories to analyse the current frontier of research and innovation, we discover many ‘signs of life’ in architecture projects, and many researchers are actively involved with ways to implement more and more aspects of life into buildings”⁵.

In his book “Information Materials”, Kretzer argues that when smart and active materials are introduced into the responsive architecture model, this latter one, surpasses the mechanical paradigm and moves towards “softness and organicism as particular behavioral properties akin to phenomena that occur in nature, which thus might foster a much more intuitive and personal human association than mechanical systems would ever allow for”⁶. Similarly, Fox and Kemp, referring to Brown Gary⁷, specifically highlight the shift of material and operational scale in the organic paradigm of responsive architecture. They recognize the introduction of a profound set of developments in materials, biomimetics, and evolutionary systems, whereby they foresee that adaptation within these systems “becomes much more holistic, and operates on a very small scale”⁸.

Within this context, it becomes imperative to identify the advancements of material science that follows the organic system [i] instead of the mechanical one, and further explore their effect in architecture within the current digitally-driven culture shifts. The emergence of a series of novel materials developed during the last decades and tested in several disciplines, can operate in a very small scale and when applied in architecture can further empower an organic paradigm of holistic responsiveness and adaptation.

[i] According to Brown Gary, “Organic system and theory emerges from the natural environment, an environment that possesses evolutionary patterns which have a base code, and an inherent programme where information is strategically related to the environment to produce forms of growth and strategies of behaviour, optimising each particular pattern to the contextual situation. In Brown Gary, *Freedom and Transience of Space*, 2002, retrieved by <http://researchonline.ljmu.ac.uk/1674/1/Freedom%20%26%20Trans%20Space%2002.pdf>, Last accessed, July 2018.

¹ M. Fox, ‘Bio-Robotic Architecture’, *Building Dynamics: Exploring Architecture of Change*, Abingdon-on-Thames, Routledge, 2011, pp164.

² See Chapter Section 1.1. *Urgency for Responsive Architecture and relevance with today*

³ M. Fox, M. Kemp, *Interactive Architecture*, New York, Princeton Architectural Press, 2009, pp. 1212

⁴ O.H. Schmitt, ‘Some Interesting and Useful Biomimetic Transforms’, *Third International Biophysics Congress*, Boston, 1969, pp.297

⁵ P. Gruber and G. Jeronimidis, ‘Has biomimetics arrived in architecture?’, *Bioinspiration & Biomimetics*, vol. 7, no. 1, 2012. <https://iopscience.iop.org/article/10.1088/1748-3182/7/1/010201/pdf>

⁶ M. Kretzer, *Information Materials*, Berlin, Springer, 2017.

⁷ Fox and Kemp refer to the introduction article of Brown Gary in *Transportable Environments 2*, edited by Robert Kronenburg, Joseph Lim and Wong Yunn Chii. London, Spon Press, 2002.

⁸ M. Fox, M. Kemp, *Interactive Architecture*, New York, Princeton Architectural Press, 2009, pp.



2. ACTIVE MATERIALS IN ARCHITECTURE

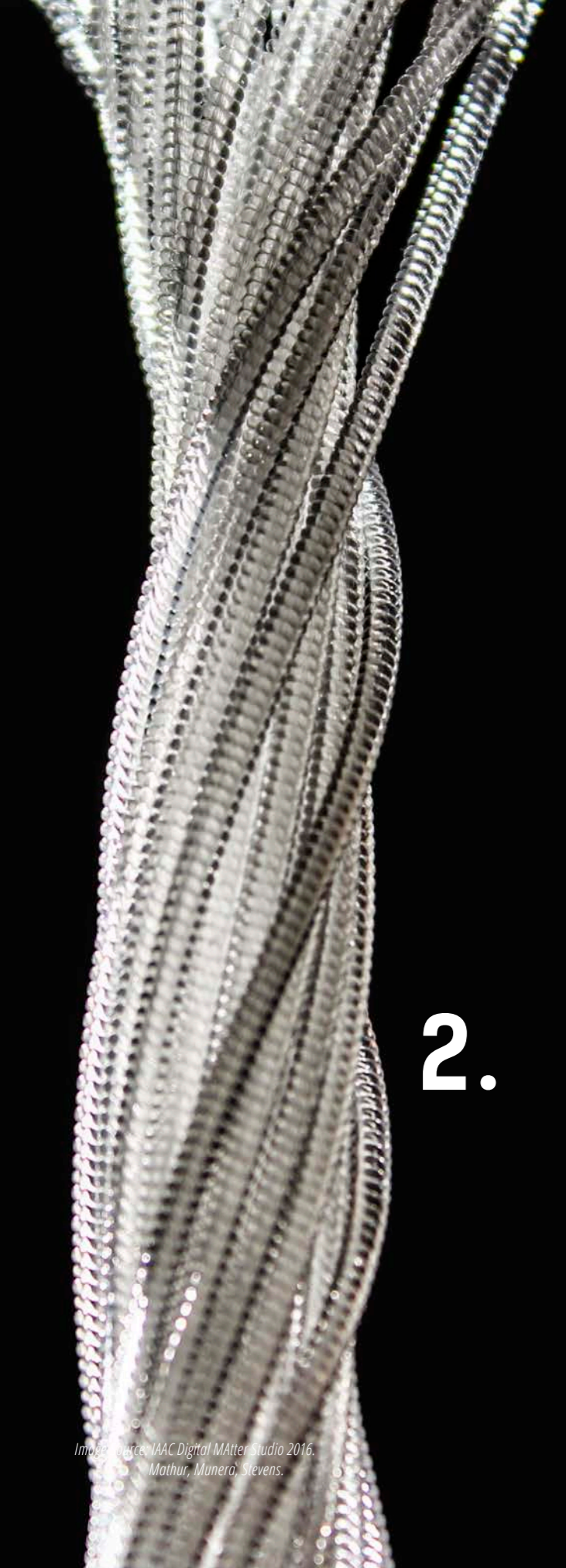
2.1 ARCHITECTURAL MATERIALISM

- 2.1.1 NEW MATERIALISM IN PHILOSOPHY
 - 2.1.2 DIGITAL MATERIALISM AND FOLD IN ARCHITECTURE
 - 2.1.3 DIGITALLY FABRICATED MATTER
 - 2.1.4 PROGRAMMABLE MATTER AND BEYOND
 - 2.1.5 NEW MATERIALISM IN CONTEMPORARY ARCHITECTURE
-

2.2 MATERIALLY RESPONSIVE ARCHITECTURE

- 2.2.1 SMART MATERIALS
 - 2.2.2 SMART MATERIALS AND THEIR EFFECT UPON DISCIPLINES
 - 2.2.3 SMART MATERIALS ADVANTAGES AND LIMITATIONS
 - 2.2.3 DESIGN'S VALUE FOR SMART MATERIALS
 - 2.2.6 RESPONSIVE MATERIALS AND MATERIALLY RESPONSIVE ARCHITECTURE
-

2.3 CONCLUSIONS



2.

ACTIVE MATERIALS IN ARCHITECTURE

Image source: IAAC Digital Matter studio 2016.
Mathur, Munera, Stevens.

2.1

RESPONSIVE ARCHITECTURE AND BEHAVIORS

2.1.1 NEW MATERIALISM IN PHILOSOPHY

The extensive work of philosopher Manuel DeLanda highlights the emergence of a new framework in relation to the material world. “New Materialism” [i], as DeLanda names it, is the philosophical framework of an entirely new conception and understanding of materiality; one that overcomes the Aristotelian or the Newtonian view. Under the scenario of Aristotle¹, named “hylomorphic model”, matter is separated from, and a passive recipient for, form. Similarly in the Newtonian view, matter is homogeneous and as such, is an obedient agent following general external laws of equilibrium while all its properties are formed by, and powered by these transcendent laws². For matter, therefore, to exist in these views, a form is required to be imposed upon it from outside, without any concern on the actual properties of the matter itself.

Throughout the 20th century, modern architecture mainly deals with matter in a similar way. From the work of modernism on forming concrete through top down - outside of the system - molds, to the most contemporary interactive architecture work of hierarchically

[i] The term New Materialism has been used simultaneously from different scholars in the 1990s. The two most prominent authors have been Manuel DeLanda and Rosi Braidotti. Other important new materialism writers and thinkers include Karen Barad, and Quentin Meillassoux.

For a more extended view on writings and thinking of New Materialism, see: R. Dolphijn, and I. van der Tuin, *New Materialism: Interviews & Cartographies*, Ann Arbor, Open Humanities Press, 2012.

¹ Stanford Encyclopedia of Philosophy, Form vs Matter, <https://plato.stanford.edu/entries/form-matter/> (accessed March 2019).

² M. DeLanda, “The new materiality”, in A. Menges (ed.), *Material Synthesis—Fusing the Physical and the Computational*, Wiley, Architectural Design, vol. 85, no.5, November 2015, pp. 16–21.



Figure 1.
View of "P Wall", by Andrew Kudless, Matsys, 2006. Wall structure investigating the self-organization of plaster and elastic fabrics that become flexible molds deforming following gravity and structural patterns.
Image Courtesy: Matsys, Andrew Kudless

[ii] Specifically Deleuze and Guattari write: "...to the essential properties of matter deriving from the formal essence we must add variable intensive affects, now resulting from the operation, now on the contrary making it possible: for example, wood that is more or less porous, more or less elastic and resistant. At any rate, it is a question of surrendering to the wood, then following where it leads by connecting operations to a materiality instead of imposing form upon a matter: what one addresses is less a matter submitted to laws than a materiality possessing a *nomos*. One addresses less a form capable of imposing properties upon a matter than material traits of expression constituting affects." G. Deleuze and F. Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia*, London, Athlone Press, 1988, p.450.

[iii] Deleuze and Guattari has also used other architectural examples to explain the difference between "major" and "minor sciences", such as the comparison between Gothic and Romanesque churches. In this example they argue for a static relation between form and matter in the Romanesque, versus a dynamic relation of material and forces in the Gothic. See G. Deleuze and F. Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia*, London, Athlone Press, 1988.

³ N. Leach, "Matter Matters: A philosophical preface", in S. Tibbits (ed.), *Active Matter*, Boston, The MIT Press, 2017, pp. 18-22.

⁴ A. Menges, "Polymorphism", in M. Hensel, A. Menges and M. Weinstock (eds.), *Techniques and Technologies in Morphogenetic Design*, Wiley, Architectural Design, vol. 76, no.2, May 2006, p. 79.

⁵ M. DeLanda, *A Thousand Years of Nonlinear History*, New York, Zone Books, 1997.

⁶ M. DeLanda, "The new materiality", in A. Menges (ed.), *Material Synthesis—Fusing the Physical and the Computational*, Wiley, Architectural Design, vol. 85, no.5, November 2015, pp. 16-21.

⁷ G. Deleuze and F. Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia*, trans. Brian Massumi, London, Athlone Press, 1988, p.450.

implementing wires, sensors and motors for matter to open, close or physically change in a predicted manner, it becomes clear that the perception of matter is one of a distinct agent from form, or performance (Figure 1).

Architectural critique Neil Leach, argues that the main characteristics of the 20th century thinking (and therefore architectural production), are subject, linear operations, representation and interpretation³. Similarly, architect Achim Menges, highlights that the current architectural practice is driven by hierarchy and the priority of creating form, independently from its materiality⁴. In contrast to that, the new conception and understanding of the material world provided by the new materialism views, brings forward a focus towards the object as well as towards non-linear processes, rather than linear operations and predicted outcomes. New materialism marks a radical shift towards process-oriented thinking. In his book "A Thousand Years of Nonlinear History" DeLanda looks at the history and domains of geology, biology and even language, defining "processes" rather than final closed operations, and highlighting a non-linear and "isomorphic" model that can describe their evolution⁵.

While in the "hylomorphic" model of Aristotle, matter does not have any ability of creating form (morphogenesis) unless an external pattern is imposed to it, in the new materialism model, matter becomes an active agent in form generation and definition.

"[...] linear causality and its necessary and unique outcomes, gives us a picture of matter as something incapable of giving birth to form by itself. In this old view, morphogenesis can only take place if an external agency acts on inert matter, either by incarnating an essence (formal cause) or by forcing it to acquire a form (efficient cause.) A richer conception of causality linked to the notion of the structure of a possibility space, gives us the means to start thinking about matter as possessing morphogenetic powers of its own"⁶

Deleuze and Guattari in the "A Thousand Plateaus", similarly describe a model where matter is not homogenized but it is considered as flow and, therefore, it "can only be followed". "To the formed or formable matter[...]", they write, "[...]we must add an entire energetic materiality in movement, carrying singularities [...] that are already like implicit forms that are topological, rather than geometrical, and that combine with processes of deformation: for example, the variable undulations and torsions of the fibers guiding the operations of splitting wood"⁷. Rather than opposing a form to matter, as seen in the "hylomorphic model", they highlight the importance of following the properties of the material itself [ii]. Although Deleuze and Guattari's literal examples of matter and architectural formations (such as wood with diverse fibers and porous) mainly refer to the differences between Royal and nomadic science [iii], their texts have influenced a lot of thinkers and designers, who interpreted their texts as the description of a new morphogenetic and bottom up model for design.

The framework of new materialism in philosophy, opened up possibilities for a different understanding of many aspects and disciplines of our time. From architecture and building perception, to geological and biological evolutions and to the society in itself, the new materialism brings forward the notions of processes, variation of unpredicted results, as well as non-linear system's operations. More than anything, though, it defines a theoretical turn away from the traditional persistent dualisms of form/matter, form/performance or form/information.

