Performance Software Approaches for Kinetic Architecture: Programmable Matter Based Simulations

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Performance Software Approaches for Kinetic Architecture:

Programmable Matter Based Simulations

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Universitat Internacional de Cataunya

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Keywords: kinetic architecture, shape memory materials, simulation, building performance, parametric modeling.

Abstract_

The Ph.D. project is basically an investigation and development concerning kinetic architecture design software support that will be used to simulate the behavior of shape memory materials (SMM--specifically Nickel-Titanium --Ni-Ti-- alloys, Linear -LCP- and multi-block co-polymers -MBCP-) and which will work as either a plug-in, an add-on or a script in an already existing design platform (like Rhino/Grasshopper or Processing) preferably (but not limited to) Open Source that can give architects and engineers the ability to design and test-run kinetic components and, hopefully someday, entire buildings in a digital work space, before having to do so in a laboratory environment.

The project's theoretical framework is based on William Zuk's and Michael Fox's kinetic architecture concepts, Dan Raviv and Skylar Tibbits's work on programmable matter within the Self Assembly Lab at MIT while it also touches some of Dennis Dollens ideas about utilizing generative software tools and methods to address architectural design (specifically, a paper called *The Cathedral Is Alive: Animating Biomimetic Architecture*). Its most important theoretical objective is to find ways in which to utilize these materials within the conception and development of passive kitnetic architecture systems (K. A. which is, as of today, mostly computer controlled --therefore, electricity consuming).

The material science aspect of the project is being informed by Otsuka & Wayman's research about Nickel-Titanium[1] (Ni-Ti) alloys, Lendelein & Kelch's research about shape-memory polymers[2], Rottiers et al.'s research about SMM and their applications[3]. To test and develop the software

[1] Otsuka, Kazuhiro - Wayman, Marvin Clarence, *Shape Memory Materials*, Cambrige University Press (1998)

[2] Lendlein, Andreas, Kelch, Steffen, "Shape-Memory Effect: From temporary shape. . . T > 46 °C . . .to permanent shape", *Angewandte Chemie*, WILEY-VCH Verlag GmbH, 69451 Weinheim, Germany, (2002)

[3] Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. (https://lirias.kuleuven.be/bitstream/123456789/384788/1/PAPER_SMM_def_rottiers_vdb_peeters_arras.pdf)

functionality it is needed to analyze certain examples of kinetic architecture (as case studies) and to understand how to mathematically model (and subsequently code in the program's application programming interface -API- and/or user interface -UI-) the material's properties in order to compute and simulate their behavior in the program's work space (in relation to their stimulus/form/movement). This thesis will carry out experiments in that direction and arrive at conclusions about the subject matter.

Aproximaciones de *Software* de Desempeño para Arquitectura Cinética:

Simulaciones Basadas en Materia Programable

Escola Tècnica Superior d'Arquitectura

Universitat Internacional de Cataunya

2015

Palabras clave: Arquitectura cinética, materiales de memoria de forma, simulación, desempeño, modelado paramétrico.

Abstracto_

El proyecto de tesis es, básicamente, una investigación y desarrollo de *software* de diseño de soporte para arquitectura cinética que será usado para simular el comportamiento de materiales de memoria de forma (SMM - específicamente aleaciones de níquel-titanio --Ni-Ti--, co-polímeros lineales y multibloque --LCP y MBCP--) y funcionará, ya sea como plug-in, complemento o un script en una plataforma de diseño ya existente (como Rhinoceros / Grasshopper o Processing) preferentemente de código abierto (pero no limitados a éste) y que le dará a arquitectos e ingenieros la capacidad de diseñar y probar componentes kinéticos y, con suerte, algún día, edificios enteros en un espacio de trabajo digital, antes de tener que hacerlo en un ambiente de laboratorio.

El marco teórico del proyecto se basa en los conceptos de William Zuk de y Michael Fox sobre arquitectura cinética (KA), el trabajo de Dan Raviv y Skylar Tibbits en el seno del MIT, mientras que también toca algunas de las ideas de Dennis Dollens sobre la utilización de herramientas y métodos de *software* generativo para abordar el diseño arquitectónico (específicamente un documento llamado "The Cathedral Is Alive: Animating Biomimetic Architecture"). El objetivo teórico más importante de ésta investigación es encontrar maneras de utilizar estos materiales dentro de la concepción y el desarrollo de sistemas pasivos de arquitectura cinética (KA, la cual es, al día de hoy, mayormente controlada por computador -por tanto, consumidora de electricidad).

El aspecto de ciencia de los materiales en el proyecto está siendo informado por la investigación Otsuka y Wayman sobre aleaciones de Níquel-Titanio[4], el de Lendelein y Kelch de sobre polímeros de

[4] Otsuka, Kazuhiro – Wayman - Marvin Clarence, *Shape Memory Materials*, Chapter 1: Introduction, Cambrige University Press,(1998)

memoria de forma[5], la investigación de Rottiers et al. sobre SMM y sus aplicaciones[6] así como otros autores. Para poner a prueba y desarrollar funcionalidad de los *softwares* es necesario analizar ciertos ejemplos de arquitectura cinética (como casos de estudio) y para también entender cómo matemáticamente modelar (y posteriormente escribir el código en la interfaz de programación del *software* -API- y/o interfaz de usuario -UI-) las propiedades del material con el fin de computar y simular su comportamiento en el espacio de trabajo del programa (en relación con el estímulo / forma / movimiento). Esta tesis conducirá experimentos en dicha dirección y llegará a conclusiones sobre el tema en cuestión.

[5] Lendlein, Andreas - Kelch, Steffen, section: *Shape-Memory Polymers*, Angewandte Chemie, WILEY-VCH Verlag GmbH, 69451 Weinheim, Germany, (2002)

[6] Ward, Rottiers - Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. (https://lirias.kuleuven.be/bitstream/123456789/384788/1/PAPER_SMM_def_rottiers_vdb_peeters_arras.pdf)

*General objectives_*

1. To write a book, 463 pages long, that concisely summarizes the history of kinetics in architecture, its relationship and subsequent utilization and consolidation in the discipline and in general.

2. To determine the process by which architecture changes regarding the technology of the time and vice-versa.
   viada
3. To conduct research on kinetic architecture and art, CAD and programmable matter technology, its influence in the fields of contemporary architecture and its influence on the design/decision making process within the latter.

4. To obtain input information about the processes generated from the use of these technologies in contemporary projects and the theory that has prompted and has been generated from them.

5. To research on the edge between computation, material science and kinetic architecture in the making of a general theoretical framework to address specific questions about the state of the discipline at the beginning of the XXIst century.

6. To build a general conceptual theory that addresses the problem of *Kinesis* as opposed to *Stasis*, a concept that refers to life in architecture (taking movement, or *Kinesis* as a basis for its definition).

7. To define a comparative balance between types of software and analog tools and the produced architecture from their application in design.

8. To develop kinematic and kinetic software simulations that explore material behavior and optimize CAD visualization in the context of kinetic applications.

9. To conduct experiments that support or discard the assumptions and speculations proposed by the initial theoretical hypothesis.

10. To draw conclusions which contribute to the general definition of architecture and its relationship with science and technology.

*Specific objectives_*

1. To define the historical relationship between animation and architecture, their mutual influence in the way they're used as research tools as joint and separate disciplines.

2. To conduct research addressing material properties of shape-memory materials (SMM), specifically shape-memory alloys (SMA) and shape-memory polymers (SMP) and their implementation in a wide range of design disciplines as a potential image to its impact within the manufacturing and architecture, engineering and construction industry (AEC).

3. To define a state of affairs concerning the nature of particular software capable of providing solutions to the design problems arising from the use of these materials (SMM) in the analog and digital construction/fabrication processes, this within the Architecture Engineering and Construction (AEC) industry of today.

4. To develop design methods utilizing available software tools and potentially develop further their functionality , based on observation of nature as a framework and initial basis.

5. To develop a piece of code that can deal with current design tendencies and material behavior through simulation in a phenomenological and efficient manner; drawing information from intrinsic and extrinsic variables according to specific contexts stimuli such as environmental, thermal differential conditions and specific materials properties, hence material performance.

*Scope and contributions_*

This thesis project's most important theoretical objective is to find ways in which to utilize these materials within the conception and development of passive kinetic architecture systems (K. A. which is, as of today, mostly computer controlled --therefore, electricity consuming). Specifically, this will be done using simulation models, these new coded simulations will give architects and engineers the ability to design and test-run kinetic components and hopefully, someday, entire buildings in a digital work space before having to do so in a lab. All this, trying to provide an answer to Angeliki Fotiadou's question about "*the possibility of using a scripting language in the software*" that asks if "*only by this way* [scripting] *it will be possible to modify the chosen software and create new functions that there* *might be needed*[?][7]"specifically within the kinetic architecture and programmable matter simulation joint field. Our initial hypothesis is that it is the only way that current software allows for such customization.

*Methodology_*

In the introductory phase, this thesis seeks to reveal how all these come together while borrowing concepts from engineering, computer science, material science, art and biology, in the practice of producing design methods that in turn make possible a kind of truly autonomous, programmable matter based kinetic architecture. In the theoretical phase, this thesis will concentrate on kinetic architecture's origins and historical development and how it knots with computational design to address both geometric and dynamic complexity. The experimental phase of this research will carry out investigation concerning previous academic thesis, scientific papers and laboratory work about kinetic architecture, material science and computational design (more specifically parametric modeling) driven by laboratory, experimentally proven facts from all these disciplines and their authors, provided properly cited. In the experiments phase, digital experiments will be developed based on data from previous laboratory investigations of different authors, specifically within the fields of architecture, digital simulation, software engineering and development while also all the previously named sciences. This will be achieved using:

1.**Multiple case studies:** According to Daniel Davis, *"by employing multiple case studies, the anomalies of one can be balanced by the rest"*[8]. Robert Stake calls this a *"collective case study"*[9] *where multiple projects "are chosen because it is believed that understanding them will lead to better understanding, and perhaps better theorising, about a still larger collection of cases."* [10] In total, six case studies will be conducted whereby to experiment oriented on this thesis's objectives and from which to draw conclusions using what Davis and Donald Schön call "reflective practice"; a method that

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7 Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* Master of Science Graduate Thesis, Department of Building Physics and Building Ecology, TU Vienna, Vienna, Austria, in requirements for the degree of Master of Science (2007) P. 17

8 Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, School of Architecture and Design College of Design and Social context, RMIT University (2013) P. 11

9 Stake, Robert. 2005. "Qualitative Case Studies." In *The SAGE Handbook of Qualitative Research*, edited Norman Denzin and Yvonnas Lincoln, 443-466. Third edition. Thousand Oaks: Sage.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 11

10 Idem.

borders on inductive and abductive reasoning and which resembles *"Kemmis and McTaggart's (1982) cycle of 'planning, acting, observing and reflecting' on actions in practice."*[11] Meaning that, during the research process the path to follow will be one of "theorizing", "drawing data form other pertinent, similar work", "running experiments based on the the provided data" and lastly "observing again" and "reflecting" on the given results. The case studies are divided into two main groups themselves derived from *Dynamics*: *kinetic* models (or vector-force based self-organizing systems) and *kinematic* models (or geometry based self-assembly systems) depending on the particular goals of the given case examples (both design and simulation oriented) following "Ockham's razor" principles which dictate that "Among competing hypotheses, the one with the fewest assumptions should be selected" to choose the modeling paths.

2.**Developing own research instruments:** Daniel Davis, Paul Gruba and David Evans agree that a research instrument ***"****is any technique a scientist might use to carry out their 'own work'."*[12] *Typical examples include interviews, observations, and surveys.*[13] Unfortunately, there are no explicit research instruments to measure kinetic architectural design correctness or accuracy, let alone to evaluate it in realistic terms. Yet there exists a thesis that measured "difficulty" using *Autodesk's 3Dmax* (an exercise that prove to be too complicated and with too much issues to solve concerning basic and advanced software functionality) which is used as a base of knowledge to choose our design research's platform and direction, the thesis in question was an investigation carried out by Angeliki Fotiadou in 2007, where she compared several software packages regarding file basic functionality, modeling and animation tool availability and so on (a study that will be elaborated in chapter VI. In her investigation , she developed "difficulty" rating metrics that included: *"importing 2D drawings", "create primitive elements shape", "deform mesh", "copy elements/mesh", "create bones/skeleton/IK chain", "define constraints of rotation", "layout objects" and finally "animate".*[14] Her evaluation shows that using this software package gives rise to too many problems and cannot address complex form developed from kinetic criteria, therefore, even thought considering it a crucial contribution to the field of kinetic design, this research will not pursue its direction and chosen platform, considering that there are better

[11] Kemmis, Stephen, and Robin McTaggart. 1982. *The Action Research Planner*. Geelong: Deakin University.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 11
[12] Evans, David, and Paul Gruba. 2002. *How to Write a Better Thesis*. Second edition. Melbourne: Melbourne University Press, P. 85.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 11
[13] Davis, Daniel, *Op. Cit.* P. 11
[14] Fotiadou, Angeliki, *Op. Cit* (2007) P. 17

ways to address programmable matter based kinetic structures. Therefore methods that, by analyzing previous techniques, using, discarding or combining them in different, sometimes new ways create models meant to effectively address the matter of kinetic architectural design and simulation will be developed in chapter IX. An investigation and development will be conducted concerning kinetic architecture design software support that will be used to simulate the behavior of shape memory materials (SMM--specifically Nickel-Titanium --Ni-Ti-- alloys, Linear -LCP- and multi-block co-polymers -MBCP-) and which will work as either a plug-in, an add-on or a script in an already existing design platform (like Rhino/Grasshopper or Processing). The project's general theoretical framework is based on William Zuk's and Michael Fox's kinetic architecture concepts, Dan Raviv and Skylar Tibbits's work on programmable matter within the Self Assembly Lab at MIT while it also touches some of Dennis Dollens ideas about utilizing generative software tools and methods to address architectural design (specifically, a paper called *The Cathedral Is Alive: Animating Biomimetic Architecture*). The material science aspect of the project is being informed by Otsuka & Wayman's research about Nickel-Titanium[15] alloys, Lendelein & Kelch's research about shape memory polymers[16], Rottiers et al.'s research about *SMM and their applications*[17] as well as other authors. This research tentatively analyzes ways to understand how to mathematically model the selected material's properties in order to compute and simulate and subsequently code their behavior, in relation to their stimulus/form/movement relationships, in the program's application programming interface and work space (-API- and/or user interface-UI-) through the development certain examples of kinetic architecture simulation as case studies.

Thesis structure_

This thesis is composed of ten (10) total parts, these are: One (1) introduction: State of Affairs chapter, one (1) general framework chapter, one (1) historical context chapter, three (3) theoretical basis chapters, two (2) technical data chapters, one (1) case studies chapter and one (1) conclusions chapter.

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15 Otsuka, Kazuhiro - Wayman, Marvin Clarence, *Op. Cit.* (1998)
16 Lendlein, Andreas, Kelch, Steffen, *Op. Cit.* (2002)
17 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris - Arras, Peter, *Op. Cit.* (2011)

"Music has already undergone the transition that architecture now faces…its entire theoretical, compositional, and performative logic had to be revised." [18]

-Marcos Novak

[18] Novak, Marcos, "Neuro, Nano, Bio: New Atomism and Living Nanotectonics," *Innovation from Experimentation to Realization,* ed. Alexandra and Andreas Papadakis, London (2003) P. 14

*1-Introduction: The state of the Arts_*

When justifying research into kinetic architecture, the answer was not as evident as it might seem now when this dissertation project started in 2010. At the time I did not know much about the field, except some online videos about shape-memory materials that a masters degree fellow had shown me while developing one of the studio projects (specifically Alberto t. Estévez's design studio at the Bio-digital masters degree in January 2009). At first it looked like a straight forward way to embody an idea that was not clear about how to achieve its construction (or should we say fabrication). The idea at hand was to come up with a dynamic facade shading system that, analogically and gradually, changed its opening and closing according to environmental parameters, namely sunlight irradiation. When I saw the *youtube.com* video I exclaimed: “That's it!!!” Sunlight can be transformed into heat when it touches any material, either the facade system itself or any part of the building, in which case it could be transmitted to the facade system and regulate, through temperature change, its aperture and closure cycles.

That was pretty much this thesis's author's introduction to shape-memory materials and kinetic architecture both at the same time and with almost non-existent knowledge about the field at any level, but with one practical idea to solve and develop. At the time it seemed complicated and difficult to design the specific parts to build and operate such a feature. There are a series of projects that experimented with kinetic facades but, as one might expect, these mechanically driven, electricity consuming components, which have normally thousands of very small, precisely manufactured and assembled parts, brake all the time. To a point that Jean Nouvel's facade for the *Institute for the Arab World* in Paris, France is continuously broken and a lot of them have not been working *at all* for a (very) long time.

Now, almost six years later and after a lot of research, it comes across as obvious that kinetic architecture and design is a field that is not only full of possibilities but full of probabilities, meaning that, if we develop it deeply enough, it has the potential to change every aspect of human life, even space exploration. Not only by making easier, more efficient and efficacious a virtually limitless amount of products, domotics, engineering, construction, manufacturing, transportation applications, but revealing totally new totally unprecedented applications in the process; very much like the internet and the telegraph re-arranged human activity and society in their time, at the very least. As Angeliki Fotiadou sates in her 2007 thesis *Analysis of Design Support for Kinetic Structures:*

Truly kinetic architecture cannot be seen as anything else but the future of architecture. The mobility, the transformation and the transportation that it shows cannot be compared with any other kind of architecture where stability and permanency is their characteristic. In the future inhabitancy, where even the scenarios of other planets are included, kinetic architecture can only be in the service of the future human. And in addition to that, a tool that will be used for the expression of this architecture cannot be thought but essential.[19]

This transformation potential has, as a background, the urge of architectural and product design to make objects that adapt to its environment and even to people themselves, resembling more to a living being than an inert object. Michael Weinstock warns the world-changing nature of this never before seen, heard or felt before kind of revolution.

"We are within the horizon of a systemic change, from the design and production of individual 'signature' buildings to an ecology in which evolutionary designs have sufficient intelligence to adapt and to communicate, and from which intelligence (sic) cities will emerge."[20]

*1.1-Transdisciplinarity_*

Bernard C. K. Choi and Anita W. P. Pak agree that:

"Multidisciplinarity draws on knowledge from different disciplines but stays within the boundaries of those fields. Interdisciplinarity analyzes, synthesizes and harmonizes links between disciplines into a coordinated and coherent whole. Transdisciplinarity integrates the natural, social and health sciences in a humanities context, and in doing so transcends each of their traditional boundaries."[21]

In the context of this dissertation, *transdisciplinarity* is the key concept to describe the kind of investigation that will be carried out and its general framework positioning. This thesis aims to synthesize three fields of science and accentuate their convergence. If we would define the actual scientific field to which this thesis pertains to it would be that of a fringe science. One that stands at

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19 Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* Master of Science Graduate Thesis, Department of Building Physics and Building Ecology, TU Vienna, Vienna, Austria, in requirements for the degree of Master of Science (2007) P. 59

20 Weinstock, Michael, "Morphogenesis and the Mathematics of Emergence", Emergence: Morphogenetic Design Strategies, *Architectural Design,* Wiley Academy Press, United Kingdom (2004) P.17

21 Choi, B. C. K. - Pak , A. W. P., "Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services", No. 29, education and policy: 1-Definitions, objectives, and evidence of effectiveness, *Clinical and Investigative Medicine* (2006) P. 351–364

the edge of computation, material science and kinetic architecture as it looks into the historical origins of animation as a kick-start to kinetic art and architecture and ties it down with the systemic domain of simulation thus accentuating their convergence, all this driven by computation and material knowledge to bring together programmable matter, kinetic architecture and simulation under the same roof and as a "synthesized, coherent whole".

"The idea of animation as simulation provides architects with an additional opportunity to explore new methods of design ideation by approaching design as a set of parameters responding to dynamic, material and variable contextual forces over time."[22]

Kolarevic is positive that both mediums, nonetheless being different, they provide the possibility of world-changing scenarios of multidimensional proportions. After this thesis is done, the ways in which the three fields intertwine and inform each other will be clear, a phenomenon that will be explained to its fullest in chapter II. As of now there has been no other devised conceptual framework around the matter of simulating programmable matter through computer processes than that of transdisciplinarity. Each discipline offers unique paradigms and knowledge and redirects all this information into a single space: one that is neither the previous three, but that translates a multiplicity of parameters, variables an relationships to a new systemic ontology hence transcending its predecesors. Michael Fox, a long time defender of the development of kinetic architecture, explains the fact through an analogy that can clearly be understood as *Bio-digital*[*]. Quoting Guy Nordenson, he summarizes kinetic systematic creation as something close to a biological process.

"The engineer Guy Nordenson describes the phenomenon in embedded kinetic systems as creating a building like a body: A system of bones and muscles and tendons and a brain that knows how to respond. In a building such as a skyscraper where the majority of the structural material is there to control the building during windstorms, a great deal of the structure would be rendered unnecessary under an intelligent static kinetic system. If the building could change its posture tighten its muscles and brace itself against the wind, its structural mass could literally be cut in half. In deployable and dynamic kinetic systems as well, much of the structure will be reduced through the ability of a singular

22 Kolarevic, Branko (ed): 2003, Architecture in the digital age - design and manufacturing, Spon Press, New York, pp.13-28.
As quoted by: Attar, Ramtin -Aish, Robert - Stam, Jos - Brinsmead, Duncan - Tessier, Alex - Glueck, Michael - Khan, Azam, "Physics-Based Generative Design", *CAAD Futures Conference* (2009) P. 231-244. Autodesk Research, Canada, P.2.

* A concept created by Estévez, Alberto T. at the School of Architecture of the Universitat Internacional de Catalunya at the end of the 1990's. And which has spawned a masters degree program of the same name, of which the author is an alumni.

system to facilitate multi-uses via transformative adaptability."[23]

This relationship between dynamic, almost alive architecture is something that has long been understood at the *School of Architecture* (EASRQ), where biology's consonance with computation has been advocated and promoted since 2000 almost uninterrupted a similar concept has spawned Kas Oosterhuis's *Hyper-Body* laboratory at TU Delft in the Netherlands, itself drawn from his theoretical paradigm of the same name: buildings as bodies. These two paradigms, kinetic design and programmable matter (two central spheres in the development of this dissertation) are to be understood in a larger context: that of genetic architecture, and is to be understood as its consequence. Therefore, for them to be fully comprehended, it is imperative to define the relationship between the two ingredients of genetic architecture (computation and genetics) but, according to Karl Chu, to answer this, first of all, we need to ask ourselves the question:

"*Could the world be moving 'into the so-called Post-Human era, which will bring forth a new kind of biomachinic mutation of organic and inorganic substances'? How can architects reconfigure the practice of their disciplines in order to meet the demands of this computational and biogenetic revolution?"*[24]

The biogenetic revolution, for kinetic architecture, means that we are now capable, at least technically, of realistically designing and building systems with embedded intelligence at the core of their material constitution from which dynamics are drawn and into which rules are programmed to actuate under multi-parameter circumstances that act and react to phenomenological stimuli, placing real adaptable systems within our reach. Systems which their building does not stop once the building is "finished" and, in fact, that is precisely were their evolution takes off: *after it ends*. This will be outlined more accurately in chapter II. These dynamic systems have been theorized by many architects and engineers, Michael Hensel argues that the search for such systems has to be accompanied by a parallel tool development to fit its criteria of evolutionary dynamic shape-shifting nature:

" The complex dynamic interrelation between material form and environment requires a multiple control parameter set-up. Traditionally, form-finding methods focus mainly on mono-parametric

23 Fox, Michael - Yeh, Bryant, *Intelligent Kinetic Systems*, Kinetic Design Group, Massachusetts Institute of Technology, Department of Architecture (2001) (http://profamateus.no.sapo.pt/mitharvard2.pdf) (06-02-2014) P.8
24 Chu, Karl, Metaphysics of Genetic Architecture and Computation, *Genetic Architectures*, ESARQ/SITES Books (2005) P. 39

structural behavior of material form. This constitutes one way causal relations, far from the feedback required to evolve form and tool-set together."[25]

It is the immediacy of this "multi-parameter control setup" that has triggered and driven this research project. It has been widely understood that our design tools at the time (even though they had evolved greatly and had already changed the architecture landscape for the better) were not yet sufficiently developed and the ones that were, from a design perspective (this meaning creating contingency and creative novelty as Karl Chu would put it) were not being used in the needed direction. In short, to be able to grasp adaptability in our buildings, we need to also do it within the tools we use to produce them. Blueprints and linear drawing, although useful as documents and for patenting purposes, are not suited to engage with a complexity that, on top of that, evolves continuously. *Form-in-transition must be able to perform in all relevant ways at all times, and not switch form one steady state to another.*[26] In this optic, simulation seemed as a more suitable candidate at the time of figuring out how to make my dynamic facade actually work in real world, under continuously changing conditions. As much as we can simulate in our minds (like exceptional coders and engineers sometimes can do), when the degree of complexity rises, it becomes almost impossible to visualize the specifics of a given design and predict unforeseen circumstances, let alone arrange contingent systems. In their seminal book *Vector Mechanics for Engineers: Dynamics,* Ferdinand P. Beer & E. Russell Johnston Jr define kinetics as a branch of dynamics (itself a branch in physics that studies moving bodies) that studies:

"...the relationship that exists between the acting forces on a given body, the mass of the body and its movement. Kinetics is used to predict the movement caused by given forces or to determine required forces to produce a certain movement."[27]

Often confused with kinematics, which studies the *geometry of movement. Kinematics is used to relate displacement, velocity, acceleration and time, without making reference to the cause of the movement.*[28] It is imperative not to confuse the two (something that is more often then not the case) and clearly define and understand the two fields for their subsequent integration in the aid to produce kinetic

25 Hensel, Michael, Finding Exotic Form: " Evolution of form finding as a Design Method", Emergence: Morphogenetic Design Strategies, *Architectural Design*, Wiley Academy Press, United Kingdom (2004) P.29

26 Idem.

27 Beer, Ferdinand P. - Johnston, E. Russell, *Vector Mechanics for Engineers: Dynamics*, McGraw-Hill Higher Education, 6th edition, USA (1999) P. 582

28 Idem.

architecture. The actions of forces (kinetics) and their trayectory (kinematics) are central to the construction of adaptable systems and design processes like form-finding. *Dynamic form evolves through morphogenesis under changing force-cases, including both generation and adaptation of form.*[29] One of the major aims of this thesis is to prove that, through vector based and non-vector based simulation, we can arrive at specific yet contingent form-finding processes that not only address structural matters, but that take in account solar, heat, water stimuli and use these as start-pause-stop "switches", for lack of a better word, and that, potentially, can continue to trigger adaptation and change of the building to its surroundings, in theory, forever. *Form finding processes extend in this way beyond the design and construction phases towards a process of adaptation of the built environment.*[30] This thesis uses as this speculation a premise: the demand for such a parameter set as a driver to achieve this desired and needed tool-set. Yet this required development in design tools and, more particularly, software packages that aid in this process, is far from established as common practice, as we will wee in this thesis, the research documents and cases are scarce, which suggests that it is not a very popular field of study (although it has gotten a lot of attention in recent years) and stays, almost always, within a small group of researchers, whom, to call *avant-garde* would be an understatement. There are also questions concerning how creativity will fit in the picture of programmable matter and Hensel's theorized multiple-parameter setup.

"Multiple-parameter experiments involving many formative forces acting together are fairly new undertaking, particularly when assessment criteria incorporate such diverse items as spatial, structural, material and habitational characteristics. This becomes further complicated by the fact that the variables and the assessment criteria of a multiple-parameter form-finding experiment do not necessarily coincide. One example would be a form-finding experiment that yields a desirable spatial organization that was not anticipated."[31]

This thesis will address these matters from a ground up perspective, meaning that it will brake down geometrical construction to various fundamental truths and it will work its way up from there. While at the same time tackling the question of "efficiency", as Hensel has expressed concerns regarding the definition of the term in the context of this systemic change, both in the tool-set as in materiality, he

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29 Beer, Ferdinand P. - Johnston, E. Russell, *Op. Cit.* (1999) P. 582
30 Hensel, Michael, *Op. Cit.* (2004) P. 29
31 Idem.

states:

"A crucial aspect in multiple-parameter experiments is the redefinition of the notion of efficiency. For instance, if only one structural parameter needs to be considered, for example in Gaudi's hanging models, the performance of the model can be optimized to a specific force case. With multiple-parameter set-ups each result is a negotiation towards a best possible overall performance, with a great deal of overall redundancy [future potential] *built into the material arrangement so that shifts from one force-scenario to another con be accommodated. However, negotiated performance criteria in multiple-parameter form-finding processes do not necessarily lead to mean advantage solutions: rather specific performance profiles may emerge in relation to the specific set of influences that yields a particular material form. The difference between a the best possible overall solution on the one hand and the mean average on the other is defined by the ability of the former to shift priorities between control parameters or even to involve new parameters on the basis of recognizing opportunities in transitory states."*[32]

The specificity of the material composition and higher level arrangement, will be demonstrated, play a crucial role in how to define kinetic systems with embedded intelligence within their configuration. And will be proven to be the root of a "bottom-up" *Material Design* philosophy that will be made all the more evident in chapter VI. There is also the concern of building impact on its site and environment, something that has been established as central to contemporary architecture and becomes "interactively predictable" running parametric computer simulations that make a tortuous and long analog process become a fluid and intuitive one. *Adaptation material systems in situ therefore engages a third task for form finding that commences after the construction process and proceeds by means of analysis and feedback of the impact of inhabitants and habitat onto the built environment.*[33] A fluency that can be achieved, for the first time in history, throught the medium of computation: the birth of autonomous architecture and objects. This is a topic that will be addressed in this thesis as a basis to position its particular idea about what kinetic architecture is and what programmable matter represents to it: *a monumental change in the way we exist.* Also, it proposes that the aims of genetic architecture fuel and drive the endgame of kinetic architecture, this will be established clearly in chapter II, for the time being we will summarize this world-making process in the voice of Karl Chu:

32 Hensel, Michael, *Op. Cit.* (2004) P. 29
33 Idem.

"As controversial and provocative as it may seem, the underlying ambitions of computation are already apparent: the embodiment of artificial life and intelligence systems either through abstract machines or through biomachinic mutation of organic and inorganic substances and, most significantly, the subsequent sublimation of physical an actual worlds into higher forms of organic intelligence by extending into the computable domain of possible worlds."[34]

"Design should not freeze the status-quo, locking individuals, communities, and whole cities into immutable yet soon-to-be-outdated patterns"[35]

*1.2-Tool making and interactive digital design in architecture_*

"To behold, use or perceive any extension of ourselves in technological forms is necessarily to embrace it. By continuously embracing technologies, we relate ourselves to them as servo-mechanisms."[36]

-Marshall Mcluhan

This quote probably best describes how we relate to and therefore mold our future selves in accordance (and direct co-relation) with our tools.*They're symbols of ourselves* [37], as Wilson Miner affirms in his talk titled *When we build,* at the *Build conference* in Belfast, Ireland in 2011. As tools, and more recently digital ones, have always paved the way throughout the process of civilization this makes us wonder, how or why is this tradition such a profound part of it, how does the activity of ***tool-making*** exactly affects us and, by extension, society? what makes it so special? And certainly, why are we prone to build endlessly day in and day out? According to Miner, it has to do with them changing the way we see the world when we are exposed to their use and understanding, for each tool opens a new perspective in the way we can live, tools are life changers, *when they enter the world, they change our outlook, our attitude, how we feel about things, because they change the environment, therefore, how we act and behave*.[38] So then, changing our environment and ultimately, in this thesis case, architecture.

[34] Chu, Karl, *Op. Cit.* (2005) P. 39-40
[35] The New Building Block, Research Report Number 8, Canter for Housing and Environmental Studies, Cornell University, Ithaca, USA (1968) P. 35
As quoted by: Zuk, William, Clark, Roger, *Kinetic Architecture*, Van Nostrand Reinhold (1970) P. 2
[36] McLuhan, Marshall, *Understanding Media: The Extensions of Man***,** McGraw-Hill, (1964). (29-01-2014) P. 56.
[37] Miner, Wilson, *When we Build,* speaking at *Build 2011* in Belfast (2011) (http://vimeo.com/34017777) (29-01-2014)
[38] Idem.

We become what we behold. We shape our tools and then our tools shape us.[39] The history of invention and conception is shaped and enabled thrive by the depth, flexibility, adaptability and extension that we build into and get out of our tools , as this research will demonstrate, architecture is constantly challenged by and the way we produce it, in other words, it changes in accordance and parallel to the tools (including, but not limited to the conceptual and physical) which we, as architecture's creators and inventors, are exposed to and learn to use At historical length, the importance of tool-making, not only within the realm of architecture, but of technology and implementation at large, may seem a bit obvious to all of us at first glance, but what is not obvious is that it very well may be the most important driver of our whole civilization's *modus operandi*.

In Archeology and Anthropology, Civilization's chronological development used to be basically divided in a Prehistoric three Age system: ***stone age, bronze age and iron age*** [40] (created by Christian Jürgensen Thomsen-1788–1865) after which the stone age was subdivided into ***palaeolithic,*** [41]***mesolithic*** *and* ***neolithic*** *sub-ages*.[42] They are most notably divided according to the use of certain materials that defined the technological advancement with which we identified the most with or changed the *power, production and cultural* structures of each particular age in time, but under that guise of materialistic division lies the question, why this particular material? This research argues that ***it very well is because of the types of tools it let us produce with it***, and how these tools were able to somehow enable us to change the way civilization's structure was to be re-arranged within this new-found technology composed within a specific set of possible applications and usage patterns, thus constructing a specific archetypal ***paradigm*** for civilization**.** In this research we will make evident that this relationship is also a fact between architecture and tool-development.