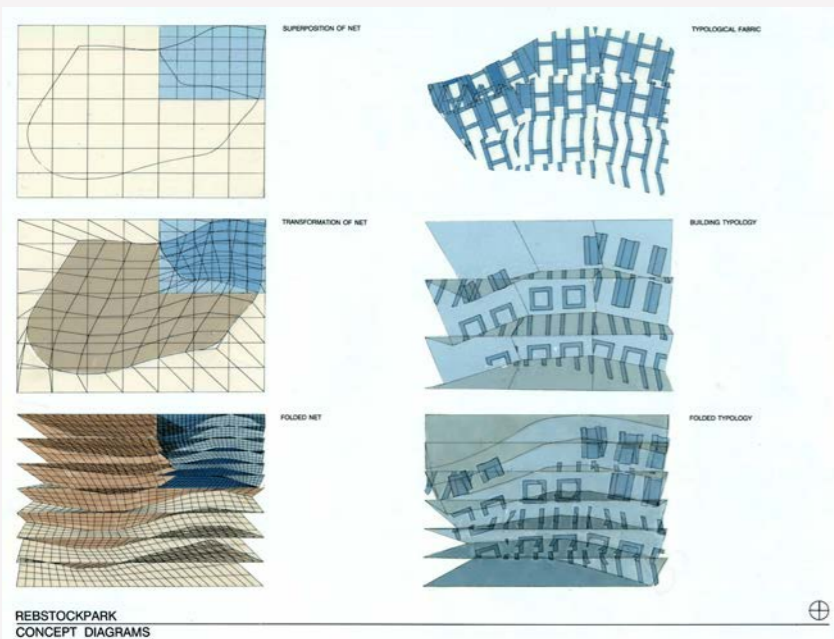
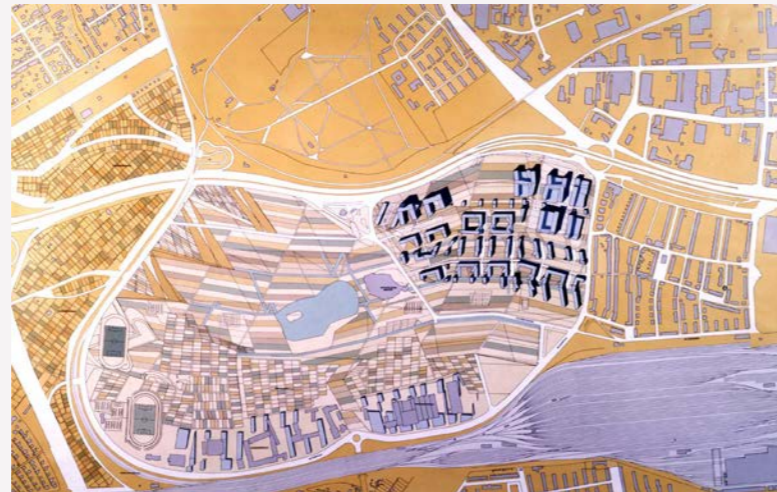
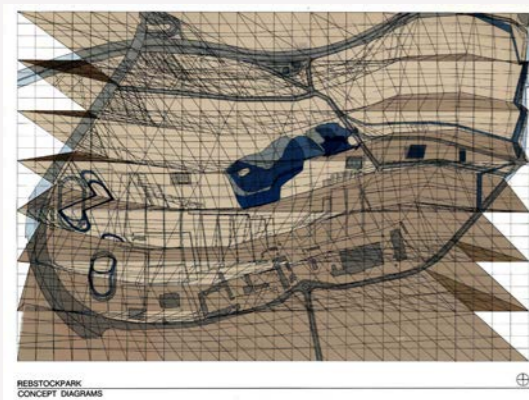


Figure 2.
 Concept Diagrams, plan and drawings of Rebstock Park Masterplan by Eisenman Architects in 1990-1992.
 Eisenman introduces the idea of fold as a strategy to connect with the context, create alternative specialities and initiate new organizations of urban space while reframing existing ones.
 Image Courtesy: Eisenman Architects



[iv] In the "Fold" Gilles Deleuze analyzes the writings of Leibniz as the grounding elements of a Baroque philosophy that can be used for analyzing contemporary science, art and aesthetics as well as contemporary views of "subject", events and space. Gottfried Wilhelm Leibniz was a philosopher working on mathematics and history and he is considered to have conceived the notions of calculus becoming the most significant inventor in the mechanical calculators field. Deleuze uses the term "fold" to characterize the Baroque science and art as an operation that "folds" together two distinct levels, such as interior and exterior or body and mind, that although fold together they remain heterogeneous. Although Deleuze's "Fold" has been translated and reinterpreted by architects (such as Greg Lynn and Peter Eisenman) as a theory that could eventually relate to space, others such as Michael Speaks, the editor of Bernard Cache's *Earth Moves: The Furnishing of Territories* argues in an article in the same book that Deleuze's "fold" does not relate to the architectural space but it's a wider approach to the idea of folding and merging of different disciplines in science. For more info see: M. Speaks "Folding toward a new architecture", in B. Cache, *Earth moves: the Furnishing of Territories*, Cambridge, The MIT Press, 1995.

⁸ M. Carpo, *The Digital Turn in Architecture 1992 - 2012*, Architectural Design, Chichester, Wiley, 2012, pp. 8-11.

⁹ G. Deleuze, *The Fold: Leibniz and the Baroque*, Minneapolis, University of Minnesota Press, 1993, pp. 15.

¹⁰ M. Carpo, *The Digital Turn in Architecture 1992 - 2012*, Architectural Design, Chichester, Wiley, 2012.

¹¹ P. Eisenman, "Visions Unfolding: Architecture in the Age of Electronic Media", in M. Carpo, *The Digital Turn in Architecture 1992 - 2012*, Architectural Design, Chichester, Wiley, 2012.

2.1.2 DIGITAL MATERIALISM AND FOLD IN ARCHITECTURE

Starting from the 1990s, following advancements of both Computer-Aided Design (CAD) and animation software, a series of new design principles, methodologies and theories directly connected with the electronic media, the computer and the digital, take the stage of the architectural scene.

Deleuze's writings on the "fold" [iv] and "singularities" become the starting point for architects, such as Greg Lynn, Peter Eisenman or Bernard Cache to explore new ways of thinking in design and form making thinking, that are directly connected with digital technologies and electronic mediums. More specifically Deleuze reinterprets Leibniz's concept of "monad" in terms of folds of space, movement and time and applies it to the view of the world that he considers as "a body of infinite folds and surfaces that twist and weave through compressed time and space". Deriving it from the Leibniz mathematics of continuity, one of the focus of Deleuze was the idea of "calculus" that describes variations of variations, similarly to the contemporary parametric modelling model⁸, and includes "inflection" which is the "genetic elements of the variable curve, or fold" and the "authentic atom, the elastic point"⁹.

Peter Eisenman in his article "Visions unfolding: Architecture in the Age of Electronic Media" published at the *Architectural Design (AD)* issue of 1992 refers to Deleuze's theory of "fold" as a new strategy for questioning the traditional dichotomies between drawing and constructing, or between interior and exterior. He foresees the possibility of folding through electronic media, as the possibility of breaking the Cartesian order and creating form that is not standardized or repetitive but, the same as in digital photography, it is derived from a series of number-based notations, or files, that can morph and change all the time"¹⁰. Eisenman, envisioned the possibility of "continuity" in architectural space and the creation of an environment that dislocates vision on how its interior and exterior is perceived (Figure 2). This environment:

"...does not seek to be understood in the traditional way of architecture yet it possesses some sense of 'aura', an ur-logic which is the sense of something outside of our vision. Yet one that is not another subjective expression. Folding is only one of perhaps many strategies for dislocating vision - dislocating the hierarchy of interior and exterior that preempts vision"¹¹

In the following year 1993, the *Architectural Design (AD)* published an issue named "Folding in Architecture" edited by Greg Lynn. Clearly influenced by Deleuze's theory of fold, Lynn develops his "curvilinearity" theory, which defines a new style in architectural design and production related with the production of round, smooth, continuous surfaces and curves that were possible with the current digital design and fabrication techniques. According to theorist Mario Carpo, this new style that Lynn describes of "smooth transformations" stands

in between “Post-Modernism (classical composition, unity and order, or contextualism) and Deconstructivism (angularity, disjunctions, conflict and oppositions)”¹². Greg Lynn foresees the new architectural products as “smooth mixtures (that) are not homogeneous”, consisting in norms of “pliancy” that “implies first an internal flexibility and second a dependence on external forces for self-definition”¹³.

“The smooth spaces described by these continuous yet differentiated systems result from curvilinear sensibilities that are capable of complex deformations in response to programmatic, structural, economic, aesthetic, political and contextual influences”¹⁴

The theory of Lynn has significantly influenced the further evolution of digital architectural practice, highlighting the need of the creation of fluid and dynamic spaces that fold their material or location and they are subject to change, based on new inputs in their non-homogeneous, but overall smooth, system.

Motion, movement and flexibility have been also the main characteristics in the visions and work of Marcos Novak, an architect and theorist who introduced the idea of “liquid architecture”. Specially focused on the introduction of the digital aspect of matter, Novak foresees an architectural space that is mediated by both the virtual and the physical world and is able to mutate, change or move by external and internal inputs¹⁵.

In the last years before the entrance to the 21st century a series of additional pioneering proposals, theories and visions including the essays on Liquid Modernity by Zygmunt Bauman (1995), the Complex Organic Forms by Karl Chu (1997) as well as the Animated Form by Greg Lynn (1998), marked **a new architectural thinking towards the creation of variations instead of final forms and towards flexible, responsive capacities of architecture**. The new thinking has been, on the one hand, the outcome of the need to explore what comes next to Postmodernism or Deconstructivism, and how architectural form and expression can respond to a new society exposed to novel digital mediums. On the other hand, it was the outcome of a direct exploration of the possible applications of software coming from the film animation industry such as *Catia V1* (1995-1996) or *Maya 3d Modelling Animation* (1996-1998), that allowed users to model and animate complex forms that had been impossible to do until then.

Revising the principles of new materialism, we can certainly observe an important effort, on *processes, variation of results* as well as *non-linear system's operations*. Much of this work, however, dominates the digital aspect of our constructed environments and it, most of the time, **excludes the significance of physical materiality as a medium that participates in the creation of form**.

Would the variations of Lynn’s “blobs” [v] change, if the material itself is a non-homogeneous part of the whole? (Figure 3).

[v] In 1995 Greg Lynn coined the term “blob architecture” as an acronym for Binary Large Object action in Wavefront software. With this command it was possible to create large single surfaces out of small individual sphere components.

¹² M. Carpo, *The Digital Turn in Architecture 1992 – 2012*, Architectural Design, Chichester, Wiley, 2012, pp. 27-28.

¹³ G. Lynn, “Architectural Curvilinearity: The Folded, the Pliant and the Supple”, in M. Carpo, *The Digital Turn in*

Could the dissolution of perception of “inside and output” be achieved with a material that is able to change transparency?

Although, the novel “folded”, “animated”, “virtual” or “liquid” architecture brings a radical shift in the process of design towards adaptive outcomes, this adaptability mainly remains in the virtual aspect of the architectural operation, leaving, once again, the non-homogeneous morphogenetic matter of new materialism, out of the focus.

Within this context a series of questions in relation with non-homogeneous matter and adaptability in architecture emerge:

- How can non-homogeneous materials participate in the formation of physically adaptive environments?

- Which kind of smooth, seamless systems, today, can result in complex deformations as a result from their interaction with the environment?

2.1.3 DIGITALLY FABRICATED MATTER

In parallel to the flexible form and design thinking, the fall of costs of Computer Numerical Control (CNC) machines and the rise of Computer Aided Manufacturing (CAM) software, contributes in bringing the digital materialism to a new level, one directly related with digital fabrication and manipulation of matter.

During the 90s Bernard Cache develops the concept of “Objectile” that Deleuze will further evolve and include in “The Fold”. The “objectile” defines a technological object as a mathematical function rather than one of a static and definitive form. This, literally translates into the possibility of defining numerous possible variations for a form. For both Deleuze and Cache, within this new object “fluctuation of the norm replaces the permanence of a law; where the object assumes a place **in a continuum by variation**”¹⁶.

Architecture 1992 – 2012, Architectural Design, Chichester, Wiley, 2012, pp. 29-48. Article initially published on G. Lynn, *Folding in Architecture*, Wiley, Architectural Design Profile 102, vol. 63, no.3/4, March/April 1993, pp. 8-15.

¹⁴ Ibid.

¹⁵ M. Novak, “Liquid Architectures in Cyberspace”, in *Cyberspace: First Steps*, Cambridge, The MIT Press, 1991, pp. 225–254.

¹⁶ B. Cache and P. Beaucé, “Towards a Non Standard Mode of Production”, *Objectile Patrick Beaucé + Bernard Cache*, Vienna, Springer, Consequence Book Series on Fresh Architecture, vol. 6, 2007.

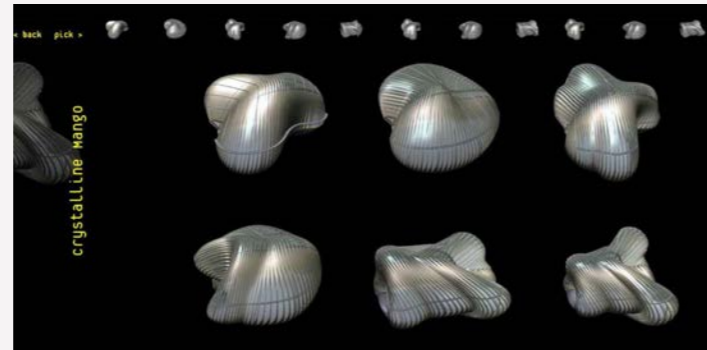
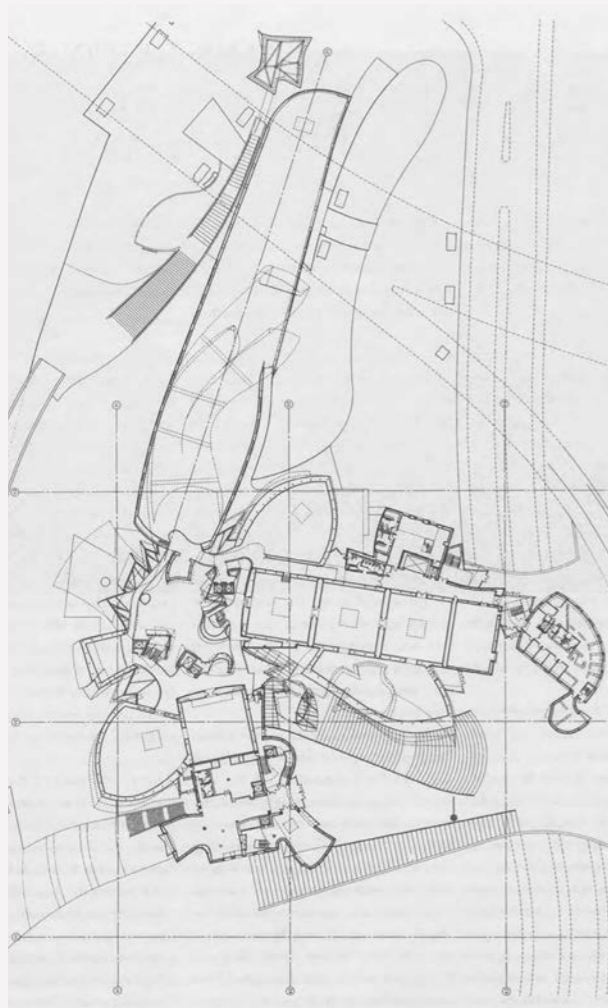


Figure 3.
Top right: Digital design of Embryological House by Greg Lynn in 1998-9.
Image Courtesy: Greg Lynn FORM



Figure 4.
Left and bottom right: Groundplan of first floor and view of the Guggenheim Museum in Bilbao by Gehry Partners, 1991-1997.
(left) Image Source: "Les Infos Du Paradis, Kurt W. Forster
(bottom right) Image Copyright: David Heald

[vi] Bernard Cache initially names them Computer-Assisted Conception and Fabrication (CFAO) systems. He argues that such systems are contributing to the quickest production of ideas and manufacturing but apart from offering quicker ways to do the same things done by hand, they offer no other possibilities. Based on this limitations, he envisions the creation of new systems that he calls "second generation systems" in which "objects are no longer designed but calculated". This calculation transforms the object into numerical parameters that can be altered. Therefore, he foresees the creation of more complex forms such like "surfaces with variable curves and some volumes" (impossible to create otherwise) replacing the traditional simple contours. Furthermore, the variation of the parameters for their fabrication could allow the nonstandard objects produced industrially.