"Man, in all ages and in all stages of his development, is a tool-making animal."[43]

[39] Cogan Robert in "Mcluhan Misunderstood: Setting the Record Straight", *Understanding Media, Today: International Journal of Mcluhan Studies*, (2011) P. 45, remarks that it is rightly attributed to Culkin, John (1967) and often, wrongly mistaken with McLuhan, Marshall, *Understanding Media: The Extensions of Man***,** McGraw-Hill, (1964) yet does not provide the publications name, I have checked on the web and and in Mcluhan's book there is no factual evidence of it so it will be attributed Culkin (29-01-2014) (http://www.mcluhanstudies.com/live/files/assets/basic-html/page47.html)

[40] Gräslund, Bo, *The Birth of Prehistoric Chronology. Dating methods and dating systems in nineteenth-century Scandinavian archeology.* Cambridge: Cambridge University Press. (1987), P. 24 (http://www.upbo.org/catalogue/catalogue.asp?isbn=9780521322492&ss=fro) (30-01-2014)

[41] Term coined by Westropp, Hodder in M., Linder, F., *Social differentiering i mesolitiska jägar-samlarsamhällen.* Institutionen för arkeologi och antik historia, Uppsala universitet. Uppsala, (1997) P. -

[42] Lubbock, John, *Pre-historic times. as illustrated by ancient remains, and the manners and customs of modern savages*. London & Edinburgh: Williams and Norgate. (1865). P. 75 (https://archive.org/details/prehistoric00lubb) (30-01-2014)

[43] Westropp, Hodder M., "XXII. On the Analogous Forms of Implements Among Early and Primitive Races", *Memoirs Read Before the Society.* Publications of the Anthropological Society of London II. London: Anthropological Society of

Hodder Westtopp asserted in 1865:

"I think one o the things that separates us from high primates is that we are tool builders."[44]

Steve Jobs also stated in the 1980s, acknowledging the fact that we create tools and they create civilization or, at least, differentiate its ages. Even more deeply was civilization's paradigm pattern construction shifted with the invention of ***language*** (arguably our most important tool-development to date that probably originated about 100,000 years ago[45]). In a 2011 article in The Royal Society's *Philosophical Transactions B* article, Stout and Chaminade remark:

"*Accumulating evidence is increasingly supportive of technological hypotheses of language origins, and goes a long way towards allaying concerns that the similarity in the hierarchical, combinatorial organization of the two domains is a superficial one or that the 'imitative' learning of toolmaking skills is fundamentally distinct from intentional communication."*[46]

We had such a deep correlation with this particular tool in such a (day to day/collective/individual) manner that it changed the way we relate to each other, to the world and to ourselves. Mcluhan states:*"In our time, study has finally turned to the medium of language itself as shaping the arrangements of daily life, so that society begins to look like a linguistic echo or repeat of language norms."*[47] This profound latent significance that underlines, not so much in language itself (its is notably obvious that language is one of the basis in our sense of identity), but the fact that the relationship we have with it undeniably shapes our spectrum of psychological and social behavior and belief system, it even made a very powerful and dominating concept to arise, it translated the idea of God from thought to communication, it allowed us to transfer it to information, and more profound than that, it allowed us to manifest ***belief*** in far more complex, direct and articulate ways. and construct ***organized religion***. Later in history, in the contemporary world, the tool-making trend for classifying the types of civilization is still a basic and recurrent systematic differentiation method (added social

London, (1866) P. 288–294 (http://en.wikipedia.org/wiki/Three-age_system#cite_note-33) (30-01-2014)

44 Jobs, Steve, *Bicycle for the Mind*, Youtube video (https://www.youtube.com/watch?v=j0m3sPU8sVU)

45 Nichols, Johanna, "The origin and dispersal of languages: Linguistic evidence", in Nina Jablonski and Leslie C. Aiello, eds., *The Origin and Diversification of Language,* (Memoirs of the California Academy of Sciences, 24.) San Francisco: California Academy of Sciences (1998) P. 127-70. (https://www.zotero.org/stephenself/items/itemKey/MG6CN6KG) (30-01-2014)

46 Stout, Dietrich-Chaminade, Thierry, "Stone tools, language and the brain in human evolution", *Philosophical Transactions B*, © The Royal Society, London (2011) P. 82 (http://rstb.royalsocietypublishing.org/content/royptb/367/1585/75.full.pdf) (03-03-2015)

47 McLuhan, Marshall, *Op. Cit.* (29-01-2014) P. 60

content, communication technology, which are all tools in their basic sense). And what they ***all*** share is the common denominator that they were all possible, one way or another, by particular technological tool developments available or wanted within a certain context that made possible, directly caused or produced certain particular historic events that marked specific periods. We could say that ***the history of man could very well be the history of his tools***. Marshall Mcluhan thought of mediums as tools that change our environment, as extensions of our natural senses, the cloth is an extension of our tact (skin), a telephone and extension of our hearing (ears), a book an extension of our sight (eyes), the electrical network an extension of our central nervous system (neurons). To illustrate these relationships he used the example of the light bulb, that it changes the schedule, hour ratio, how long we interact, in which places and, more importantly, ***how*** we interact between and ourselves and each other. It is not the same to read draw in broad daylight than to do it at pitch black night, when, under unlit circumstances, it is practically impossible to do, the light bulb (candle or any light providing tool) changes our whole perspective on ***how*** or ***when*** we can do the very act of drawing and, by extension, living; because so far it is part of our ***lifestyle*** and it has been changed forever by this medium in a very profound way. And while the *car defined the environment of the twentieth century in which we live in now a days it is the screen that will define the environment for the twenty first century.*[48] This meaning path from driving (unilateral communication) to *physiovirtual*[49] interactivity (multilateral communication). In this sense, computers have the ability, not only to change our environments, but to ***change the way we think***, better yet, to improve the way we think and expand our natural capacities to levels not yet fully understood.

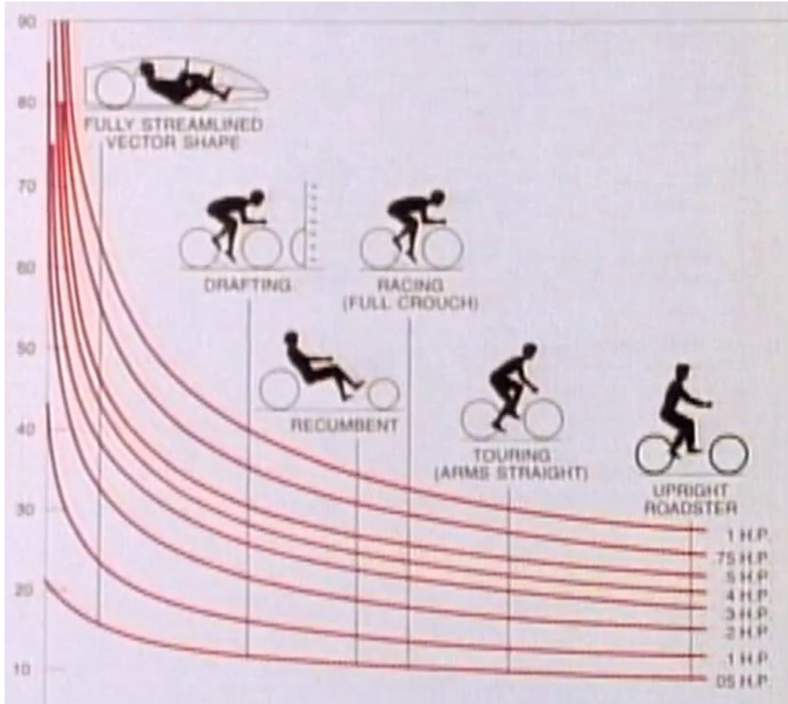
"The computer is Bicycle for our minds"[50]

-Steve Jobs

[48] Miner, Wilson, *Op. Cit.* (2011) (http://vimeo.com/34017777)

[49] Term coined by Karl Chu for lack of a term to address the inextricable linkage and dependency of the physical with the virtual, in Chu, Karl, *Op. Cit.* (2005) P. 172

[50] Jobs, Steve, As paraphrased by Miner, Wilson, *When we Build,* speaking at *Build 2011* in Belfast in November 2011, (http://vimeo.com/34017777) also in his own words (1990) (http://www.brainpickings.org/index.php/2011/12/21/steve-jobs-bicycle-for-the-mind-1990/) (02/03/2015)



Efficiency of locomotion for a man on a bicycle, Scientific American (not dated) original graphic which inspired the aforementioned coment. (http://www.worldwidecyclingatlas.com/journal/steve-jobs-on-why-computers-are-like-a-bicycle-for-the-mind-1990/) (02/03/2015)

A bicycle can make a normal human out perform the condor at first place in the chart, it works as an amplifier to what we already bear biologically. In addition, to Jobs, *the computer is the most remarkable tools we have ever come up with.*[51] This represents a very unique condition in our existential construction, but what happens with the makers? This is the main leitmotif in this doctoral thesis: **to delimit the tool makers impact on the tool-making/using/reshaping process.**

This is where design comes into the tool-making game. *Design is the choices we make about the world we want to live in.*[52] This broad and vague definition sheds light into the relatively short history of the word itself.

Design[53] (*Design: 1540s, from Latin designare "mark out, devise", from* ***de-*** *"out" +* ***signare*** *"to mark," from signum "a mark,sign." Originally in English with the meaning now attached to designate; many modern uses of design are metaphoric extensions)* has very old roots, but it is a relatively new word in

51 Jobs, Steve, (Steve Jobs on Why Computers Are Like a Bicycle for the Mind (1990))(2010) http://www.brainpickings.org/index.php/2011/12/21/steve-jobs-bicycle-for-the-mind-1990/) (02/03/2015)
52 Miner, Wilson, *Op. Cit.* (2011) (http://vimeo.com/34017777) (02/03/2015)
53 Design. (n.d.). *Roget's 21st Century Thesaurus,* Third Edition (29 /01/ 2014) (http://thesaurus.com/browse/design)

the English language, dating approximately five centuries back from now, but manufacturing has a very old lineage of tradition behind it, it actually comes from long traditional tool making and knowledge keeping feedback that was then processed and in some sense “condensed” to produce better artifacts, thus creating certain types of ideas to prevail within a broader spectrum of possibilities, that would then be used as rules for the subsequent creative process, or designated to become guidelines for a particular craft to create new assertions of the same or similar problem to be solved, which later became design.Design is a tool in itself and a the rosetta stone for ancient, renaissance, modern and contemporary Architecture, from the Pyramids to the work of *Vitruvius* and later *Brunelleschi, Bramante* and *Palladio* architecture, as a discipline, has been aided and developed within its use of design, mostly relying on the production tools that where available or developed by other disciplines (as in the likes of: Construction, Carpentry, Drawing, Painting, Civil Engineering and, in later periods, Electrical Engineering and so on). Although its because at that time the two main building disciplines (Engineering and Architecture) were developed by the same people so they were practically the same practice, but even so, architecture did develop its own conceptual tools like Brunelleschi's (re) found graphic technique called ***Linear Perspective*** (that we will get back to further on as reference) in the italian *Renaissance* (circa 1,420 A.D.) which added an edge and transformed, not only the discipline, but other arts as well, like painting, which at the time completed *"the most influential artworks* [of] *the entire European Renaissance".*[54] Painting would go on to base all its later production in the next four hundred years on these techniques as linear perspective spread, not only in Italy, but throughout Western Europe. It quickly became, and remains, standard studio practice. This research intends to demonstrate that architecture has been following, for at least fifty years, a universal trend into the world of concepts and its immaterial existence. First, in the advent of electrical technology, it started to incorporate lighting technology that forever changed our way of understanding and lately it has undergone a long awaited transformation into a kind of information based science, which will be detailed in the next section), and which its theory scope is broadening as some of its most important tools have been transformed from physical to software instruments and are developed as such.

[54] Edgerton, Samuel Y, *The Mirror, the Window & the Telescope: How Renaissance Linear Perspective Changed Our Vision of the Universe*. Ithaca, NY: Cornell University Press (2009) P. 5 (31-01-2014)

*2-Architecture becoming Information/ Information becoming Architecture_*

"You write a few lines of code and suddenly life is better for a hundred million people."[55]

–Charles Simony, inventor of Microsoft Word.

We begin the discussion about information age architecture or digital design architecture (although they are not the same, so we will use them interchangeably for practical matters) with the next question:

"Are the 'traditional' conceptual models of modern thought, inspired by the abstract mechanisms of motors, being replaced by new conceptual models, based on the abstract mechanisms of computers?"[56]

This Karl Palmas assertion implies that our ontological vision of the world, and thus its meaning and impact on culture, is shaped by our abstract mechanisms of thought that, in turn, are reflected and transformed by our product in technology, today being information the latest of that product. While Stephen Hawking speculates on the nature of information saying that [57]*all matter and energy maybe described as a specific state of information..."* for *information is always subject to a continuous process of transformation* [58] (as the same is for energy in Einstein's energy conservation principle, in accordance with Deutsch's constructor theory), then architecture as such is probably becoming (as everything else, to our perception) also information. This has always been an underlying universal process but, within architecture, we're just starting to acknowledge it as Kas Oosterhuis observes that *scientists observe a universal evolution from purge energy (the initial stage of our universe) towards pure information (the final stage of our universe)*[59] and being the state of architecture today one of continuous flux and translation, therefore, transformation as well. But on the other end of the spectrum, what about the notion we are beginning to foresee which is that *information is also transforming into architecture?*

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55 Silver, Mike, "Towards a Programming Culture in Design Arts", Programming Cultures: Art and Architecture in the Age of Software, *Architectural Design*, Wiley Academy Press, United Kingdom (2004) P.8

56 Von Busch, Otto and Palmas, Karl, *Abstract Hacktivism: The Making of the Hacker Culture*, London and Istanbul (2006), P.23

57 Hawking, Stephen.
As Paraphrased by Oosterhuis, Kas, *Hyper-Bodies*, Brikhaüser (2003) P.26

58 Oosterhuis, Kas, *Op. Cit.* (2003) P.26

59 Idem.

In this chapter , we will see the trans-disciplinary orientation central to SA as a mirror to outline the contemporary architectural practice and its link with IT and computation and we will prove it via an example case project which operates at translating certain disciplines into other ones.

This is relevant and worth discussing to its bare bone because its transforming the discipline and its production methods to a point of utter and unexpected fluctuation in both its output and the way that it produces it, not to mention the way that we use it, for this is an act of the hack and if we affirm that *hacking is the production of production*[60], then it's a hacking of both (information technologies - IT - and architecture) crafts at large. This "translation" from one realm to the other is haking a new practice that is consonant with the *infiltration in architecture from miscellaneous disciplines such as engineering, physics, math, biology, botany*[61] and lately at center stage, ***computer science.*** Yet architecture is doing the same with the IT world; there are architects, engineers and designers learning how to program or script systems and, on the other hand, IT engineers trying to understand and work with/utilizing architecture's concepts (with interchangeable professional fields such as software architecture, systems architecture -SA – and so on) In fact SA goes back as far as the 1960s and the birth of software engineering :

"*When systems were comparatively small, we all drew abstract diagrams in order to understand designs and communicate them to others. These small systems did not always need abstractions to help in the design process; nevertheless, they helped.*"[62]

This shows that the question at hand is not only some inner thing of the practices themselves but also a question of each other's shared aims, ideals, products and production methods. [63]*However, very soon, systems grew in size and ambition, and structured descriptions became essential, were used very*

60 Wark, McKenzie, *Hacker's Manifesto 4.0*, Paragraph 8 (http://subsol.c3.hu/subsol_2/contributors0/warktext.html.) (20/09/2009)

61 Beukers, Adriaan -Van Hinte, Ed, *Lightness: The Inevitable Renaissance of Minimum Energy Structures*, 010 Publishers (2005), (http://books.google.fr/books?id=cBML479VZsEC&pg=PA5&lpg=PA5&dq=adriaan+beukers+lightness&source=bl&ots=hSmZoBnbNJ&sig=BW6B4QY8tNL95kpJ_-d6TThgulc&hl=en&sa=X&ei=QlnhUs_PFcrB0QWR04HwAg&ved=0CFAQ6AEwAw#v=onepage&q=adriaan%20beukers%20lightness&f=false) (25/03/2014)

62 Barroca , Leonor - Hall, Patrick – Hall, John, *An Introduction and History of Software Architectures, Components, and Reuse*, Springer London (2000) P. 2 (http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.66.7240&rep=rep1&type=pdf) 10/05/2015)

63 Idem.

naturally — more or less without thinking — and derived from similar practices in other branches of engineering.[64]

Leonor Barroca et al. go on to define it as they propose that *the essential idea of software architecture is that software at a high level of abstraction can be described as a number of distinct elements or subsystems together with their interconnection and interactions.*[65] The comparison with architecture of buildings is subjected to the same one that would arise if we were to compare the terms *build* (a the term used in SA to define internal versions of certain stages of a software ensemble) and *building*. It is clear that this invasion of each others realms is consistent with the contemporary paradigm of genetic code encryption and its convergence with computation (as SA itself stems *from similar practices in other branches of engineering*[66]) bringing about the *post -human* era, an extension of condition of being originally coined in 2003 by Robert Pepperell, altogether with ***genetic architecture (GA):***

"Humanists saw themselves as distinct beings, in an antagonistic relationship with their surroundings. Posthumans, on the other hand, regard their own being as embodied in an extended technological world."[67]

The Posthuman Manifesto

In Chu's terms, GA has been, historically, the *extension and transformation of utopic ideas implicit within the avant garde to create new worlds by drawing on new sciences and technologies*[68] and which can only be possible, in the world of today, with and through computation and digital technology. The current state of affairs is that we are working at the boundaries of design, trying to decode the crypto-systems of architecture, nature and reality such as they are today and re-code them to more fluid states in contemporary society or, to be more specific, uncover their inside language's grammar, translating it from nature and back through the processing of information: ***Computation***. Karl Chu's definition of computation is based on the notion of iteration, which is itself intertwined with the information

64 Barroca , Leonor - Hall, Patrick – Hall, John, *Op. Cit.* (2000) P. 2
65 Idem.
66 Idem.
67 Pepperell, Robert, *The Posthuman Condition Consciousness beyond the brain*, Intellect Books, U. K. (2003)
68 * It should then be noted that genetic architecture is neither a representation of biology nor a form of biomimesis; instead, its theoretical origins, insofar as genetic architecture is concerned, can be traced to John Von Neumann's invention of the celular automaton the so called "Von Neumann's Architecture" for self-replicating systems. Chu, Karl, Metaphysics of Genetic Architecture and Computation, *Genetic Architectures*, ESARQ/SITES Books (2005) P. 170

paradigm.

"In its simplest form, computation is a system that processes information through a discrete sequence of steps by taking the results of its preceding stage and transforming it to the next stage in accordance with a recursive function. Such an iterative procedure based n recursion has proved to be astonishingly powerful and is classified as belonging to a class of universal machines." [69]

NAMES	classical past	modern present	genetic future
chronology	... up to the 19th century	20th century	from the 21st century onwards ...
formal system	verticalising	horizontalising	organicising
structural system	compressed structures	tractioned structures	live structures
material system	stone, brick, wood	concrete, steel, plastic	vegetal, flesh and bone
process or production system	manual production of each different and/or same part, one by one	mass automated machine production of all equal parts	automated machine production of different parts and natural growth

Diagram of the "Three Ages of Archiecture", Alberto estévez (2005), © this diagram shows a synthesized narrative of the process of arriving at our probable genetic architectural future. (Estévez, Alberto T., Biomorphic Architecture, *Genetic Architectures*, P. 55)

Today's technology's apparently unlimited processing and memory capabilities, plus discoveries in fields such as molecular biology, evolutionary developmental biology and genetics have set a challenge on IT and architecture of trying to, not only 'hack' the codes and store them, but to take these new-found patterns in nature and transmute them into society as constructed metaphors or artificial life models and simulations that give rise to the witnessed complexities in the contemporary world. Chu observes that Stephen Wolfram and John Wheeler seem to agree that *the laws of physics generate the very mathematics that make those laws computable*[70]**,** which has led to the conclusion that physical processes are, in fact, forms of computation, Wolfram states this in a rather straightforward way within his ***principle of computational equivalence:***
"All processes, whether they are produced by human effort or occur spontaneously in nature, can be viewed as computations".[71]

[69] Chu, Karl, *Op. Cit.* (2005) P. 40
[70] Ibid. P. 161
[71] Wolfram, Stephen, The Principle of Computational Equivalence, *A New Kind of Science Online*, (2002)

Information managing and applying notions from fields such as biology and computer science combined hold potential to set us on a scientific research strand that can educate us about how nature computes it's phenomenology, its natural events and reactions, performance and economy of energy, leading to environmental data-driven decisions in both architecture and programming computer systems, for all this can be translated to information that can be re-injected into the 'ecosystem' of our designing (be it cyberspace or physical space), so this makes it a common goal for IT and Architecture: ***the quest for communicating and interconnecting the world at higher and more complex levels.***

Information is always changing, transforming an translating other information and, at an architectural level, it *may be sent through wires, or my be carried trough a vehicle. People are data carriers*[72], for all the signals that you encounter in a street or building are information that is interpreted by you an others as such, and thus translated into reactions and actions which are also information that *never stops to be processed, and humans are part of the process. They trigger things, they catalyze, they vector, they open doors, close windows. They are the switches themselves.*[73] And if energy is something that transforms from state to state, then we can say that information is anything that translates into something else by means of communication, even energy itself, Starting with language and following a path with no apparent end. We can also say that it can be captured and processed be it through action, reaction, transportation, records, signal, symbol, graphics, light, shadow or environmental graphics; to this extent, architecture becomes, not only a craft of form and space but also an information shaping and sending one, as well as a translating and processing discipline, so:

"if one applies this notion of information processing to buildings and architecture, then one realizes that buildings are continually absorbing information, processing information and producing new information."[74]

Being isolated pieces of information processing devices, but connected with other buildings within the information flow that is the city, to the users through interfaces and signs, to the world trough internet networks *All the processes run by buildings, products and users together play a key evolutionary role*

(http://www.wolframscience.com/nksonline/page-715-text?firstview=1) (13/02/2015)

72 Op. Cit. Oosterhuis, Kas, *Hyper-Bodies*, Brikhaüser (2003) P.22

73 Idem.

74 Idem.

in the worldwide process of the formation and transformation of information[75], as the furniture, the switches, the lights, the people inside them and the assets that inhabit them are in constant flux, being moved and displaced from one place, building or room to another, thus ever changing their position, condition and relation to the entirety of the the whole, the bigger network, the 'information flow', the *e-designer*[*] gives shape to the flow of data, (s)he is ***a sculptor of information*:**

Sculpting information is a very important responsibility of the digital architect. Becoming masters in the art of sculpting information will place the profession of architecture back in the genetic heart of product revolution.. ....and you [we]- *certainly must not resist the invasion of new media and nanotechnology into the very fabric of architecture.*[76]

And if we don't recognize the actual flow of information in the way we mold society and 'sculpt' it to better, more advanced meaning and new values, we may end up loosing the train of production flow that's taking place in society today. Possibly architecture will not become obsolete, but *we architects* sure can. *Working with the flow of data, stepping into running processes, inventing flow charts of design processes, running the processes in real time*[77], formulating language with techniques that are not likely of architecture but that have found usefulness and entered its static position and striven to change it forever, adapting it to the computation, styling of changes and unpredicted responses comprising interrelated domino effect processes and influences of materialization and de-materialization of components, records of events, applications and chunks of information we can grow as "digital architects".

Currently, and as a consequence of this technological process, there is a "movement" that has risen and claims to address this paradigm shift: ***"parametric architecture"***, which strives to make data and information the key terms and concepts of arranging and re-arranging architectural components and, although not coined by him (the term was actually coined in the 40s -according to Robert Stiles (2006), in architecture, by architect Luigi Moretti, *which he defines as the study of architecture systems with*

75 Op. Cit. Oosterhuis, Kas, *Hyper-Bodies*, Brikhaüser (2003) P.22

* E-motive environmets (where the idea of the e-designer stems from) are defined by Kas Oosterhuis as situations that simulate us physically and mentally, environments that incite us in ever-changing degrees to active, communicative behavior, thus the term e-designer defines a person that shapes these kinds of environmets. In Oosterhuis, Kas, *E-motive Architecture*, 010 Publishers (2002) P.21

76 Oosterhuis, Kas, *Op. Cit.* (2003) P.11

77 Idem.

the goal of "defining the relationships between the dimensions dependent upon the various parameters" [78], Patrick Schumacher has become one of its most influential and notorious advocates, he explains what he calls *parametricism* in his 2011 article *Let the style wars begin* that aims to establish it as a style, much like *modernism* or *post modernism* and which, according to him, has its roots in *deconstructivism;* cataloging the later as a transition phase. Although Daniel Davis, in his thesis called *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture,* and Owen Hartley have both agree that "*parametric design is not defined by an architectural style as perhaps the nearest proof that there really is an avant-garde [of parametric design] although perhaps Schumacher has little to do with it..*"[79] Non the less, the term comes from Mathematics and its precedents date as far back as to the writings of James Dana around 1837.[80] As Davis remarks in his thesis, the *Concise Encyclopedia of Mathematics* defines the term *parametric* it as a s*et of equations that express a set of quantities as explicit functions of a number of independent variables, known as 'parameters.*[81] This definition sets forth two critical criteria:

- *A parametric equation expresses "a set of quantities" with a number of parameters.*
- *The outcomes (the set of quantities) are related to the parameters through "explicit functions*[*]*."*[82]

$$x(a,t) = t$$
$$y(a,t) = a \cosh\left(\frac{t}{a}\right)$$

Example of a parametric equation: the formulae that define a catenary curve, Daniel Davis (2013) (Davis, Daniel, *Modelled (sic) on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 20)

[78] Bucci, Federico and Mulazzani, Marco, *Luigi Moretti: Works and Writings*. New York: Princeton Architectural Press, (2000), P. 21
As quoted by:
Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, School of Architecture and Design College of Design and Social context, RMIT University (2013), P.18

[79] Davis, Daniel, *Op. Cit.* (2013) P.18

[80] Idem.

[81] Weisstein, Eric, *CRC Concise Encyclopedia of Mathematics.* Second edition. Boca Raton: Chapman & Hall/CRC, (2003), P. 2150
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P.21

[*] An *explicit function* is a function whose output value is given explicitly in terms of independent variables. For example, the equation $x \cdot x + y \cdot y = 1$ is the implicit function for a circle. The function is implicit since the outputs (x and y) are defined in terms of one another. To make the function explicit, x and y have been defined in terms of an independent variable. Thus, the explicit function of a circle becomes: $x = \cos(t)$, $y = \sin(t)$. In Davis, Daniel, *Op. Cit.* (2013) P. 20

[82] Davis, Daniel, *Op. Cit.* (2013), P.18

Therefore affirming that, in fact, parametricism is not at root, any kind of movement or sytle but a specific set of quantities that are *expressed as explicit functions of a number of parameters*[83] within geometrical constructions. Math, not style.

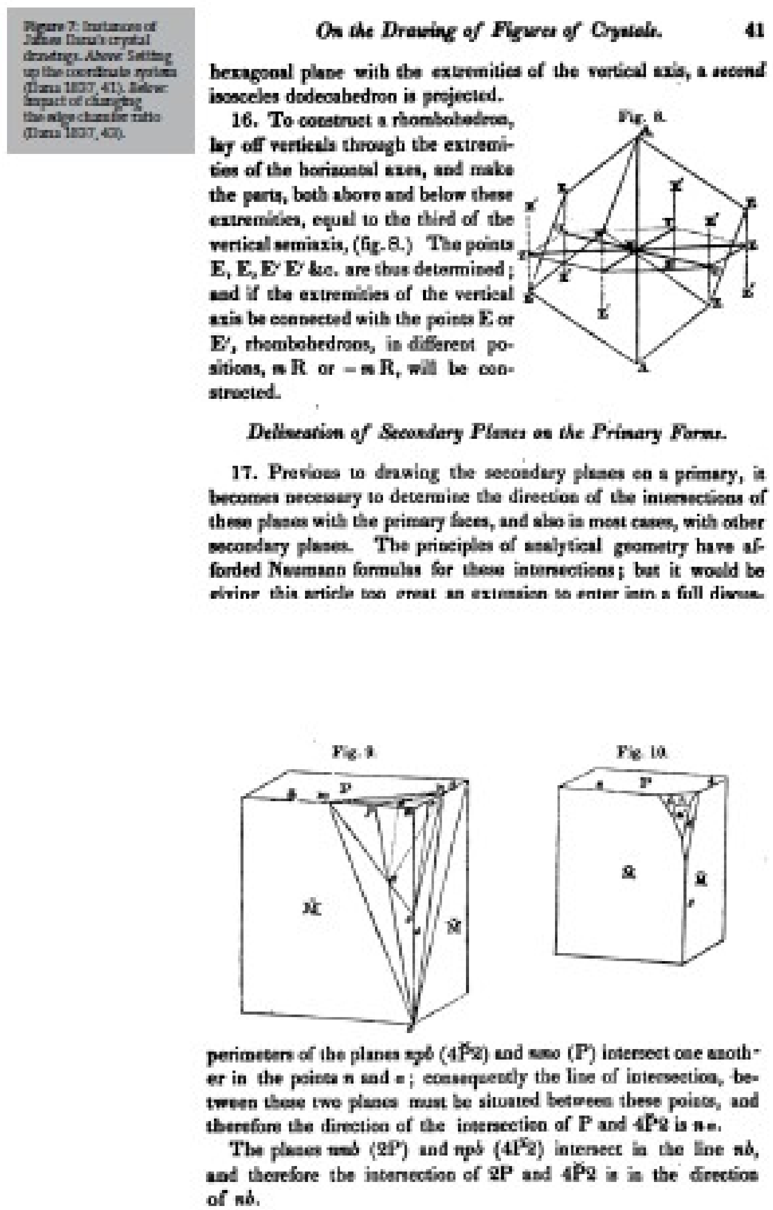

Figure 7: Instances of James Dana's crystal drawings. Above: Setting up the coordinate system (Dana 1837, 41). Below: Impact of changing the edge chamfer ratio (Dana 1837, 43).

On the Drawing of Figures of Crystals. 41

hexagonal plane with the extremities of the vertical axis, a second isosceles dodecahedron is projected.

16. To construct a rhombohedron, lay off verticals through the extremities of the horizontal axes, and make the parts, both above and below these extremities, equal to the third of the vertical semiaxis, (fig. 8.) The points E, E, E′ E′ &c. are thus determined; and if the extremities of the vertical axis be connected with the points E or E′, rhombohedrons, in different positions, m R or − m R, will be constructed.

Fig. 8.

Delineation of Secondary Planes on the Primary Forms.

17. Previous to drawing the secondary planes on a primary, it becomes necessary to determine the direction of the intersections of these planes with the primary faces, and also in most cases, with other secondary planes. The principles of analytical geometry have afforded Naumann formulas for these intersections; but it would be giving this article too great an extension to enter into a full discus-

Fig. 9. Fig. 10.

perimeters of the planes *npb* (4P̄2) and *nmo* (P) intersect one another in the points *n* and *o*; consequently the line of intersection, between these two planes must be situated between these points, and therefore the direction of the intersection of P and 4P̄2 is *no*.

The planes *nmb* (2P) and *npb* (4P̄2) intersect in the line *nb*, and therefore the intersection of 2P and 4P̄2 is in the direction of *nb*.

James Dana's drawings, Daniel Davis (2013) based on James Dana (1837)

Above: Setting up the coordinate system. Below: Impact of changing the edge chamfer ratio. (Davis, Daniel, *Modelled (sic) on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 20)

83 Davis, Daniel, *Op. Cit.* (2013), P.18

Whereas Schumacher sees architecture and design as a parametric style, itself based upon the notions of *game theory, agent based* and *swarm systems*; a sort of topological entanglement encompassing the differentiation/correlation duality, Oosterhuis (which also theorizes upon games and other recursive systems) goes a bit beyond that and tries to tie it to the notion of the universe as a computational system in itself. Once established this ontology, buildings begin to look like natural systems as, at a fundamental level, they are no longer any different. According to Oosterhuis, in his *hyper-body* paradigm, *architectural bodies may need to develop an e-motive intelligence of their own* [84], referring to *Para-SITE* (1996), turning them into samples and processing them in computers that produce complex *sound-scapes,* taking information and transforming it into a higher state of information.