See more at: B. Cache, *Earth Moves: The Furnishing of Territories*, Cambridge, The MIT Press, 1995, p. 87.

[vii] File-to-factory technologies is a term that started to be used in architecture in first decade of the 21st century describing the workflow of connecting the digital design with the fabrication process. The workflow involves direct transfer of the data of a digitally 3d modelled design to a CNC machine.

Although the advancements in CAD, CAM and CNC have contributed for designers to bridge the gap between digital and physical, File to Factory workflows, it is considered a process that usually does not allow any feedback between materiality and design and, therefore, lacks flexibility.

¹⁷ B. Cache, *Earth Moves: The Furnishing of Territories*, Cambridge, The MIT Press, 1995.

¹⁸ B. Kolarevic, "Information Master Builders", *Architecture in the Digital Age: Design and Manufacturing*, New York, Spon Press, 2005, pp. 55-62.

¹⁹ N. Leach, "Digital Morphogenesis", *The Business of Research*, Wiley Architectural Design, vol. 79, no.1, January/February, 2009, pp. 32-37.

Cache takes this idea of variation further into the physical production of the object introducing the possibility of "nonstandard mode of production". This includes the use of Computer Numerical Control (CNC) machines [vi] and file-to-factory technologies [vii] for the serial reproduction, at no extra cost, of objects of the same family, with slightly customized variations in their geometry or size. The CAD and CAM technologies for Cache represent the possibility for the production of an industrial continuum". He foresees its effects in design and matter:

"From the mold we move toward modulation. We no longer apply a preset form on inert matter, but layout the parameters of a surface of variable curvature. A milling machine that is commanded numerically does not regulate itself according to the build of the machine; it rather describes the variable curvature of a surface of possibility. The image-machine organization is reversed: the design of the object is no longer subordinated to mechanical geometry; it is the machine that is directly integrated into the technology of a synthesized image" ¹⁷

Already in 1992, the Great Fish Sculpture of Frank Gehry has been the first big scale demonstration of digital design and digital fabrication of complex structures out of components where each one is distinct from the other in terms of geometry or scale. Frank Gehry has been a pioneer practitioner in exploring the possibilities of CAD/CAM in architecture. For the realization of the specific project, and a series of others developed later, including the Guggenheim Museum of Bilbao, Gehry customized CATIA, a software coming from aerospace industry (Figure 4). The customized new version of the software included a visual interface suitable for architecture work and named "Digital Project". Since its creation it has been used for the design and fabrication of a series of complex big scale architectural projects including the Sagrada Familia in Barcelona and the Walt Disney Concert Hall in Los Angeles.

The years that followed Cache's writings and Gehry's first experiments, saw an extreme fall in the costs of industrial CNC machines and CAM software, that had already been present since the 1960s but they had not found their way yet to the small scale workshops of laboratories, schools or professionals. Academic and research centers such as the MIT and Harvard in Boston, the Sci-Arc in Los Angeles, the ETH in Zurich, the TU Delft in Delft, the AA and The Bartlett in the U.K. and the IAAC in Barcelona where the pioneers on bringing CNC machines (and even industrial robots) into their workshops, with the goal to fully engage students and researchers with the possibilities of these digital fabrication tools in the architectural production and in the exploration of the line that connects design and materialization.

The stronger the connection between digital design and fabrication was becoming, the more possibilities were arising in the explorations of architecture as a material-based practice. Of course, architecture always implies "making" and it has always been a material-based practice, especially in the epochs where the role of master-builder was synonym to the role of architect. During the industrial revolution, though, with the introduction of steel, automated manufacturing and mass production, the connection of architectural design, craft and materiality have loosen their bond. The knowledge has been fragmented among different roles (architect designers, builders, constructors) and the lack of knowledge of the architect in the fields of the other roles, enhanced his/her disassociation from the construction and materialization of his/her designs¹⁸.

Some argue that much of the early digital architecture still relies on top down processes and approaches, where designers use the computer tools simply to realize their designs without any significant feedback from the material limitations and possibilities¹⁹. In response to that, the seamless integration of design and construction through the introduction of digital



Figure 5.
View of Structural Oscillations presented in the 11th Venice Architectural Biennale. Images of the brick wall has been assembled on site by a mobile robotic arm (R-O-B Unit).
Image Courtesy: Gramazio and Kohler Research, ETH Zurich

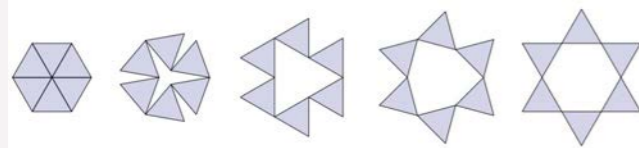
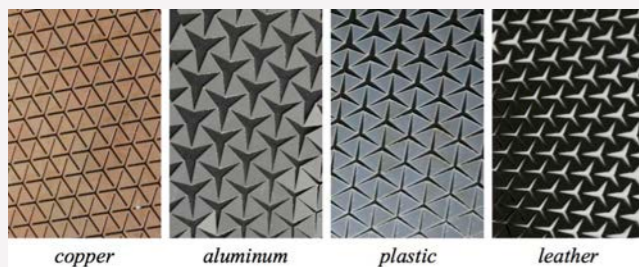


Figure 6.
View of different patterns applied in different materials for achieving various degrees of elasticity.
Image Source: Mina Konaković



[viii] Structural Oscillations was an installation inside the exhibiton "Explorations" which was the Swiss contribution in the Giardini Pavillion at the 11th Architectural Venice Biennale in Venice. The installation consisted in a 100 meter brick wall and 14,961 bricks. The design of the wall's design was based on parameters that defined the exact position of each brick in order to achieve the desired curve. The wall has been assembled by the R-O-B mobile robotic fabrication unit of ETH Zurich that includes an industrial robotic arm carried on a track that could move anywhere in order to be able to fabricate on site. More info at "Research", Gramazio Kohler Research, [website], 2016, <http://gramaziokohler.arch.ethz.ch/web/e/forschung/142.html>, (accessed March 2019).

[ix] National Centres of Competence in Research (NCCRs) is a research fund of the Swiss National Science Foundation.

[x] Second order cybernetics is described as the cybernetics of "observing systems" whereas the first order cybernetics is that of "observed systems". The first order cybernetics places the individual (observer) outside of the system. The second order cybernetics widely known as "cybernetics of cybernetics", recognizes the observer as part of the observed systems systems interacting and influencing its processes that consist in principles of self-organization and autonomy. For more info see: Heylighen, Francis. "Cybernetics and Second Order Cybernetics." Encyclopedia of Physical Science & Technology, 2001. Retrieved by: https://www.academia.edu/297899/Cybernetics_and_second_order_cybernetics. Last Accessed January, 2019

²⁰ J. Willmann et al., "Digital by Material", in S. Brell-Çokcan and J. Braumann (eds), *Robotic Fabrication in Architecture, Art, and Design*, Rob | Arch 2012, Vienna, Springer, 2013.

²¹ M. Konaković et al., "Beyond developable: Computational design and fabrication with auxetic materials", *ACM, Transactions on Graphics*, vol. 35, no.4, July 2016, p. 89.

models of fabrication, **opens up new possibilities for reconnecting architecture with its material aspect, starting from the early stages of design.** Fabio Gramazio and Mathias Kohler identify a unique moment of intersection of material with digital data, and foresee a new "Digital Materiality" where materials are being informed by data and therefore become an inherent condition in the architectural design and production.

*"A digital materiality is emerging, where the interplay between data and material is seen then, in a new light, as an interdependent structuring of architecture and its material manifestations. Digital materiality is thus not incidental, nor supplemental, nor is it a process of embellishment; instead it corresponds to an extensive collaboration, which can be analytically developed and implemented on an architectural scale. **This leads as well to a new form of architectural expression and its material sensuality**"²⁰*

The recent explorations of digital fabrication take into important consideration the specificities of the material that eventually provide the necessary information for the machine to operate and for the design to be adjusted. Digitally fabricating a complex vault, for instance, will not result in the same geometry if the vault is out of earth bricks or steel. Advancements in simplified digital simulations software (CAD), compatible with the current software that architects are using, allow for the structural simulation of the material's behavior in a specific structure, from the early stages of the design. Different mechanical properties of brick and steel will result in different spans, or geometries for the vault in order to retain structural integrity. On the other hand, computer aided manufacturing software (CAM) as well as the possibility of rapid prototyping in digital fabrication allow users to collect data on how the vault surface should be paneled, and how the fabrication machine should be programmed in order to produce the components that would, then, assemble the entire structure. While components out of steel could be probably cut by a milling machine and then, bended by automated bending machines, brick components would probably require a robotic arm to position them directly into the structure, similar to the digital robotic fabrication strategy used by Gramazio and Kohler in their "Structural Oscillations" installation [viii] (Figure 5).

NCCR [ix] researcher Mina Konaković, is among a series of researchers that explore different possibilities of manipulating matter with the possibilities of digital fabrication. Since many common sheets of materials that are not elastic, present limitations in how they can be formed, Konaković and the group at the Computer Graphics and Geometry Laboratory (LGG) at the EPF Lausanne, are studying how digital fabrication can be used in order to cut patterns of thin slits in such inelastic materials enabling their irregular deformation (Figure 6). An algorithmic software is developed to couple material and fabrication properties so that different patterns are simulated in relation to the different levels of elasticity and stretching that they can offer to each surface material²¹. Such an approach, deals with the immense possibilities of digitally manipulating materials in order to enhance or "hack" their properties (inelastic materials acquires elastic properties) and expand their applications in architecture or other fields.

Although the possibilities of digital fabrication in enhancing material performance are immense, material functions in reality execute patterns and behaviors that have been **previously established by the software or the designer**, meaning external entities to the system. Similarly, digital fabrication machines are programmed to execute computer orders. In this sense, this paradigm is merely aligned with automated behaviors and operations that belong to the first order of cybernetics, which understands the individual as an observer of the system acting outside of it. Circular feedback or degree of autonomy, as described in the second order cybernetics [x] can hardly be found in the current explorations of digital fabrication and architectural behavior.

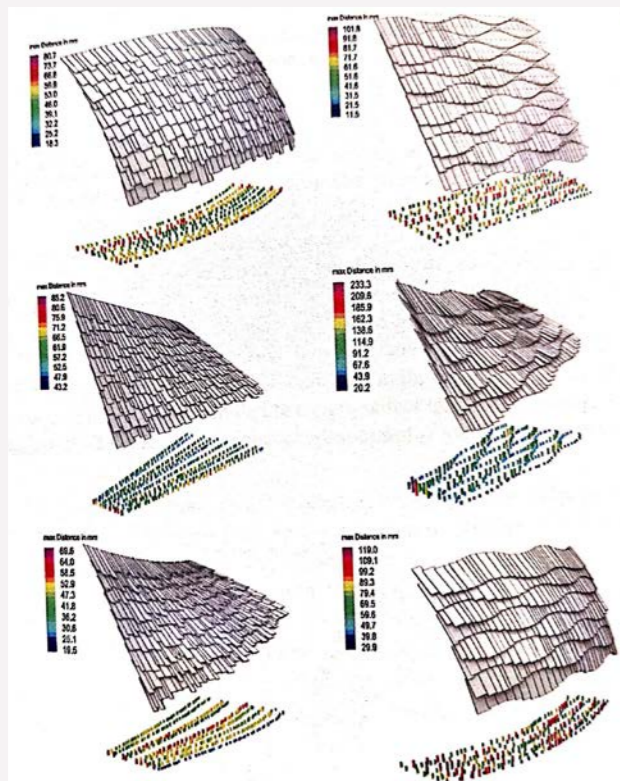
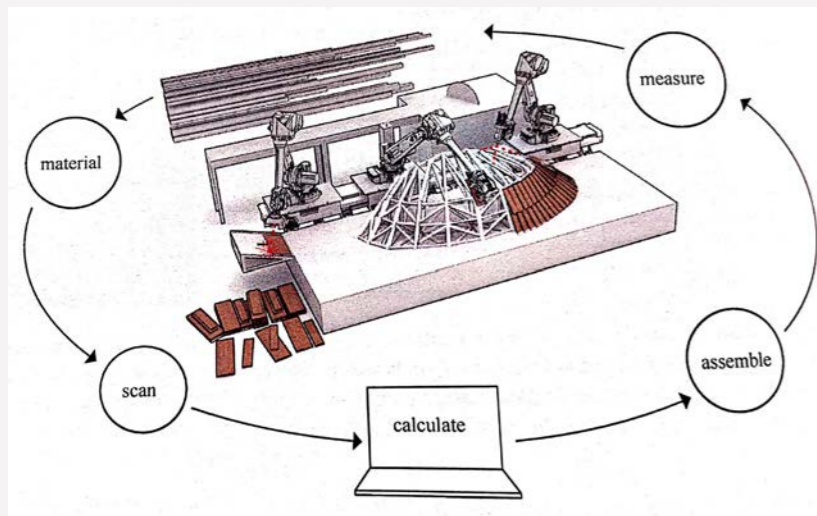
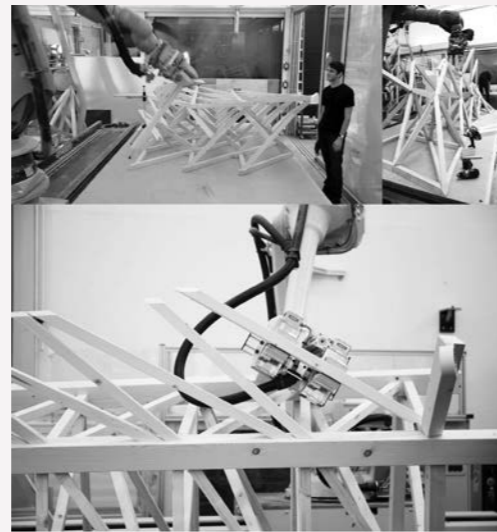


Figure 7.
Geometric adaptability for assembly of varied elements. Right: Assembly of timber truss. Left and Bottom: Robotic fabrication workflow-Feedback process.
Image Source: Eversmann P., 2018



As Manuel Kretzer argues, there are two important aspects that digital production neglects. The first is the fact that the digital fabrication machines should be equipped with a feedback system that can evaluate the material, and secondly, these computer-controlled machines should be able to learn and respond to these evaluations by self-adjusting their fabrication strategy. According to Kretzer, the current digital production practises require that material homogeneity increases while the complexity of material manipulation only increases with the use of different tools²².