Para-SITE, ONL-Oosterhuis y Lenard- (1996), a project that took data samples that, processed via computer software,

[84] Oosterhuis, Kas, P. 20 (2003) P.14

produced complex soundspaces. (http://onl.eu/sites/default/files/styles/portfolio_image_gallery_780x584/public/portfolio-gallery-img/Byday1_0.JPG?itok=2aUsY0sp) (22/01/2015)

Vaulted Willow, Marc Fornes (2014) Where the objective is to solve and define skin, structure and ornamentation in a single unified whole. (https://theverymany.files.wordpress.com/2011/12/img_6299_ps_fornes_s.jpg) (22/01/2015)

It is the hacker's attitude to do things that are unorthodox or (at times) 'illegal', just to see where they carry him/her and subsequently producing new and/or improved public knowledge, which is *my personal view*. To understand this, first we need to briefly differentiate ***computation*** from ***parametric*** and ***digital****:* The first being a universal mode of managing information and computing it to solve problems or emergent situations (be them natural or abstract), the second a subset of mathematics that emphasizes in multidimensional variable conception for problem solving most notably in Geometry (not the way the term has been misused by most architects) and the later a wave of technology (based on a noise threshold theorem by Claude Shannon, which has translated in using discreet values -a symbol- replacing continuous ones – a wave function) that emerged as a medium through which computation and multimedia have reconfigured society and *together* given birth to what we call the *information age*, and with it the duality of *software and hardware*. (These concepts are, for the time being, oversimplified for readability but in later chapters they will be addressed more thoroughly). As an example, a chain model in fact (expressed explicitly by the curve's length, weight and its two anchor points, plus gravity) is a parametric set without a computer environment (yet it is not the set that originates this form of natural computation, but the laws physics themselves), thus showing the difference between computation and parametric modeling, needless to say that there is no discrete data-driven interface to call this process digital, in fact, it is analog. This means that Gaudí's hanging models or *catenarias,* were parametric, yet not computerized nor digital. So then the question arises: *"How, then, do we determine the relationship between computing and architecture?*[85] As Mike Silver writes in *Architectural Design* in its 2006 edition *Programming Cultures: Art and Architecture in the Age of Software. "What forms, practices and techniques will seem most relevant if the internal structure of software and the theories that drive its developments are changed at the same time?"* [86]

This predicament is still being debated today and is the central problem of the already established computational model oriented *praxis:* ***The parametrization of emergent new embodiments in architecture through combining computational methods and digital technology.***

And as a consequence another question arises, after we put them in the same sentence:

"Can we even define computational architecture? The answer to this last question is that we cannot. ...computers are universal machines. Unlike classical machines (clocks, steam engines and tin openers) they can perform a wide variety of tasks without significant changes to their physical design. Through the writing of new programs, very different operations can be executed on a single device."[87]

This means that the nature of computation is universal and it is very difficult to frame it in a single dogma or some kind of orthodoxy: that its pluralistic nature opens many different paths to its practice yet they are still held under the same paradigmatic umbrella. Maybe we can try to define it as a duality (as almost always happens) in Schumacher's words:

"*Parametricism aims to organise (sic) and articulate the increasing diversity and complexity of social institutions and life processes within the most advanced centre of post-Fordist network society. It aims to establish a complex variegated spatial order, using scripting to differentiate and correlate all elements and subsystems of a design. The goal is to intensify the internal inter dependencies within an architectural design, as well as the external affiliations and continuities within complex, urban contexts."*[88]

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85 Silver, Mike, *Op. Cit*. (2004) P.9
86 Idem.
87 Idem.
88 Schumacher, Patrick, "Let the style wars begin," Critics section, T*he Architect's Journal*, London (2011) (http://www.architectsjournal.co.uk/the-critics/patrik-schumacher-on-parametricism-let-the-style-wars-begin/5217211.article) (06-05-2010)

Yet according to Karl Chu, all claims aside, current architecture is *best characterized by the use of computation still operating under the vestiges of the old paradigm. In others words, architecture has still yet to incorporate the architecture of computation into the computation of architecture.*[89]

And while Oosterhuis argues his *hyper-body*'s separation from the order (or movement) that preceded it as a relationship between *Mass production* opposite *Mass customization* (using industrial fabrication concepts instead of style oriented ones) we can establish a certain common ground between their seemingly different yet, in reality, very similar fundamental concerns towards the definition of today's dominant architectural paradigm. As noted by karl Chu, *within the contemporary landscape of architectural discourse there are two divergent trends with theoretical motivations: the morphodynamical and morphogenetic systems approaches in the design and construction of buidlings*[90]; being morphodynamical the more dominant of the two. This classification would place both of them (*Parametricism* and *hyper body*) in the same category, to which I agree, although I can affirm that Oosterhuis's approach embodies some reminiscence to morphogenetic systems rather than just Morphodynamical ones and, in this sense, *parametricism* is not so different than Rem Koolhaas's approach as the primordial architecture of globalization, which is also a part of the morphodynamical cosmos. The fact that morphogenetic systems are in *an embryonic state*[91]*,* makes it currently not possible to be accessed by real world architecture hence genetic architecture is still at large for the most part as it theorizes an architecture of autonomous logic and *will to being*[92], which no well known project to date, with notable exceptions, exhibits. *These two systems are reminiscent of a strikingly similar problem that exists in modern biology, which is still attempting to synthesize the differences that exist between molecular biology, on the one hand, and developmental biology on the other*[93], and that ,to be complete, the theory of architecture needs in *a similar synthesis of the two*. [94]

We can all agree that, in both visions within the morphodynamical, repetition brings about simplicity: the understandable, the separated, a set of parts put together by mechanical means. The printed word and book are renditions of repetition in its most enduring fashion, they reside within the *tectonic* (or, in

89 Chu, Karl, *Op. Cit.* (2005) P. 162
90 Idem.
91 Idem.
92 Idem.
93 Idem.
94 Idem.

Animate From, *Mechanical*) *paradigm* which, according to *Gregg Lynn*[95], has to do with building and fabricating objects through parts to assemble a whole, yet inert, object (system hierarchy and assembly, arrangement of components, discrete layering and superposition). Opposite what Lynn calls the *plastic paradigm*[96], which has to do with fusing material in a matrix, layering without distinction, fibers over members and woven orientation to then produce the whole, much like fiberglass boat designing. In the *tectonic paradigm,* the parts of the whole are related to one another in a purely mechanical way, opposite an organic and continuous way as Schumacher states that: [97] *"The modernist order of separation and repetition is being supplanted by the Parametricist order of continuous differentiation and intensive correlation."*

Deleuze and Guatari, on the subject of differentiation and correlation, argue that:

"One certainly cannot say that the milieu determines the form; but to complicate things, this does not make the relation between form and milieu any less decisive. Since the form depends on an autonomous code, ***it can only be constituted in an associated milieu that interlaces active, perceptive, and energetic characteristics in a complex fashion, in conformity with the code's requirements****; and the form can develop only through intermediary milieus that regulate the speeds and rates of its substances;* ***and it can experience itself only in a milieu of exteriority that measures the comparative advantages of the associated milieus and the differential relations of the intermediary milieus.*** *Milieus always act, through selection, on entire organisms, the forms of which depend on codes those milieus sanction indirectly."*[98]

Having established the common points regarding these two opposites and the uniformity within all these theories, we can agree that the opposition between flexibility and rigidity are the key tools to define the architecture/computation relationship, we could even go all the way up to Universality (not meaning uniformity) and down to specificity (not meaning particularity), the *Top-down/Bottom-up* opposition. In its stylistic approach *parametricism implies that all architectural elements and complexes are parametrically malleable. This implies a fundamental ontological shift within the basic,*

95 Lynn, Greg, *Animate Form*, Princeton Architectural Press , USA (1999) P. 10
96 Idem.
97 Schumacher, Patrick, *Op. Cit.* (http://www.architectsjournal.co.uk/the-critics/patrik-schumacher-on-parametricism-let-the-style-wars-begin/5217211.article) (06-05-2010)
98 Delleuze, Gilles - Guatari, Felix, The Geology of Morals, *A thousand Plateaus,* translation and foreword by Brian Massumi, University of Minnesota Press (1987) P.72-73

constituent elements of architecture. [99]

Schumacher goes on:

"Instead of classical and modern reliance on rigid geometrical figures – rectangles, cubes, cylinders, pyramids and spheres – the new primitives of parametricism are animate geometrical entities – splines, nurbs and subdivs. These are fundamental geometrical building blocks for dynamical systems like 'hair', 'cloth', 'blobs' and 'metaballs' that react to 'attractors' and can be made to resonate with each other via scripts." [100]

This line of thought describes the leading (yet not the most politically correct) tendency in the discourse regarding architecture and computation. It even has dogmatic considerations coming from this last decade's work at Zaha Hadid Architects which follow as noted:

Parametricism's Negative principles (taboos):

- *Avoid rigid forms (lack of malleability)*
- *Avoid simple repetition (lack of variety)*
- *Avoid collage of isolated, unrelated elements (lack of order)*
- *Avoid rigid functional stereotypes*
- *Avoid segregative (sic) functional zoning*

Positive principles (dogmas):

- *All forms must be soft*
- *All systems must be differentiated (gradients) and interdependent (correlations)*
- *All functions are parametric activity scenarios*
- *All activities communicate with each other*[101]

These dogmas do not get us very far in creating our own language to deal with these dialectics, instead of obsessing about style and superiority, it is probably more productive to shift our focus to what its actually the craft that binds IT and architectural design: the tools themselves and the attitude we have towards them; even if it means to build our own tools to lever the weight between concept and fabrication. The idea of architects customizing their own software is somewhat of an elusive one but *to*

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[99] Schumacher, Patrick, *Op. Cit.*
[100] Idem.
[101] Idem.

a great extent this shift is becoming a necessity. Large, unanticipated gaps in the computer-aided design and construction process can only be bridged by the creation of special software.[102] The end justifies the means when it comes to getting things done in the real world in feasible, creative, complex and, ideally, universal ways.

Computational architecture *"..explores the power of code by encouraging artists and architects to become more involved in the creation of home-made, task-specific tools. Through individual labor or by collaborating with skilled developers, designers can harness the power of universality."*[103] Computation turns architecture into a hack: embedding *code inside it.* As David Rutten, developer of Grasshopper affirms that *anybody involved in any job that ultimately creates instructions that are executed by a computer, machine or **even a biological entity**, can be said to be programming.*[104] Be it visual or script programming:

"as specific programming languages are less mysterious and easier to master, 'home made' software will most likely become a familiar part of design culture. This move by the design community to take an active role in the production of code transcends the limitations of prefabricated software tools." [105]

Our theoretical hypothesis is that, by building our own customized tools, we can approach the current state of affairs in the architectural discourse (and therefore face kinetic architecture's challenges) with the right conceptual and methodological framework to begin thinking about a building reality beyond what we can envision by current means.

Some (as Mark Burry and Michael Weinstock) have noted that *we are moving rapidly from an era of being aspiring expert users to one of being adept digital toolmakers*[106] and to an age in which *to be a craftsman in the digital age, you have to be a tool maker, you have to make digital and fabrication tools.*[107] Our senses and sensitivity are transformed and,why not? expanded through the looking glass of

102 Silver, Mike, *Op. Cit.* (2004) P.11
103 Idem.
104 Rutten, David, Programming, *Conflicting Perspectives,* I Eat Bugs For Breakfast (blog) (2012) (https://ieatbugsforbreakfast.wordpress.com/?s=anybody+involved+in+any+job+that+ultimately+creates+instructions+) (11/02/2015)
105 Silver, Mike, *Op. Cit.* (2004) P.11
106 Burry, Mark, *Parametric Design and the Sagrada Família*, Scripting Cultures. Chichester: Wiley, (2011)
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P.26

107 Weinstock, Michael, *Op. Cit.* (2015) (https://www.youtube.com/watch?v=LiNvucaCd5E) (18/03/2015)

computational methods through which:

"the computer is no longer used as a tool for representation, but as a medium to conduct computations. Architecture emerges as a trace of algorithmic operations. Surprisingly enough, algorithms -deterministic in their form and abstract in their operations- challenge both the design conventions and perhaps even more surprisingly, some of our basic intuitions."[108]

This abstraction oriented nature, lets us worry about higher matters in the design train of thought. It creates a space/time fluid connection between our erratic, yet highly intuitive, senses and the algorithm's precise world of computational mathematics; where we can dive into certain *Metaphysical* concerns that transcend our sensory and cognitive realms, therefore beginning to question things we could not have even thought about before thus, at times, ***dismantling thought itself***:

"Unlike computerization digitization (sic), the extraction of algorithmic processes is an act of high level abstraction…Algorithmic structures represent abstract patterns that are not necessarily associated with experience or perception…. In this sense algorithmic processes become a vehicle for exploration that extends beyond perception."[109]

There has also been some share of controversy and concern regarding the concepts of authorship and materiality embedded to architecture as a building science, where some have denounced some disregard in both matters. Ingeborg Rocker states that:

"Most if not all, explorations into algorithmic process-and form- generation generally neglect the structural and material integrity of architecture. Nevertheless, some projects do present a significant development within the production and discussion of design, and many have recast the authorial role of the architect, upsetting the guardians of the humanist school." [110]

But, in a less defeatist approach, as much as a problem to solve, it is also a reality to face, meaning that the almighty architect of the XX century no longer exists. From a determiner of results, he has turned

[108] Rocker, Ingeborg, "When Code Matters", Programming Cultures: Art and Architecture in the Age of Software, *Architectural Design*, Wiley Academy Press, United Kingdom (2004) P. 24
[109] Ibid. P. 23-24
[110] Ibid. P. 24

into a controller processes, shifting from *humanism* to *post-humanism*, and this implies a deep shift in civilization:

We are no longer the center of the universe. At last, architecture caught up with philosophy.

This singular place in our situation of thought enables us to relocate our aims towards a more biological, environmentally complex and responsive approach to design and architecture. We can begin to think about kinetic systems in a real and tangible manner, algorithmic methods allow us to model material as well as geometrical behavior, encompassing chemistry and even translating language and feelings into the built environment.. All this points out that a new research area exists, the one that I'm proposing:

Performance driven, digital simulations that make kinetic architecture's decision making process more fluid, feasible and intuitive, placing responsive nano-tectonics and autonomous buildings within our reach.

Opposites again we face between the organic and inorganic, our interpretation of life itself puts under question our central idea about civilization, that which sets us apart from that which is not civilized: concept of organization itself. Ilona Lenard states that, when placed facing each other:

"*In reality, life is a movement, materiality is the inverse movement, and each of these two movements is simple, that matter which forms a world being an undivided flux, and undivided also the life that runs through it, cutting out in it living beings all along this track. Of these two currents the second runs counter to the first, but the first obtains, all the same, something from the second. These results between them are a modus vivendi, which is organization."*[111]

The relationship between these opposed kinesis is established as central to the phenomenon of life thus opening wide, transverse and uncharted territory to develop a different kind of nature, not as it currently is or as it should be, ***but as it could be***.

[111] Bergson, Henry, "Creative Evolution" As quoted by: Lenard, Ilona, "PowerLines", *BCN Speed and Friction: The Catalunya Circuit City*, Various authors, Lumen Inc. / Sites Books, Esarq., Barcelona, (2004) P. 155.

K. Oosterhuis suggests looking at architecture, at large (and I would add reality for that matter), as an "open source" phenomenon, and to think about it as a "program, writing code" to make this concept actually work as an open architecture in real time, an open source architecture: for today's architect must work with the information flow and mold it. *"These programs can be both simple, generative codes that produce complexity (see, for example, the articles by Stephen Wolfram and Karl Chu), or complex programs that help make difficult tasks easy.*[112] Using not only traditional CAD software, but more developed generative, game design and animation software programs (as Dollens has also stated) like *Maya, Virtools, Cinema-4d, 3D-max*, *Grasshopper* and *Paracloud,* just to name a few. His task is to design a game, that produces projects, *the design is the formula*, he states, *and playing the game means to set the parameters*. [113]

"Programs have become pervasive mainly because their instructions can be applied to so many diverse problems (for example, one piece of software in the stealth bomber actually counteracts the plane's poor aerodynamics and prevents its falling from the sky even when the pilot deliberately initiates a fall)."[114]

This Thus underlines another issue within this paradigm: ***control as a mean of organization and flux permeation*** and which in turn compels us to pose ourselves another important question:

How do these systems deal with stability, failure or precision?

*2.1-BCN Speed and Friction: The Catalunya Circuit City (or just C^3)_*

A significant empirical proof about translating methods from these previously analyzed abstract design concerns to specific, tangible cases (in a universal manner) was the Esarq's (@ the Universitat Internacional de Catalunya) 2003 workshop called ***BCN Speed and Friction: the Catalunya Circuit City*** (or just ***C^3***, lead by Kas Oosterhuis and Ilona Lenard from ONL) which takes this last notion from Oosterhuis and takes it to actual design methodology with tangible results and *relates form to movement and behavior of outside data (gotten from cars and vehicles on a race track circuit).*[115] The

[112] Silver, Mike, *Op. Cit.* (2004) P.11
[113] Oosterhuis, Kas, *Op. Cit.* (2003) P.16
[114] Silver, Mike, *Op. Cit.* (2004) P.11
[115] Lenard, Ilona*, Op. Cit.* (2004) P. 197.

workshop, divided in 12 sectors designed by 14 teams, dealt with the reshaping of the *Barcelona-Catalunya Circuit* (a popular formula 1 grand prix race track) into a city/race track shared program, thus changing its configuration for the rest of the year (the circuit is only used once a year -3 days- at the already mentioned *Grand Prix*) and it did it with *an interesting way to calculate or delineate form for a shape shifting material to become an architectural element*[116], the authors proposed a computational approach that dealt with various layers of duality encompassing the flexibility/rigidity dichotomy. This juxtaposition between city and race track circuit is challenged and opened with uncertainty about its relevance in the "real" world, thus contradicting Ingeborg's concerns about certain projects not being based on the materiality of the real/physical:

"How can we charge the circuit with such power to become a major attractor for urban life?

What kind of city will emerge from that power battery?

What sort of activities could be suited to make this bold transformation from circuit to city feasible?

Can the circuit be charged by the strength of an urban concept alone? How excessive can be (sic) the power of a design proposal?

Will it be powerful enough to be an influence on the real case of the Catalunya City?

Are we tutors and students alike dreaming in a parallel world, or could we indeed change the course of the information flow in our actual(sic) society in such a way that it eventually might happen?"[117]

Still showing the concerns that have been detailed before: Information flow as a means for embodying and programming architecture. In sector 05 they pose an interesting, almost paradoxical, departure point for the envelope of one of the buildings:

"Imagine a membrane or enclosure system that is both structure and envelope, both solid and plastic,

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116 Lenard, Ilona, *Op. Cit.* (2004) P. 197.

117 Oosterhuis, Kas, "Temporarily transformation of the city", *BCN Speed and Friction: The Catalunya Circuit City*, Various authors, Lumen Inc. / Sites Books, Esarq., Barcelona, Spain (2004) P. 11.

a super-skin that could be used either as a temporary structure or incorporated into an existing structure. This enclosure system must be highly flexible as a delineator of space and go easily from one plastic configuration to another, yet still retain solid structurally stable positions. Domed structures could easily satisfy one criteria of such a structure, but they take up large amounts of ground area, and must retain uniform shape. Could a structure be developed that is a hybrid between domed structures and conventional planar structural systems?"[118]

This study explores both the tectonic feasibility of such a structure and a digital visualization/ representation of its elemental attributes: Joint termination/ stresses/ loads/ modular expansion/ form.

Sector 12's Concept *The Glove,* the program had to enclose:

- *Hospital*
- *Spectator stands*
- *Garden and Parking rings*
- *Apartments and offices*
- *Access*[119]

Along with what they called "building ambitions":

- *To give spectators, residents and hospital patients a race experience.*
- *To absorb the roaring energy and movement of the race car, transforming it to the quiet of a hospital.*
- *To materially register the passing race cars energy.*
- *To transform movement into information streams.*[120]

From which relationships they built a formula derived from actual race car driver perspectives and conditions:

[118] Lenard, Ilona*, Op. Cit.* (2004) P. 169
[119] Ibid. P. 197.
[120] Idem.

Formula:

*Y= R (v/d*d) * Sin (w*t)*

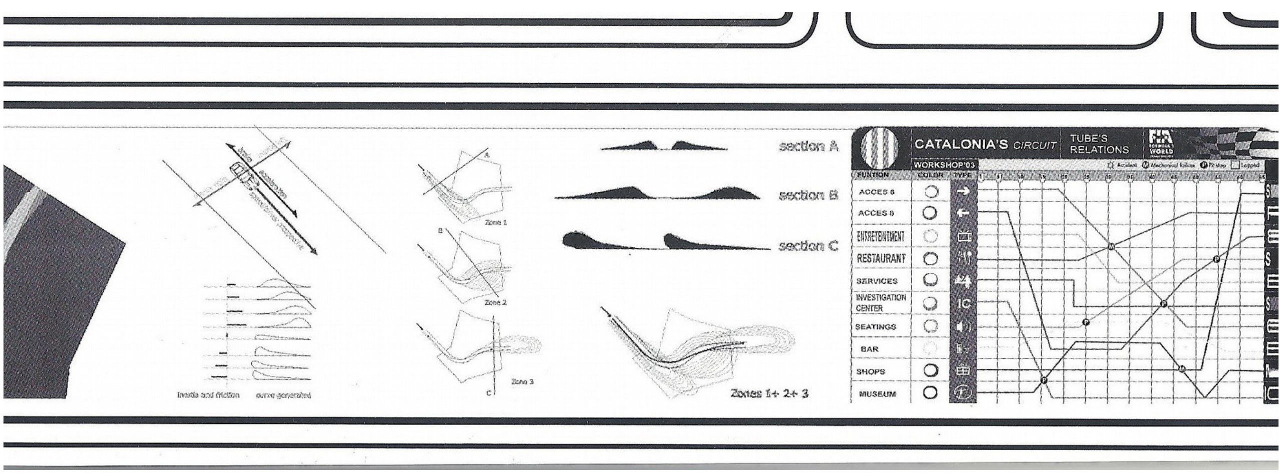
where:

R: Rhosp=1 , Rcirc= 0.5

v= car's speed

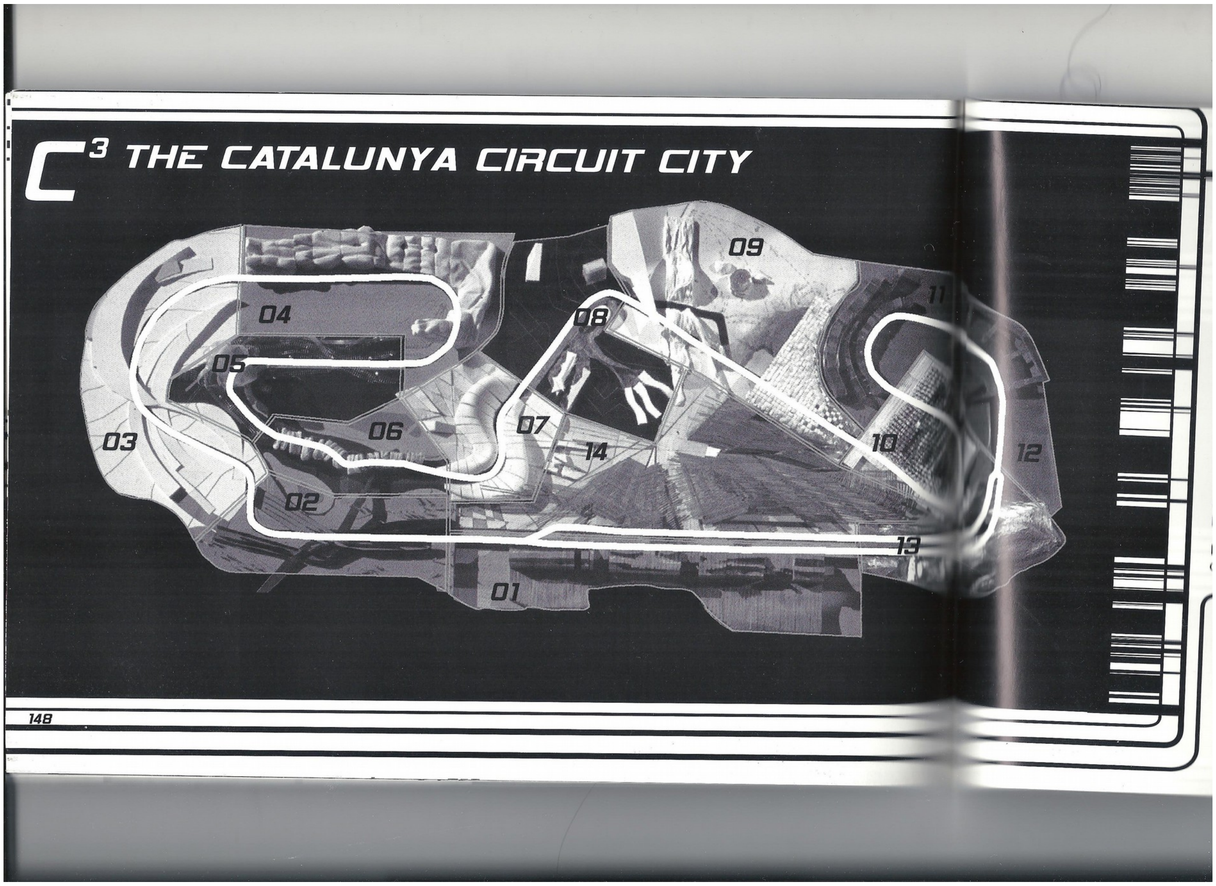
d= distance betwe[e]n car and skinw= angular speedt= time

Y= skin position.[121]



C^3, The Catalunya Circuit City, parametric matrices concerning form and performance relationships, Kas Oosterhuis, Ilona Lenard, Alberto Estévez yand ESARQ students (2004), the C3 project that proposed to fuse an F1 racetrack with a city. (Top) (Oostherhuis, Kas – Lenard, Ilona – Estévez, Alberto T., *BCN Speed and Friction: The Catalunya Circuit City*, P. 148 -177)

[121] Lenard, Ilona*, Op. Cit.* (2004) P. 169.



C[3]*, The Catalunya Circuit City, Masterplan* Kas Oosterhuis - Ilona Lenard - Alberto Estévez and ESARQ students (2004), the C3 project that proposed to fuse an F1 racetrack with a city. (Top) (Oostherhuis, Kas – Lenard, Ilona – Estévez, Alberto T., *BCN Speed and Friction: The Catalunya Circuit City*, P. 148 -177)

These computational approaches to design show that buildings today arise also from extrinsic information (not just from their own intrinsic logic) that is translated into an architectural state. *The design process is, like a game, also a goal oriented process. The ultimate goal of the design process is to describe a future building so that it can be realized*[122] affirms Michael Bitterman, researcher for the *hyper-body* laboratory in TU Delft and tutor for the workshop. So we can, without a doubt affirm: architecture is becoming information, while at the same time, information is becoming architecture. The world changed, Cyberspace is our reality of choice, hacking is our *Ethos*, nature our *Logos* and, to paraphrase Carl G. Jung[*], *the meeting of the two disciplines is like the contact of two chemical substances: if there is any reaction, both are transformed.* And, in this case, neither will be the same ever again.[123]

[122] Bitterman, Michael, "Hyperbody Paradigm", *BCN Speed and Friction: The Catalunya Circuit City*, Various authors, Lumen Inc. / Sites Books, Esarq., Barcelona (2004), P. 46

[*] Attrituted to Jung, Carl G. I have tried to locate this quote but nowhere does it appear with any reference about any of Jung's books, it has just appeared in one PDF format book and a couple of quoting sites, it will be used for its metaphorical value as not for its authenticity.

[123] Dehart, Paige, Unmasked: One Soul's Journey from Anonymity to Identity, tate publishing (2006) P. 177

*3-Animation in Architecture: A historical perspective_*

“There are currently several architectural practices which use animation software and techniques as method of generating new forms and spatial experiences. Some architects even propose that architecture needs to adopt behaviors and react to or interact with the user.”[124]

The work of several architects (e. g. Dennis Dollens, Mark Goulthorpe, Kas Oosterhuis,Greg Lynn) can prove this tendency in their dedication to develop projects that expand building capacities in ways that could only be defined as moving or *animate*. They are a small part of an emerging kind of architect that take the new technologies and incorporate them into, not only his/her design methodology and process (using a variety of digital tools and software ranging from *Maya, Xfrog, Virtools, Top Solid*), but into their theoretical discourse as well. But, nevertheless these emerging practices that devises what in Kas Oosterhuis's words is “a new kind of beauty”, the discipline at large remains in a “*static”* mindset and methodological stagnation. How can the discipline of architecture adopt responsiveness if is deals with, not just inert material, but also inert and static concepts and ideas, we have always operated in the realm of static pictures and painting as expression methods. We develop static models, static drawings, therefore our understanding of the craft is solely based on a “*snapshot”* type of imagination. Lately the attraction from multidisciplinary approaches has taught us that *a key phenomenon in animation is its ability to simulate metamorphosis and its digital progression, the morph'*.[125] This day in age, architecture as a practice and craft has turned to the abstract and complex methods of disciplines so diverse as biology, botany and even animation to acquire conceptual, metaphoric and real physical means to diversify and broaden the design and methodology spectrum available, since *animation is an instrument in a virtual architectural process: it is an interactive, generative, exploratory tool. These new techniques allow explorations of new forms and experiential potentials, which were not possible to describe with traditional drawing methods.*[126] Animation's own beginnings are quite counter intuitive, it could be argued that it has its origins in *Johann Wolfgang Von Goethe*'s concept for studying plant growth called *morphology*, which later on would help develop something called *allometry*, a part of morphology that studies the of part to whole relationship in Biology. Although, as it is shown in the

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[124] Mikelides, Electra - Sabatelli, Valentina -Amman, Delphine, *Animation in Architecture*, research for Design as research I (Prof. Christopher Hight lecture) at the Architectural Association, London (2002) P. 1 (http://www.aiborg.net/blitzinbits/AAdrl/animation.swf) (12-11-2010)

[125] Buchan, Suzanne, editor for Animation journal, personal communication to Dollens, Dennis, (12 October 2005) As quoted by: Dollens, Dennis, “The Cathedral Is Alive: Animating Biomimetic Architecture”, *Animation*, Sage publications, USA (2006) P. 111. (http://anm.sagepub.com/content/1/1/105) (12-11-2010)

[126] Mikelides, Electra - Sabatelli, Valentina -Amman, Delphine, *Animation in Architecture*, *Op. Cit.* (2002) P. 4

next images, you can find the earliest traces of animation-like techniques in *Sandro Botticelli's* illustrations for the first ever printed version of *Inferno* and *Paradiso's* passages from *Dante Alighieri's Divine* Comedy, dated as far back as 1481.

Goethea, Johann Wolfgang Von Goethe (1796) (https://www.uni-jena.de/unijenamedia/Bilder/einrichtungen/gartenhaus/Goethea-width-250-height-351.jpg) (13/12/2015)

Dante's Inferno, Sandro Botticelli (1481) (http://imgkid.com/botticelli-dantes-inferno.shtml) (13/12/2010*)*

Dante's Inferno, Sandro Botticelli (1481) (http://danteworlds.laits.utexas.edu/gallery/1028.jpg) (13/12/2010)

Dante's Inferno: the appearance of Satan, Sandro Botticelli (1481)*(http://danteworlds.laits.utexas.edu/gallery/1028.jpg) (02/03/2015)*

Dante's Inferno: Paradiso, Sandro Botticelli (1481) (http://danteworlds.laits.utexas.edu/paradiso/gallery/0110lunar.jpg) (02/03/2015)

As Dennis Dollens points out in his 2006 article for *Sage Publication's Animation Journal* titled *The Cathedral Is Alive: Animating Biomimetic Architecture,* "*essentially, in 1790, Goethe articulated a theory of graphic transition of plant-form development seen in morphological growth and development that may now be looked at as proto animation.*"[127] This concept would go on to define the way we look and interpret movement and how we extract important scientific data that is not shown in the snapshot, static standpoint. *His conceptualization* (Goethe's) *and discussion of plant development provide a transforming, conceptual link in the history of understanding and visualizing movement and growth that later would be replicated in early animation-like, scientific photography and still later in animation cinema*[128]*,* thus suggesting with this affirmation that the key feature was sequence and the

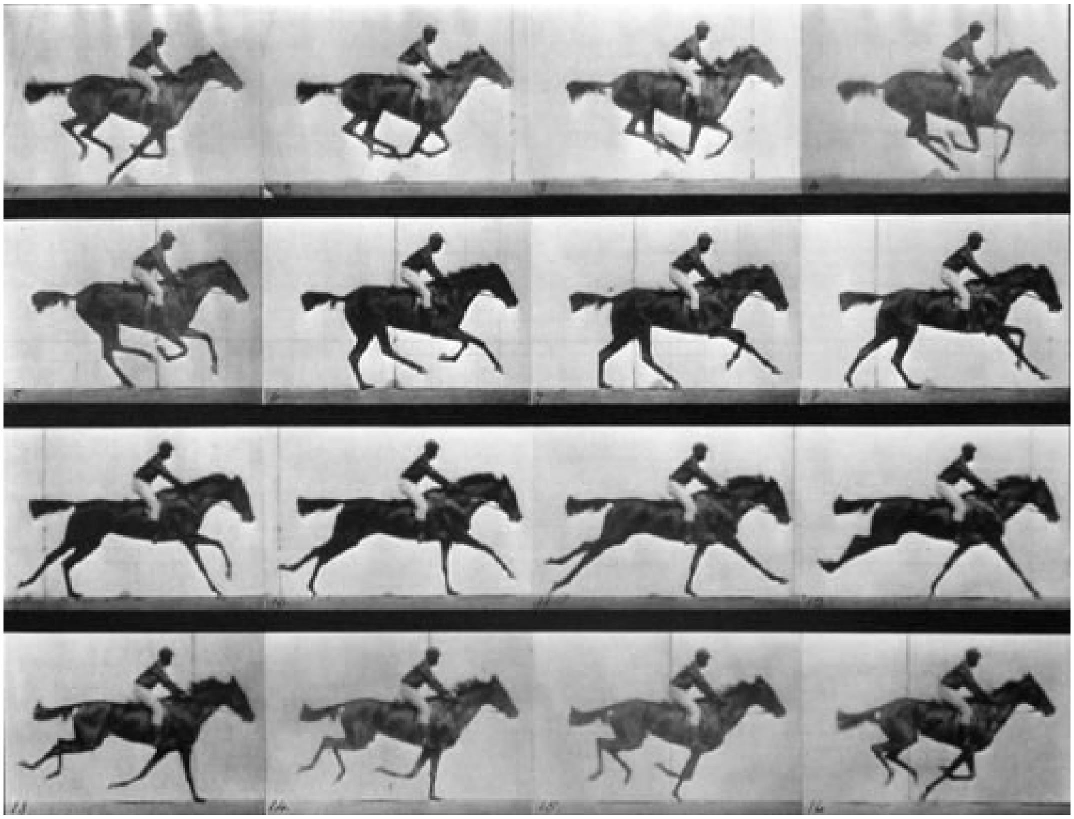
[127] Dollens, Dennis, *Op. Cit.* (2006) P. 111
[128] Idem.

change in form or position at every instant, thus generating a totally different output and intake through the means of a different process -the breaking down of movement into tiny instants of detailed information that could not be seen before this technique was developed. For example, Dollens remarks that:

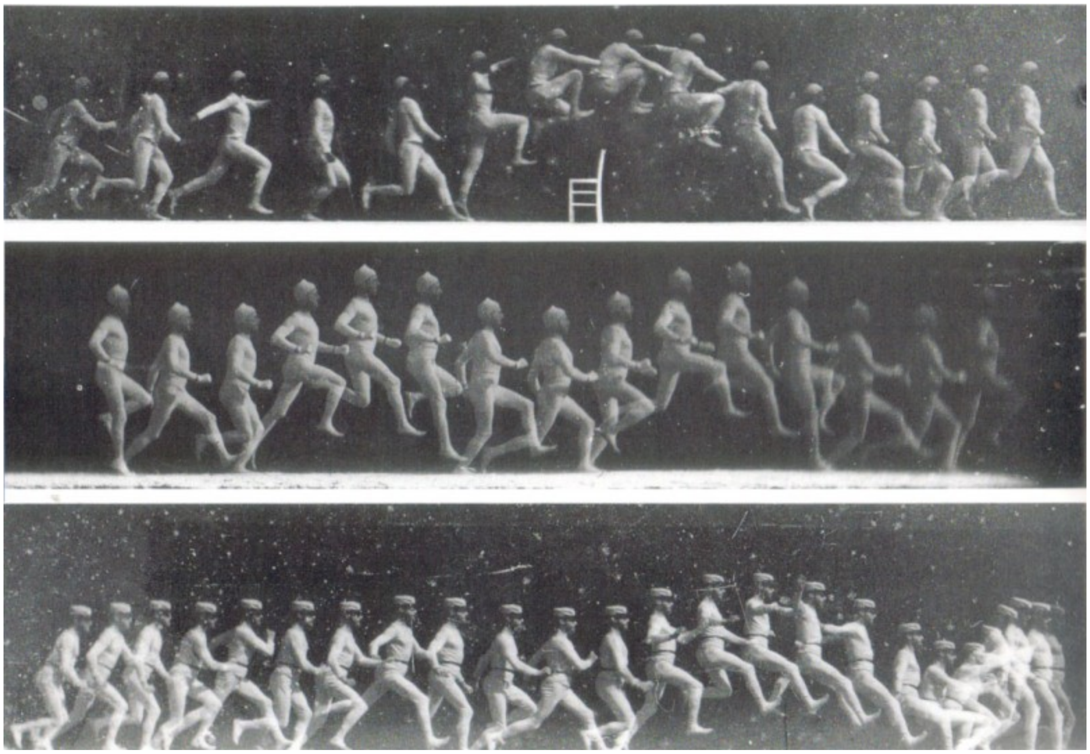
"in the research images of Eadweard Muybridge or Etienne-Jules Marey, where stop action in photography became the cousin of the morph as well as a morphological tool: cells of graphic information yielding data derived by capturing form-in-motion (but only revealing scientific data when analyzed sequentially)"[129]

This was graphic illustration's introduction to the notion of progression, its venture into the passing, progressive quality of time, a concept that, used inversely, would go on to produce what we today understand as *cinematography.* "*Today, while morphology is no longer the primary route of biological research, its methods as well as its definition –the study of form and transformation – , are embedded and central to visualizing movement and critical to animation* [as an art and craft]*"* [130]

[129] Dollens, Dennis, *Op. Cit.* (2006) P. 111
[130] Idem.