A feedback system, thus, would expand the possibilities of digital fabrication to include materials that are not homogeneous, such as for instance wood, or other non-synthetic materials. Furthermore, such a system would, then, exhibit autonomous behavior in contrast to the automated one, placing it in the second order cybernetics.

Few recent research work in digital fabrication, tend to answer towards the limitation of homogeneous materials. Philipp Eversmann, for instance, developed a system of digital robotic fabrication for what he calls "Material of Unknown Geometry". Eversmann develops a feedback system where data from scanning non-homogeneous (in both consistency and size) wood pieces are collected. These data are then processed in an algorithmic software that finds an optimum arrangement of the different pieces in a specific geometry. This arrangement is then translated in code that programs a robotic arm to automatically arrange the pieces in what Eversamnn calls a "one continuous real-time workflow"²³ (Figure 7). Although, such research adds extreme value in the possibilities of materials becoming an active agent in the formation of architectural structures, it is still unclear how the circularity of the system can be defined, since once the structure is built there is no further dialogue between matter and form.

Analyzing approaches of different nature in digital production, we can observe that these processes and technologies influence architectural production in a manner that brings it closer to its material identity, almost reestablishing the lost relation of master builder with its built products. However, one could argue that much of their operation presents no essential difference from the already well established automated processes of the assembly line that characterized the Industrial paradigm of the 20th century production model. Although some paths drawn by new materialism are further explored or even fulfilled, once again, as seen in the "fold" architecture model, genesis of form has no strong bound with the "singularities" or the "topological (rather than geometrical) implicit forms of matter.

This bring us to a series of questions relevant to the development of this thesis:

- Can digitally producing materials open up possibilities for an autonomous architectural behavior rather than automated execution of pre-established patterns?
- How can non homogeneous matter be in a constant dialogue and feedback with both the design process and the digital machine's operation? Would that require a certain intelligence found in matter itself?

²² M. Kretzer, *Information Materials*, Switzerland, Springer International Publishing, 2017, p. 52.

²³ P. Eversmann, "Robotic Fabrication Techniques for Material of Unknown Geometry", in K. De Rycke et al. (eds), *Humanizing Digital Reality*, Singapore, Springer, 2018.

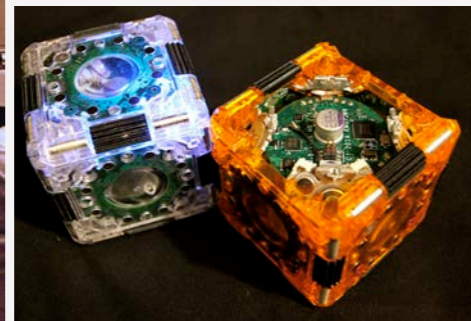
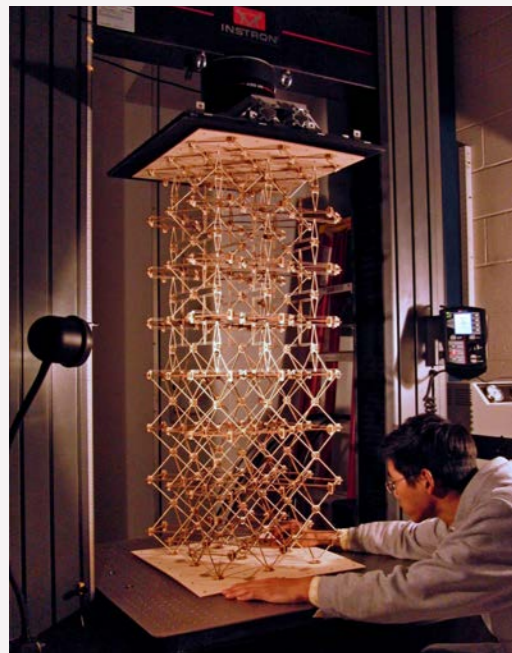


Figure 8.
 Left: Example of physical prototypes of “universally foldable strings” (moteins).
 Bottom: A Motein prototype consisting in folded strips. Visualization of parallel folding possibilities of the chains of the module geometry.
 Image Copyright: Cheung et al.²⁹
 Right: M-Blocks are cube-shaped very small robots that are capable of propelling themselves without any external moving parts.
 Image Courtesy: MIT, Distributed Robotics Laboratory



[x] The Defense Advanced Research Projects Agency (DARPA) is an agency developing research and investments in breakthrough technologies for national security. Under the United States Department of Defence, DARPA has been connected with the most contemporary innovations and inventions such as the Internet, the Global Positioning System (GPS) receivers found in every device today or the automated voice recognition and language translation. More information on DAPRA can be found in their [website] <https://www.darpa.mil/>

[xi] Programmable Matter is a DAPRA multidisciplinary programme that opened in 2007 with the goal to demonstrate a new functional form of matter, based on mesoscale particles, which can reversibly assemble into complex 3D objects upon external command. These 3D objects will exhibit all the functionality of their conventional counterparts. The Programme involved five teams, two from Harvard University, two from the Massachusetts Institute of Technology (MIT) and one from Cornell University, all working towards the convergence of chemistry, information theory, and control applied into a new materials design paradigm referred to as “InfoChemistry”—building information directly into materials. Information retrieved by DARPA official page of Programmable Matter programme https://www.darpa.mil/dso/thrusts/physci/newphys/program_matter/index.html, (accessed February 2019).

²⁵ T. Toffoli and N. Margolus, “Programmable matter: concepts and realization”, Elsevier, *Nonlinear Phenomena*, Physica D, vol. 47, no.1/2, January 1991, pp. 263–272, (1991).

²⁶ M. Kretzer, *Information Materials*, Switzerland, Springer International Publishing, 2017, p. 53.

²⁷ “Research, Development, Test and Evaluation, Defense-Wide, Volume 1”, *Defense Advanced Research Projects Agency*, [website], [https://www.engineering.com/LinkClick.aspx?link=http%3a%2f%2fwww.darpa.mil%2fattachments%2f\(2G8\)%2520Global%2520Av%2520-%2520About%2520Us%2520-%2520Budget%2520-%2520Budget%2520Entries%2520%2520FY2009%2520\(Approved\).pdf&tabid=6551&portalid=0&mid=429](https://www.engineering.com/LinkClick.aspx?link=http%3a%2f%2fwww.darpa.mil%2fattachments%2f(2G8)%2520Global%2520Av%2520-%2520About%2520Us%2520-%2520Budget%2520-%2520Budget%2520Entries%2520%2520FY2009%2520(Approved).pdf&tabid=6551&portalid=0&mid=429), (accessed March 2019).

²⁸ M. Alba, *The Promise and Peril of Programmable Matter*. Article published at Engineering.com, <https://www.engineering.com/DesignerEdge/DesignerEdgeArticles/ArticleID/14967/The-Promise-and-Peril-of-Programmable-Matter.aspx>, (accessed March 2019).

2.1.4 PROGRAMMABLE MATTER AND BEYOND

The concept of “Programmable Matter” has been initially used in 1991 to describe small fine-grained computed substrates (small machines) that can operate in a non-linear way, and as Toffoli and Margolus argue, they can change their form or their individual properties and assemble themselves collectively in different configurations in space²⁵. Programmable matter described the possibility of fine-grained computer nodes that they are able to communicate among them in space, and create variations of three dimensional assemblies. These assemblies can vary their global formal outcome according to certain input or certain computing logics embedded in the system. By varying their individual or collective formation as well as by their ability to communicate among them, it is possible to produce a new kind of synthetic matter, that is dynamic and reconfigurable²⁶. That is, because each computed element of this system is dynamic and so small (nano or micro scale), that **when assembled with others it can build up, from inside out, a new state of matter.**

In 2006 the Defense Advanced Research Projects Agency (DARPA) [x] commissioned a study on “Realizing Programmable Matter” which foresaw a big growth in programmable matter applications within a decade from then. Convinced by the outcome of this study, DARPA invested 4 million USD and two years later opened the “Programmable Matter” programme [xi]. In one of the investment reports DARPA describes that the goal of the programme is to create a new form of matter that is functional, and therefore able to assemble in different forms upon external input.

“The Programmable Matter program will develop a new functional form of matter, constructed from mesoscale particles that assemble into complex 3-dimensional objects upon external command. These objects will exhibit all of the functionality of their conventional counterparts and ultimately have the ability to reverse back to the original components”²⁷

The programme developed a series of innovative projects related to miniaturized robots that could sense, assembly and perform. Taking knowledge from previous research on different fields such as modular robotics, programming ensembles, or nanomaterials its objective was to scale up the process to the “human” scale. The project “Moteins” (motorized proteins), for instance, developed 3 dimensional assemblies out of folding strips that are in its essence robotic modules. Using previous research on how any 2D and 3D shape can be formed by “folding strings made up of simple robotic subunits”, Motein consisted in folded electronics and geometries²⁸ (Figure 8).

Besides their innovative nature and scientific contribution, much of the projects of the DARPA programme, use traditional engineering, electronic and mechanized ways of actuation. Similarly to the programmable matter of Toffoli and Margolus, computation,

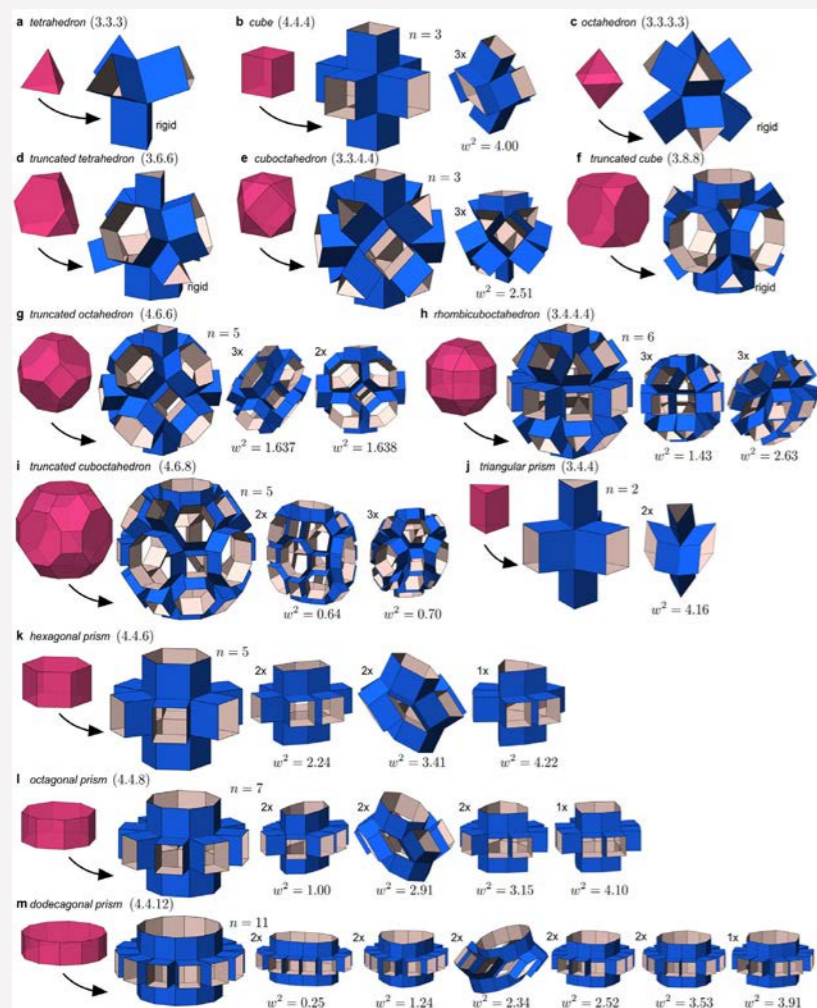


Figure 9.
 Bottom left: Metamaterials based on regular polyhedron. Because the folding lines of their shapes are less stiff than the surfaces, these building blocks can reconfigure in different shapes.
 Image Copyright: Johannes Overvelde, James Weaver, Chuck Hoberman and Katia Bertoldi, Rational design of reconfigurable prismatic architected materials, Nature, 541, 347-352, 19 January 2017, doi:10.1038/nature20824
 Bottom right: Example of 3d reconfigurable metamaterials in different forms.
 Image Copyright: Johannes Overvelde/Harvard SEAS



electronics and mechanics, as well as notions of software, hardware and computer stimuli are the key guides for each programmed element in order to create a physical 3dimensional assembly.

Other approaches on programmable matter include research on “metamaterials”, and “claytronics” [xii], both initiatives aiming for the creation of sub-millimeter reconfigurable computing elements that they can communicate, self-assembly and aggregate among them into bigger forms and eventually any kind of materiality (Figure 9). Initiators of the Claytronic project at the Carnegie Mellon University Goldstein and Mowry highlight the possibilities of these approaches to create “synthetic realities”:

“...programmable matter will allow us to take a (big) step beyond virtual reality, to synthetic reality, an environment in which all the objects in a user’s environment (including the ones inserted by the computer)are physically realized. (...) the idea is (...)to create a physical artifact that will mimic the shape, movement, visual appearance, sound, and tactile qualities of the original object”³⁰

Although such approaches resemble science fiction scripts and might look far away from being applied today, they are highly researched under huge amounts of funds and investment especially in USA, as explained later in this chapter. Besides the innovative nature of this research, one could not avoid to depict the downside of the massive applications of such technology, in many aspects, including replication of weapons or the creation of new dangerous objects never imagined before.

Programmable matter has been a crucial starting point to rethink the way changes can happen in the physical world. However, **the approach is mainly disconnected from the materiality in which these tiny intelligent elements are being manufactured.** Instead of any concern in that material aspect, scientists drive their efforts in resolving the complex computations required for the “coordination and communication of sensing and actuation across such large ensembles of independent units”³¹. Furthermore, the programmable approach makes full use and pays full tribute to engineering, mechanics and electronics.

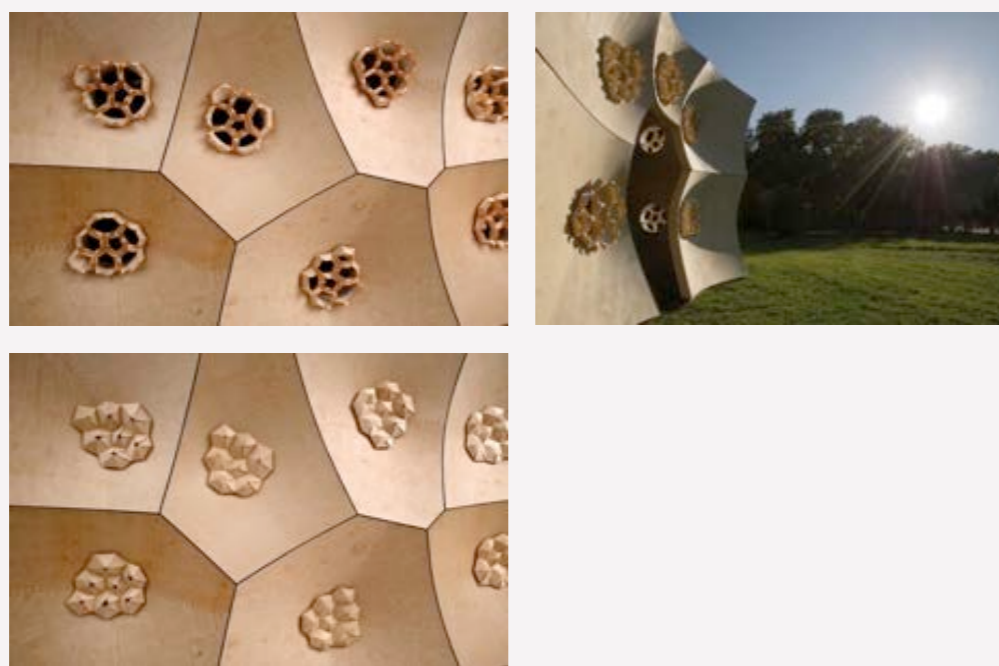
A different approach towards “smart” or “functional” materials introduces the possibilities of creating materials that present inherent properties of sensing and actuating discarding the need of any complex or costly additional software or electronic hardware.

[xii] Claytronics project has been initiated in Carnegie Mellon University by Seth Goldstein and Todd Mowry. The project focuses on the development of tiny scale computing machines (named catoms or claytronic atoms) that can form 3dimensional assemblies and objects that can mainly interact with users respond to their needs and input. Metamaterials are artificially and synthetic materials that derive their properties from their structure rather than their components. Reconfigurable metamaterials are metamaterials that contain within their structure multiple functions.

²⁹ K. C. Cheung et al., “Programmable Assembly With Universally Foldable Strings (Moteins)”, IEEE, Transactions on Robotics, vol. 27, no. 4, August 2011, pp. 718-729.
³⁰ S. C. Goldstein and T.C. Mowry, “Claytronics: an instance of programmable matter”, Wild and crazy ideas session of ASPLOS, Boston, October 2004.
³¹ A. Guin, Programmable Matter – Claytronics, Proceedings 58th International Instrumentation Symposium, San Diego, 4-8 June 2012.



Figure 10.
 Top: Biological hygroscopic principle found in nature and how it could be applied in the design of passive shape changing wood components.
 Bottom: Views of open and closed wooden components based on the humidity levels of the environment.
 Image Courtesy: Institute for Computational Design, 2013



2.1.5 NEW MATERIALISM IN CONTEMPORARY ARCHITECTURE

Contemporary architects and researchers couple the discourse of their work with the main concepts of new materialism or digital materialism. A series of terms such as “morphogenesis”, “emergence”, or “self-organization” alternate in a number of contemporary works that seek for a unification of matter, form and function in architectural design and production. Driven by principles of natural structures, such as flocks of birds, or of biological characteristics such as growth and self-repair, this significant number of contemporary work bring into architectural applications the theoretical discourse of new materialism.

Achim Menges, professor and the director of the Institute for Computational Design at Stuttgart University, argues that the current design logics and tools in the architectural discipline creates a panorama of operations where geometrical definition becomes the most important aspect of architecture that is mainly not considering the morphological and performative capacities of the employed material systems.

Part of his built work includes responsive pavilions that respond to climate and humidity such as the HygroSkin Pavilion. This latter one, takes advantage of the hygroscopic property of wood to attract moisture from the surrounding atmosphere. The plywood panels used for the pavilion are designed to bend when exposed to certain levels of humidity and as a result the openings of the pavilion are able to open and close in response to humidity levels³² (Figure 10).

Learning by natural morphogenesis, Menges considers that architecture needs to follow an alternative model where **formation and materialization are inseparable**:

“An alternative morphological approach to architectural design entails unfolding morphological complexity and performative capacity from material constituents without differentiating between formation and materialisation processes...the core of such morphogenetic approach is an understanding of materials systems not as derivatives of standardized building systems and elements facilitating the construction of pre-established design schemes, but rather as generative drivers in the design process”³³

Skylar Tibbits, the director of Self Assembly Lab at the MIT argues that the relationship of architects and designers with matter has been always “passive” while matter in its molecular scale is always “active”. In contrast to the current model of recombining matter (from top to down) to form geometries and behaviors, he calls for a new model of using properties of the digital world and the natural world applied to the formation of a new dynamic and

³² D. Korrea et al., *A climate-responsive prototype project based on the elastic and hygroscopic properties of wood*, Adaptive Architecture in proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Cambridge, 24-26 October 2013, pp. 33-42.

³³ A. Menges, “Polymorphism”, in M. Hensel, A. Menges and M. Weinstock (eds.), *Techniques and Technologies in Morphogenetic Design*, Wiley, Architectural Design, vol. 76, no.2, May 2006, p. 79.

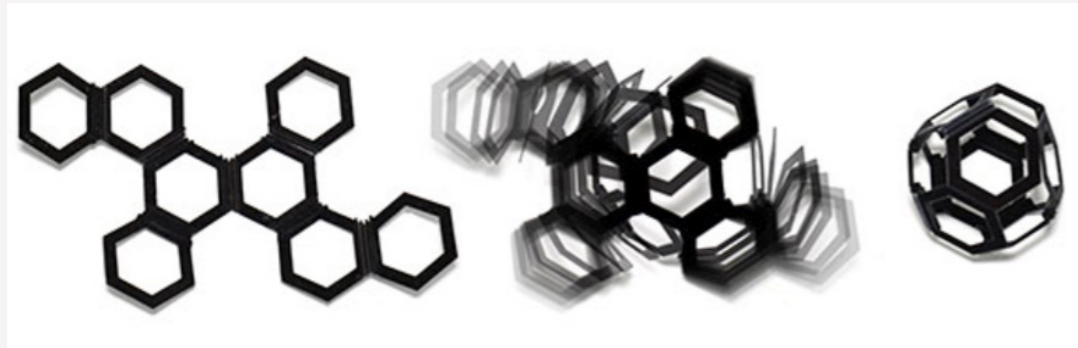


Figure 11.
4D printed self-folding truncated octahedron demonstrating the "transformation over time" when submerging in water.
Image Courtesy: MIT Self-Assembly Lab

Figure 12.
View of Silk Pavilion constructed by a swarm of silk worms at the hall of the MIT Media Lab.
Image Source: MIT Mediated Matter Group, Copyright: Steven Keating



behavioral synthetic world. The work of the Self Assembly Lab includes polymers in form of octahedrons that are able to fold and unfold based on humidity levels and create a planar or a 3 dimensional form. This process is what Tibbits calls "4d printing"³⁴ :

*"Our new model of programming matter can be seen in [...] synthetic biology and DNA computing, where we can fundamentally change the structure, functionality, and information embedded within the medium to create new desired traits from the inside out"*³⁵(Figure 11).

Neri Oxman, director of the Mediated Matter group at the MIT Media Lab argues that dichotomy among material, form and structure led to a design culture that prioritizes geometry and form over material. She calls for a design shift towards a "material aware design" approach, where material precedes shape and where the generation of form emerges through the "structuring of material properties as a function of structural and environmental performance"³⁶.

In some of her work, Oxman even gets to experiment with living organisms (such as silkworms) that following the environmental stimuli, generating a series of structural silk skins (Figure 12).

The thinking of "active" materialism finds a series of architectural translations in contemporary work that accepts non-homogeneous materiality as an active agent to define form. The work arising, underlies a new paradigm of thinking in design, one in that form is not the final outcome of a top down operation, but, similarly to the new and digital materialism, is the outcome of a series of bottom up and emerging processes that **place matter in the centre of the form finding and making process**. New materialism in architecture opens up novel possibilities but also challenges related with what kind of design tools can simulate material performance, which manufacturing and assembly processes can facilitate such performance, or which are the limits upon which material performance cannot be appropriate for architectural applications.

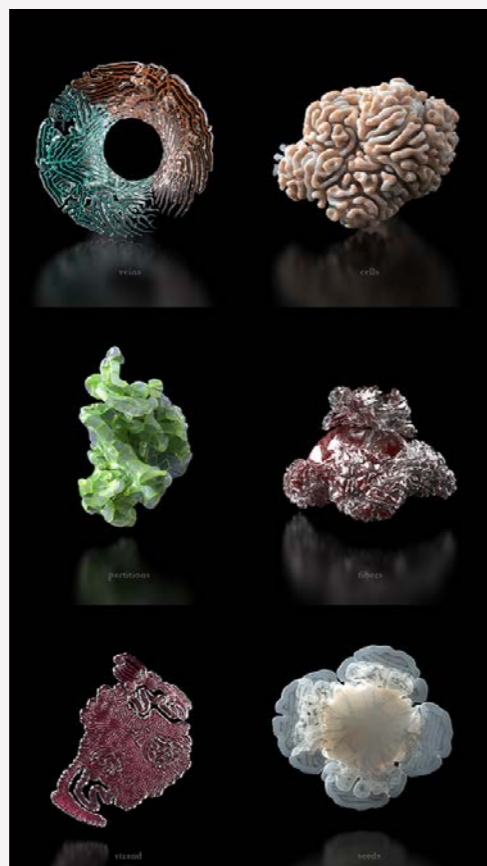
³⁴ S. Tibbits, "4D Printing: Multi-Material Shape Change", *High Definition: Zero Tolerance in Design and Production*, Wiley, Architectural Design, vol. 84, no.1, January/February 2014.

³⁵ S. Tibbits, *Active Matter*, Boston, The MIT Press, 2017, pp. 12-17.

³⁶ N. Oxman, "Material-based design computation", PhD dissertation, Massachusetts Institute of Technology, 2010.



Figure 13.
View of the 3d printed (Stratosys)
series of synthetic wearables
produced by Neri Oxman,
The Mediated Matter Group,
Christoph Bader and Dominik
Kolb.
Photo Credit: Yoram Reshef
Courtesy: Neri Oxma



2.1.6 BIO AND SYNTHETIC MATTER

The search for true material feedback for responsive architecture has been the goal of a series of contemporary research that envisions further interactions of the material built space with other agents in the environment beyond humans.

In his "Posthuman Critical Theory", Rosi Braidotti urges for "rethink(ing) subjectivity as a collective assemblage that encompasses human and non-human actors, technological mediation, animals, plants and the planet as a whole"³⁷. Consequently, Gausa and Vivaldi argue that the human body should be understood as an "aggregate made up of biological processes and computer processes" [xiii].

The emerging post humanistic views of a **novel symbiosis among humans, technologies and other non-human species have started to affect the architectural discipline** where emerging experimental approaches focus on the use of biological organisms for the creation of "symbiotic" material (and even alive) systems. Although, biological materials are not the focus of this thesis, a short description of some of the most representative examples is considered significant for underlying the common principles and goals with the processes of creating materially responsive environments as this thesis studies.

In 2014 Neri Oxman and the Mediated Matter Group of MIT Media Lab presented a series of 3d printed wearable elements, each of which is inserted with biological matter and bacteria. Titled "Wanderers: An Astrobiological Exploration" the project seeks to create a new synthetic material that both contains and generates life-sustaining elements. The forms produced include a series of biological organisms such as algae, which is able to purify the air and according to the authors to produce and store oxygen (Figure 13). Through the cavities and capillarity of their form these biological organisms are capable not only to produce oxygen, but also photons for light and eventually energy and nutrients for other species. Initially thought as an extension to the body that could allow inhabitation on other planets, the project represents the ability to create responsive micro habitats in a unique collaboration and interactivity with their surrounding environment. According to Oxman, such environments emerge from a thinking that discards the dualism of body and environment, merging these two in a unique artificial process with unpredicted biological outcomes [xiv].