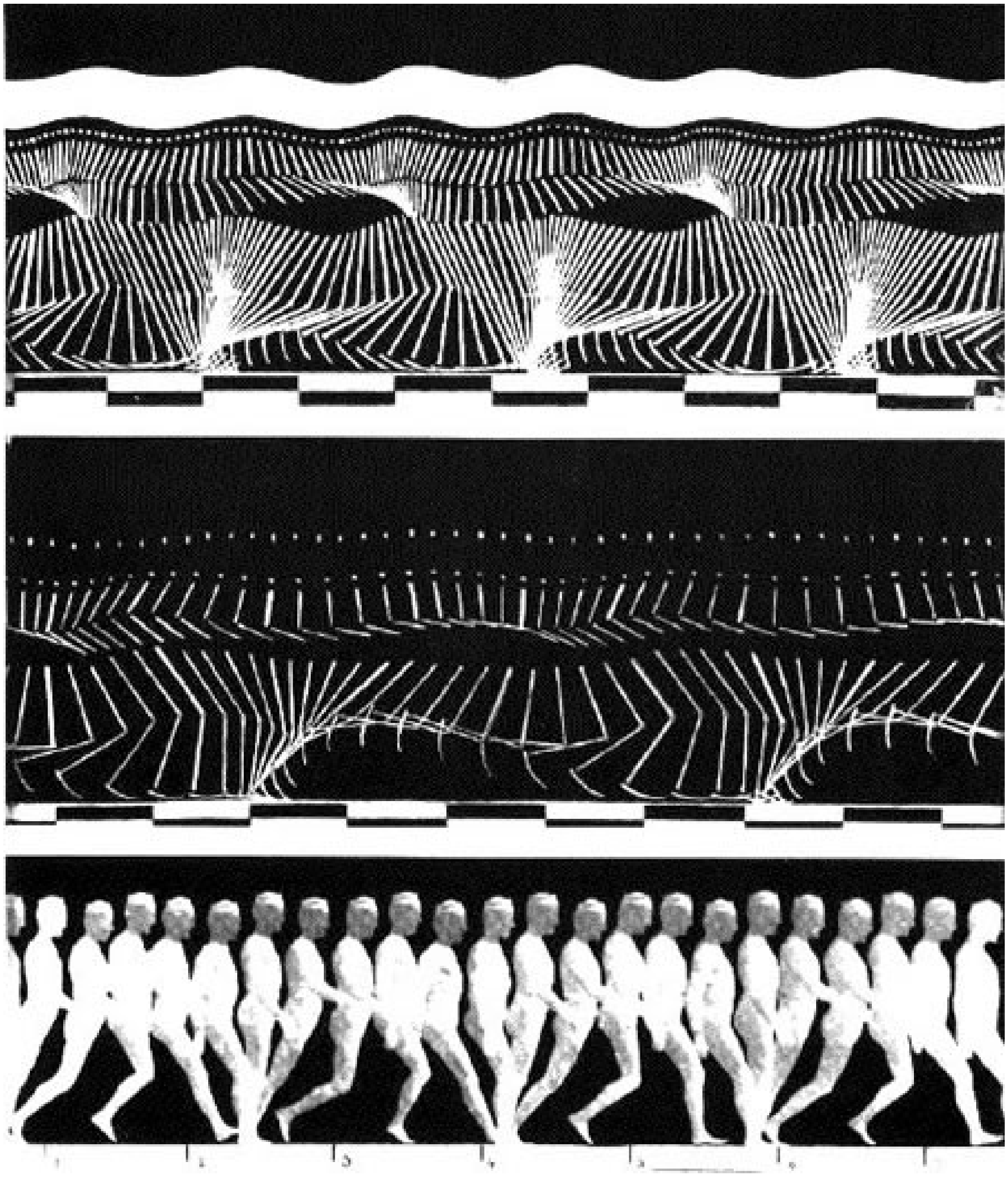


Human and Animal Locomotion, Eadweard Muybridge (1887)
(https://es.wikipedia.org/wiki/Eadweard_Muybridge#/media/File:Le-galop-de-daisy.jpg) (13/12/2010)



Moving Bodies in Space, Etienne-Jules Marey (circa 1887-1889 or 1894[*]). Research images in early examples of morphology studies trough crono-photography. Concepts derived from Goehte's 'morphology'. (http://maimtoplease.wordpress.com/2009/07/08/etienne-jules-marey/marey12/) (13/12/2010)

[*] Molderings, Herbert , *Duchamp and the Aesthetics of Chance: Art as Experiment,* Columbia University Press (2010)



Locomotion humaine , Etienne-Jules Marey (circa 1886) (http://www.memoireonline.com/02/13/7036/Contribution--la-caracterisation-mecanique-des-criteres-de-qualites-du-depart-de-la-course-vi.html) (13/12/2010)

"Just a few years earlier, 1909, Filippo Tommaso Marinetti had published the 'Foundation Manifesto' for the Futurist movement. In it he praise(d) danger, movement, crowds, and above all, speed as a new form of beauty, an ***éloge*** *to mechanism and abstract energy of all kinds including war and automobilism."*[131]

[131] Kwinter, Stanford, *Architectures of Time: Toward a Theory of the Event in Modernist Culture*, , MIT Press, Cambridge, Massachusetts (2001) P. 55
As quoted by: Mikelides, Electra - Sabatelli, Valentina -Amman, Delphine, *Op. Cit.* (2002) P. 17

Development of a Bottle in Space, Umberto Boccioni (1912) the subject, the bottle, dissolves and extends into the context. The force lines can now be seen as the abstract units that can articulate the object's relation to its consistent field.[132] (http://pictify.com/170405/the-development-of-a-bottle-in-space-by-umberto-boccioni-1912) (03/12/2010)

*3.1-Kinetics in architecture: a short history_*

According to TheArStory.org, kinetics had their conceptual base in XIX century's impressionism and early XX century's futurism[133]**,** and was later called kinetic art, which can be said to have its earliest instance in the *Bicycle wheel* by Duchamp, however, as demonstrated in the previous section, it actually had its earliest beginnings in the work of Botticcelli and Goethe. As for *kinetic* architecture, Dina El-Zanfaly, in her 2011 masters thesis at MIT's department of architecture, argues that they have been around at least since the XIII century, since Leonardo Da Vinci had *designed a crane that can* (sic) *move and carry heavy things*[134]*,* though it was not until *russian constructivism*, within Vladimir

[132] Kwinter, Stanford, *Landscapes of Change: Boccioni's Stati di Animo as a General Theory of Models*, assemblage 19, MIT Press Cambridge, Massachusetts. USA (1992), P. 68.
As quoted by: Mikelides, Electra - Sabatelli, Valentina -Amman, Delphine, *Op. Cit.* (2002) P. 18

[133] *Kinetic Art*, TheArtStory.org website (2015) (http://www.theartstory.org/movement-kinetic-art.htm) (27/02/2015)

[134] El-Zanfaly, Dina, El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures, Master of Science Graduate Thesis,* Architecture Department, Massachusetts Institute of Technology, in requirements

Tatlin's work, that the first kinetic fully mobile object emerged, shortly after along with a list of artists like, most notably, Alexander Calder and his *Arc of* Petals, which *combines subtle lines and biomorphic forms with natural movement to examine the behavior of an object in space*[135.] Adding their share of contributions, drawing some interesting analogies between the machine and the human body.

"*Rather than regarding machines and human bodies as radically different - one being soulless and functional, the other being governed by the sensitive, rational mind - they used their art to suggest that humans might be little more than irrational engines of conflicting lusts and urges, like a dysfunctional machine. This idea has deep roots in Dada, and betrays Kinetic art's debt to that earlier movement.*"[136]

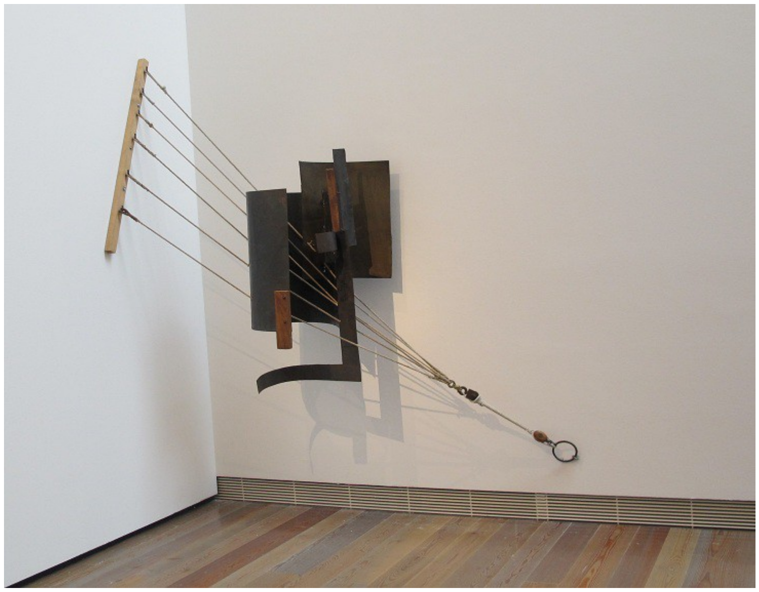
This affirmation suggests setting kinetic art as a proto-disciplinary approach to bionics, although, according to the portal *theartstory.org*, as a movement, kinetic art would not start until 1954.

Bicycle wheel Marcel Duchamp (1913)(http://www.moma.org/learn/moma_learning/marcel-duchamp-bicycle-wheel-new-york-1951-third-version-after-lost-original-of-1913) (25/02/2015)

for the degree of Master of Science in Architecture Studies (2011) P. 13

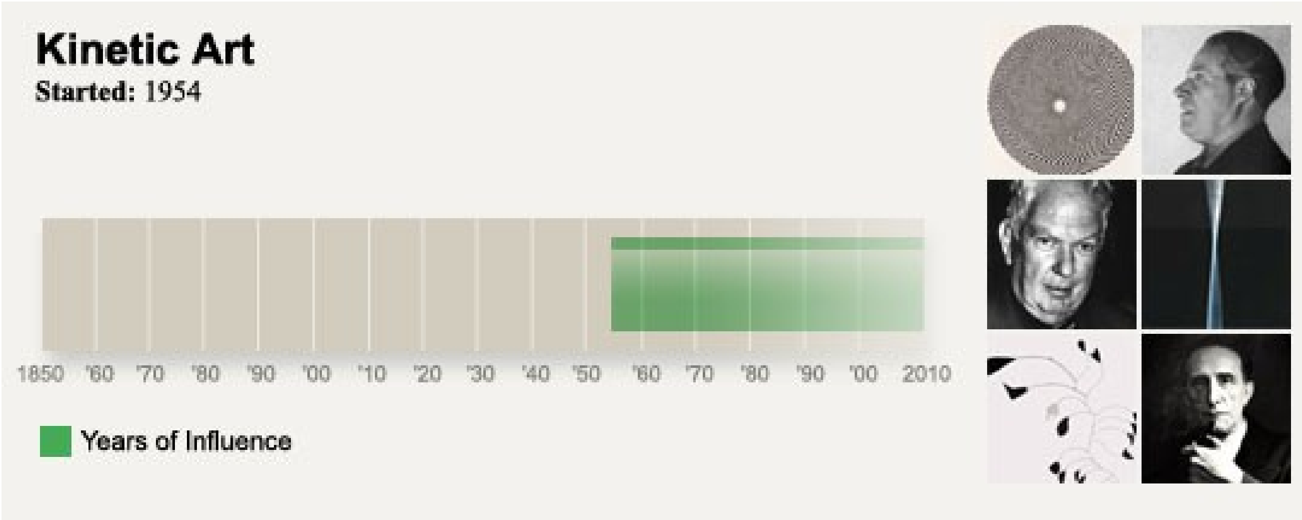
135 *Kinetic Art*, *Op. Cit.* (2015)

136 Idem.



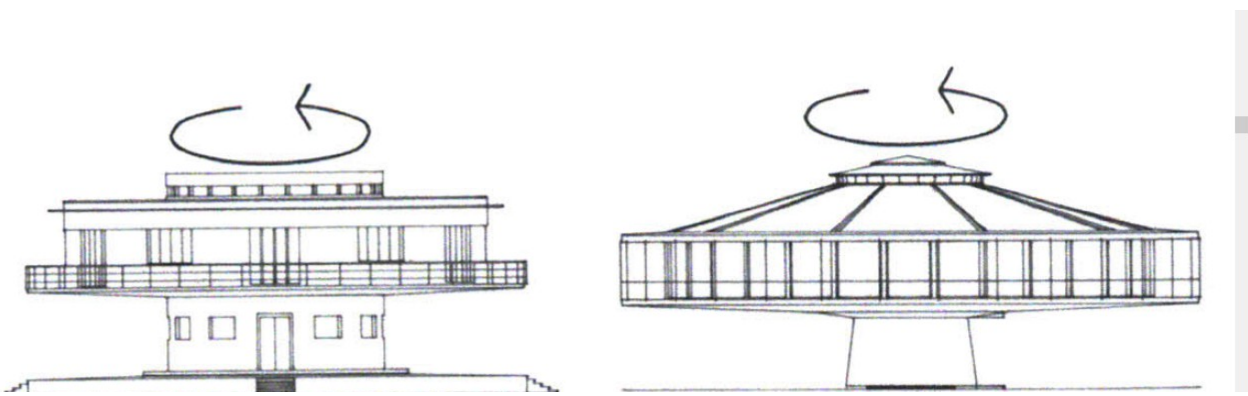
Contre-Reliefs Liberes Dans L'espace, Vladimir Tatlin (1915) http://www.rivagedeboheme.fr/pages/arts/peinture-20-21e-siecles/l-art-abstrait-avant-1945.html) (25/02/2015)

Arc of Petals, Alexander Calder (1941) (http://www.guggenheim.org/new-york/collections/collection-online/artwork/745) (25/02/2015)



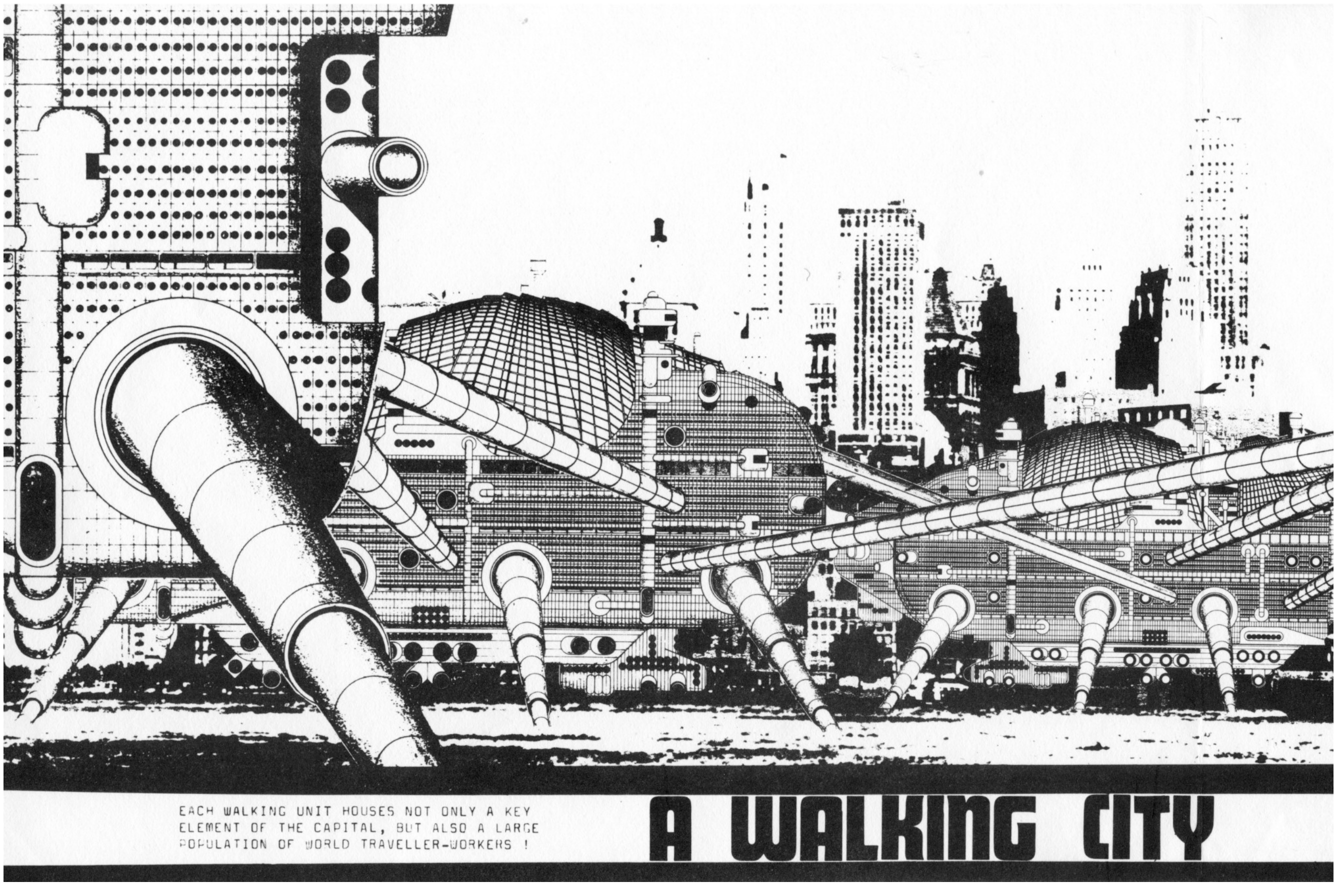
Kinetic art timeline (2015) (http://www.theartstory.org/movement-kinetic-art.htm) (25/02/2015)

In the architecture of the XX century though, these implementations were scarce, from some intents to build two revolving houses by Pierre Nervi in 1934 and Richard Foster in 1960[137] to Ron Herron and Archigram's *Walking City* in 1964 that, though never built, stand as three of the few examples of the earliest speculations in kinetic architecture at the building and even urban scale -as in Herron's walking city (and the only ones that this research was able to find appropriately documented).



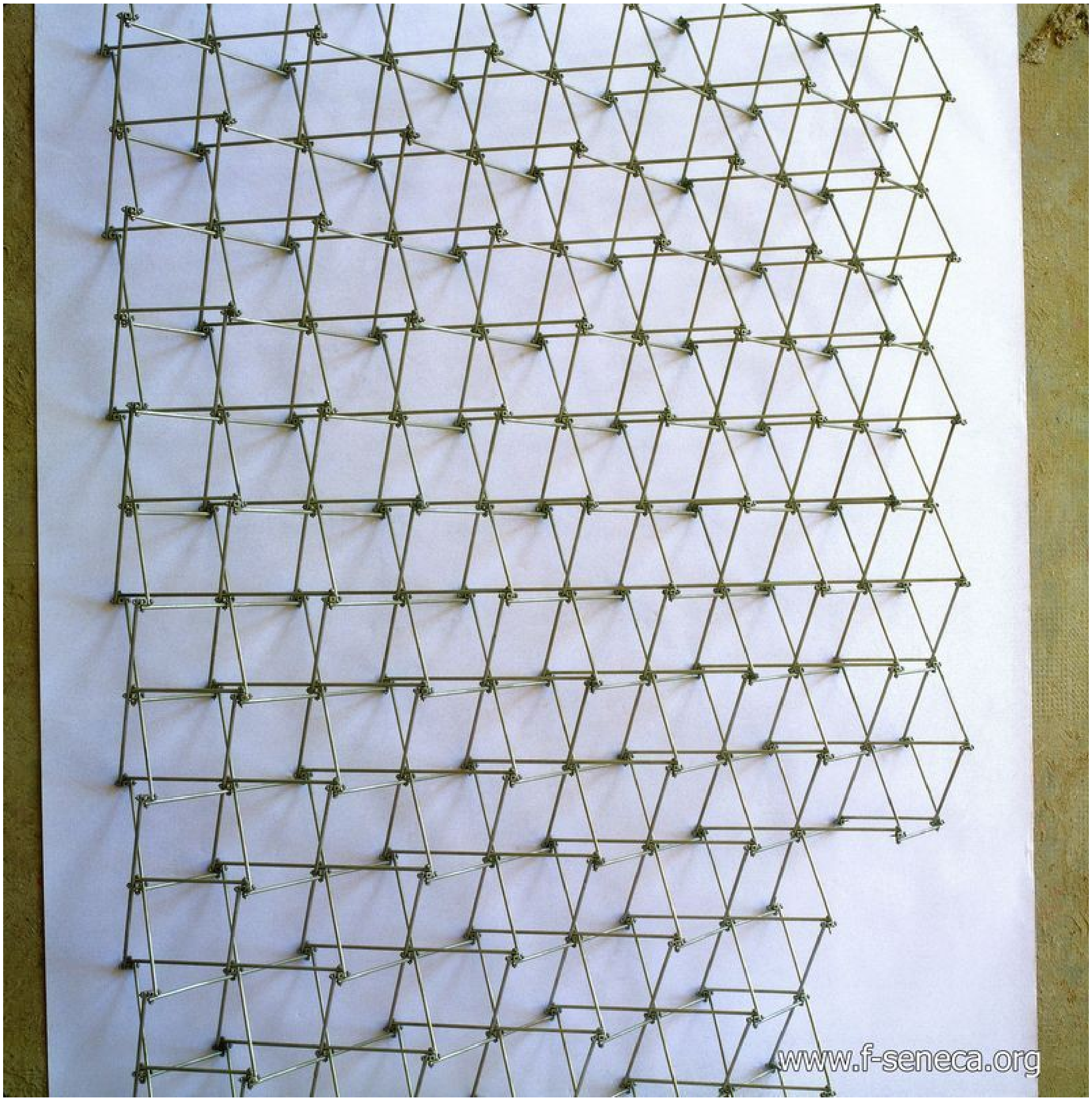
Revolving houses, Pierre nervi (1934) and Richard Foster (1969) respectively (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P.14)

[137] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 13-14.



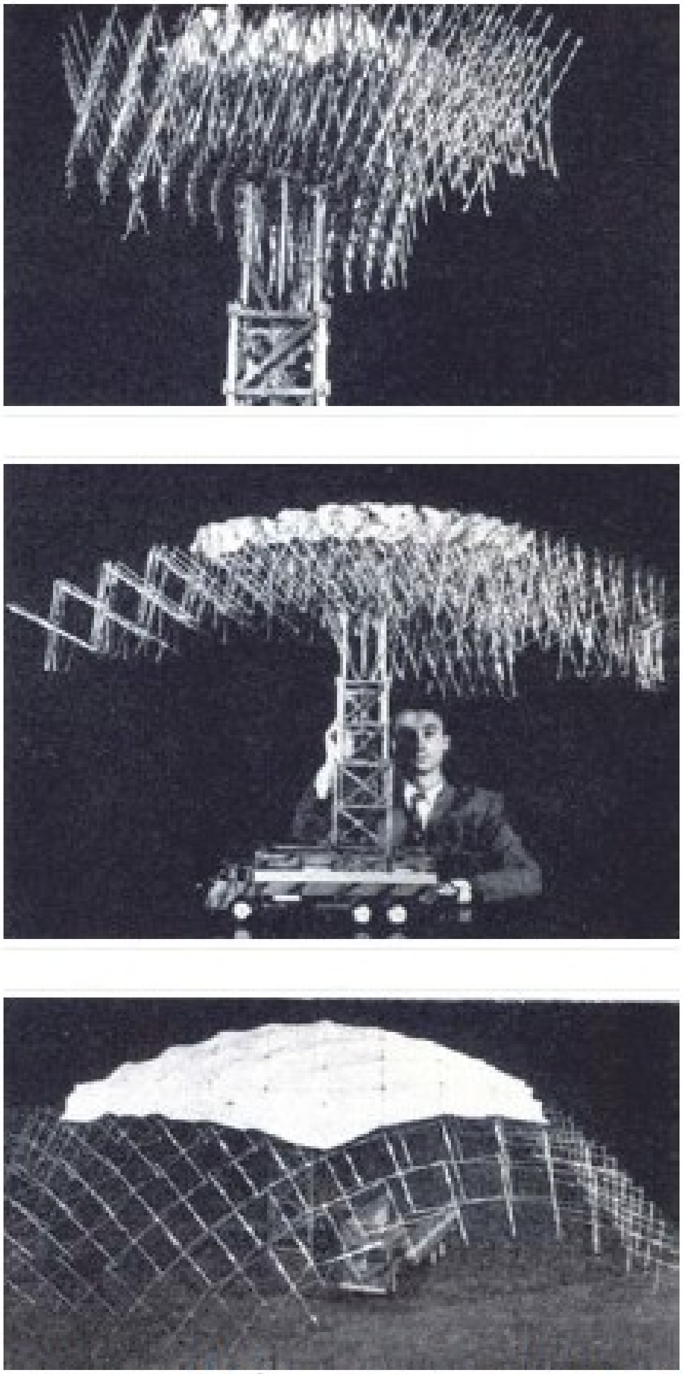
A Walking City, Archigram (Ron Herron) (1964) (http://archkiosk.com/2013/11/10/cities-on-the-move-from-archigram-to-cruise-ships/).

None the less, a Spanish architect by the name of Emilio Pérez Piñero, was one of, if not the first, architect to directly address architectural design within the kinetic implementation framework; in his case, deployable structures in the real world of construction, which we will look at in more detail later in this chapter. His work in the *"Pabellón Transportable de la Exposición conmemorativa de los XXV Años de Paz"* (1969) in Madrid was ground braking for the time and laid the foundations for future retractable planar structures.



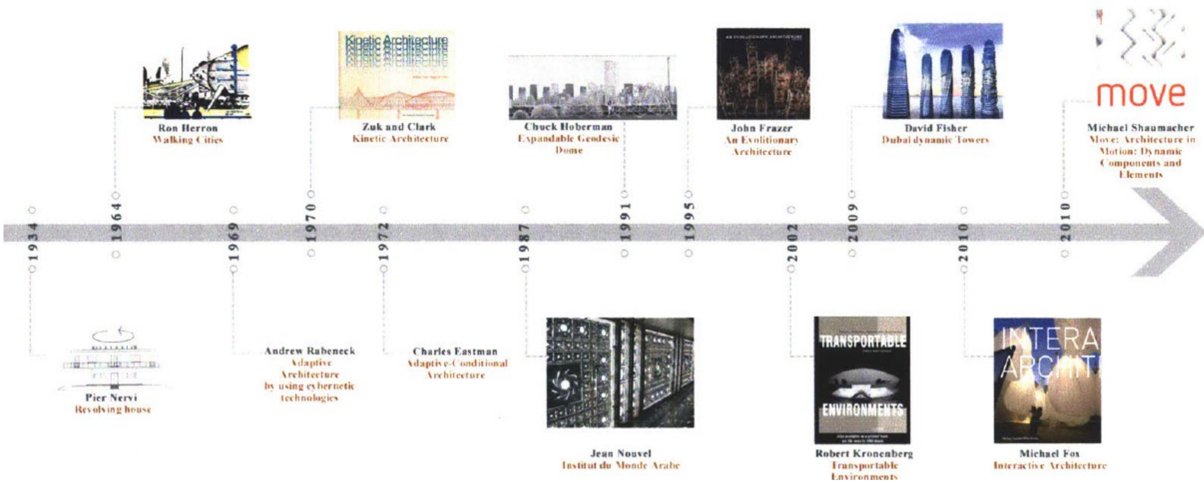
XXV years of peace transportable pavillion, Emilio Pérez Piñero (1969) model (http://fseneca.es/secyt10/imagenes/galeria_exposicion/Imagen02.jpg) (25/02/2015)

XXV years of peace transportable pavillion, Emilio Pérez Piñero (1969) low quality picture of the actual pavillion (http://www.vedoque.net/emilio/?page_id=64) (25/02/2015)



Working study model for a traveling deployable theatre (*Emilio Perez Pinero Foundation* 2012).

Emilio Pérez Piñero (not dated) spanish architect that was one of the first to work with depoyable structures (Earle, Jen*,* *Deployable Architecture: A Seasonal Thetatre for the Halifax Commons,* P.8)



Kinetic architecture relevant books and projects timeline Dina El-Zanfaly (2011) (El-Zanfaly, Dina *Active Shapes: Introducing guidelines for designing kinetic architectural structures,* P.14*)*

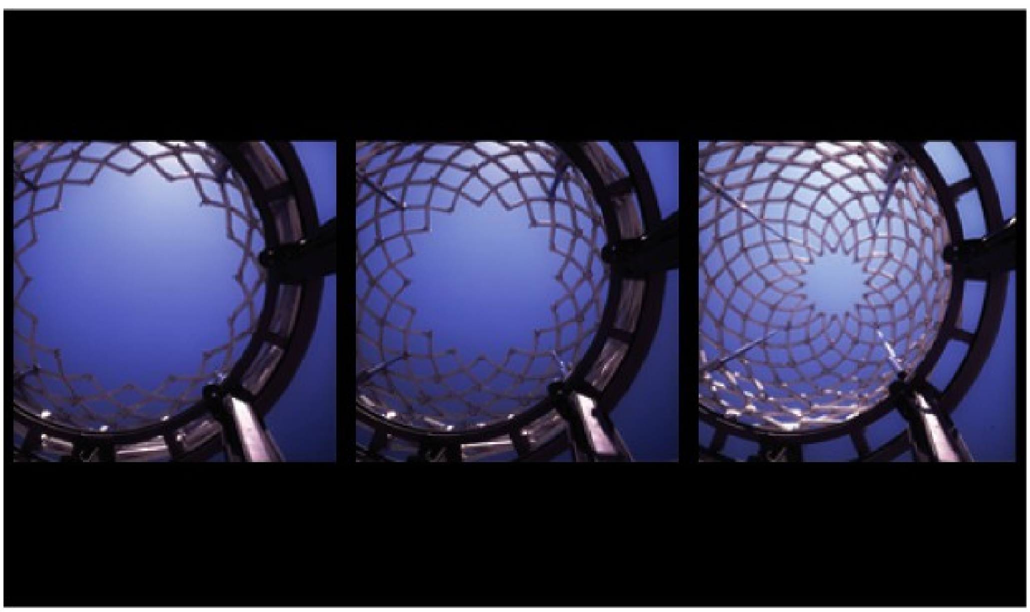
As part of the thesis, Dina El-Zanfaly constructed a time-line chart comprising the short history of kinetic architecture and its earliest examples and books, providing an overview about its development stages and relevant research, yet, none the less she does not mention Pérez Piñero, therefore, considering how important his work has been to designers that followed, its is slightly incomplete (although very clarifying) as a tool to map its chronology. After these short periods of production,later in the 1980's and 90's, Chuck Hoberman was one of the few people who were working with these systems while addressing the architectural scale, mainly for the aerospace industry (being not an architect, but a mechanical engineer). While in parallel his work took some of these paradigms and tried to implement them in human scale artifacts and architectural objects, echoing much of what Pérez Piñero had researched and built (although it is not clear if Pérez Piñero's work was a direct influence), in a series of projects like the *expanding geodesic dome* (1991), the *iris dome* (2000) and the *olympic games Hoberman* arch (2002) that, as a consequence of his research, made what he calls "*transformational structures",* his company's main focus:

A sequential image of the erection Hoberman's expanding geodesic dome, 1991 (Hoberman Associates 2012).

Expanding Geodesic Dome, Chuck Hoberman (1991) (Earle, Jen, *Deployable Architecture: A Seasonal Thetatre for the Halifax Commons,* P.2)

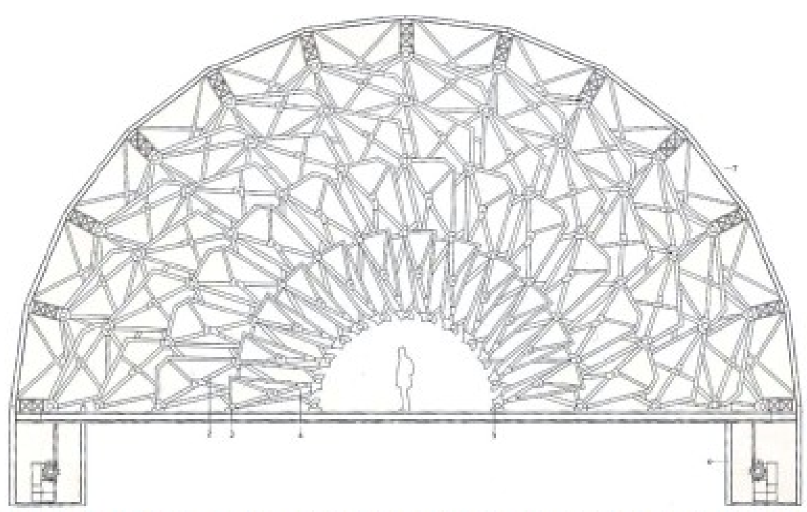
Iris Dome

Hanover, Germany | 2000 | World's Fair



Iris Dome, Chuck Hoberman (2000) (http://www.hoberman.com/portfolio/irisdome-worldsfair.php?myNum=26&mytext=Iris+Dome&myrollovertext=%3Cu%3EIris+Dome%3C%2Fu%3E&category=&projectname=Iris+Dome) (25/02/2015)

Hoberman Arch, Chuck Hoberman (2002) (http://www.hoberman.com/portfolio/irisdome-worldsfair.php?myNum=26&mytext=Iris+Dome&myrollovertext=%3Cu%3EIris+Dome%3C%2Fu%3E&category=&projectname=Iris+Dome) (25/02/2015)



Section showing the placement of the motors used to control the opening of the curtain (Schumacher 2010).

Hoberman Arch, Chuck Hoberman (2002) (Earle, Jen*, Deployable Architecture : A Seasonal Thetatre for the Halifax Commons,* P.7)

However, none of these designers were working directly with animation software or techniques to design their complex animated structure (with the possible exception of Hoberman who did use digital fabrication to prototype lots of his projects thus implementing digital tools in the process). Animation as a tool for design would not be known to have an impact in kinetic architectural design until Mark Goulthorpe and *deCOI architects* started their practice in the early 1990's and who's collaborations with other disciplines, new technologies and digital software (as dance, computer science and mechanical engineering) would bring about the coming into being of an animation *"renaissance"* within architectural design, framed within the digital design and fabrication paradigm.