Biochemist and expert in architecture Rachel Armstrong, in a radical proposal for preventing the foundations of the city of Venice from collapse, proposed the creation of an artificial reef that consists in protocells. Protocell technology, as the author of the project explains, is an emerging field of synthetic biology in which "cocktails of non-living chemicals are combined to exhibit the properties of living organisms". The simple metabolism of the protocells, that are photophobic and therefore exist in the deep dark surface of water,

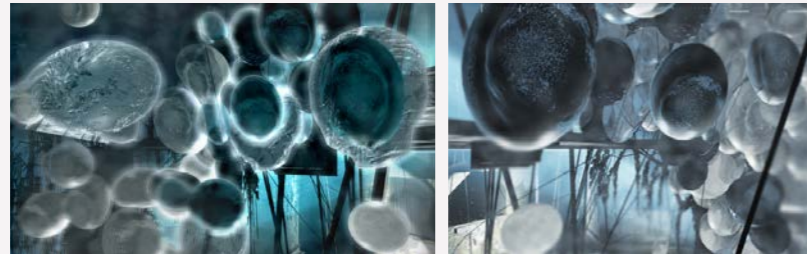
[xiii] Manuel Gausa, Jordi Vivaldi. Advanced Age Architecture 1990-2020. Theory and Evolution of the Architecture in the Informational Era, Barcelona, IAAC. Internal document of analysis for the seminar of "Theory for Advanced Knowledge" at IAAC, Institute for Advanced Architecture of Catalonia. Book in editing process.

[xiv] Neri Oxman in Material Ecologies, 2014, More info at: <https://neri.media.mit.edu/projects.html>, (accessed January, 2019).

³⁷ R. Braidotti, "Posthuman Critical Theory", Penn State University Press, Journal of Posthuman Studies, vol. 1, no.1, January 2017, pp. 9-25.



Figure 14.
Above: Visualization of the
protocell structures in Venice.
Below: Visualization of Details of
Protocells.
Image Copyright: Christian
Kerrigan Image Source: DEZEEN,
2014



[xv] Rachel Armstrong, interviewed by Ben Hobson for DEZEEN Magazine, May 2014. Available at: <https://www.dezeen.com/2014/05/30/movie-rachel-armstrong-future-venice-growing-giant-artificial-reef/>, (accessed March 2019).

[xvi] Marcos Cruz Interview with Jordi Vivaldi at the IAAC BITS, Advanced Architecture Group Journal, Issue 9: *Black Ecologies*, 2019, Internal document, Issue in editing process.

[xvii] Manuel Gausa, Jordi Vivaldi. Advanced Age Architecture 1990-2020. Theory and Evolution of the Architecture in the Informational Era, Barcelona, IAAC. Internal document of analysis for the seminar of "Theory for Advanced Knowledge" at IAAC, Institute for Advanced Architecture of Catalonia. Book in editing process.

reacts with minerals in the water. This reaction produces a light breaking in their chemical bonds, allowing them to grow similarly to a limestone material and reinforce the wood piles that Venice stands on [xv] (Figure 14).

Architect and associate professor at The Bartlett in UCL, Marcos Cruz, works with the idea of "bio-receptivity" in nature. A series of research work developed both in his practice and in his academic research studios at the UCL and IAAC in Barcelona, merge bacteria with traditional construction materials such as concrete or clay seeking to create an architecture that is in symbiosis with its environment. Cruze's bio-receptive architecture is **a built space that is able to grow, degrade or even be inhabited by other species** [xvi].

A group of other architects such as Terreform ONE or Ecologic Studio, similarly explore the creation of a symbiotic architecture with both humans and non-humans. An important common aspect of such approaches with Materially Responsive Architecture is the clear shift towards the creation of material systems that exhibit autonomous and unpredicted behaviors, not as an external input of the system, but **as agents within the same system that governs them** [xvii].

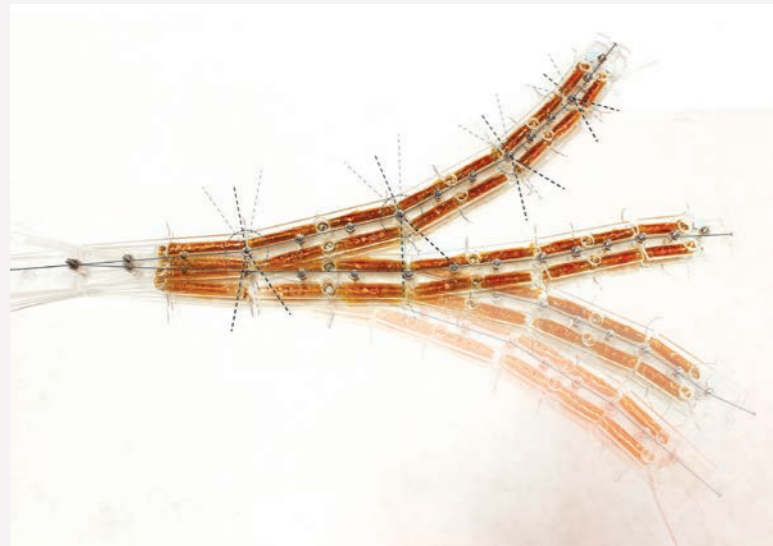
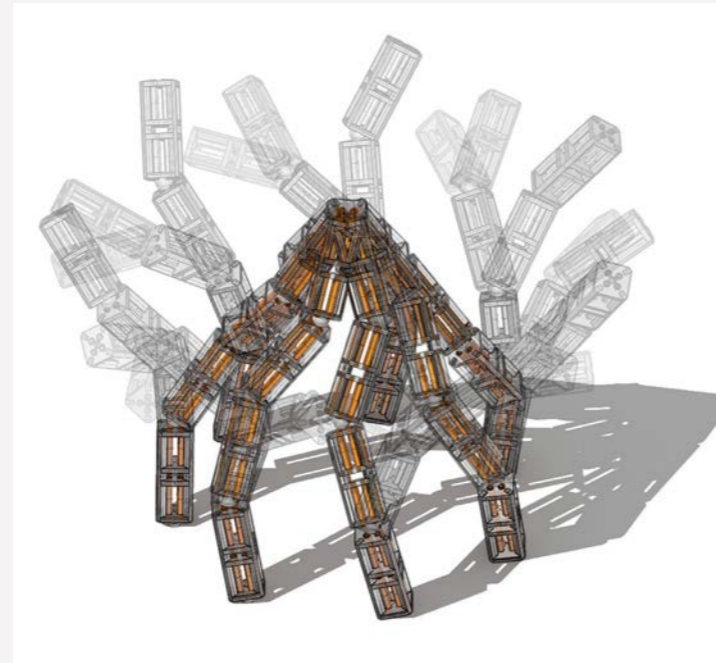
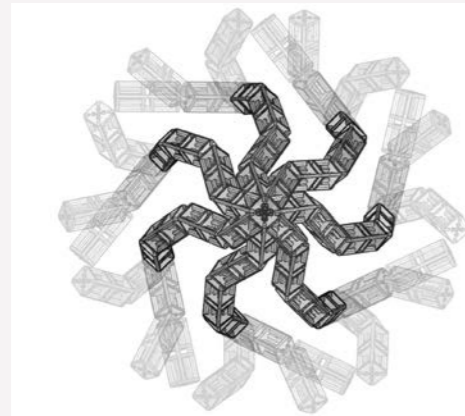


Figure 1.
 Top Left: Heat actuated nylon muscles that are actuated at 60-75°C and are able to twist, turn and lift in multiple axes and directions.
 Bottom Left and Right: Digital Simulations of multiple aggregated elements for responsive structures.
 Images Credit: IAAC Digital Matter Studio 2015.
 Mathur, Munera, Stevens.



[i] Vincenzo Casciarolo in 1603 obtained luminescent barium sulfide by a stone that contained barium sulphate with coal.

[ii] See more info in section 3.2.1 Case Study 1: Bloom, Thermo *Bimetals for building skins that react to temperature for passive cooling*.

^{1,2} A. Ritter, *Smart Materials in Architecture*, Interior Architecture and Design, Basel, Birkhäuser Architecture, 2006, p.8.

2.2

MATERIALLY RESPONSIVE ARCHITECTURE

2.2.1 SMART MATERIALS

“Smart materials” is a term used to describe materials that have dynamic properties, meaning that they are able to change their shape and colour in response to an environmental physical or chemical stimuli. Such stimuli include light intensity, temperature, humidity content, PH level, changes in atmospheric pressure, stress, bio-chemical reactions and electric or magnetic field. **“Smart materials” describes highly engineered, and therefore artificially made, materials that respond to their environment (Figure 1).** Since in many cases, the change of their properties is related with a change on physical form and since their ability of change is inherent, meaning they do not require any external mechanical system to change, they have been also named “kinetic”, “dynamic”, “functional” or “multifunctional” materials. Between the smart materials and the non-smart that do not exhibit these abilities, we find the semi-smart materials that they are able to change upon a specific stimuli, but only once or for a few times, while in the smart materials those changes are repeatable and most of the times reversible¹.

Smart materials is not a new invention, neither does define a totally artificially made matter. Humans have discovered the possibilities of such materials since early times and they have been using them in an informal way. According to Ritter, one can go back to the age of “pouring hot water over wood to induce it to swell and split rock”², or to the beginning of 17th century that amateur alchemist Vincenzo Casciarolo discovered the property of “Luminescence” (storing light and releasing it in the dark) in the so-called Bolognian stone [i]. The widest application of smart materials, though, is found in the beginning of the industrial revolution, in the famous “thermostat”. Thermostat is a thermoelectric switch which performance is based on the property of bending and curving of two joint metal strips that have different thermal expansion coefficients [ii].

Other examples of “smart materials” include photochromic or thermochromic compounds able to change their colour upon exposure to light or temperature accordingly. The vast category of shape memory materials, consist in materials that are able to change their

BUILDING SYSTEM NEEDS	RELEVANT MATERIAL OR SYSTEM CHARACTERISTICS	REPRESENTATIVE APPLICABLE SMART MATERIALS
CONTROL OF SOLAR RADIATION TRANSMITTING THROUGH THE BUILDING ENVELOPE	Spectral absorptivity / transmission of envelope materials	Suspended particle panels Liquid crystal panels Photochromics Electrochromics
	Relative position of envelope material	Louver or panel systems -Exterior and exterior radiation(light) sensors -- Photovoltaics, photoelectrics -Controls/actuators -- shape memory alloys, electro and magnetostrictive
CONTROL OF CONDUCTIVE HEAT TRANSFER THROUGH THE BUILDING ENVELOPE	Thermal conductivity of envelope materials	Thermotropics, phasechange materials
CONTROL OF INTERIOR HEAT GENERATION	Heat capacity of interior material	Phase-change materials
	Relative location of heat source	Thermoelectrics
	Lumen/watt energy conversion	Photoluminescents, electroluminescents, light-emitting diodes
ENERGY DELIVERY	Conversion of ambient energy to electrical energy	Photovoltaics, micro and meso energy systems (thermoelectrics, fuel cells)
OPTIMIZATION OF LIGHTING SYSTEMS	Daylight sensing illuminance measurements Occupancy sensing	Photovoltaics, Photoelectrics, Pyroelectrics
	Relative size, location and color of source	light-emitting diodes (LEDs), electroluminescents
OPTIMIZATION OF HVAC SYSTEMS	Temperature sensing, Humidity sensing Occupancy sensing CO2 and chemical detection	Thermoelectrics, Pyroelectrics, biosensors chemical sensors, optical MEMS
	Relative location of source and or sink	Thermoelectrics, phase-change materials, heat pipes
CONTROL OF STRUCTURAL SYSTEMS	Stress and deformation monitoring Crack monitoring Stress and deformation control Vibration monitoring and control Euler buckling and control	Fiber-optics, piezoelectrics, Electrorheologicals (ERs), magnetorheologicals, shape memory alloys

Figure 2.
Mapping typical building system design needs in relation to potentially applicable smart materials.
Adapted diagram from Michelle Addington and Daniel L. Schodek, 2005

shape or length when exposed to certain temperatures and remember their previous shape in to which they reverse upon appropriate stimuli. The most common material of this category is the nitinol wire, usually found in the form of spring that when heated expands its shape and length and when cooled, comes back to its initial shape. Other smart materials include Magnetorheological fluids that are able to move in order to follow certain magnetic fields or piezoelectrics that are able to generate electric charges under a specific stimuli of stress (compression or tension).

Michelle Addington and Daniel Schodek highlight that although materials in the 20th century are given additional roles -“ideological [...] iconographic and the very pragmatic one of saving in industry”- in the contemporary practice “materials continue to be chosen not so much for how they perform, but what they connote”³. In contrast to that, in his book “Material Invention”, Ezio Manzini refers to the importance of identifying materials by “what they do” instead of simply what they consist of and their applications. Manzini emphasizes the importance of bringing the notion of performance in the characteristics of the materials beyond their simple functionality⁴.

Much of today’s smart materials are engineered and artificially made materials. This indicates that their performance and behavior can be controlled during their manufacturing. In the nitinol wires for instance, if the wire will be “programmed” during high temperatures in a shape different than a spring, then when cooled down will reverse to that initial shape that has been molded. **The fact that the response of smart materials can be controlled, opens up great possibilities in the design field.** Firstly, any object that is made by these materials (if its design does not prevent the material’s performance) could be transformed accordingly into a “smart” or “responsive” object, able to exhibit autonomous behavior upon a specific stimuli. Secondly, the design in which these materials can be integrated in, could enhance, delay and eventually control this behavior. For instance the use of nitinol wires in tensegrity structures, as we will study in the next chapter [iii], can contribute in animating the structure if placed in certain joints or locking it to static position, if placed in others.

Although the architectural practice gives privilege to static materials, since uncontrolled changes in materials could encompass a series of risks, (from structural to human health ones), smart materials open up possibilities for selecting or engineering “the properties of a high performance material to meet a specifically defined need”⁵. Design discipline, therefore, a discipline that is inherently a material based one, becomes an appropriate field for the research and applications of such behavioral materials (Figure 2).

Although a long list of smart materials are available as products in industrial scale, they usually require complex manufacturing processes as well as highly equipped laboratories, machinery and personnel. This rises its value, making them in many cases extremely expensive and inaccessible. However, taking into consideration the increasing degree of accessibility for much of the processes involved in their production (machinery and knowledge), smart materials present immense possibilities for their mass and customized applications.