" [And now] *while motion served as an inspiration to architects for many years, these new digital tools are allowing architects to explore new concepts about time and space. Many also use animation software as a tool in the form generating process, others insist on creating actual 'animated architecture.'"* [138]

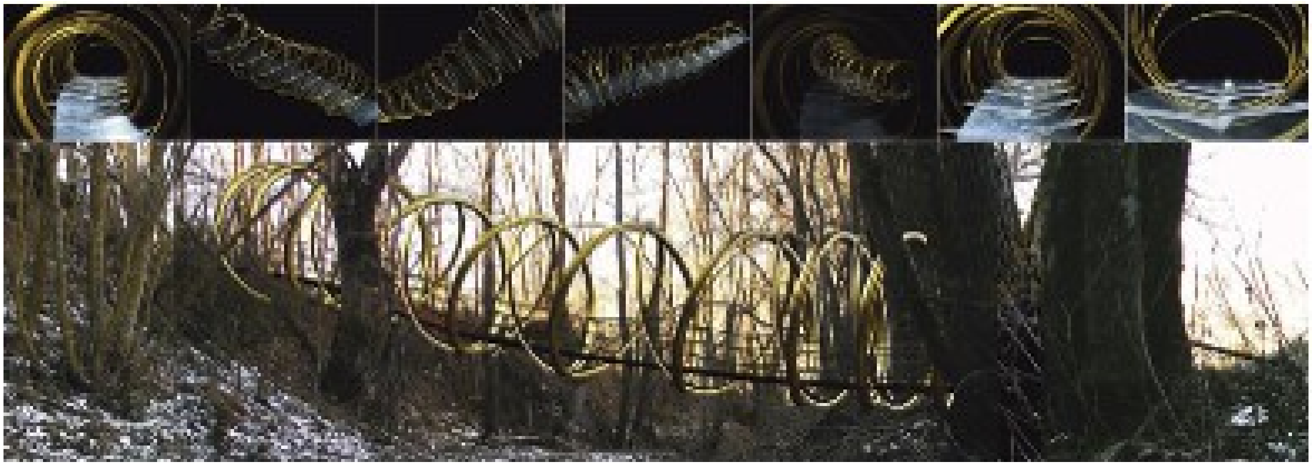
Dennis Dollens proposes an approach to the methodological aspect of the design craft that lies between the intuitive process that comes from the visual nature of the medium of animation and the awesome accuracy with which architectural objects and parts can be thought and produced, which they were able to implement in a research project for a bridge in the french mountains of the *Pyrenées,* in which him and *Igansi pérez Arnal* designed, with the aid of a software called Xfrog (A software that is used normally to model plant growth) which produced animated outputs when toggled with to address form-finding development, according to them:

" *animations became our way of visualizing not only aesthetics, but also several pre-engineering processes determining the bridge's relationship of parts, materials, and their scale."*[139]

This suggests that, using these tools, the designer is now capable of catching eye on things that were previously hidden from his sight (phenomena, processes, positions, possible angles); what makes the possibilities for permuting the outcomes, to our perception, endless. This "expanded vision" in thought and design served as a platform for discourse crafting and rearranging methodology cause, when they were confronted with the design tasks, they used Xfrog's ability *to visualize and understand the*

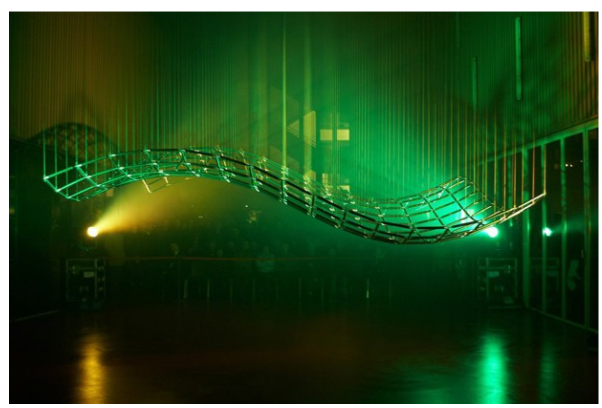
[138] Mikelides, Electra - Sabatelli, Valentina -Amman, Delphine, *Op. Cit.* (2002) P. 2
[139] Dollens, Dennis, *Op. Cit.* (2006), P. 113

changing and shifting geometries of our variously different, intersecting, curving, and tapering spirals, [and when it came to analysis] *I* [Dollens] *created study animations.*[140]



Spiral Bridge Group, Dennis Dollens - Ignasi Pérez Arnal (2006). Top: Animation sequences for the *Spiral Bridge*, French Pyrenees. Bottom: Rendering of the bridge on the site. Bridge design: D. Dollens and Ignasi Pérez Arnal (2006) Animation: D. Dollens. (2006) (Dollens, Dennis, *The Cathedral Is Alive: Animating Biomimetic Architecture*, P. 112)

After the mentioned period (1990-2006), there has been an increasing interest in kinetics and a hand full of artists that have ventured into this unknown world like Reuben Margolin, who works with all sorts of materials and electronic servo-motors to animate his *Waves* series of kinetic sculptures (echoing Fox's indications about sensors, computation and adaptation).



Magic wave, Reuben Margolin (not dated)(http://www.reubenmargolin.com/waves/Magic/magic_2.html) (25/02/2015)

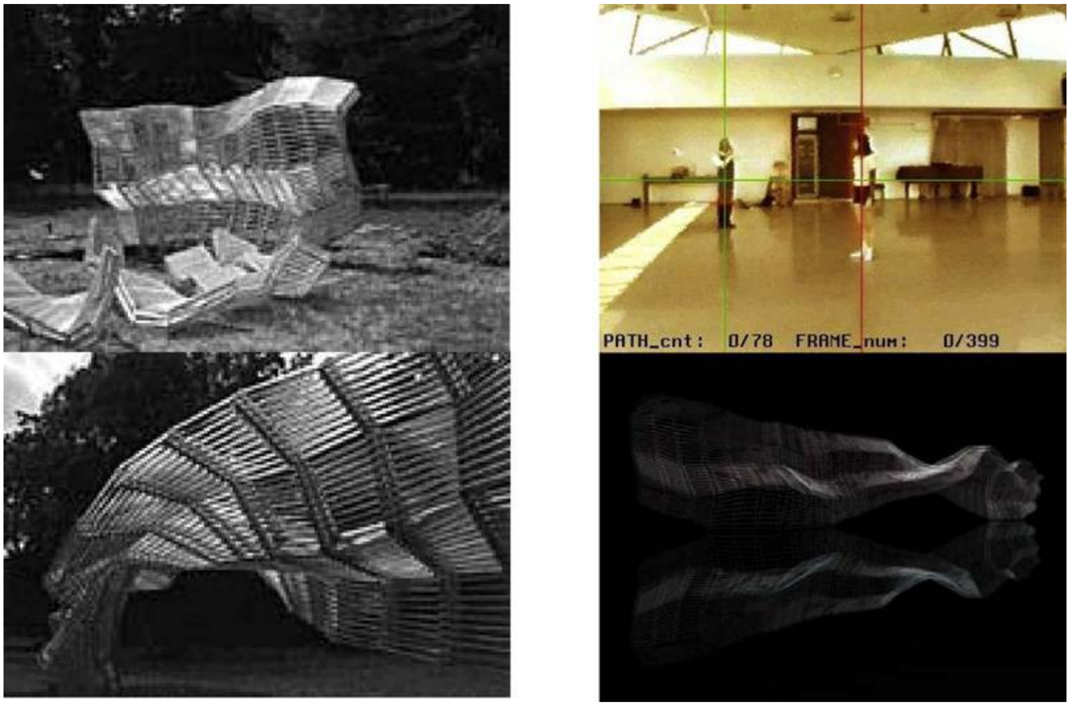
To come back to "chronophotography's" early beginnings and how it influenced animation's own

[140] Dollens, Dennis, *Op. Cit.* (2006), P. 113

genesis and techniques, we need to go back to Goulthorpe et al.'s work. In a 2002 research assignment for a masters class at the Architectural Association in London, carried out by Electra Mikelides, Valentina Sabatelli, Delphine Amman and under the guidance of Professor Christopher Hight for the "Design as research I" course, they remark that eve though "*mark Goulthorpe does not like this project to be compared to the work of Marey and Muybridge, and indeed it is very different, however, there are some very basic aspects their works have in common."*[141] His work with movement very much inherit its central concerns and *modus operandi* to the earlier XIX century work in motion capture. In fact, *Muybridge or Marey, both used photography to capture a series of still images which, when reassembled could represent the movement of the subject*[142], with their main attention being *focused on the animation of the subject and how to best capture this motion in various media*[143] much like (yet in a more reversed fashion) Goulthorpe's contemporary work resided in capturing a certain aesthetics that reside in motion as a means of composition as his project *Ether/I* which was a sculpture *derived by video capture of the difference between repeated sequences of a balletic duet (Forsythe's Quintett*) [144] did exactly the same to produce its morpho-genesis .

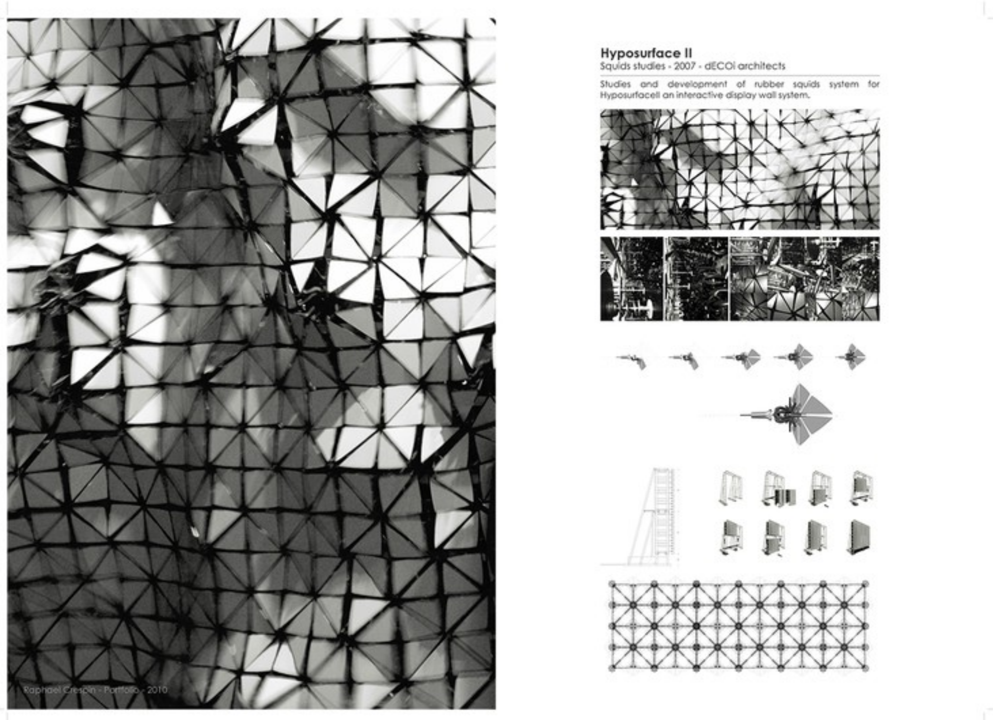
Ether/I, Mark Goulthorpe (1995) (http://www.newitalianblood.com/show.pl?id=687)

[141] Mikelides, Electra - Sabatelli, Valentina -Amman, Delphine, *Op. Cit.* (2002) P. 13.
[142] Idem.
[143] Idem.
[144] Goulthorpe, Mark, *The Possibility of (an) Architecture*, Taylor & Francis Group, London (2009) P. 78.



Ether/I, Mark Goulthorpe (1995) (http://www.ad.ntust.edu.tw/grad/think/97_2_Selected_Architects_of%20the %2020th_Century_finalreport/MarkGoulthorpe/MarkGoulthorpe.htm)

Furthermore, for the *Aegis hyposurface* (2001), deCOI architects developed a mechanically animated surface that expressed motion through computer controlled methods and computational design and digital fabrication techniques, this work marked the before and after for kinetic architectural aspirations; for the first time a design could, not just represent movement, but actually control it at the designer's will implementing computed morphology and geometry in turn harnessing inherent universality in relation to how it could move (see Mike Silver's remarks on computation and universality on chapter II).



Aegis hypo-surface, Mark Goulthorpe (2001)
http://www.raphaelcrespin.com/projects/2014/10/16/3orwa8ly1uwwf5c16fto0n0sy7h0kc)

"*Computer-Assisted Conception and Fabrication Systems* [as used in mechanical engineering, building as well as the automobile and aeronautic industries] *have certainly increased the productivity of the idea, but fundamentally they offer no advances over the work done by hand. Now we can envisage second-generation systems in which objects are no longer designed but calculated. The use of parametric functions opens two great possibilities for us. First, the mode of conception allows complex forms to be designed that would be difficult to represent by traditional drawing methods… Second, these second-generation systems lay the foundation for a non-standard mode of production."*[145]

And meanwhile, insofar as the full building scale is concerned, although not much had been done since Pérez Piñero in the 1960's (aside from Hobeman's work); contemporary practice and research is shifting its attention towards kinetics again as in the work of *Kinetura* (a kinetic design team established in 2006, composed by Barbara van Biervliet and Xaveer Claerhout). They have been successful in proposing a full scale tower building facade in which its elements respond to sunlight and users inside, thus proving empirically that Fox's remarks are not far fetched and that they are, in fact,

[145] Cache, Bernard, *Earth Moves, The Furnishing of Territories*, translated by Anne Boyman, Cambridge, MIT Press, Boston, Massachusetts (1995) P. 88

implementable in real world projects.

Kinetower, Kinetura (2011) (http://blog.kineticarchitecture.net/2011/02/kinetura_kinetower/) (26/03/2014)

These few but substantially important projects all echo Michael Fox's propositions that *sustainable strategies should integrate adaptability both in terms of physical transformations and in terms of computer control mechanisms used to optimize resources to dynamically suit user needs.* [146] This meaning that there are two sides to intelligent kinetic design considerations: *physical transformation* and *control* (computer control, in Fox's case). *Morphing architecture simultaneously involves embedded computation and kinetic elements*[147], their correlation in this case allows for the development of responsive environments. *The co-existence of these systems allows for the environment to "respond, react, adapt, and be interactive.*[148] Once you have adaptability, computational resources and structural performance, as Fox has noted, the embodiment and introduction of *intelligent kinetic systems* becomes a consequence of this convergence, an ideal for architecture and a motivation to extend our architecture to enhance our human condition.

"*Adaptive response to change must intelligently moderate human activity and the environment and*

146 Fox, Michael, *Sustainable Applications of Intelligent Kinetic Systems*, Kinetic Design Group, Massachusetts Institute of Technology, Department of Architecture (2001) P. 4 (http://profamateus.no.sapo.pt/mitharvard2.pdf) (06-02-2014)

147 Fox, Michael and Kemp, Miles, *Interactive Architecture*, 52.
As quoted by: Fenwick, Tess, *Progamme: Morphosis, Master of Architecture Graduate Thesis,* Unitec Institute of Technology, Auckland, New Zealand, in requirements for the degree of Master of Architecture (2011) P. 27

148 Idem.

build upon the task of enhancing everyday activities by creating architecture that extends our capabilities. Such systems introduce a new approach to architectural design where objects are conventionally static, use is often singular, and responsive adaptability is typically unexplored. Designing such systems is not inventing, but appreciating and marshalling the technology that exists and extrapolating it to suit an architectural vision."[149]

Contemporary to Fox, Kas Oosterhuis proposes a *real-time* vision of kinetics in his *hyper body* paradigm, proposing therefore interactivity, a concept that is slightly out of kinetics scope, which focuses on premeditated repetitive movement, in his kinetic world, things are as bodies (much like kinetic artists of the XX century saw the machine-boy relationship). *Movement inspires a new dimension in the way a participant experiences and interacts with a space or building and when done in real-time the experience is the most powerful.*[150] Adding real time into the kinetic equation gives a game theory flavor to intelligent kinetic design from which, according to Oosterhuis, gives rise to interactive architecture, something that goes beyond merely predicting activities and suiting them in a changeable structure. *Exploiting kinetic strategies provides the opportunity to provoke architecture now, and for users and inhabitants to play the buildings 'game'.*[151] This denotes an inevitable paradigm shift in architectural design, that is not yet fully here with us but very close to being fruitful and viable. As Michael Fox remarks, *it appears that kinetic architecture is not at the beginning, nor is it by any means at the end; but it is, in a sense, at the end of the beginning.*[152]

*3.2-Conclusions_*

1. Kinetic art and architecture both descend from animation, which in turn comes from chrono-photography, a consequence of morphology, that itself derives from painting.

2. Botticelli's Drawings for the *Paradiso* and *Inferno* in Dante Alighieri's *Divine Comedy* (1481)

[149] Fox, Michael, *Ephemeralization*, Kinetic Design Group, Massachusetts Institute of Technology, Department of Architecture (2001) P. 6 (http://profamateus.no.sapo.pt/mitharvard2.pdf) (06-02-2014)

[150] Kas Oosterhuis, *2006 MUSCLE - Basis for a True Paradigm Shift in Architecture*, http://www.oosterhuis.nl/quickstart/index.php?id=545. (Accessed March 21, 2011). As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 21

[151] Idem.

[152] Fox and Kemp, *Interactive Architecture*, 247. As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 147

are established as the oldest known drawings representing the dimension of time in the work.

3. *Contre-Reliefs Liberes Dans L'espace* (1915) by Vladimir Tatlin is established as the first kinetic art piece ever exhibited.

4. *XXV years of peace transportable pavillion* (1969) by Emilio Pérez Piñero is established as the first kinetic building scale construction.

5. Chuck Hoberman continues Pérez Piñero's path constructing building scale kinetic arches.

6. Goulhorpe revolutionizes kinetic architecture with his *Aegis hyposurface* (2001) in that is fully controllable and re-programmable.

7. Dollens and Pérez Arnal propose using animation software as design and exploration tools.

8. Kinetura proposes kinetic design as a means to address thermal conditions in buildings in their *Kinetower* project in 2011.

9. Kas Oosterhuis proposes "interactive architecture" adding game theory into its ontological framework.

10. This general framework sets the stage for the development of kinetic and interactive buildings and environments and make it, not just a possibility, but both a necessity and an obligation.

*4-Towards an Architecture of movement, chaos and controlled uncertainty: Intelligent Kinetic Systems_*

"Nothing retains its own form"[153]

-Pythagoras-

*4.1-Architecture at the beginning of the XXI century: The advent of physical movement in architecture_*

Our perspective of Architecture in the last century has pretty much been that of a fairy tale, meaning that we've thought for a very long time (and still think) that we, architects, bring order into the world and therefore make it viable for society to develop conditions for the built environment that allows it to blossom into something that transcends its primitive state and catapults it to a higher level of understanding of the universe itself, but at the advent of society's current nightmare of financial chaos and crisis we wonder, if all that we thought was actually not just an autistic, schizophrenic delusion of dreams about order and stability which sometimes can be confused with ***Stasis***, a concept that, in the voice of Greg Lynn, argues our discipline's long retard compared to others in both science and technology, *these concerns are not merely technical as architecture presently expresses also the cultural diagrams of stasis*[154]*,* which will be outlined later in this chapter.

Traditionally, architecture portrays a static stance with qualities such as permanence, sturdiness, and solidity.[155] Architecture's point of understanding the process of the building and being of an edifice has been a constrained, static permanence in which things do not adapt to changing content (besides doors, windows and drawbridges), circumstances or contexts; architectural *stasis is a concept which has been intimately linked with architecture in at least five important ways, including 1) permanence, 2) usefulness, 3) typology, 4) procession, and 5) verticality.*[156]

Relatively speaking (based on Einstein's *special relativity*), *stasis* has never taken into account that the world is a chaotic place/construct and that reality is an illusion of our senses, therefore that which we

153 Hensel, Michael, paraphrasing Pythagoras on *Op. Cit.* (2004) P. 27
154 Lynn, Greg, *Op. Cit.* (1999) P.14
155 Fenwick, Tess, *Op. Cit.* (2011) P. 9
156 Lynn, Greg, *Op. Cit.* (1999) P.14

perceive as plain (like the horizon) is actually spherical at the scale of the earth, that the things we think and build are actually thought as rigid and non-flexible, yet they start dying at the same moment that they are being built, that decay, in a way, is our very own sense of existence, that we decay permanently and so does everything else, things change all the time, they become something else sometimes rapidly, sometimes slowly and this is the only truth, it is not true what *ecology* tells us about nature being in steady balance, nature is always in flux and it is chaotic, it doesn't stop evolving, shifting, adjusting, folding, varying, correcting what needs to be fixed and, although it can maintain similar patterns for some time or lapse, it always recurs to its everlasting ways of change, keeping only what works in all cases given. "*Geographical areas can only harbor a sort of chaos, or, at best, extrinsic harmonies of an ecological order, temporary equilibrium between populations"*[157] as Deleuze and Guatari put it, change is everywhere and we can overlook it but it doesn't overlook us. *Conversely, it is pertinent to assume uncertainties in future building uses with evolution and time.*[158]

The architectural discipline has had to follow this ongoing pattern without any saying in the process, the universe and its systems tend to complicate, this can be traced into thermodynamics within the entropy principles, organic and inorganic systems tend to complicate gradually but maintaining (most of the time) a balanced and consistent distribution, even though that symmetry can change over time, here, the key word is ***change over time***, ***balance is a process, not a fixed state,*** to illustrate *this distinction between stasis and orbital or dynamic stability is important* [e. g] *In the case of a more complex concept of gravity, mutual attraction generates motion;* ***stability*** *is the ordering of motion into rhythmic phase.*[159]

"In the simple, static model of gravity, motion is eliminated at the beginning. In the complex, stable model of gravity, motion is an ordering principle. Likewise, discreteness, timelessness, and fixity are characteristic of stasis; multiplicity, change, and development are characteristic of stability."[160]

Change implies movement. It suggests that the energy and heat (in thermodynamics case) moves around from element to element through a distribution pattern until the whole system is in balance. This tells us that in the end everything moves, you move, I move, we move, everybody moves, the sun moves, the moon moves, the earth moves, the solar system moves and ultimately the universe expands

157 Delleuze, Gilles - Guatari, Felix, *Op. Cit.* (1987) P.69
158 Fenwick, Tess, *Op. Cit.* (2011) P. 9
159 Lynn, Greg, *Op. Cit.* (1999) P.14
160 Idem.

at an seemingly ever accelerating rate, therefore suggesting that the very constitution of everything existing is based on movement and we must treat our existence as such in terms of change and movement patterns. Also quantum theory compels us to think that our very own constitution (in the micro universe that is matter's inner structure) is also based and modeled on movement, quantum particles both vibrate and oscillate in uncertain moving patterns, and although protons do not move if you think about it from the atom's point of reference, they do in of the embodiment it helps constitute (at a given point in the up scaling, something within which the atom exists is moving: be it a body, a vehicle, a planet or a solar system and ultimately, the universe) but the point apparently lies in the question of at which point in matter's cosmological scales does the movement threshold appear? does it concern architecture with its well defined scale of working? to put it another way: does architecture have to move? Maybe this could be argued from the responsive design approaches developed in the last few decades of the prior century and the ongoing research about sensory type artifacts and installations being bred in the computer science, bio-medical and mecha-tronics fields, which have become the pioneers and forerunners of these types of concepts and applications while *constant innovation and transformation in related disciplines should be embraced and buildings designed to reflect this.*[161] The Aero-spatial and automotive industry, which have been powered by the emerging Mecha-tronics discipline, have taken these ideas and expanded them to a wider, broader range of applications and development. *Introducing movement addresses the issue of spatial adaptability by allowing more flexibility and control over the building environment.*[162] Our perception has always played a determining role in the way that we, as civilization, have understood the universe and our place in it, be it in scale, materiality or spirituality, mysticism has historically played a role in everything we build and so has our ability to create legends and fairy tales, narrative has always been there from the start of civilization, after all, language was our FIRST technology; words define and ears interpret, our whole belief system was the perpetrator of architecture's most significant buildings in the ancient world, this notion of ***Stasis*** (which we will define in more detail later) has always been there to lead us, to give us the meaning we needed, the excuses we wanted, to build and to conceive our world in terms of what we believed was true, be them deities in Egypt, Greece or India, always the main buildings where temples, with the exception of king's palaces which also played a dominant role in the ancient world's Architecture, but most of them have succumbed to the forces of time, gravity and/or nature at large so the ones that are still standing today are (or at least most of them) religious temples or (in the case of

[161] Fenwick, Tess, *Op. Cit.* (2011) P. 9
[162] Idem.

the Middle East and Europe) Churches, maybe with the exception of the Pyramids and the Roman Empire's Architecture, which can be still seen in Giza and Rome comes from an imperialistic ideology, the most notably known and significant buildings that at the time of utilization were of religious or mystical content and are, today, touristic attractions. The Greeks and Egyptians believed in reaching the divine through the concept of *permanence*, the eternal, a mystical way of defining the static dream of order, *the idea was the same as with Imhotep: whether the dwelling belonged to a pharaoh or a god, it had to last forever*[163]*,* but they knew that to overcome that brutal force of change they would have to conceptualize that *architecture was once the most lasting of the arts, reaching as it did into the caverns of the earth, changing only as slowly as the planet itself changes*[164], thus explaining their monumental buildings and long stood footprint, yet as of today (also following the change pattern) *in many ways architecture has become the least durable of the arts*[165]*,* as Lynn points out, *with the example of permanence, the dominant cultural expectation is that buildings must be built for eternity when in fact most buildings are built to persist for only a short time.*[166] consonant with the advent of computation and material science development which harness the possibility of constructing a somewhat process-based building methodology and implementation of movement on functional and spiritual means, adding *movement inspires a new dimension in the way a participant experiences and interacts with a space or building and when done in real-time the experience is the most powerful.*[167] The power structures around the world were all defined by religion for most of written history, this defined our whole existence in the making and unmaking of the world, at some point we are also identified with religion or some kind of spiritual aspiration and religion is identified with dogma, belief at its most primitive state, which, in terms of propagation and structuring, survives and lives off repetition, this was the modern age's way of saying "we are here, we are this or that, we exist, we can mass produce and repeat objects (limited to the production lines characteristics) *ad infinitum*", this defined our whole age and civilization for more than 500 years, modernity was based on *the printing machine* (*Guttemberg's* invention) and the *steam engine* (developed by *Watt)*, which were modeled on classical mechanics (see chapter II). Going back to the *Italian Futurists* back in 1909, Filippo Tommaso Marinetti and Antonio Sant'Elia had expressed their disdain for stasis:

163 Estévez, Alberto, "Biomorphic Architecture", *Genetic Architectures*, ESARQ/SITES Books (2005) P. 161
164 Novak, Marcos, "Liquid Architectures in Cyberspace"*, Cyberspace: First Steps, MIT Press, London* (1991) P. 2
165 Idem.
166 Lynn, Greg, *Op. Cit.* (1999) P.13
167 Fenwick, Tess, *Op. Cit.* (2011) P. 21

"We have lost the taste for the monumental, the heavy, the static and we have enriched our sensibility with the taste for the light, the practical, the ephemeral, and the fast. […] *The futuristic city similar to an immense building in construction, tumultuous, nimble, mobile, dynamic, in each of its parts, and the futuristic house similar to a huge machine."*[168]

*4.2-Kinesis opposite Stasis_*

The word *stasis* (sta·sis) is traceable back to ancient Greek and is defined by the Merriam-Webster online dictionary as follows:

noun\ ˈstā-səs, ˈsta-*: a state or condition in which things do not change, move, or progress*. [169]

Greg Lynn's concept of *stasis*, where architectural objects are *defined by Cartesian fixed-point coordinates*[170] argues it is an important, if not the most, factor in our discipline's long retard compared to others in both its science and technology.

"Stasis is a concept which has been intimately linked with architecture in at least five important ways, including I) permanence, 2) usefulness, 3) typology, 4) procession, and 5) verticality."[171]

The need to outline the opposition between modern "permanence" and current "fluctuation" is supported by the current tendency in the philosophical deduction and political activism processes that shaped the birth of the internet, plurality, multiculturalism and adaptability. It is imperative, to better understand intelligent kinetic systems and their impact on architecture, to outline its relationship to its opposite, we will use Greg Lynn's theory of animate design to illustrate this relationship: the opposition (not reaction to) between ***stasis and kinesis.*** Kinetic architecture's ground is founded upon the notion that the universe is full of movement, even if we do not see it or perceive it. And, architecturally, opposed to our sense of order and centrality, of machine-like identity and civilization construction and, as outlined earlier in this chapter, the mechanical paradigm which has driven us to build a world based

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[168] Marinetti, Filippo Tommaso, *Manifestos and futuristic texts*, Del cotal Ed., Barcelona, Spain (1978) P.221-224. As quoted by: Estévez, Alberto, "The fascination of speed in Architecture and Design", *BCN Speed and Friction: The Catalunya Circuit City*, Various authors, Lumen Inc. / Sites Books, Esarq., Barcelona, Spain (2004), P. 75.

[169] "Stasis." Merriam-Webster, n.d., *Merriam-Webster.com*. (http://www.merriam-webster.com/dictionary/stasis) (04-02-2014)

[170] Lynn, Greg, *Op. Cit.* (1999) P.11

[171] Ibid. P.13

on a mythical definition of permanence itself grounded in legends and religious belief. Whereas in the world of today that invisible cage, that lead us to stasis and empires, is starting to crumble in the face of technologies that are available to, theoretically, anybody.

[172] *The approach defines a needed means by which issues of energy efficiency and the environmental quality of buildings could be technologically enhanced to be more efficient, affordable, and reach a broader audience of users.*

This "democratization" of technology has set in motion a change in the way we see and construct our own reality, not only meaning that we can fabricate things that, previously, were only possible via factory mass production structure but that we can also think in different more egalitarian modality. Now a days, the *status quo* both in nature and social structure, is challenged by an ever changing and mobile present state. The present no longer has to do so much with how things are right now, thus implying permanence, but more with how things are advancing or transforming into new phases or completely different processes from the previously known or seen that *is no longer about appearance, and certainly not about representation, but is concerned with apparition, the coming -into- being of what has never before been seen or heard or experienced*[173]*,*as the concept of *cyberception*[174] asserts it. Referring less to balance, in the traditional sense of the word, and more to *balanced morphing* patterns. This shift in processes has been, among other phenomenons, fueled by social, urban, economic and communication processes and facing them in a whole different perspective. *The increase in social and urban demands paired with issues of sustainability has brought to light the need for architecture to be flexible, changeable and adaptable to different situations.*[175] As previously established in this chapter, *all this indicates that change is not a state, rather than a process*. The potentiality that kinetic systems have to remold social structure and building performance is not (as of today) sufficiently researched to outline a broad definition of it as a formalized specialty within architectural design, yet *as building technologies advance, potentially developing a different, more adaptable, sustainable and economic type of architecture, it is all the more valuable to investigate kinetic architecture as a future direction.*[176]

172 Fox, Michael, *Op. Cit.* (2001) *(b)* P. 8
173 Ascott, Roy, *The Architecture of Cyberception*, (1994) (http://www.cyberday.de/news/ausgabe_100017_THE-ARCHITECTURE-OF-CYBERCEPTION.htm) (04-02-2014)
174 Idem.
175 Fox, Michael and Kemp, Miles, *Interactive Architecture*, 18.
As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 22
176 Fenwick, Tess, *Op. Cit.* (2011) P. 30

I have found only one paper stating the inefficiencies and shortcomings of kinetic systems, called *Ambient Intelligence*, and which we will look at by the end of this chapter, this can be attributed to the lack of research in the subject matter. Within the last hundred years of research, according to M. Fox, it was Buckminster Fuller who first addressed kinetics beyond its obvious aesthetic potentiality, the idea that architectural or structural systems could engender adaptability and motion was introduced by the latter in a concept called *ephemeralization*, which argued the virtuosity of the *concept of material reduction*[177], which involved *creating spaces and objects that can physically re-configure themselves to meet changing needs.*[178] Fox outlines it in a straight up building metaphor:

"In a building such as a skyscraper where the majority of the structural material is there to control the building during windstorms, a great deal of the structure would be rendered unnecessary under an intelligent static kinetic system. In other systems as well, much of the structure will be reduced through the ability of a singular system to facilitate multi-uses via transformative adaptability. Buckminster fuller who coined it."[179]

Fox' vision of adaptive architecture drives a certain modeling from this *ephemeralization* theoretical framework adaptation into a kinetic expressive theory that tries to map its spirit of the times to the scale of a global phenomenon as *worldwide you can feel and see that kinetic architecture is the next step within a larger evolution where people and societies from all over the world are trying to connect.*[180] And at the same time addresses current topics such as energy efficiency, sustainability and social transformation, and also *with sustainability becoming such a big presence in architecture, and generally in how we live, it is thought that kinetics is the next logical step in the progression of architecture.*[181]

His theory outlines a consonant, yet slightly divergent, direction with the democratic tendencies of *kinetura's* framework, an affirmation that everybody in this line of research seems to agree on: that *pragmatic flexibilities enhance everyday activities and possibly suggest new ways in which users' and*

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[177] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4

[178] Fox, Michael, *Ephemeralization*, Kinetic Design Group, Massachusetts Institute of Technology, Department of Architecture (2001) (http://profamateus.no.sapo.pt/mitharvard2.pdf) (06-02-2014) P. 1

[179] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4 (http://profamateus.no.sapo.pt/mitharvard2.pdf) (06-02-2014)

[180] Xaveer Claerhout, interview by Van Poucke, *Kinetower + Exclusive Interview with Kinetura* (http://blog.kineticarchitecture.net/2011/02/kinetura_kinetower/.) (26/03/2014)

[181] Fenwick, Tess, *Op. Cit.*(2011) P. 30

spaces can interact to complete tasks.[182] Flexibility is then the way to not only solve architectural problems but to expand our ideas about them, yet at the same time, it is highly strung on the user and his/her needs, a condition that in turn drives the whole discourse thus weaving cross-scalar, interactive connotations to his theoretical model; all this made possible trough and thanks to computational applications. This all supporting the claim that kinetic systems can go from human to urban scale in their promise of embedding unforseen interaction into the built environment, something that it is not quite clear yet as no research has been found, over the course of this investigation, that implements these theories at an urban scale and which is **outside** of this thesis project's scope.

*4.2.1-Intelligent Kinetic Systems_*

"Can architecture finally break free from the limitations of the static towards an engineered future of intelligent responsiveness and adaptation?"[183]

Or, to paraphrase Dennis Dollens, can buildings begin to think?

If architecture es what is between walls, that is, the shape of the space, then *...the cube is an ideal example of neutralization of space, as a multi-purpose space it is general enough to house almost anything which results in an averaging out and homogeneity of all possible events.*[184] This is what modernist and functionalist currents regarded as their sacred ground: that functionality resided in ambiguous shape and in the particular reality that Le Corbusier's *five points* and the *modulor* were somehow an indestructible truth and that the substructure to all human activity was embodied as a subset of a machine like void,. Since Adolf Loos *Ornamen and crime,* the question of the obsolete and the moralizing dictation that followed like a gospel sat the basis for a static, planned, specific and clear, imagined, non changeable yet accommodating space. This implied the idea that civilization would remain the same for as long as the building was to exist or, at best, that it would be demolished or renovated to new uses; that somehow walking along a straight line was more civilized and intelligent than doing so in zigzags, this would not only turn out to be not true, but also a delusion. The house, as Le Corbusier stated, was a *"machine à habiter"*; yet *the implementation of such a general space for*

182 Fox, Michael and Kemp, Miles, *Interactive Architecture*, 27,
As quoted by: Fenwick, Tess, *Op. Cit*. (2011) P. 27

183 Markopoulou, Areti – Dubor, Alexandre, Digital Matter Intelligent construction systems for responsive buildings, *What's the Matter? Materiality and Materialism at the Age of Computation,* various authors, Copyright by the authors and ENHSA (2014) P. 401.

184 Spuybroek, Lars *"The Structure of Vagueness,"* in *Performative Architecture – Beyond Instrumentality,* ed. Branko Kolarevic and Ali M. Malkawi (New York, New York: Spon Press, 2005), P. 163.
Paraphrased by: Fenwick, Tess, *Op. Cit.* (2011) P. 25

'spatial adaptability' implies that all decisions have been made prior[185]*, as the architecture does not engage as situations emerge.*[186] The architectural discourse produced a new kind of beauty; the one sprung from function itself, this was great progress but, in fact, what it really left us with were lifeless, dead, static buildings; an unresponsive kind of space and which at the same time trivialized the cube (a total misinterpretation of Loos moral judgment towards *Art Nouveau*) and that became modernity's insignia during the XXth century. The architectural program became a rigid grid under any excuse to justify its reigning dictatorial position which did not respond to any local cultural framework; it imposed its "civilized" modern man view of things onto cultural sets. This *empty openness, previously implied in the cube, needs to be replaced by a solid vagueness.*[187] Modernism surely did not leave us with any tool to deal with uncertainty as it only addressed content flexibility (which is very important, but totally left physical flexibility very much undisscused) as a way of thinking, even on moral grounds (even though, to be fair, Le Corbusier's modulor did consider some multi-functional spacial connotations).

In this chapter, we will be subdividing *kinesis*, the etymological root in kinetic systems, at a philosophical level in three major ontological and epistemological aspects:

- Kinesis as Language.
- as a system.
- as structure.

Within the theory of kinetic architectural systems there are two leading theoretical frameworks: that of William Zuk & Roger Clark and that of Michael Fox. Kinetic systems are a topic that has not gotten enough insight, or at least the attention that it deserves, unlike other topics in the scientific history of architecture; it has been explored in the past by few artists like Calder, some space programs at NASA and aerospace industry companies but especially in the theoretical arena; it has not been addressed and pushed forward very much since its inception into the printed world of concepts by Zuk and Clark's *Kinetic Architecture* seminal book publication in the early seventies (1970); adjudicating themselves the coining of the term although in recent years it has received a well deserved rescue from certain

185 Fenwick, Tess, *Op. Cit.* (2011) P. 25
186 Spuybroek, Lars, *"The Structure of Vagueness,"* in *Performative Architecture – Beyond Instrumentality,* ed. Branko Kolarevic and Ali M. Malkawi, Spon Press, New York, New York (2005) P. 163
187 Idem.

research lines at schools and universities across America, Asia and Europe as Angeliki Fotiadou points out in her thesis:

"Searching and evaluating a subject such as Kinetic Architecture and especially a specific area of it, is not an easy issue. The lack of proper documentation but at the same time the new inventions and researches that are performed and are constantly being presented, make difficult the overall view...However, this means that kinetic architecture is positioned in the middle of the interest and that it is a promising area in the field of construction."[188]

The concept of intelligent kinetic systems itself is not the end of a process, as it is a process in itself; one that enables the embodiment of movement into the realm of physical reality. Rooted in animation but not defined by it (as was elaborated and established in chapter III) that addresses the multi-functional and multi-tasking reality that is reflected in our everyday lives. One hundred and fifty years after the birth of animation, kinetic systems themselves carry on current responsibility for defining what *dynamics* and *flexibility* mean in the contemporary architectural context. They have given birth to the theoretical foundations that weave together responsive, adaptive and transformable systems in architecture and, as of today, *these explorations have lead to the notion of adaptive architecture through the use of transformable mechanisms to control and optimize the environmental and sustainable performance of the buildings.*[189] In an ever more sustainable world scenario, *contextual flexibility in terms of form and climate are just as important as programmatic adaptability.*[190] And it is a great, even almost mandatory, asset for a building structure: *to be able to adapt and respond to changes in geometrical, environmental, programmatic, demographic or even financial contextual shifts*. In a world that is characterized by change as a central pivot in the structure of things, however, *"rarely are the two combined into a single system"*.[191] Spuybroek believes *the problem of flexibility is not so much 'to open up space to more possibilities,' but the concept of possible itself.*[192] This makes the emergence of kinetic systems a necessary path to walk and new territory to uncover.

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188 Fotiadou, Angeliki, *Op. Cit*. (2007) P. 58

189 Rosenberg, Daniel, *Designing for uncertainty: Novel Shapes and Behaviors using Scissor-pair Transformable Structures, Master of Science Graduate Thesis, Chapter I,* Architecture Department, Massachusetts Institute of Technology, in requirements for the degree of Master of Science in Architecture Studies (2009) P.21

190 Fox and Kemp, *Interactive Architecture,* 40.
As quoted by: Fenwick, Tess, *Op. Cit*. (2011) P. 25

191 Idem.

192 Spuybroek, Lars, *Op. Cit*. (2005) P. 163

"Kinetics may address a small part in providing a solution to the growing need for the increasing density of the urban environment which, right now, stands static and fails to address escalating needs for differentiation through changeability, responsiveness, and dynamics."[193]

Zuk and Clark define kinetic architecture as *the architectural form* [that] *could be inherently being displaceable, deformable, expandable nd in some other manner capable of kinetic movement* [194] and describe its particular design as a kind of adaptive process that *will not stop when the building is erected.*[195] What is interesting about this vision is that it defines an emergent, open-ended approach towards *kinesis* itself as it is placed in a higher dimensional plane than that of just the realm of architecture; it places kinetic systems in the plane of a philosophy, not a mere practical matter but a life defining one. Reinterpreted within an architectural discourse, it could imply the life of a building which is consistent with the fact that energy and material are both scarce resources to preserve. Michael Weinstock agrees in that *...the logic of emergence demands that we recognize that buildings have a life span, sometimes of many decades, and that throughout that life they have to maintain complex energy and material systems.*[196] Michael A. Fox, on another hand, states that *kinetic architecture is defined generally as buildings and/or building components with variable mobility, location and/or geometry.*[197] This statement clearly sets kinetic systems within the archetypal building and construction oriented vision of the world; thus grounding it in a manner that is still accessible enough for application in real world constraint sets. Intelligent kinetic systems is also a trans-disciplinary born hybrid science (see chapter I for examples on trans-disciplinarity) since, according to Fox, *intelligent kinetic systems* ***arise from the isomorphic convergence of three key elements: structural engineering, sensor technology and adaptable Architecture***[198]. Adding to the fact that these systems are an *integration of computational devices within architectural components as an environmental moderating system*[199] makes their subdivision into ***ways*** (folding, sliding, expanding, *and transforming in both size and shape)* ***and means*** (pneumatic, chemical, magnetic, natural or mechanical)[200] easier to categorize; therefore, for practical matters, we will use Fox's classification system while although also addressing

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193 Fenwick, Tess, *Op. Cit*. (2011) P. 30
194 Zuk, William - Clark, Roger, *Op. Cit*. (1970) P. 11
195 Ibid P. 9
196 Weinstock, Michael, *Op. Cit*. (2004) P.17
197 Fox, Michael, *Op. Cit.* (2001) *(c)* P. 2
198 Fox, Michael - Yeh, Bryant, *Op. Cit* (2001) *(a)* P.1
199 Fox, Michael, *Op. Cit* (2001) *(b)* P. 8
200 Fox, Michael, *Op. Cit* (2001) *(c)* P. 2

Zuk's ideas which have a clearly emergent essence to them that can provide clearer regarding as to what are the relevant guidelines within complexity that resonate with environmentally friendly responses to design questions.

4.2.2-Emergence and dynamic systems_

Emergence studies *the properties of a system that cannot be deduced from its parts.*[201] It posits that nature is composed by inner, crypto-systems that operate at invisible substrata holding the cryptographic information within seemingly non understandable phenomena which it tries to uncover for scientific study. But just what exactly does emergence mean to us? according to Helen Castle *Emergence is the scientific mode in which natural systems can be explored and explained in a contemporary context.*[202] Meaning the observation of natural phenomenona aimed at gaining insight on complexity and cryptosystemic logic within the mentioned systems, thus harboring millions of years of natural “knowledge”; on the basis that this “knowledge” has already worked in nature for millions of years. In a design oriented scenario this signifies a monumental source of examples for modeling since *it provides models and processes for the creation of artificial systems that are designed to produce forms and complex behavior, and perhaps even artificial intelligence’.* [203]

For Weinstock, the question of emergence has a systemic dimension to it that makes mathematical modeling a potential key tool for its study and development.

“...this means we must search for the principles and dynamics of organization and interaction, for the mathematical laws that natural systems obey and that can be utilized by artificially constructed systems. We should start by asking: What is it that emerges, what does it emerge from, and how is emergence produced?”[204]

The breaking down of natural systems goes down to the core of decision-making where material constitution (which will be addressed thoroughly in chapter VIII) plays a decisive role in SMM systems and which this thesis's objectives want to focus on. This functionality involve thousands of modes by

201 Castle, Helen, “Editorial”, Emergence: Morphogenetic Design Strategies, *Architectural Design*, Wiley Academy Press, United Kingdom (2004) P.5
202 Idem.
203 Idem.
204 Weinstock, Michael, *Op. Cit.* (2004) P.11

which material nature sets its conditional procedures. *In natural systems most sensing, decision-making and reactions are entirely local, and global behavior is the product of local actions, with a high degree of functionality in the material itself.*[205] According to Casey Reas (the creator of Processing, an interface based in Java that allows artists and designers to implement relatively simple code scripts to achieve computational design visual and controller applications): *"emergence refers to the generation of structures that are not directly defined or controlled".*[206] Defining emergence from a systemic standpoint, he resorts to agent based systems as means to address the matter; this implies scaling up from simple patterns (of code, movement, geometry, actuation, timing an so on). *"Instead of overtly determining the entire structure. I write simple programs that define the interactions between elements. Structure emerges from discrete movements of each element as it modifies itself in relation to its environment."*[207]

4.2.3-How does Emergence relate to Kinetics?_

Helen Castle's concept of emergence can shed light into aspects within *emergence* that hold the possibility of re-configuration and accommodation that is most useful in kinetic design whistle its capacity to code natural behavior; it can provide insight within more organic relationships between elements in natural (and artificial) ecosystems. *In this brief definition, emergence already surfaces as a model capable of sophisticated reflexive attributes exceeding any mechanistic or static notion of architectural form-one that could perhaps define new levels of interaction within natural* [and artificial] *ecosystems.*[208] The emergence of natural systems can help explain intelligent kinetic systems and their proceses of adaptation through embedded intelligence because of their efficiency and precision when dealing with uncertain situations, processes and unforeseen outcomes. An emergent system "knows" how to "improvise" based on experience and memory as it *examines natural dynamics systems, the material behavior that enables adaptation, and presents the case for implementation of these models in architecture and engineering."*[209] Dynamic systems are characterized by two fundamental pivots: form and behavior; and the union of these two ideas is very interesting since *form and behavior emerge from process.*[210] Behavior can be defined as the iterated execution or conjunction in unison of form,

205 Emergence and Design Group, "Emergence in Architecture", Emergence: Morphogenetic Design Strategies, *Architectural Design*, Wiley Academy Press, United Kingdom (2004) P.9
206 Reas, Casey, "Process/Drawing", Programming Cultures: Art and Architecture in the Age of Software, *Architectural Design*, Wiley Academy Press, United Kingdom (2006) P. 27
207 Idem.
208 Castle, Helen, *Op. Cit.* (2004) P.5
209 Emergence and Design Group, *Op. Cit.* (2004) P.9
210 Weinstock, Michael, *Op. Cit.* (2004) P.13

movement or growth, triggered by stimuli and regulated by the internal code in a given system; be it natural or artificial, its capacity to respond to theses stimuli is called *responsiveness*, another key concept in dealing with unexpected situations. *All natural material systems involve movement, often without muscles, to achieve adaptation responsiveness.*[211] These relationships with the environment dictate an organism's (or system's) success probabilities at survival; in itself, *this process consists of a complex series of exchanges between the organism and its environment.*[212] Through these interactions, an organic or artificial system develops *a capacity for maintaining its continuity and integrity by changing aspects of its behavior.* [213] This inner logic can be modeled mathematically. In an article titled *Morphogenesis and the Mathematics of Emergence'* Michael Weinstock *traces the origins of the concepts and provides an account of the mathematical basis of processes that produce emergent forms and behaviors, in nature and in computational environments*[214] (This topic will be engaged in chapter VII *The Need for Performance-driven Simulation Software*) yet for now we will concentrate on its implications as a philosophical concern and leave its technical-scientific implications for later on. It is an arguable fact that *forms are related by morphogenetic tendencies, and there is also the suggestion that some, if not all, of these characteristics are amenable to being modeled mathematically.*[215] These assertions have set the grounds for certain research projects to emerge that are aimed towards the systematic modeling of smart materials or, more accurately, programmable matter (materials that have embedded intelligence into their molecular constitution). Which means that they can be programmed (also a paradigm that we will analyze in later chapters);and this has been developing while, in a parallel manner, *in recent years architecture and engineering have been preoccupied with processes for generating designs of forms in physical and computational environments.*[216] This situation allows for the possibility that *mathematical models can be used for generating designs, evolving forms and structures in morphogenetic processes within our computational environments*[217] and can be subsequently automated in the forms of parametric models or full bundled software packages that can simulate behavior and its relationship with environmental constraints as it will be further clarified in later chapters (specifically chapter *The need for Performance Driven Simulation software*). Yet, as far as emergence is concerned, Frei Otto suggests that the issue is far from being settled, he argues that the

211 Emergence and Design Group, *Op. Cit.* (2004) P.9
212 Weinstock, Michael, *Op. Cit.* (2004) P.13
213 Idem.
214 Emergence and Design Group, *Op. Cit.* (2004) P.7
215 Weinstock, Michael, *Op. Cit.* (2004) P.13
216 Idem.
217 Emergence and Design Group, *Op. Cit.* (2004) P.7

our current conceptual means are still very vague and not optimum when it comes to fully grasping natural systems:

" *A technician observing living nature just cannot grasp living objects which die so quickly, are so sensitive, so complex and both so un-imitable (sic) and strange. A biologist looking in technology sees how imperfect technical activity is. Both recognize today that technical and biological objects will never be the only optima which can be thought of, but only short-term stations in a flow of unique biological-technical developments without a recognizable target."*[218]

Non the less, this concern might have been answered in an earlier paper titled *Ephemeralization* by Michael Fox, which was concerned with and underlined the imminent and *necessary are the use of advanced computational design tools, material development and embedded computation.*[219] to achieve kinetic design. This affirmation is consistent with a research project that focuses on geometric and material programming called *4D printing* (this approach will be further analyzed in chapter *Programmable matter: Material Design & Programming as a vehicle for Architectural Design*), one out of at least 4 projects being developed by Skylar Tibbits, a researcher at the Self Assembly Lab at the Massachusetts Institute of Technology. Which, to sum it up, *is like robotics without wires or motors.*[220] Basically, the project advocates for designing materials to behave in programmed manners, embedded in what he calls the *programmable matter paradigm*. [221]*The big idea is to create objects that can change after they are printed, making them self-adapting. The act of printing is no longer the end of the creative process but merely a waypoint.* This changes everything in terms of the design process, and it just might have given some answers to Michael Hensel's, Weinstock and Menge's ideas about material performance in natural systems since *"...it's like naturally embedding smartness into the materials."*[222] This research aims to find way to mitigate these limitations by building additional tools and changing our cognitive relationship with model building and engaging with issues from the likes of *change blindness* and other phenomena that interrupt and obstruct our vision within the decision making process in the context of intelligent kinetic systems.

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[218] Otto, Frei, "Frei Otto in Conversation with The Emergence and Design Group", Emergence: Morphogenetic Design Strategies, *Architectural Design*, Wiley Academy Press, United Kingdom (2004) P.20

[219] Fox, Michael, *Op. Cit.* (2001) *(c)* P.1 (http://profamateus.no.sapo.pt/mitharvard2.pdf) (06-02-2014)

[220] Tibbits, Skylar, "Brilliant Robot Scraps Can Form Selves Into Anything", *Wired.com* magazine, section: Bussiness (2013) (http://www.wired.com/2013/02/4d-printing-at-ted/) (29/04/2014)

[221] Idem.

[222] Idem.

4.2.4-The issue of flexibility_

"By making use of the flexible characteristics of specific materials combined with motion-based technologies, objects transform in a silent and nearly imperceptible way into a contrasting shape with a completely different functionality and expression. As if an extra dimension were involve."[223]
-Kinetura's concept

The concept of flexibility, inherent to kinetic systems, besides from its obvious mechanic and structural interpretation, can be seen as a medium for argumentation and as the kind of instrument that can bring about a certain sort of chaotic, distorted or blurry categorization within space. An almost unclassifiable object emerges as the embodiment of uncertainty in the hands of flexibility, almost as if flexibility and kinesis gave rise to each other, yet they are different things. Lars Spuybroek argues that *flexibility can often result in an undetermined architecture, in an averaging out of programme and equalization, even neutralization, of space.*[224] This specific quality of neturalization of space is explained in what he calls ***vagueness***. According to Lars Spuybroek:

"*Vagueness allows clearly defined goals and habits for as yet undetermined situations. A behavioral vagueness needs to co-exist with an architectural vagueness; - a behavior epitomizing constant grouping and regrouping, of coagulating into particular configurations and then abruptly liquefying, and regrouping into various other fixed states."*[225]

In this statement, vagueness is addressed as a conceptual platform that allows for uncertainty to give rise to unexpected situations and arrangements in space and activity, as a nob to a door of multi-behavioral, change driven, blurred, recursive, almost liquid vision of the nature of organization between space and time, event and process, building and context. Today's world is a one that is driven by permanent change. The forces that mold reality are always mutating into altered states, often more than one state at the same time, where they are sometimes difficult to define.

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223 Xaveer Claerhout, interview by Van Poucke, *Kinetower + Exclusive Interview with Kinetura,* February 28, 2011, (http://blog.kineticarchitecture.net/2011/02/kinetura_kinetower/.) (26/03/2014)
As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 21
224 Spuybroek, Lars, *Op. Cit.* (2005) P. 356.
225 Fenwick, Tess, *Op. Cit.* (2011) P. 25

"Form and behavior have an intricate relationship. The form of an organism affects its behavior in the environment, and a particular behavior will produce different results in different environments, or if performed by different forms in the same environment. Behavior is non linear and context specific."[226]

"***The question is then: How can we approach form finding*** [and behavior programming, for that matter] ***if material form continuously transmutes in responsive to an equally dynamic force-context?"***[227]

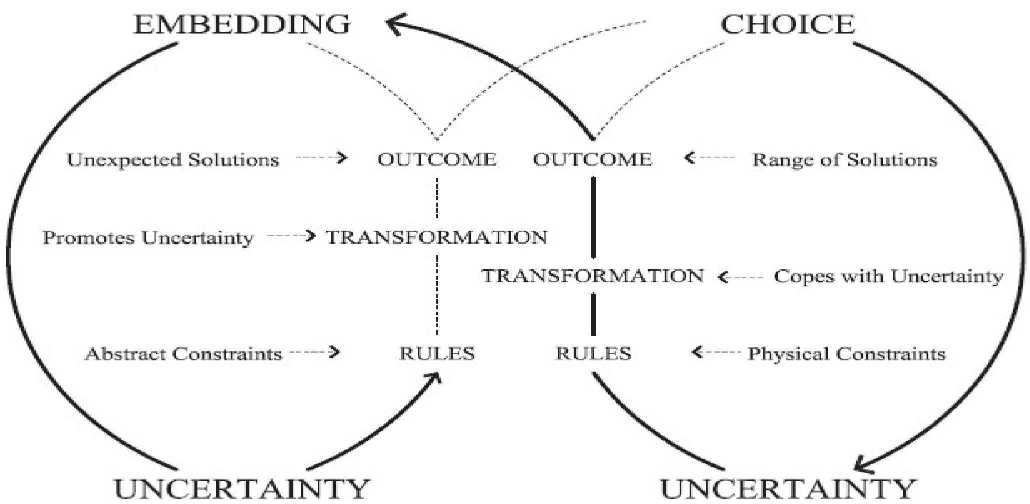
4.2.5-The problem of uncertainty_

According to Zuk and Clark, *basic to the philosophy of kinetic architecture is the importance of being able to accommodate the problem of change,*[228] thus being able to respond to it with precision , efficiency and accuracy therefore, in this sense, uncertainty has to do with an inherent capacity for redefining and evolution, mutation if you like, of intelligent systems that self-assemble in real time or across time scales. An intelligent kinetic system *shows how uncertainty can be extended to the real world, proposing physical in-becoming buildings able to re-define themselves throughout their lives.*[229] Intertwining concepts from adaptable architecture and kinetic architecture we can uncover the experimental paths that can clear out *how uncertainty can foster creativity and to show how the problem of terminating the design process offers novel and unexplored possibilities*.[230]

Daniel Rosenberg argues that this can be done throughout a rigorous process of rules, constraints, instructions sets, relationships and iterations, where each outcome is evaluated and used as optimizing information for the next cycle (meaning recursion). Uncertain patterns will arise and will bring with them unexpected situations that will inform our transformation patterns that will subsequently loosen the system's capacity to change and optimize its performance thus addressing adaptability and flexibility. These kinds of responsive patterns can be found, as emergence points out, in organic natural systems:

226 Weinstock, Michael, *Op. Cit.* (2004) P.13
227 Hensel, Michael, *Op. Cit.* (2004) P.27
228 Zuk, William - Clark, Roger, *Op. Cit.* (1970) P. 9
229 Rosenberg, Daniel, *Op. Cit.* (2009) P.19
230 Ibid. P.21

"Organisms are bundles of relationships that maintain themselves by adjusting their own behavior in anticipation of changes to the patterns of activity all around them. Anticipation and response make up the dynamic of life." [231]



Uncertainty diagram, Daniel Rosenberg (2009) (Rosenberg, Daniel, *Designing for uncertainty: Novel Shapes and Behaviors using Scissor-pair Transformable Structures,* P. 15)

Talking about seeing and Doing, George Stiny (1970) (Rosenberg, Daniel*, Designing for uncertainty: Novel Shapes and Behaviors using Scissor-pair Transformable Structures* P.20)

[231] Weinstock, Michael, *Op. Cit.* (2004) P.13

Another issue in addressing kinetic systems is their relevance and success probabilities in the real world of capital and financial accountability, this implies that *criteria for selection of the 'fittest' can be developed that correspond to architectural requirements of performance, including structural integrity and 'buildability'.*[232] Maziar Asefi wrote a book on transformable structures and kinetics titled *Transformable Kinetic Structures* [233]where he explains the difficulties of selecting and designing a ***"proper transformable structural system that mostly suits the design requirements"***.[234] To optimize the evaluation process he proposed that ***"a number of existing alternative, design criteria"***[235] should guide the general approach and selection process within transformable structures. He presented these general guidelines in 4 categories:

1) ***Design****, which covers Expansion and flexibility, compactability and transportability, structural stability and deformability, Architectural obstruction and Operating system.*
2) ***Construction and Operation*** *which includes reliability and safety, Auxiliary equipment and manufacture and shipment.*
3) ***Maintenance and costs****, which includes life expectancy, maintenance management strategies, capital cost, Running and maintenance costs.*
4) ***Application*** *by defining the scale of the application (small-scale, medium-scale, or large scale).* [236]

In this research we will only address two of these that encompass the scope of the thesis which are the ***design*** and ***application*** criteria, according to Asefi's classification. This project will leave it to others to determine kinetic system's maintenance and costs as well as Construction and Operation implications.

*4.3-Kinesis as language_*

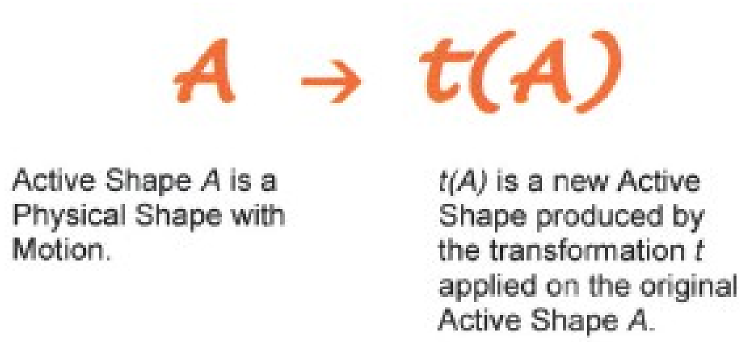
Although most artists, architects and engineers that have worked within the kinetic sphere have their own methodology, that of *active shapes* by Dina El-Zanfaly, offers a straight forward, clear and rule based step by step methodological path that allows to break systems down to basic grammar and

[232] Weinstock, Michael, *Op. Cit.* (2004) P.17
[233] Asefi, Maziar (2010),
As quoted by: El-Zanfaly, Dina, *Op. Cit.*(2011) P.16
[234] Idem.
[235] Idem.
[236] Idem.

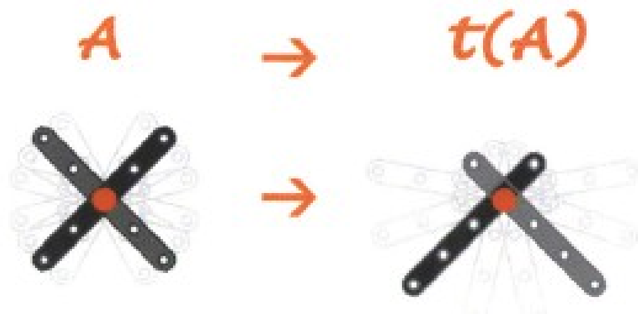
syntax, much like language, which will be proven useful in chapter IX. El-Zanfaly groups a number of conceptual tools in her method for guidelines to model kinetic movement patterns (*A* in El-Zanfaly's notation). It is a concept brought from the medical imaging terminology known as *active shape model* (ATM first coined by Tim Coots and Chris Taylor) in her masters degree thesis *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, which attempts to use the term Active Shape (*A*) to *describe physical shapes in motion in kinetic structures*, which is based on *shape grammars.*[237] "*Shape Grammars were one of the earliest algorithmic systems for creating and understanding designs directly trough computations with shapes, rather than indirectly through computations with text or symbols."*[238]George Stiny and James Gibs introduced [239] *shape grammars* in 1972 as a new visual approach to design and analysis. These computations in shapes are performed in two steps. First recognizing a particular shape and second applying a rule that specifies which shape it could be replaced with, and how it could be replaced. The rule consisted of two shapes separated by one arrow in which the stage on the right side is replaced by the shape on the left side by applying transformation operations contained in the rule. Which are basically algebraic function notations used to model actions that satisfy the any given system in any given case and behave like an idiomatic language. This conceptual basis proposes *design guidelines for kinetic architecture structures in which rules based on shape grammars are used for motion capturing and design*[240], where, analytically, the rule ***A-> t(A)*** *is introduced as design guidelines for designing kinetic architectural structures*[241]. The rule can be summarized like this:

"***A*** *means any given active shape in which* ***A*** *is a physical shape with movement or motion created by a given design or designer. The expression* ***t(A)*** *designates the operation from which a new active shape produced by one or more transformations* ***t*** *applications onto the original active shape* ***A*** *to produce novel motion."*[242]

[237] El-Zanfaly, Dina, *Op. Cit.* (2011) P.16
[238] Knight, Terry, *Shape Grammars in Education and Practice: History and Prospects*, International Journal of Design Computing 2(2000).
As quoted by: El-Zanfaly, Dina, *Op. Cit.* (2011) P. 26
[239] Stiny, George and Gibs, James (1972),
As quoted by: El-Zanfaly, Dina, *Op. Cit.* (2011) P. 26
[240] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 28
[241] Ibid. P.16
[242] Idem.



Active shape principle, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, Active Shapes: Introducing guidelines for designing kinetic architectural structures, P.28)



(El-Zanfaly, Dina, Active Shapes: Introducing guidelines for designing kinetic architectural structures, P.28)

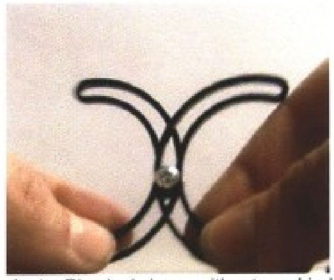


Figure 14: Just a Physical shape without any kind of motion.

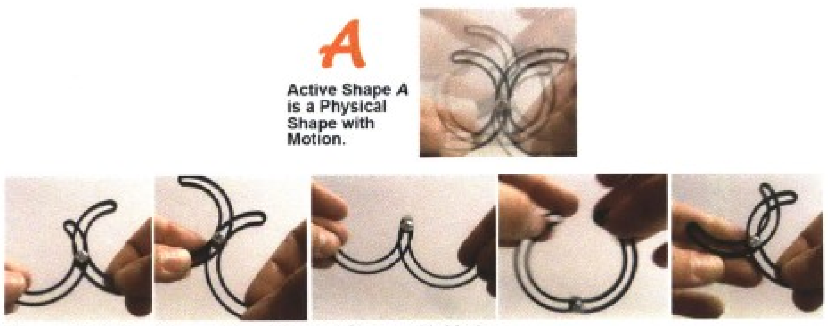


Figure 15: Active Shape *A* is a Physical Shape with Motion.

Active shape with physical motion, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, Active Shapes: Introducing guidelines for designing kinetic architectural structures, P.27)

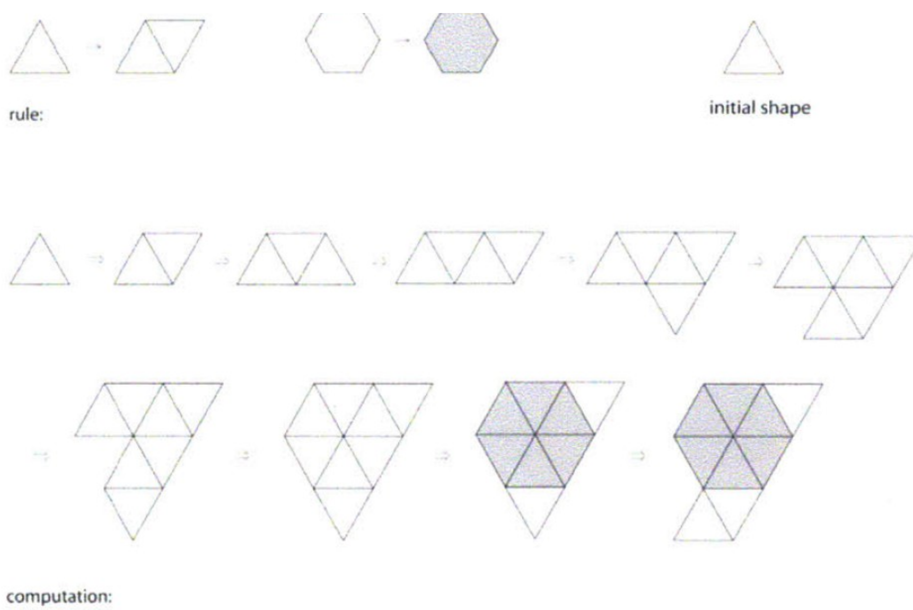


Figure 13: Rules for a triangle as an initial shape and its computation.

Rules for a triangle as an initial shape and its computation, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures,* P.26*)*

These computations can be triggered by what she calls *motion controllers*, which, in turn, model morphing transformations and kinetic changeability between shapes ***A*** and ***t(A)***. According to El-Zanfaly, these transformations could be:

1. *A transformation of the motion control means between the parts of the Active Shape.*

2. *A transformation of the motion control means between the parts of the Active Shape, such as actuators, hinges and linkages.*

3. *A transformation of the geometry pf the parts of the Active Shape or it can be any other transformation such as a* **transformation in the materiality** *of the Active Shape.*[243]

Later in this research, we will see that to model microscopic actuated, macroscopic material transformation we will need more than shape grammars and will have to implement ***vector analysis calculation and matrix composition*** to be able to accurately model these shape shifting properties. Out of all these we will concentrate in the ***materiality transformations*** that can induce macroscopic behavior that in turn induces motion and morphing capability. Yet, although there are all kinds of *motion control means,* it is useful to take a quick look at their most representative types. This is of use because they can be auxiliary methods that can clear out some motion path and mechanical property visions even if we are dealing with self assembly materiality and programmable matter, especially at the nano-scale.

[243] Zanfaly, Dina, *Op. Cit.* (2011) P.16

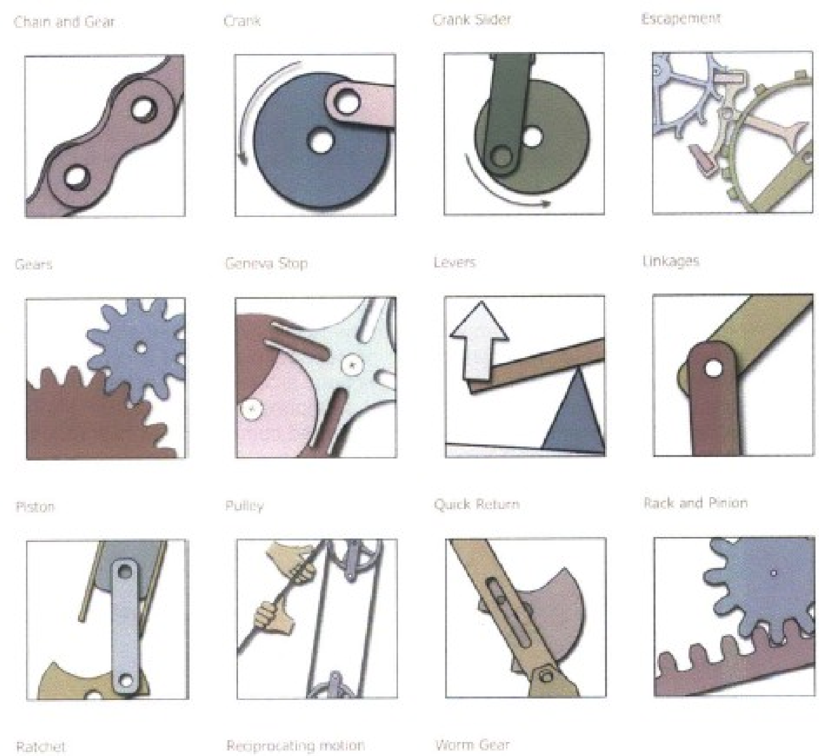


Figure 17: *Some examples for motion controllers.*

Examples of motion controllers, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, Active Shapes: Introducing guidelines for designing kinetic architectural structures, P.29)

Active shape grammar is composed solely of two guidelines: ***geometry*** and ***motions.***

In this brief study we will look at motions first and, although they are both important, in self assembly systems the geometry is the most crucial of the two and we will leave it for a latter, most incisive scrutiny later in this thesis. In her research, El-Zanfaly analyzed basically three types of movement *rotation, translation* and a combination of them as a third possibility: *rotation and translation*. Although they have a mechanical flavor to them and we are arguing a more organic approach, it is fair to note that far more complex movement can be built from them, as they graphically formalize a wide range of situations regarding these three basic means and that, as such, they act as a basis for further development in the matter. This research's contributions to the original investigation will be to asses possible usefulness to its findings.

Rotation

In this case, as in all the others, the base of the analysis is to apply the same motion onto different shapes. It is a very simple yet very illustrative methodological tool. In the case of rotation, *one pivot point as a control mean (sic) is used to create a rotational motion from the components of the active shape* ***(A)****. In order to create a matrix between the transformation in the geometry of the components* ***t*** *of the Active Shape* ***(A)****.*[244] Outputs are as simple as inputs, the geometry can have a relatively ample range and freedom, as for motion type, at first glance, they are still useful for simple applications ranging from drawbridges to door and window mechanisms.