[iii] See chapter 3.2.3.2 Case Study 2: Remembrane: Shape changing adaptive structure that incorporates user control project

³ M. Addington and D. L. Schodek, *Smart Materials and Technologies for the architecture and design professions*, Architectural Press, Elsevier, Oxford, 2005, p. 201.

⁴ M. Bengisu and M. Ferrara, *Materials that Move*, Springer Briefs in Applied Sciences and Technology, Cham, Springer International Publishing, 2018, p.1.

⁵ M. Addington and D. L. Schodek, *Smart Materials and Technologies for the architecture and design professions*, Architectural Press, Elsevier, Oxford, 2005, p. 3.

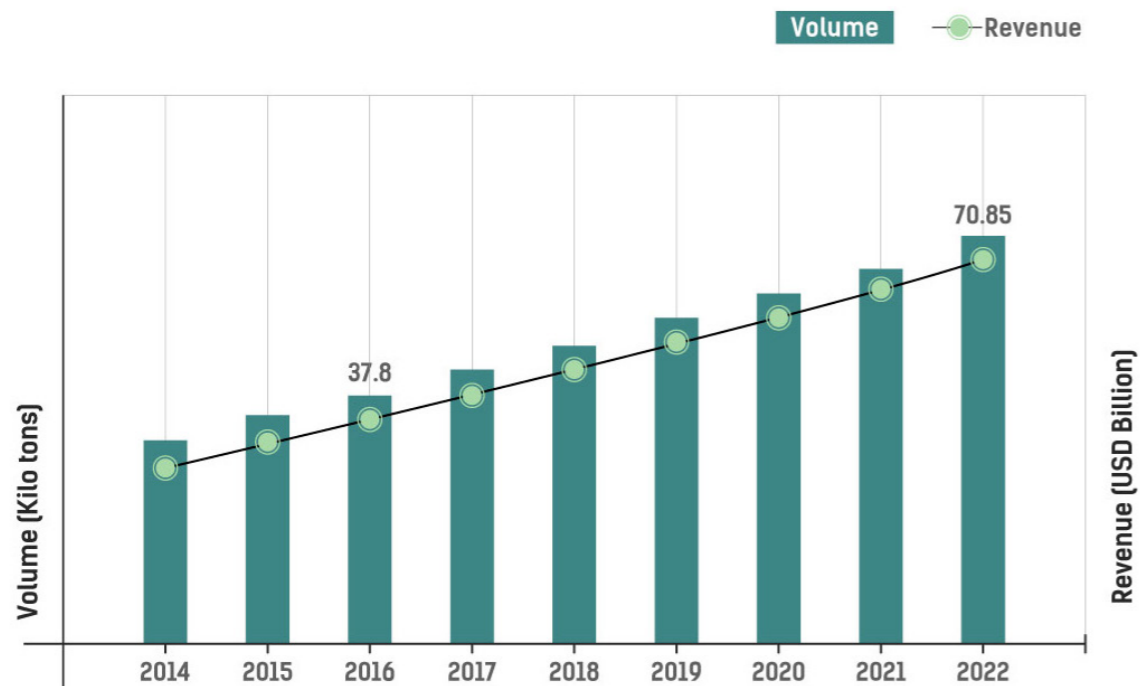


Figure 3.
Global Smart Materials Market, 2014-2022
(Kilo Tons) (USD Billion).
Adapted diagram from Zion Market Research report in 2016⁸

[iv] According to Addington and Schodek the first commercial application of smart materials was skis for snow in 1992. For more see: M. Addington and D. L. Schodek, *Smart Materials and Technologies for the architecture and design professions*, Architectural Press, Elsevier, Oxford, 2005.

[v] Compound annual growth rate (CAGR) is used to evaluate the value of an investment.

⁶ "Smart Materials Market Size & Forecast Report, 2014 – 2025", *Grand View Research* [website], 2019, <https://www.millioninsights.com/industry-reports/smart-materials-market> (accessed March 2019).

^{7,8} "Smart Materials Market (Biomimetic Materials, Piezoelectric Materials, Thermally responsive Materials and Others) Market for Actuators & Motors, Sensors, Transducers, Structural Materials and Other Applications: Global Industry Perspective, Comprehensive Analysis, and Forecast, 2016 – 2022", *Zion Market Research*, [website], 2019, <http://www.zionmarketresearch.com/report/smart-materials-market> (accessed March 2019).

⁹ "Disruptive technologies: Advances that will transform life, business, and the global economy", *McKinsey & Company*, [website], 2013, https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/Disruptive%20technologies/MGI_Disruptive_technologies_Executive_summary_May2013.ashx, (accessed March 2019).

2.2.2 SMART MATERIALS AND THEIR EFFECT UPON DISCIPLINES

Since the first commercial application of smart materials in 1992 [iv], a growing interest and investment has been observed in different disciplines. Although demand cannot always be easily predicted, the latest 2017 report of Grant View Research, positions aerospace engineering and defense industry as the key drivers for getting the smart materials global market to 98.2 billion dollars by 2025⁶, with a predictive growth at CAGR [v] of 13.5 percent through. According to this report, the increase on demand for smart materials will be driven by the increase of demand for electronic devices such as sensors and actuators. Since smart materials present inherent properties for sensing and actuation, they become a substantial replacement for electronics that can easily be integrated in different existing materials and systems.

Similar results and predictions can be found in the report of Zion Market Research that foresees substantial growth in the smart materials market from 37,9 US billion dollars in 2016, to 70,85 US billion dollars in 2022 (Figure 3). According to this report the growth is partially predicted due to the relevant advancements in automotive, military, aerospace, construction and manufacturing fields⁷.

McKinsey Global Institute, in their report titled "Disruptive technologies: Advances that will transform life, business, and the global economy" identify 12 technologies that will bring massive disruption, and economic impact in the next decade. **Advanced Materials is ranked in the 10th position surrounded by other technologies such as the Mobile Internet, the Internet of Things, Renewable Energy or Autonomous vehicles** (Figure 4 and 5). As Advanced materials McKinsey report define the "materials that have superior characteristics such as better strength and conductivity or enhanced functionality such as memory or self healing capabilities" listing graphene, piezoelectrics, carbon nanotubes and shape memory materials among the most influential ones⁹.

In another report of Envisioning, a company studying emerging technologies, we can observe the level of maturity of Material and Manufacturing Technology. The report collects data on Technology Readiness Levels (TRL) for each technology, and intends to create a quantitative mapping of the technology matureness. Compared with 20 more categories within Materials and Manufacturing Technology, smart materials (or Reactive Materials and Structures as named in the report) stand in the 4th position (just above smart fabrics, on-demand manufacturing and high performance coatings) in terms of development and maturity technology¹⁰ (Figure 6).

Aligned with these reports, we observe a number of projects coming from fields such as the aerospace engineering, automotive or the product design to invest in research and applications on smart materials. Not surprisingly, (taking into consideration the exponential

ADVANCED MATERIALS

Materials that have superior characteristics such as better strength and conductivity or enhanced functionality such as memory or self-healing capabilities

Potential economic impact across sized applications



Nanomedicine could be used to



Component Technologies

Graphene Nanoparticles Carbon Nanotubes Other Advanced Materials

Key Applications

Nanoelectronics Enhanced Chemicals and Catalysts Nanomedicine Energy Storage

Figure 4.
Potential economic impact of Advanced Materials and their key applications.
Adapted from McKinsey Global Institute report, *Disruptive technologies: Advances that will transform life, business, and the global economy*, 2013

A GALLERY OF DISRUPTIVE TECHNOLOGIES

Estimated potential economic impact of technologies across sized applications in 2025. \$ trillion, annual

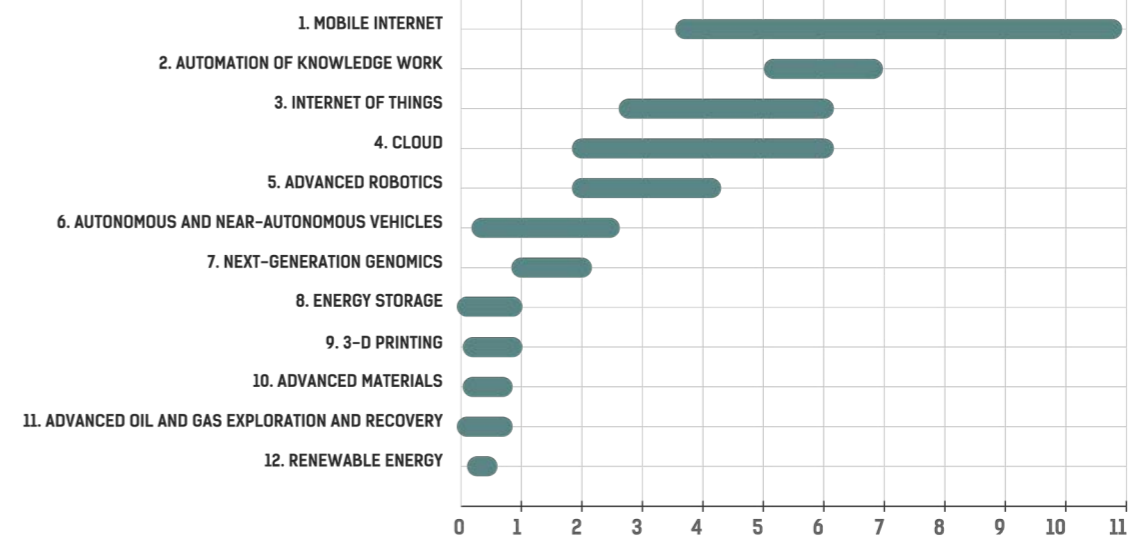


Figure 5.
Gallery of top 12 Disruptive Technologies with big economic and life style impact.
Adapted from McKinsey Global Institute report, *Disruptive technologies: Advances that will transform life, business, and the global economy*, 2013

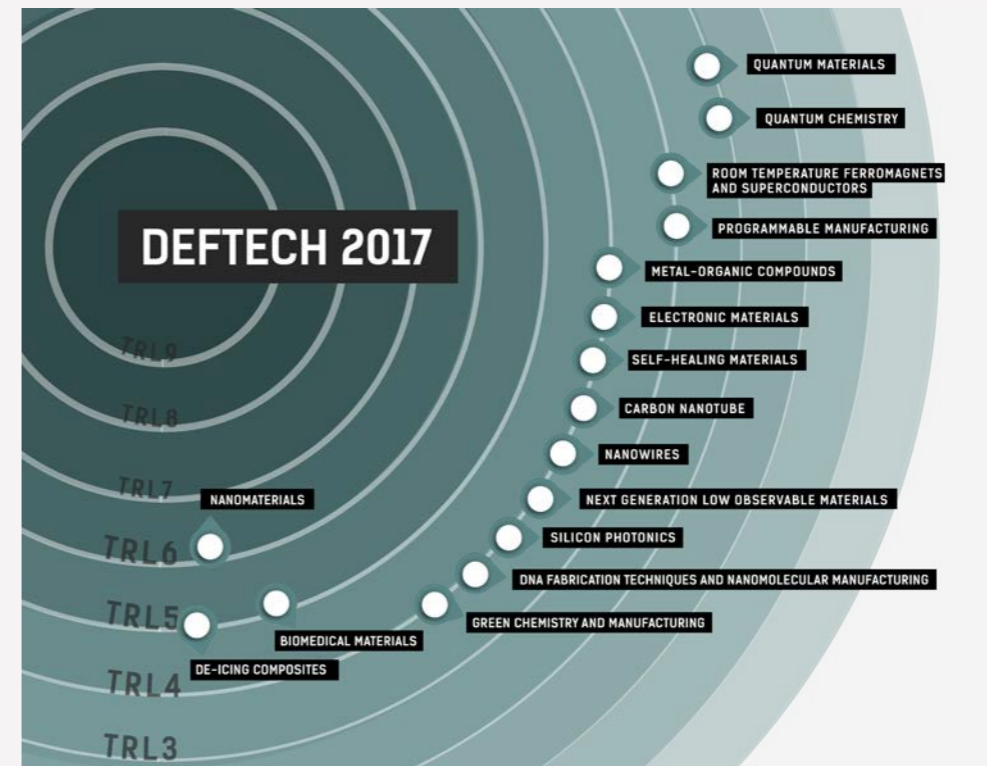


Figure 6.
Diagram of technology maturity of Smart Materials.
Adapted from Deftech 2017, *Envisioning*

interest of architects in materials) several of them, emerge as collaborations of industries or research centers with architectural research laboratories.

Carbitex, a company of carbon-fiber composites joined forces with the Self Assembly Lab, of the MIT, directed by architect Skylar Tibbits for researching new dynamic carbon fiber composites. Together, they have developed a new composite embedded with temperature sensitive polymers that is able to fold and twist in a completely passive way. The new carbon fiber composite found a series of applications such as the production of non-mechanical morphing car airfoils in collaboration with Briggs Automotive for optimizing the speed of race cars. Furthermore, the Self-Assembly lab in collaboration with Airbus SAS developed similar composites for the a jet engine air inlet that is able to fold and unfold for controlling and optimizing the flow of air into the engine of the aircraft [v].

Similarly, as we will further study with more details in this thesis, the Digital Matter Studio of the Institute for Advanced Architecture of Catalonia (IAAC), has been collaborating with the Italian Institute of Technology (IIT) and the Smart Materials group for developing graphene enhanced composites that could be applied in the construction sector [vi] or graphene-based membranes appropriate for both building skins as well as for sails in the sailing industry. Other multidisciplinary collaborations include fashion and product design industries and NASA for the creation of dynamic textiles that change their color based on humidity and temperature or the creation of shape shifting furniture and aircraft wings.

Finally, it is worth mentioning that the European Agency has been investing increased funds for the research of intelligent materials in architecture. In 2010, the Experimental Architecture Department of the University of Newcastle in collaboration with multidisciplinary partners, received a multi-million euros fund, for the development of architectural solutions based on biomimicry and using novel materials such as protocells or biological organisms [vii]. Similarly, in 2018 the Institute for Advanced Architecture of Catalonia under the Erasmus+ Knowledge Alliance program of the European Union has received a 1 million grant for the research “Building Intelligent Design Solutions” (BUILD’s) targeted at developing novel nature-based solutions in architectural and urban scale through the combination of biology, material science, architecture and economy [viii].