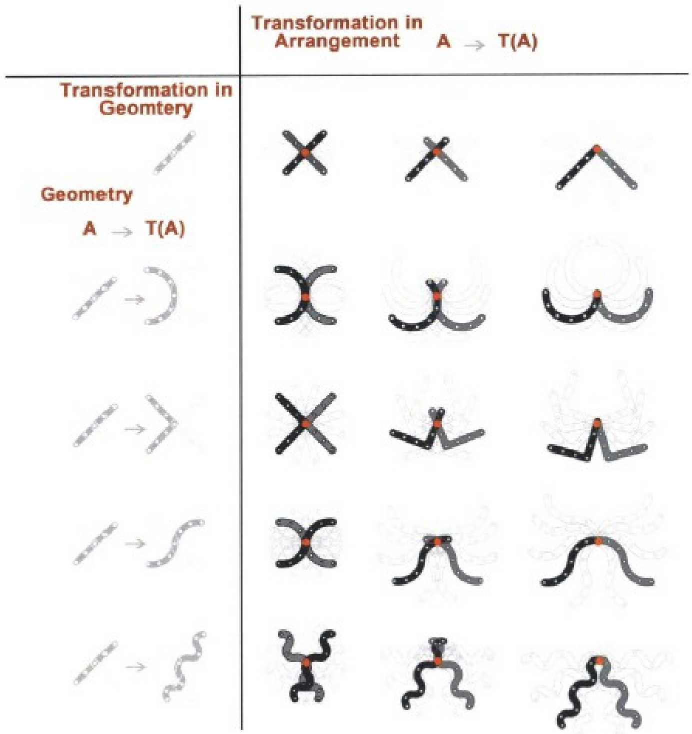


Figure 20: A table showing the change in the transformations in Geometry ***t*** of the components of the Active Shape ***(A)*** with respect to the tranfromations in the arrangment ***t*** of the componenets of the active shape **(A)**. The control mean stays the same in all the transformations in this table.

Transformations in geometry ***t*** *of the components of the active shapes*, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, Active Shapes: Introducing guidelines for designing kinetic architectural structures, P.31)

The control mean stays the same in this table, and the change is between the transformation in geometry ***t*** *and the transformation in arrangement* ***t*** *of the components of the Active Shape* ***(A).***[245]

[244] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 31
[245] Idem.

Translation

In the case of translation, complexity levels are still at the same pitch compared to rotation but geometry has to be more intricate and precise to fulfill the systems intended needs and it is important to note that the whole has less freedom, in motion terms, compared to rotation therefore it is more closed shape grammar. This case was composed by a slider to achieve translation, *all active shapes have the same motion and control means, but they vary as transformation **t** in the arrangement of the geometry of their components occurs.*[246] In these cases, their implementation possibilities are narrower and more subject to security and transportation vehicle design aims even though there is some room within architectural applications which should remain in the range of drawbridges and secured grid entrances.

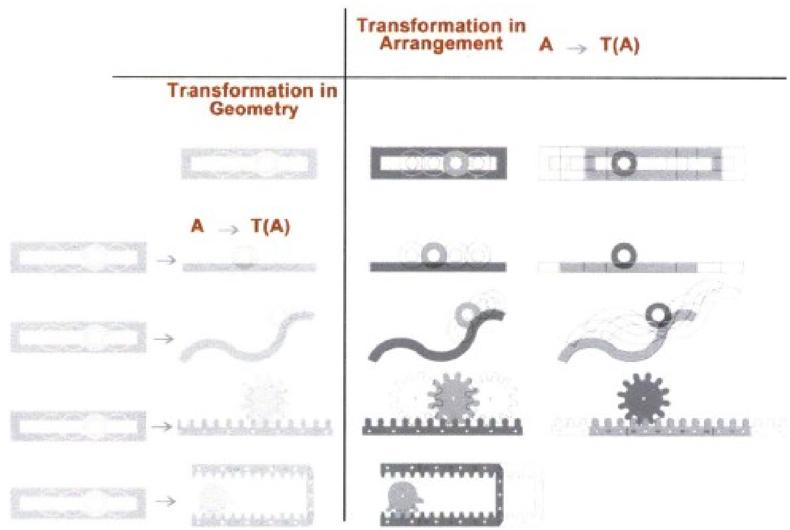


Figure 21: All Active Shapes ***(A)*** in the table have the same motion (translation), they have the same control mean, but they vary as a transformation ***t*** in the arrangement or the geometry of their components occurs.

Translation table, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, Active Shapes: Introducing guidelines for designing kinetic architectural structures, P.32)

Rotation and Translation

*A pivot and a slider are used together as control means to create rotational motion for the components of the Active Shape **(A)**.*[247] Creating a similar matrix such as the translation case *all active shapes have the same motion and control means, but they vary as transformation **t** in the arrangement of the geometry of their components occurs.*[248] These cases are where the geometry-motion combination starts

246 El-Zanfaly, Dina, *Op. Cit.* (2011) P. 32
247 Ibid. P. 33
248 Idem.

getting interesting; cause they seem to give rise to certain proto-complexity in motion programming and, even though they appear as the rotation case samples, once you apply the combined transformation operations, non-linear patterns start to appear in the outputs. This is proof that, by combining a group of single, simple motion types and different geometrical patterning, it is possible to achieve more organic seamlessness and higher complexity within the system's kinetic composition and emergent possibilities in different situations.

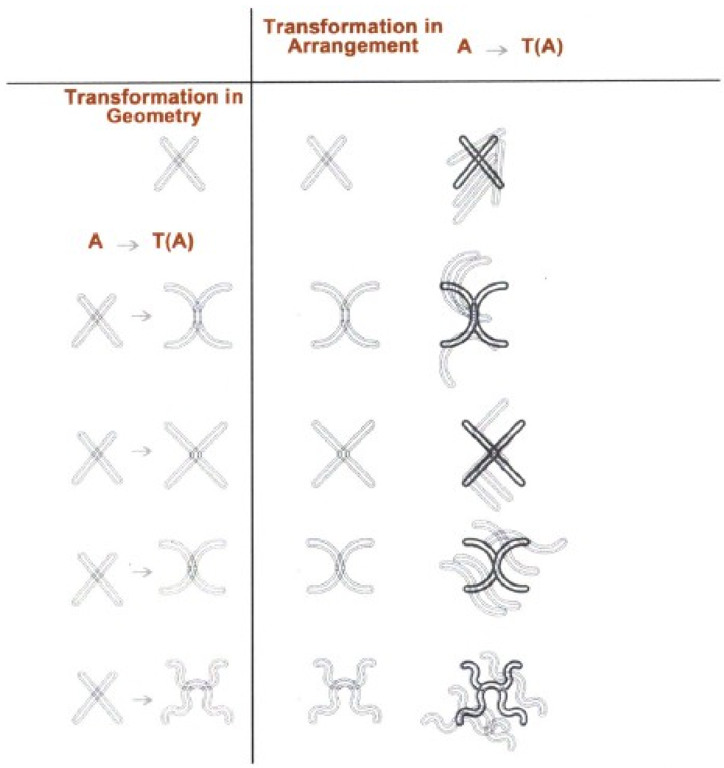


Figure 22: All Active Shapes *(A)* in the table have the same motion (rotation and translation), they have the same control mean, but they vary as a transformation *t* in the arrangement or the geometry of their components occurs.

Rotation and Translation table, Dina El_Zanfaly (2011) (El-Zanfaly, Dina, Active Shapes: Introducing guidelines for designing kinetic architectural structures, P.33)

El-Zanfaly's experiments were held on the ground of group methodology, in which 6 students conducted active shape testing grammar applications on material tables within the mentioned grammar cases. The process is defined in four stages:

- *Two design stages and two reporting stages after each design stage.*

- *In the first design stage the participants were provided with* ***physical above mentioned Active Shape****s, and were asked to choose one Active Shape with one or two arrangements. The participants were also allowed to use any* ***representational techniques such as sketching or modeling****.*

- *After reporting what they have done in the first stage, the participants started a new design stage they were asked to take a structure from their colleague and apply one of the transformations mentioned above on the Active Shape, from which the original structure consists, and design a kinetic structure.* [249]

This methodology had its toll with participants coming to the conclusion that it was, in some cases, impossible to foresee the outcome of certain of the design experiments. With one of the participants expressing concerns that *without simulation software or digital fabrication of the active shapes, it's very hard to predict the exact motion or quantify information*[250]*,* as one of their conclusions regarding motion prediction. The design & research process in this way of working is very hands on and physical by nature, which is not at all a bad starting point (actually is the closest to real conditions that you can get) if you are working with mechanically conceived part to whole assembly, but ***what happens when you need to test shape-memory materials to implement them into kinetic systems?*** This question will be addressed in later on in this research (in chapter VI: *The need for performance driven simulation software*).

*4.4-Kinesis as a system_*

The definition of *kinetic architecture* as an actual science started shortly before Zuk and Clark, for the first time in history, wrote a complete book on the subject, which formally introduced it into the recorded academia scientific sphere. Even though there is scientific thought at its roots, mainly coming from physics and biology (as established in chapter II) before it formally became a science in 1970 (when Zuk and Clark's book was published), kinetic art lacked the rigor and classification taxonomy of hard science so its integration into architecture definitely gave it a systemic boost to develop into a sort of engineered art form. The search for a broad definition in terms of technologically sound and affine

[249] El-Zanfaly, Dina, *Op. Cit.* (2011) P.34
[250] Idem.

propositions came a while later with the *Kinetic Design group's* writings at MIT. The term *intelligent kinetic system* itself was coined by Michael Fox in the late 90s and has become a defining one in the relatively unexplored range of kinetic architecture, its definition is best understood if taken in account the ways and means that produce the given system's *kinesis*. According to the *Kinetic Design Group*'s consensus, it is defined as a crossover applied science discipline distinguished by its utilization of different joint ventures integrated as one specific field. *Intelligent Kinetic Systems arise from the isomorphic convergence of three key elements: Structural Engineering, Sensor Technology and Adaptable Architecture, with adaptable architecture providing the necessary contextual framework for development.*[251] This assembles kinetic architecture into a systemic paradigm and sets the ground to produce its own intrinsic relationship and generative autonomy, these peripheral disciplines give it its vocabulary and information while they are re-contextualized, similar to software architecture when it came out from similar practices in engineering.[252]

"If the architecture itself were embedded with the intelligence of a robot with the capability of completely controlling the built form, then the development of single-task autonomous robots would by all practical means be rendered negligible. The material systemic implications of behavioral and kinetic design conceptualization demand a controlled fashion in the implementation of its procedures and protocols, this process is know to be the central axis of the whole implementation processes and its stages."[253]

This separation form "conventional" architectural practice and research formal description is constructed by two main criteria: [that] *structural solutions must consider in parallel both the ways and means for kinetic operability.*[254] From which, respectively:

"the means can be described diagrammatically as the controlled source of actuation... by which a kinetic structural solution performs may be, among others, pneumatic, chemical, magnetic, natural or mechanical. The means may also be computational... ...the ways can be described diagrammatically as mechanical motions... ...The ways in which a kinetic structural solution performs may include among

[251] Fox, Michael, *Op. Cit.* (2001) *(a)* P.1
[252] Barroca , Leonor - Hall, Patrick – Hall, John, *Op. Cit.*(2000) P. 2
[253] Fox, Michael, *Op. Cit.* (2001) *(c)* P. 6
[254] Ibid. P. 2

others, folding, sliding, expanding, and transforming in both size and shape."[255]

This epistemological *genesis* has a small but important shortcoming, it does not include (although it advocates by the use of computational tools in its discourse) material science in it. Certainly material science is an integral part of structural engineering, but it is also a separate discipline which only acts as a subset in it much like structural engineering is to architecture or civil engineering thus keeping it as a background, second-hand support subject not a fundamental discipline; therefore the definition tends towards machine-like outputs that hinder the conceptual framework that gives rise to self-sufficient, energy efficient kinetic architectural systems. This thesis hypothesis is that all of these disciplines share something: they can all be computed and in fact share important common grounds in the way they are computed; so the proposition to bring them material science to the foreground of kinetic intelligent systems in architecture consequently opens the spectrum for more organic and *live-like* kinetic systems and, by extension, the demonstration that important research like shape-memory materials (SMM, itself a subset within material science) and computation as a definition descriptor is of utter importance for further classification and understanding as a system.

4.4.1Classification consensus: non- exisent_

Zuk and Clark first classified kinetic typologies in five categories or *"kineticisms"* which are subdivided privileging motion itself as the main indicator of differentiation. In which all of them could be part of the others merged in complex systems that implement some or all of their characteristics at a given time or in a particular assembly as observed in Dina El-Zanfaly's analyzed exercises in the previous section, these are:

Closed systems:

1. *Kinetically controlled static structures*
2. *Dynamically self-erecting structures*
3. *kinetic components*
4. *Reversible architecture*

Open systems:

5. *Incremental architecture*

[255] Fox, Michael, *Op. Cit.* (2001) *(c)* P. 2

6. *Deformable architecture*
7. *Mobile architecture*
8. *Disposable architecture*[256]

One closed typology such as *reversible architecture*, and open ones such as *incremental architecture,* distinguish themselves from the first three because *can accept new outside elements which may not have existed at the time of the formal inception.*[257] Also, *deformable, mobile* or even *disposable architecture* depict applications concerning programmable matter's core challenges, including scaling up these originally light systems. As stated by Skylar Tibbits, scaling up is established as one of the fundamental challenges in the 4D printing and programmable matter context as a possible solution for *the obstacles that are hampering the rolling out and scaling up of 3D printing*[258], therefore we will work with this classification as a central pivot towards the simulation modeling process, for now we will reclassify it as a subset in one of Michael Fox's own system types (dynamic kinetic systems), which we will investigate later in this chapter. In parallel, Maziar Asefi also subdivided kinetic structures typology in accordance to a different kind of criteria, which consider structural performance as central subdivision instruments:

1. *"Transformable tensile structures (transformable tensile membranes and transformable compressive tensile architectural structures)*
2. *Transformable bending and compression structures(spatial bar structures and spatial frame structures)"*[259]

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256 Zuk, William - Clark, Roger, *Op. Cit.* (1970) P. 34-133
257 Ibid. P. 83
258 Tibbits, Skylar, "4D PRINTING: MULTI-MATERIAL SHAPE CHANGE*", Architectural Design,* John Wiley & Sons Ltd, July/August, United Kingdom (2014) P. 118. (http://onlinelibrary.wiley.com/doi/10.1002/ad.1710/pdf) (11/09/2014) (15/08/2014)
259 Asefi, Maziar, *Transformable and Kinetic Architectural Structures***,** Breinigsville: VDM Verlag Dr. Mueller (2010)
As quoted by: El-Zanfaly, Dina, *Op. Cit.* (2011) P.16

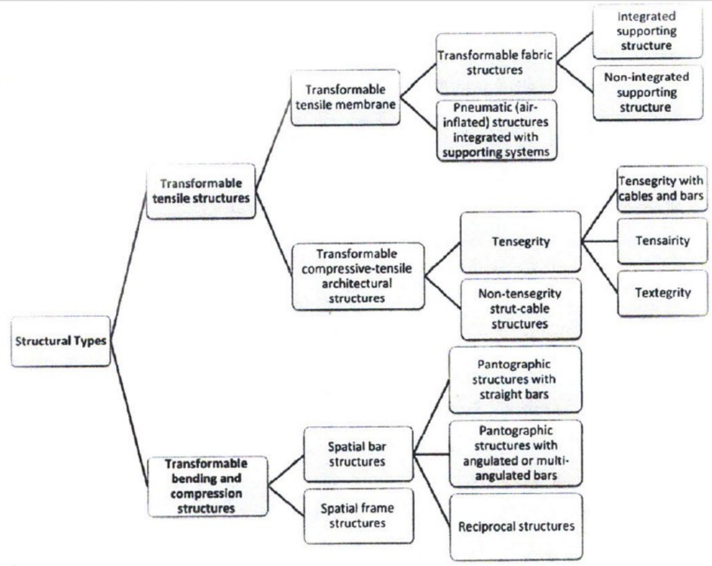


Figure 3: Classification of transformable Architectural structures according to Maziar Asefi

Classification of transformable architecturek structures, Maziar Asefi (2010) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures,* P.17)

In his book *Move: Architecture in Motion- Dynamic components and elements, Michael schumacher* (sub) *classified kinetic architectural structures to motion types of buildings and buildings elements:*

1. *Swivel*
2. *Rotate*
3. *Flap*
4. *Slide*
5. *Fold*
6. *Expand*
7. *Gather and roll up*
8. *Pneumatic*[260]

This classification is interesting because it is built around motion types, but contrary to *Active Shape's* grammatical analysis, here it is used to define the entire structure instead of being a instrument for formal model construction and, as a matter of fact, it is the exact opposite use of motion types (kown as "motion controllers" in El-Zanfaly's vocabulary but, in fact, they define the same phenomenon). This classification will prove useful in parametric setting when in the process of modeling simulation. Michael Fox came up with a classification system that is simple enough, yet at the same time could

[260] *Schumacher, Schaffer, Vogt (2010)*
As quoted by: El-Zanfaly, Dina, *Op. Cit.* (2011) P.16

group all the above classifications, to be shown on three main criteria: *embedded, dynamic* and *deployable* kinetic structures.

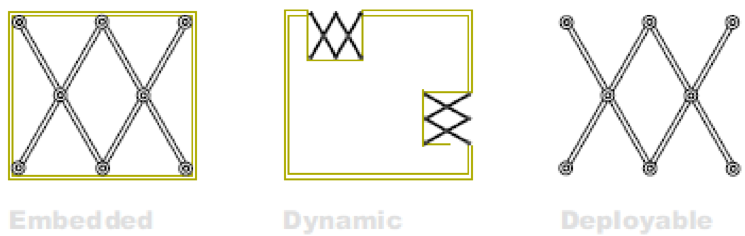


Fig. 00: Diagram of Kinetic Typologies in Architecture

Kinetic system for Kinetic Intelligent Systems, Michael Fox (2001) (Fox, Michael, *Intelligent Kinetic Systems,* P. 11)

Embedded kinetic structures

"Embedded Kinetic structures are systems that exist within a larger architectural whole in a fixed location. The primary function is to control the larger architectural system or building, in response to changing factors."[261]

Deployable kinetic structures

"Deployable Kinetic structures typically exist in a temporary location and are easily transportable. Such systems possess the inherent capability to be constructed and deconstructed in reverse."[262]

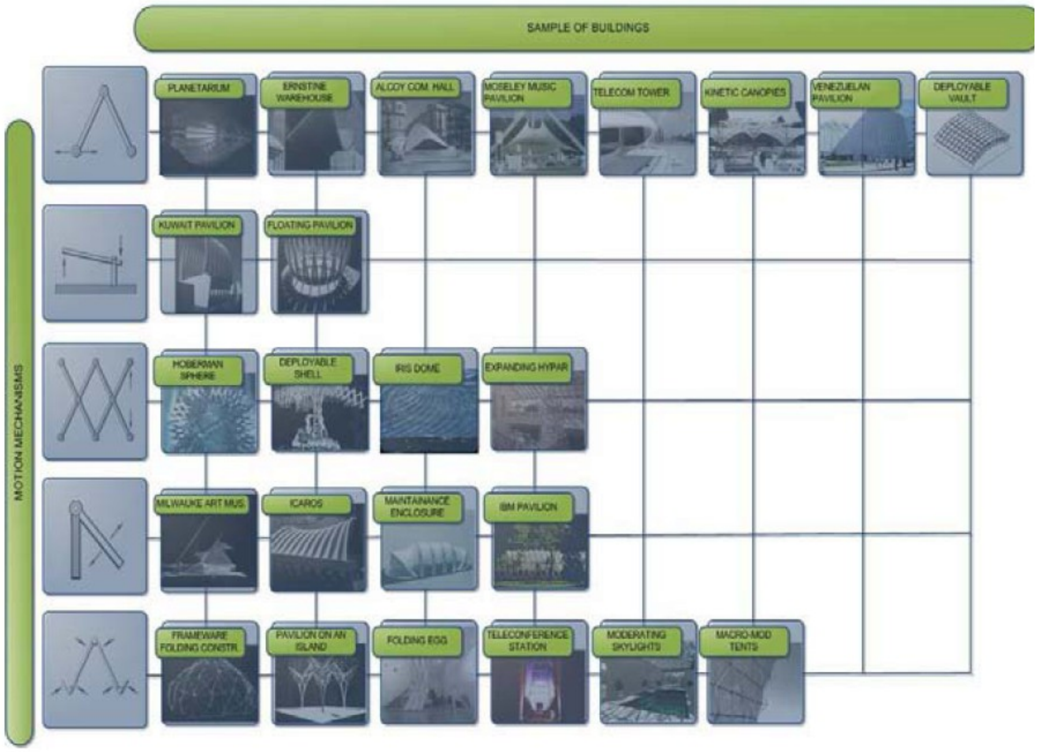
Dynamic kinetic structures

"Dynamic kinetic structures also exist within a larger architectural whole but act independently with respect to control of the larger context. Such can be sub categorized as Mobile, Transformable and Incremental kinetic systems."[263]

In 2007 Angeliki Fotiadou wrote one of the first masters degree thesis to address the issue of software support to aid the process of designing kinetic architecture titled *Analysis of Design Support for Kinetic Structures* at the Technical University Vienna, in which she conducted the first thesis focused

[261] Fox, Michael - Yeh, Bryant, *Op. Cit.* (2001) *(a)* P.2
[262] Idem.
[263] Idem.

solely in researching the software tools and digital strategies needed to design kinetic architectural structures (this thesis research will be scrutinized in detail in chapter VI).



Motion mechanisms, Angelliki Fotiadou (2007)(Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 11)

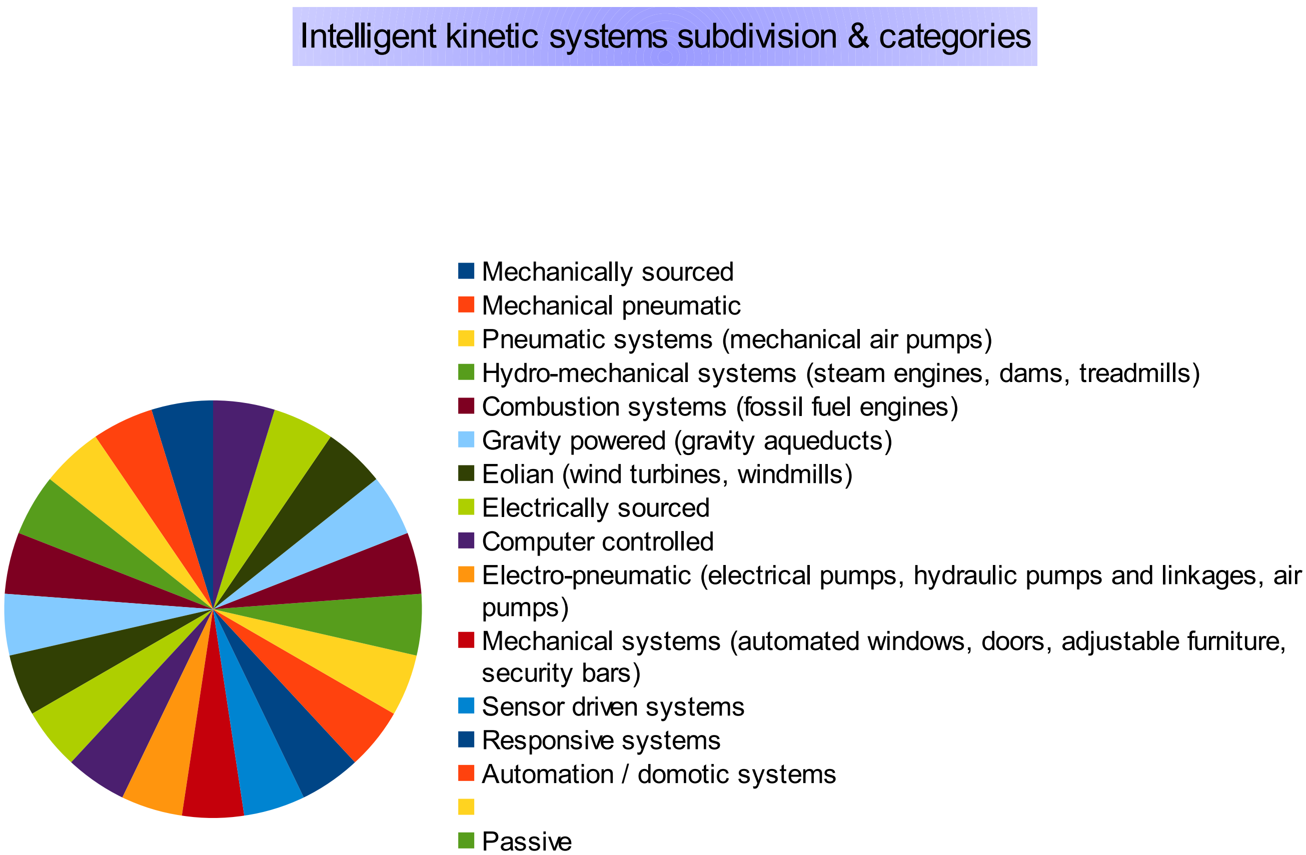
In this investigation she built a classification table that mapped kinetic buildings in relation to their motion mechanisms. What all these classifications it is made evident that, as of the writing of this research memory:

1. *There is no consensus insofar as classification is concerned*
2. *Nobody has taken a serious account of the energy consumption implications within the actuation methods in kinetic systems.*

*4.4.2- Means for kinetic structures_*

Energy consumption is an important aspect of this research's concerns, so stating energy sources becomes inherent to the process of systematic classification, especially in terms of defining a shape memory material kinetic system. During the course of this research, that precise concern becomes apparent: none of the previous researches have classified kinetic systems according to their energy source. Some of them just merely mention or imply certain energy consumption characteristics like "*Kinetically controlled static structures"* (Zuk and Clark) or *"Pneumatic"* (Schumacher), as if they just take for granted that these systems always work within electrical energy sourcing (or manual, if automation is not a necessity), meaning that automated passive systems have been not taken seriously into consideration insofar as typology is concerned. These axiomatic energy sources (or MEANS, as Fox defines them) exist in within three main subdivisions in kinetic system's energy sourcing:

1. **Mechanically sourced**
    1. Mechanical pneumatic
        1. Pneumatic systems (mechanical air pumps)
        2. Hydro-mechanical systems (steam engines, dams, treadmills)
        3. Combustion systems (fossil fuel engines)
        4. Gravity powered (gravity aqueducts)
        5. Eolian (wind turbines, windmills)
2. **Electrically sourced**
    1. Computer controlled
        1. Electro-pneumatic (electrical pumps, hydraulic pumps and linkages, air pumps)
        2. Mechanical systems (automated windows, doors, adjustable furniture, security bars)
        3. Sensor driven systems
            1. Responsive systems
            2. Automation / domotic systems
3. **Passive**
    1. Mechanical systems (windows, doors, adjustable furniture, security bars)
    2. **Programmable matter systems (abbreviated PM from here on)**
    3. Super conductor quantum locking systems (levitation)
    4. **Shape-memory material (SMM) (shape alloys and polymers, hydro polymers)**



And whereas in the real world systems tend to be the result of isomorphic combinations of the above mentioned, in the experiments and material research sections and chapters we will concentrate on the latter sub-systems category (shape-memory systems, that are within the sub-category programmable matter systems which, in turn, are within the passive systems category) which are powered by shape-memory materials (SMM) and, more specifically, shape-memory alloys (SMA) and polymers (SMP) because of their energy efficiency potential as we will see in chapters VII, VIII and IX. We will leave quantum locking systems out of the scope of this research due to the fact that, to be properly studied, they require specific competences in quantum physics that lie outside of this research's means of laboratory, time and staff requirements and the fact that their applications, although very promising, are not yet specific enough to be implemented as a tool for the practice of architecture and engineering, although that might change in the near future.

4.2.3-Control mechanisms in intelligent kinetic systems_

Michael Fox further classifies kinetic systems in therms of their control mechanism, in this classification, he secondarily addresses energy sources but, and this is very important, referencing back to Zuk, he does provide a functionality and automation assessment.

"Within each of the three typologies of kinetic structures: Embedded, Deployable and Dynamic, several levels of machines may exist simultaneously... ...Prior to describing the types of controlled movement for such kinetic systems, we will list a general breakdown of the levels of machines (Zuk, 1967)(sic) by their ability to adapt to differing needs:

1. *Singular in function*
2. *Multi-variable in function*
3. *Multi-variable in function with automatic control*
4. *Multi-variable in function with heuristic control"*[264]

This establishes a clear and simple difference between machines that only do one task, ones that can carry out different ones and multifunctional types themselves divided into automated and self-learning and problem solving types. According to these typologies, Fox and Yeh sub-divide a given kinetic system's control means.

[264] Fox, Michael - Yeh, Bryant, *Op. Cit.* (2001) *(a)* P.4

(Left) *Folding Egg Sectional prototype,* Michael Fox and KDG (2001) (*Intelligent Kinetic Systems,* P.4)
(Right) *Folding Egg Sectional prototype,* Michael Fox and KDG (2001) (*Intelligent Kinetic Systems,* P.4)

Control is a central aspect to be able to study movement properly and its design and construction relating to the constrains and issues due with its problematic, kinetic operability and maintenance, human and environmental interaction. The Kinetic Design Group has stated six principal control types, we will place shape-memory systems in each of these as an exercise of translating Fox et al's. Classification into possible re-classification, concerning control means, within the contemporary programmable matter specturm:

Internal Control
"Systems in this category contain an internal control with respect to inherent constructional rotational and sliding constraints. In this category falls architecture that is deploy-able and transportable. Such systems posses the potential for mechanical movement in a construction sense, yet they do not have any direct control device or mechanism."[265]

Shape-memory material systems fit in this control category, because their composition enables them to have certain mechanical autonomy, meaning that their inherent material construction makes them have "built in microscopic properties" that enable kinetic macroscopic ones which, in turn, are programmed

265 Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4

during fabrication. But as we will see further in this section, they can also be classified in different categories, at least within Fox's classification.

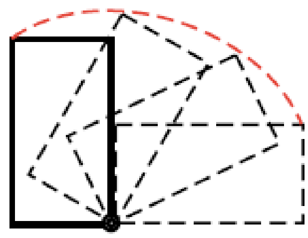
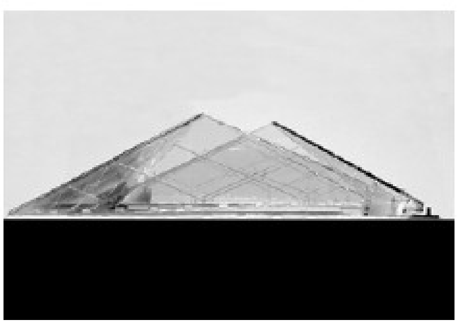


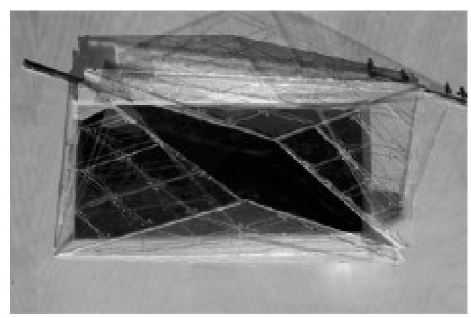
Fig. 1C: Diagram of Internal Control

Internal control diagram, Fox and Yeh (2001) (*Intelligent Kinetic Systems,* P.4)

Direct Control

"In this category, movement is actuated directly by any one of numerous energy sources including electrical motors, human energy or bio-mechanical change in response to environmental conditions."[266]





Skylight shown in Fig. 2A and Fig. 2B, Michael Fox and KDG (not dated) *(Intelligent Kinetic Systems, P.5)*

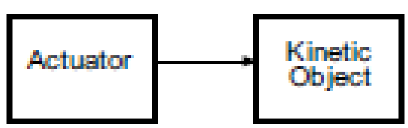


Fig. 2C: Diagram of Direct Control

[266] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4

Direct control diagram, Fox and Yeh (2001) ***(****Intelligent Kinetic Systems, P.5)*

As shape memory materials are defined as bio-mechanical and responsive, they also act in response to environmental stimulus and conditions[267], meaning that by Fox' standards, they also fall in this category (direct control), as they are chemically and mechanically programmed from fabrication, through a process called "training" which we will detail in chapter VIII.[268]

In-Direct Control (control via sensor feedback)

"In such systems, movement is actuated indirectly via a sensor feedback system. The basic system for control begins with an outside input to a sensor. The sensor must then relay a message to a control device. The control device relays an on/off operating instruction to an energy source for the actuation of movement. We define In-direct control here as a singular self-controlled response to a singular stimulus."[269]

Although, until now, the vision within shape-memory systems has been framed within the combination with sensor systems to trigger actuation(and therefore computer intervention -if not higher level control), these SMM materials harness autonomous control potential that also places their higher level shape-memory material systems, at least speculatively, in this category as well. In chapter IX we will test this speculation by putting it to experimentation.

[267] Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris - Arras, Peter, *Op. Cit.* (2011)
[268] Idem.
[269] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4

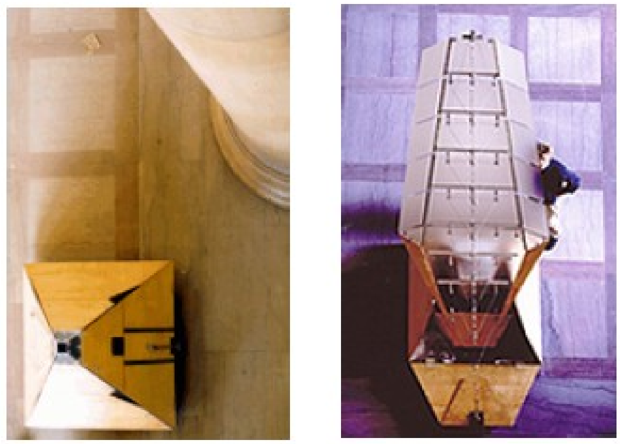


Fig. 3A, Fig. 3B: Deployable Teleconference Station

Deployable Teleconference Station, Michael Fox (1996) *(Intelligent Kinetic Systems, P.5)*

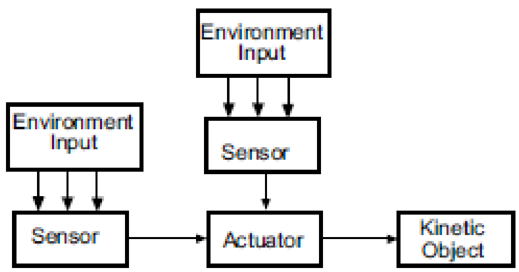


Fig. 3C: Diagram of In-Direct Control

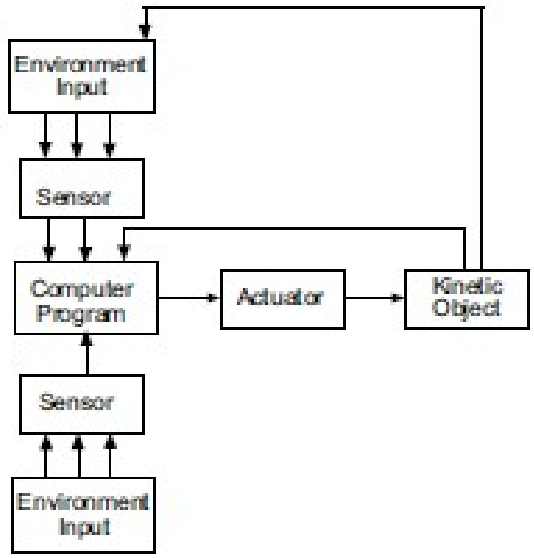
In-direct control diagram, Fox and Yeh (2001) *(Intelligent Kinetic Systems, P.5)*

Responsive In-Direct Control

"The basic system of operation is the same as in In-Direct Control systems, however the control device may make decisions based on input from numerous sensors and make an optimized decision to send to the energy source for the actuation of movement for a singular object."[270]

[270] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4

In this category, the main difference is the complexity in the information flow, something that is difficult to achieve with just material programming and maybe even unpractical (for the time being), but which suggests that shape-memory material systems can merge as sensors because of their



(Fig. 4A: Diagram of Responsive In-Direct Control

capability to sense and respond according to programmed actuation, this makes them, at least, a potential subset of this category.