The above mentioned, are only a few quantitative examples showcasing that, **the field of smart materials is exponentially flourishing presenting immense possibilities in disciplines including architecture and design.**

[v] The projects are a collaboration of Self Assembly Lab, MIT with Carbitex LLS, Center for Bits and Atoms, Autodesk Inc and Airbus SAS or Briggs Automotive.

[vi] See more in Chapter sections 3.3.6.3 *Case Study 3: Soft Smart Membranes* and 3.3.6.4 *Case Study 4: Synapse*

[vii] Living Architecture (LIAR) is received funding from the European Union’s Horizon 2020 Research and Innovation Programme with the goal to design and build a proof-of-concept “living architecture”.

2.2.3 ADVANTAGES AND LIMITATIONS

The major limitation faced when working with smart materials versus conventional materials is the degree of their study. While conventional materials have been exhaustively tested and studied, as well as evaluated in relation with their properties and impact, smart materials are relatively new, and there is not yet available **a satisfactory database on their properties**, impact, manufacturing requirements and cost.

Since this lack of study becomes a strong limitation for their use, alternative ways of working are required. Instead of following given ways on how smart materials can be manufactured, industrialized or become products, different methods of work including prototyping, experimenting and conducting pilot projects, become useful and relevant. These methods imply a different mode of action, one that fosters the tinkering on the fly, meaning calibrating, deciding, designing and eventually generating knowledge in-action through prototyping and experimentation. In contrast to top down processes that follow specific recipes previously set by others, generating knowledge and discovering in-action, is a bottom up approach that boosts creativity and innovation¹¹.

This bottom up mode of working, further contributes in **incorporating a deeper material thinking in design from its early stages**, in contrast to current top down workflows that select materials once a design is made.

Although, as we have seen, the do-it-yourself culture is increasing and as a result prototyping and learning in action becomes a common workflow for research and innovation, it is essential to understand that the technical complexity of smart materials cannot be overcome just by a one-discipline researcher, designer or “maker”. In contrast to traditional materials, smart materials are synthetic materials, meaning that they are created from scratch at a molecular level and they are not found and post-processed¹². The synthetic creation process in most cases signifies that with slight changes in the manufacturing process and conditions, smart materials can be customized and produced following specific desired outcomes.

The knowledge gaps presented when designing and working with smart materials require

[viii] BUILDs project is developed by the following partners: IAAC, Université de Lorraine, Vienna University of Economics and Business, Ersilia Foundation, ECONICK, Plant-e, City Facilitators and GreenTech Challenge.

¹¹ D. A. Schön, *The reflective practitioner: How professionals think in action*, New York, Basic Books, 1983.

¹² M. Kretzer, *Information Materials*, Switzerland, Springer International Publishing, 2017, p. 18.

multidisciplinary teams that can drive more accurate observations and results during the stage of prototyping and testing¹³. **This multidisciplinary mode of work empowers architectural design** to overcome the limitations of fragmented and disconnected sectors of expertise, setting the ground for the development of the necessarily optimized, controlled and customized architectural solutions for today's challenges. Furthermore, taking into consideration that current research on smart materials is mainly driven by fields of engineering or medical sciences, the multidisciplinary mode of work can contribute in bringing the possibilities of smart materials into the built environment.

When dealing with materials that exhibit properties of physical change, the issue of life cycle and time cycle are important factors to define their performance. As life cycle, or lifespan, is defined the total number of change cycles that a smart material can assume before failing, weakening or losing its ability to transform. Time cycle is defined as how fast a material can transform. Life cycle and time cycle vary for the different smart materials. Thermochromic and photochromic powders, for instance, present low life cycle, since they cannot be activated many times to change their color. After certain numbers of cycles the material loses its ability to transform.

It is therefore, fundamental when designing with smart materials to fully understand and **incorporate both lifecycle and time cycle**. In the case of photochromics, for instance, what is also interesting is that their cost is extremely low, which might also open possibilities for designing solutions that can be easily replaced every few years or months. Bimetals or shape memory materials on the other hand, have high life cycle and possible to be activated thousands of times before they collapse. Similarly, time cycle becomes a fundamental factor for understanding the limitations or possibilities and to design accordingly. In the case of materials with shape memory for instance fast time cycle is observed when heated because heating can be achieved by wires and electricity, while cooling can take longer if it is dependent on ambient conditions and does not use artificial means. Furthermore, other materials involved in products that include smart materials play an important role. Photochromics for instance do not exhibit similar time cycle if they are applied in glass or plastic surfaces. All these, need to be taken into consideration for successful prototyping and developing of architectural applications.

Cost and availability of smart materials is by no doubt the biggest limitation for widespread use in architecture and building industry. However, in order to fully understand the cost of a building in architecture, we need to calculate this in long term. Although, the initial cost of certain technologies such as the photovoltaic technology might initially increase the cost of a building, when calculated in long term, it actually presents extreme savings that are both economical as well as environmental. Similarly, smart materials, although might have a high cost, when integrated in architecture and buildings can contribute in extreme energy savings, since as we have seen they have the ability to produce change without the need of any external mechanical or electrical input.

¹³ M. Bengisu and M. Ferrara, *Materials that Move*, Springer Briefs in Applied Sciences and Technology, Cham, Springer International Publishing, 2018, p. 66.

As we will further analyze in the following chapter, the abilities of smart materials to perform in the afore-mentioned ways, makes them appropriate for instance as systems of passive cooling and heating, drastically decreasing the need of use of artificial systems that have both economic and environmental cost.

Smart materials, have been for long associated with disciplines such as aerospace engineering, medicine or human-computer interaction and tangible computing. After several decades of research and study, though, we can now observe significant steps to bring them into the architecture and building fields. Many support that these highly engineered materials are born as a response to the 21st century's technological needs. In an effort to expand these efforts and test the added value for architecture, Addington and Schodek recognizing both the limitations and possibilities of using smart materials in architecture they urge for liberating architecture's preoccupations "with showing off the advanced materials in a purely provocative manner"¹⁴.

Without discarding their limitations, **smart materials, open up unique possibilities for creating products that are multifunctional and that exhibit customized and selective performances**. Within this context, architects and designers can surpass the limitations of traditional materials and be empowered to select, design and customize materials that can be responsive to the environment and to society's continuously changing needs.

2.2.4 DESIGN'S VALUE FOR SMART MATERIALS

Architect Tibbits, in an effort to describe the value that design can bring in smart materials, uses the analogy of the calculator that evolved in today's programmable machines. He argues that Smart Materials in material history - much the same as the calculator did in computer history - now evolve into programmable and physically active materials that could be designed to have customized properties or sizes and for various applications. In contrast to the current state of smart materials Tibbits describes that the design and applications of smart materials in architecture "makes it possible to make any material a smart material"¹⁵.

¹⁴ M. Addington and D. L. Schodek, *Smart Materials and Technologies for the architecture and design professions*, Architectural Press, Elsevier, Oxford, 2005, pp. 16-19.

¹⁵ S. Tibbits, *Active Matter*, Boston, The MIT Press, 2017, pp. 12-17.

Through his vision, he urges for applying architectural and design thinking in the creation and application of smart materials and he foresees a radical shift of paradigm in the architectural design logics:

*“If over the past half-century we have experienced a software and hardware revolution, **we are now experiencing a true materials revolution.** We can now sense, compute, and actuate with materials alone, just as one could previously with software and hardware platforms. It is becoming increasingly clear that materials are a platform for turning digital information into physical performance and functionality. If yesterday we programmed computers and machines, today we program matter itself”¹⁶*

Manuel Kretzer points out a fundamental difference of smart materials to the matter that he names “information materials”. This difference, lies on the conscious decision (intellect) required for applying smart materials in their architectural potential and highlights that should be made by and carry on information¹⁷. This exact focus on the intellect, highlights the possibilities of smart materials’ expanded applications, as well as the ability of designers and professionals to create synthetic materials that exhibit dynamic behaviors.

“The concept thus aims at proposing and mediating a new way of thinking, liberated from a materialistic and mechanistic point of view, and instead focusing on materiability, the empowering ability to create synthetic materials with performative abilities”¹⁸

Russo and Ferrara argue that it is necessary to instill a new mindset for applying smart materials and their possibilities in architecture. Highlighting the importance of both creativity and design, they describe that this mindset should be focused towards merging design with the possibility of creating user experiences.

“...instill a mindset for applying these materials and related technologies, trusting in the cross-fertilization of design methodologies (product, interaction, and experience design) by orchestrating functions, forms, sensory experiences in different timeframes and contexts, and by designing “smart experiences”¹⁹.

The approach towards materials that do not require any external mechanical system of sensing or actuation opens up new possibilities for dealing with materials. The most important shift is the one signaling towards biology or chemistry instead of computation, robotics or engineering. Furthermore, applications of smart materials in architecture open up much more complex perspectives and logics compared to their pure industrial aspect. On the one hand, when smart materials are applied in architecture, appropriate design and intellectual decisions are required. On the other hand, these applications open up possibilities of **merging the performance of smart materials with traditional ones, creating, therefore a new synthetic matter.**

¹⁶ S. Tibbits, *Active Matter*, Boston, The MIT Press, 2017, pp. 12-17.

¹⁷ M. Kretzer, *Information Materials*, Switzerland, Springer International Publishing, 2017.

¹⁸ Ibid. pp. 52.

¹⁹ M. Bengisu and M. Ferrara, *Materials that Move*, Springer Briefs in Applied Sciences and Technology, Cham, Springer International Publishing, 2018, pp. 1-4.

2.2.5 RESPONSIVE MATERIALS AND MATERIALLY RESPONSIVE ARCHITECTURE

Within this current context, this thesis introduces the term “Responsive Materials” as the smart material systems through which, Architecture starts to exhibit inherent dynamic and adaptive properties. Although the term *Responsive Materials*, include the presence of smart materials in an architectural system, it is not limited to that aspect.

Above all, the term ***Responsive Materials* describes a material system and not a pure material itself.**

The characteristics of *Responsive Materials*, as this thesis defines, can be found below:

- *Responsive Materials* hardly ever consists just in one/some smart materials. It mostly consists in a combination of smart, non-smart and semi-smart materials, most of the times in the form of new composites or of a variation of geometries that transform in the physical space.

Since the material system follows the inherent behavior of the smart materials present in it, ***Responsive Materials* presents autonomous response upon specific environmental stimuli.**

- The term *Responsive Materials* does not describe only a material aspect of an architectural system, but additionally, the design logic(s) that is applied in order to enhance, or frame, the autonomous behavior exhibited by the presence of smart materials. In this sense, ***Responsive Materials* and its architectural applications require an essential and active part of architects and designers in its development.**

- In an effort to allow the material systems to interact not only with their environment but also with the users that surrounds their architectural applications, ***Responsive Materials* might additionally consist in user-friendly digital platforms and communication protocols that allow users to interact with them.**

- In order for the material system to learn from complex behaviours of environment and user and, therefore, acquire self-awareness, additional programming technologies (such as machine learning and evolutionary algorithms) might be included. This transforms its initially autonomous behavior to a truly intelligent behavior in tandem and in-sync with all parameters of users, environments, inherent properties and design.

In order to exhibit intelligent behaviors, then, *Responsive Materials*, might additionally consist in artificial intelligence technologies.

It is precisely these exact characteristics of *Responsive Materials* applied to architecture, that we define as ***Materially Responsive Architecture.***

2.3 CONCLUSIONS

Architecture has always been in close relationship with the materials used for its production. Although, traditionally materials have been following architectural form as an external force, the advancements of digital manufacturing, materials science, as well as the introduction of new ways of seeing the world through philosophy, have contributed in a major shift in the relationship between architecture and matter.

More specifically, the digitization of design and manufacturing through computer-aided design (CAD) and computer numerically controlled machines (CNC) allowed architects, designers or industry practitioners to **design and manufacture these designs in ways never seen before**. This has been a fundamental contribution for the cultivation of the new culture related with physical materials, and how these, can be manipulated or, how they can perform. At the same time, material and engineering advancements, life sciences and synthetic biology advancements nourished this novel culture by introducing **new possibilities of synthetically created materials that have different abilities**.

Many biological organisms and structures present inherent characteristics such as self-healing, shape-changing or self-monitoring. In the search of these kind of characteristics the building industry today develops a series of automated systems for building performance such as sensors for monitoring highway bridge vibrations, water spray mechanisms actuated by sensors of temperature and smoke, or the thermostat based systems of sensing temperature and actuating artificial cooling and heating systems. The current Building Automation Systems based on add-on layers of electronics has been the answer to achieve the adaptive capacities of biological systems that are absent from the systems designed by humans. The new domain of material science and engineering, though, is focusing on creating **artificially made materials that present similar properties to biological organisms**. The term to define these materials is usually “smart materials”.

Following principles of synthetic biology, the field of smart materials focuses on changing the fundamental structural organizations in atomic level, and therefore, the functionality, performance and information embedded in the material medium. Although, this change happens at the micro (or nano) scale of the atomic organization of materials, its effect can (potentially) be visible in the meso or macro scales of the material applications. This approach of creation from the inside out **resembles the natural operations of growth or replication** and is based on the principle of restructuring and evolution.

Smart Materials, finally, highlights new protocols and logics for the construction of our

physical space. In this logic, properties coming from the digital and computer science world, such as feedback or re-programmability are now applied into the physical world bringing (additionally to the biological) computational logics to matter and space, and, eventually, animating both.

When we deal with smart materials in architecture it becomes fundamental to understand the different levels of complexity related with all aspects of materials, design, performance and actuating agents. Within this context, **the terms of Responsive Materials and Materially Responsive Architecture introduce the basic protocols for describing the crucial aspects when applying smart materials in architecture**. In relation of matter and form as well as matter and architecture in specific, new materialism becomes the basic philosophical framework within which *Materially Responsive Architecture* operates. As previously seen, this framework describes **matter as an entity operating in non-linear logics and in direct relationship with form presenting morphogenetic capabilities of its own**. Rather than materials that follow the structure and function of the buildings we start to observe materials that themselves become the driver for creating morph.

As we will further study in the next chapter, *Materially Responsive Architecture* presents a series of unique qualities and behaviors. These include the ability to dynamically change its internal structure and form without losing equilibrium, the capacity to self-organize to create different assemblies and eventually the ability to mutate to affect its own formation.