Responsive in-direct control diagram, Fox and Yeh ***(****Intelligent Kinetic Systems, P.6)*

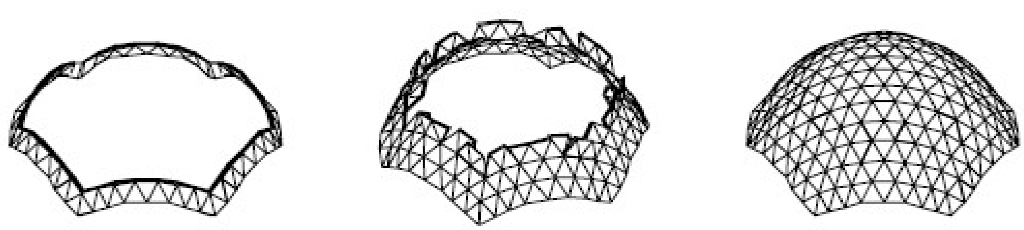


Fig. 4: Macro-Mod Folding Tents

Macro-mod folding tents, Michael Fox and KDG (2001) ***(****Intelligent Kinetic Systems, P.6)*

Ubiquitous Responsive In-Direct Control

"Movement in this level is the result of many autonomous sensor/motor (actuator) pairs acting together as a networked whole. The control system necessitates a "feedback" control algorithm that is predictive and auto-adaptive."[271]

Shape-memory systems are totally integrated to this category as it maps all of their capabilities and summarize everything that, as we will detail in chapters VII, VIII and IX, SMM are capable of actuating within such systems. This category sets the ground for this thesis research's spectrum of application within architectural and engineering systems design. What makes this typology so promising is that it ties up responsiveness and adaptability through the merging of sensors and actuators as single components, therefore opening it to the possibility of developing smarter, learning oriented kinetic systems.

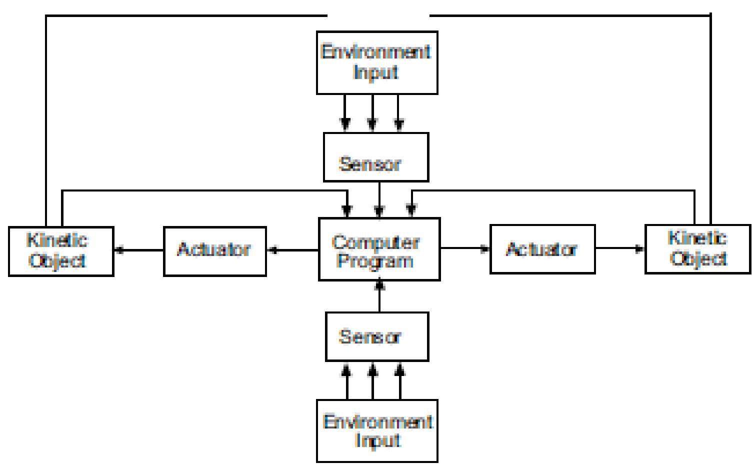


Fig. 5C: Diagram of Ubiquotous Responsive In-Direct Control

[271] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4

Ubiquotous responsive in-direct control diagram, Michael Fox and KDG (2001) ***(****Intelligent Kinetic Systems, P.7)*

Heuristic Responsive In-Direct Control

"Movement in this level builds upon either singularly responsive or ubiquitously responsive self-adjusting movement. Such systems integrate a heuristic or learning capacity into the control mechanism. The systems learn through successful experiential adaptation to optimize a system in an environment in response to change."[272]

One of this thesis's main aims is to prove through digital experiments that shape-memory systems's next step is very well the development of simulation based approaches and tool building aimed at their implementation in design projects, at the interior and architectural scale, that reside within the scope of this category. Even though there have been prototype projects like the *kinetic* wall by Bryant Yeh which address this problematic, they have not been fully developed to integrate full scale architectural projects (thus falling in earlier categories non the less being able to "learn" to adjust to certain stimulus) and were developed during a period where CAD and simulation techniques were not developed enough for these experiments to be carried out before laboratory, physical model testing.

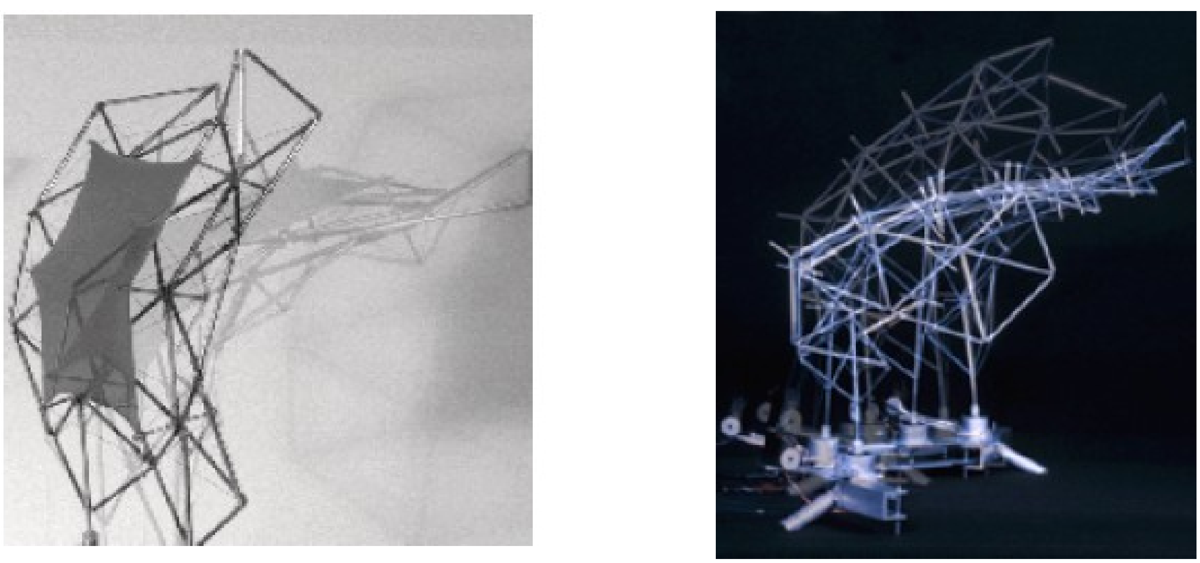
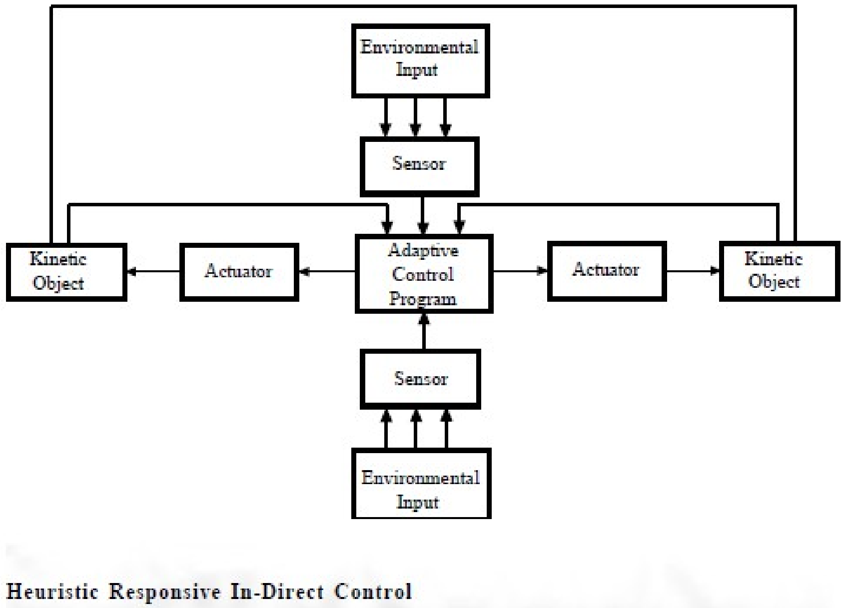


Fig. 5A, Fig. 5B: Kinetic Wall

Kinetic Wall, Bryant Yeh (1996) ***(****Intelligent Kinetic Systems, P.7)*

[272] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4



Heuristic Responsive In-Direct Control, Michael Fox and KDG (2001) ***(****Intelligent Kinetic Systems, P.8)*

4.4.4-Kinetic system's applications_

Kinetic systems have revolutionized artistic, architectural and engineering thought yet they have not been very successful at implementing their high level interactivity into the AEC industry, thus hindering building behavior to static confinement. This is largely because they are fairly difficult to predict (echoing Dina El-Zanfaly's conclusions earlier remarked -see section *kinesis as language*), model and break down to parts and parameters, in short, they are a headache for any designer, but computation and bio-mechanics are converging promising to overcome some of these obstacles.

"When we look at the higher levels of computer controlled behaviors an interesting phenomenon can be observed with respect to actual physical built form with respect to kinetic structures. What we are describing is a structure as a mechanistic machine that is controlled by a separate non-mechanistic machine: the computer."[273]

In this sense, computation and mechanics are making what artists and architects have been trying to

[273] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 3

address, almost fruitlessly, for more than four decades: transformable artifacts across all scales. In this sense, uncertainty is addressed in a local interaction based manner that gives rise to higher level systematization, a bottom-up hierarchy that can be broken down from specific applications to *multi-use interior re-organization to complete structure transformability to response to unexpected site and program issues*[274] at higher scales. *Specific applications may include intelligent shading and acoustical devices, automobile-parking solutions, auditoriums, police box stations, teleconference stations, devices for ticketing and advertising, schools and pavilions, as well as flexible spaces such as sporting, convention and banquet facilities.*[275] And, according to Fox, intelligent kinetic systems promise going beyond Fuller's material reduction in *ephemeraization*, but actually achieve existential or *component circumstantial reduction*: *Through the application of intelligent kinetic systems, we can also explore how objects in the built environment might physically exist only when necessary and disappear or transform when they are not functionally necessary.*[276] Or, what is otherwise known as *kinetic adaptability* which *further considers the rapidly changing patterns of human interaction with the built environment.*[277]

*4.5-Kinesis as structure_*

"Two notions dominate the traditional approach of engineering to the design of structure: stiffness and efficiency. Stiffness implies that structural members are optimized so that they do not easily bend, and members are arranged into whole structures that are rigid and inflexible. Efficiency characterizes the preferred mode of achieving structural stiffness with a minimum amount of material and energy. In this approach, any elasticity of the material from which it is made must be minimized, and elastic deformation of the structure under load is carefully calculated."[278]

How can we determine the physical properties of a kinetic system which is subject to change in form and disposition? The part of physics that studies movement is called *dynamics,* engineers have been developing and using it since centuries ago yet, for architecture, it has always been *statics* that has aided in the realization of architectural ideas. What they both have in common though is that they deal

274 Fox, Michael, *Op. Cit.* (2001) *(c)* P. 4
275 Idem.
276 Idem.
277 Idem
278 Emergence and design Group, "Fit Fabric: Versatility Through Redundancy and Differentiation", Emergence: Morphogenetic Design Strategies*, Architectural Design*, Wiley Academy Press, United Kingdom (2004) P.41

with the systematization of force testing and calculation. Especially in the case of this research's focused interest's systems (SMS and SMM) which can both become, potentially, self-assembly systems and self-organizing systems, therefore share an almost identical genesis and a necessity to be tested in laboratory experiments. *The characteristics and behavior of a form that has been evolved from a self-forming process have to be physically tested in experiments.*[279] This assumption is one which this research is aimed at reducing: the fact that behavior (in the case of SMS) *has to be tested* in the laboratory. This research argues that it can be implemented in computer generated simulations thus making a physical experiment relatively less necessary in the design phase. Certain complex form-analyzing methods that have been researched by relatively few people yet, most commonly, they have been grid shells and funicular structures, they are called *physical form-finding methods*, in which the form is the result of a a series of geometrical and force studies. Physical form finding experiments in architecture are thought to have begun with Gaudí and can be summarized as the development of modeling through form-finding techniques in the context of his interest in natural systems, the relation of experimental models to geometry, iterative mathematics and irregularity. These modeling processes prove immense aid with kinetic systems because they share one important characteristic: complexity and counter-intuitiveness. In a 2004 issue of *Architectural Design* magazine titled *Emergence: Morphogenetic Design Strategies*, the *Emergence and Design Group* discussed with Frei Otto certain decisive aspects of form finding since *in his work, form finding is a design instrument, based on empirical processes that utilize the self-organization of material systems under the influence of extrinsic forces.*[280] In order to clearly explain the thought and design processes leading to the constructive implementation of complex structures, according to him, *the range of possible forms is determined by the choice and definition of the conditions under which the form-finding process tales place.*[281] This means that this approach shows conceptual promise in the context of kinetic simulations as it can be, and it is in a physical way, a parametric model (see chapter II). Established the relationship between minimal surface and kinetic modeling, by extension, we can apply these principles into the digital parametric setup within computer simulations which *can be established through form-finding methods, which deploy the physical process of self-organization of a material system under the influence of extrinsic forces* [and intrinsic programmed responsive behavior to these, in the case of SMS]... ...*The range of forms* [and motions] is determined by the choice of the conditions [both

[279] Otto, Frei, *Op. Cit.* (2004) P.22
[280] Ibid. P.20
[281] Idem.

extrinsic and intrinsic] under *which the process takes place.*[282] These methods have been mostly developed in physical,scaled down material models but of considerable size for the scaling up no to be distorted by the effect of gravity; and even though Frei Otto was one of the first people to implement computer generated algorithmic methods to test theses structures, more often than not, these models are built in a shop with actual identical material at 1:1 scale, having certain difficulties with some materials as in the case of concrete.

"For testing forces the model must be made with the same materials and in the same form as the final structure. You can do this with steel wires, but it is nearly impossible with concrete. If the materials and the form are exactly the same as the final building, and if the model has the same load per square meter, then the same stresses appear in the model as in the building."[283]

Form and force are correlated, in that the form of a structure can be determined as the state in which the forces acting in and on it are in equilibrium [284]*,* this stands also true for kinetic structural systems, they are in a *process* of equilibrium, that in this case, can be said a synonym of dynamic state (even though in a another context it is seen as a different. *Furthermore, the flow of force can be shown through physical modeling.*[285] You can either focus these processes in two distinct approaches:

"The first system emphasizes the force, which acts in a surface or can be transmitted by it, or which was active during its development. The second system emphasizes the form of the developing object because its form is primary parameter in the evaluation of a structure. "[286]

In practice, though, the model's structural calculations often need to be developed from scratch since *if the form is new, then there will be no mathematical precedent and calculations are not immediately possible and models must be used.* [287] Very often the practicality of model making is addressed in an austerity measure manner, *finding the first shapes and understanding the structure is best done with small inexpensive models, some of which can be built in a few hours.* [288]

[282] Otto, Frei, *Op. Cit.* (2004) P.21
[283] Ibid. P.24
[284] Ibid. P.22
[285] Idem.
[286] Idem.
[287] Ibid. P.24
[288] Idem.

However, modeling is only a small part of the total job that an architect has to do in order to arrive at a building design, especially if the building has a complex function.[289] This meaning that the time and effort undertaken by a designer cannot be fully employed committed to calculation, in this context digital simulation play a decisive roll in the grounding of a kinetic structural design, because they can let the designer spend more time in the design aspects of the process, while the simulation runs the physical one, this shows a lot of promise for this research. This topic will be retaken in chapter IX in which research will apply some form-finding's basic concepts in the experiments phase with their implementation in computational methods (parametric modeling combined with scripting to replicate certain physical situations which arise in the behavioral conditions in SMM systems) to make physical kinetic modeling possible and reliable.

*4.5.1-Prototyping: application examples_*

In this section, we will explore some examples of application cases that have addressed, one way or another the issues concerning adaptation in architectural design. This research has focused in and will analyze three projects pertaining to three fields of research: architecture (*Responsive Skylights* -2001, *Muscle* -2003, *Topotansegrity* -2002), art (*Strandbeests* series -1990-XXXX), and an interactive media based theory called *Ambient Intelligence* (2012) (a paper that proposes an alternative towards architectural adaptability and flexibility, placed in this context as a counter point) comparing each of them, step by step, one to one with speculations about SMM and 4D printed based systems; that way sorting out which aspects to be tested during the experiments phase of the research. A certainly explanatory example is set in a series of projects within the Kinetic Design Group at MIT's development in the late 90's and early 2000's, though one specific design project stands out as to a possible "real world" architectural application because of its direct and concise addressing of a fundamental architectural problem: *the problem of regulating light into living spaces.*

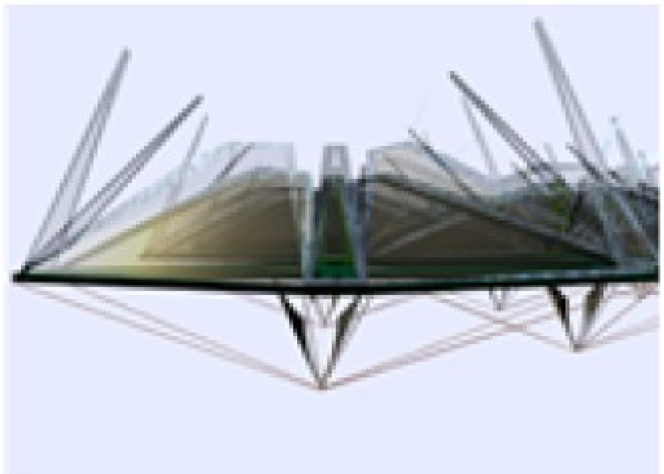
*4.5.2-Responsive Skylights_*

Architect: Michael Fox and KDG (2001)

This project was an intent to apply all of the kinetic design group's theories into practice and build some heuristics within the context of design and construction:

[289] Otto, Frei, *Op. Cit.* (2004) P.24

[290]*Responsive Skylights is exploited for the simplified prototypical attributes it displays relative to kinetic function, human interaction, adaptive control and realistic operating conditions. The project is a specific application scenario that actually affects the nature of the architectural construct. The intent is to provide an example for both further speculations in the area as well as real world applications.*

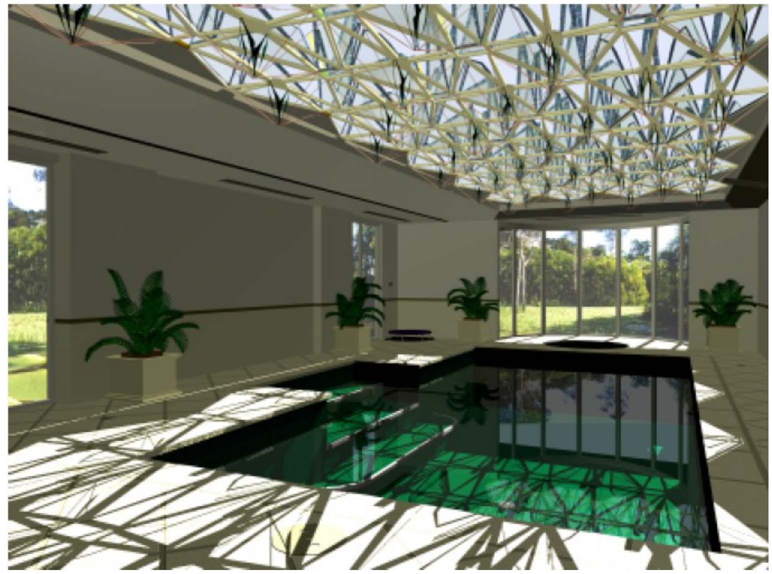


Responsive Skylights, Michael Fox and KDG (2001) *(Intelligent Kinetic Systems, P.5)*

This project is described below as:

[291]*Specifically, the design project is a networked system of individually responsive skylights that function together to optimize thermal and day lighting conditions. Primary design considerations are to utilize natural daylight in the space, to take advantage of natural ventilation and ultimately to reduce energy costs.*

[290] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 5
[291] Idem.



Responsive Skylights, Michael Fox and KDG (2001) ***(****Intelligent Kinetic Systems, P.5)*

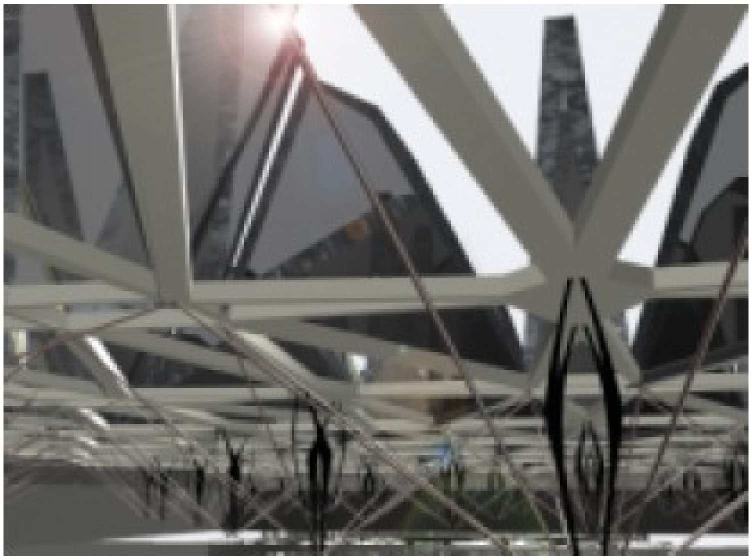
From here on, we will analyze certain aspects of the project that are in consonance with certain aspects of shape-memory based systems and 4D printed material based systems which are: ***mechanical control system***, ***embodied energy***, ***construction system*** and ***embedded computation***.

Mechanical Control System

"The prototype system contains six units. Each unit contains eight individual panels that slide along four straight lines towards the center of the panel to create an open position. The system maintains structural stability throughout all stages of deployment of the individual units. One of corner joints of a singular unit contains an individual cable attached to a servomotor that deploys the unit as an individual whole through sliding that joint towards the center of the unit. Integrated computer control is done with a system of positional sensor devices attached to each unit."[292]

In comparison to SMM and 4D printed based systems, this project are very much alike, yet one fundamental difference is clearly seen: SMM and 4D printing are aimed at eliminating computer direct control, advocating for programmed material independence, using the computer as a regulator instead of a controller (as a fail-safe intervention actuator)**.**

[292] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 5



Responsive Skylights, Michael Fox and KDG (2001) *(Intelligent Kinetic Systems, P.8)*

Embodied Energy

"An assessment of the embodied energy costs (rather than just energy consumption) inclusive of the entire energy costs for the structure should be considered. Such an assessment must be taken into account for the entire life of the structure, including raw material processing, manufacture assembly, structure life-span and energy consumption. Where the initial costs of fabrication and installation may be higher for an intelligent kinetic system, it is important to understand the long term benefits of such a system in an (environmental perspective)."[293]

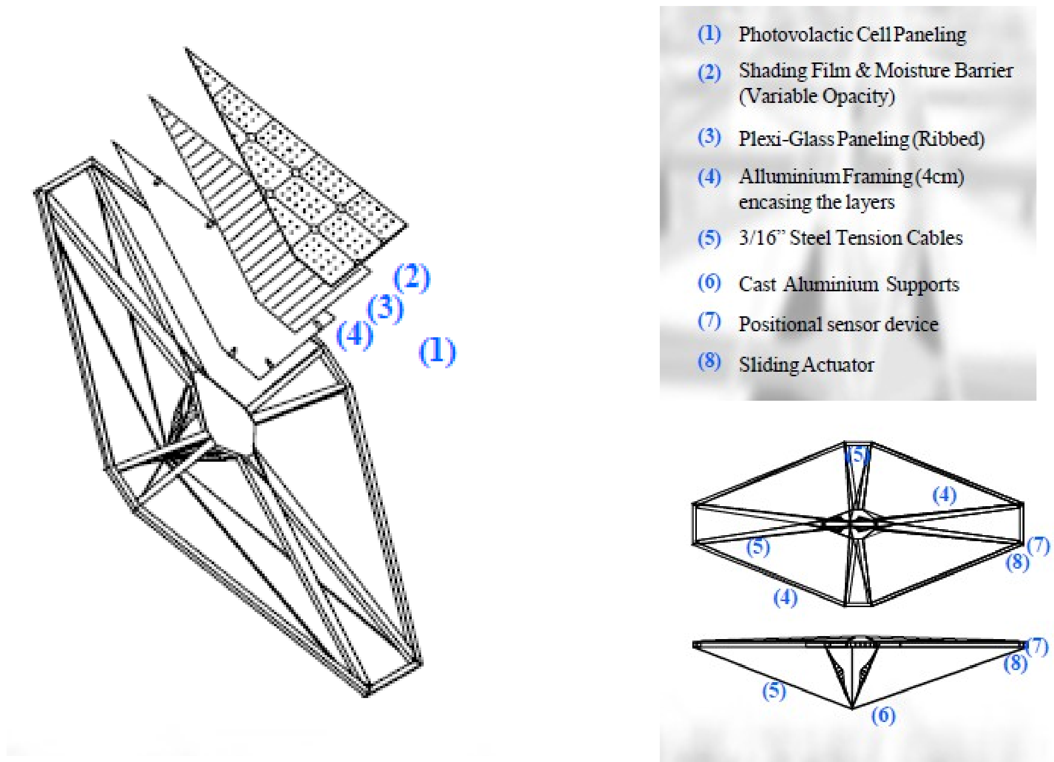
A similar assessment can be stated about SMM and 4D printed based systems, the initial investment is larger in comparison to other kinetic systems, but consideration of the long-view of its benefits, although outside of this thesis scope, are worth pursuing to further legitimize them as viable solutions.

Construction System

"Each panel consists of photovoltaic cell paneling under which lies a layer of shading film/moisture barrier of variable self-adjusting opacity. This skin is affixed to a ribbed Plexiglas panel affixed to a structural aluminum frame."[294]

293 Fox, Michael, *Op. Cit.* (2001) *(b)* P. 6
294 Idem.

In SMM and 4D printed based systems, compared to mechanical systems like this one, there should be considerable reduction in terms of the number of pieces and functionality, as far as materiality is concerned, there will be funcionalities that should be absorbed by SMM into integrated sensor/actuation mechanisms.



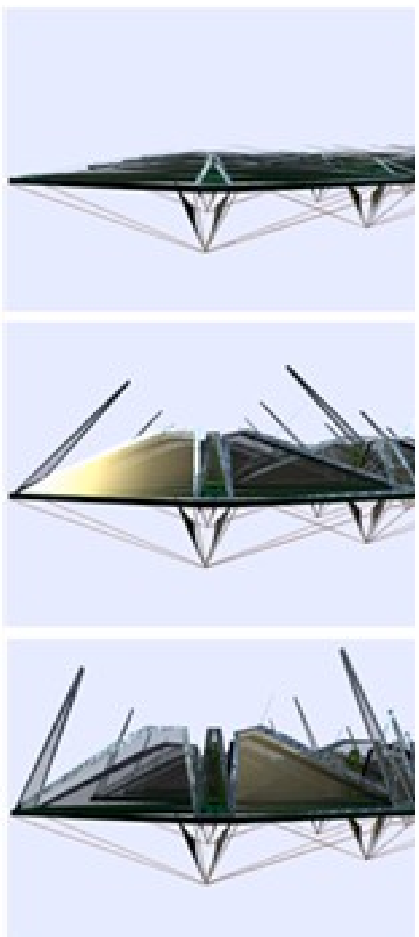
Responsive Skylights construction component detailing, Michael Fox and KDG (2001) ***(****Intelligent Kinetic Systems, P.6)*

Embedded Computation

"The systems learn through successful experiential adaptation to optimize a system in an environment in response to change. Optimum thermal and natural day lighting conditions can be achieved through the algorithmic balance between the individual deployment of the panel units and the individual opacity variances. As a user adjusts an individual Unit, for instance to provide shading, the system learns through observation to automate such needs. We believe that adaptive control of the kinetic motion will yield economic benefits under such realistic operating conditions."[295]

[295] Fox, Michael, *Op. Cit.* (2001) *(b)* P. 7

Optimization in SMM and 4D printed based systems is, arguably, directly derived from these guidelines, these performance goals are exactly why programmable matter systems are being formulated to address the built environment in the first place, although through digital implementation, separating the material's thermal conditions from that of the environment itself presupposes an energy transfer break that should not be so pronounced in pure SMM systems. Yet this is the direction that future computation driven design should take in turn to achieve most of the goals set by genetic architecture (see chapter II). This topic will be speculated upon in a later section of this same chapter (see Ambient Intelligence).



Responsive Skylights, Michael Fox and KDG (2001) ***(****Intelligent Kinetic Systems, P.7)*

4.5.3-Standbeests_

Artist: Theo Jansen (1990-XXXX)

Strandbeests, is a project by dutch artist Theo Jansen who has spent the last 21 years evolving a series of wind-powered mechanical, autonomous animals that are made of plastic tubes.

Structure and Movement

"The basic Strandbeest design is comprised of multiple pairs of legs attached to a central crankshaft. When the animals are fed by wind, they begin moving and transmuting into organic-looking creatures; or beach-animals as Jansen calls them. When walking, a galloping herd effect is produced with each leg timed to move so that the 'body' stays level and steady."[296]

Theo Jansen is a scientist turned artist, and his approach to kinetic structures a not exactly buildings edifices, yet they share with them characteristics like scale, structural performance and so on. His interest in developing intelligence into his *Strandbeests*, which mimic life like creatures, does open up an important question regarding the genetic architecture paradigm (see chapter II) and is relevant to the discussion about kinetic architecture because it addresses the same problems that kinetic systems currently face: how to adapt autonomously to uncertain circumstances. They can *sense dangerous territory, such as water and loose sand with a feeler, which sucks air, and upon a change in resistance i.e water, the Strandbeest reverses away from the hazard* [297] thus mimicking the behavior of a living entity, at least when it comes to movement and energy spending. *The resulting movement conveys the walking pattern of a four-legged animal. The makeup of the leg lengths and position of the crank affects the gait of the animal.*[298] Joe Klann, a mechanical engineer, runs a website in which he compared his own work's linkage (called *Mechanical Spider*) to the that of the S*trandbeest's.* Which further clears, by stating differences, the complexity they both achieve and share through different setups: *Both are similar in that they operate in a single plane, provide a constant axle height, use only pivot joints, a rotating crank for input, and can easily be scaled in size but there are significant differences.*[299] Scaling up is one of the most important characteristics in the *strandbeest's* bipedal system (which has been

296 Fenwick, Tess, *Op. Cit.* (2011) P. 32

297 Jansen, Theo, *Mechanism, (*http://www.mekanizmalar.com/theo_jansen.html) (Accessed Oct 10, 2011). As quoted by: Fenwick, Tess, *Progamme: Morphosis, Op. Cit.* (2011) P. 32

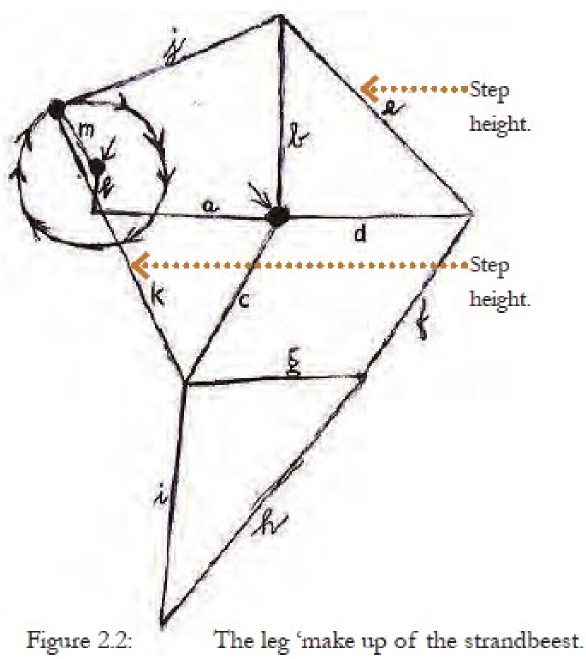
298 Idem.

299 Klann, Joe, Mechanical Spider, *Jansen – Klann Linkage Comparison* (http://www.mechanicalspider.com/comparison.html.) (05/03/2015)

shown to be a recurrent problem in SMS categories -see previous section) because it shows how relatively simple mechanisms can, in practice, be scaled up to fit specific purposes, even a certain degree of auto-adaptive autonomy.

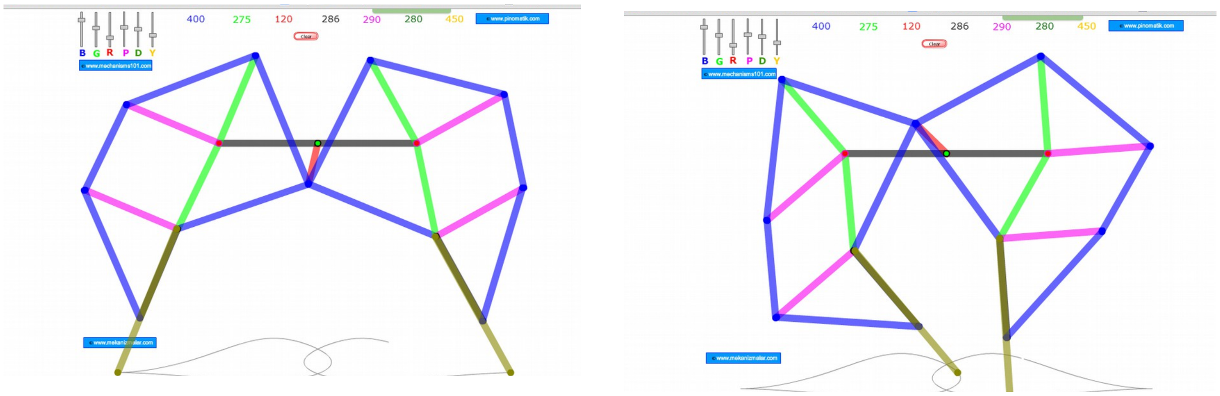
Jansen's linkage system can be broken down into three main parameters:

1. *Eight links per leg.*
2. *120 degrees of crank rotation per stride.*
3. *Step height is primarily achieved by a parallel linkage in the leg that is folded during the cycle angling the lower portion of the leg.*[300]

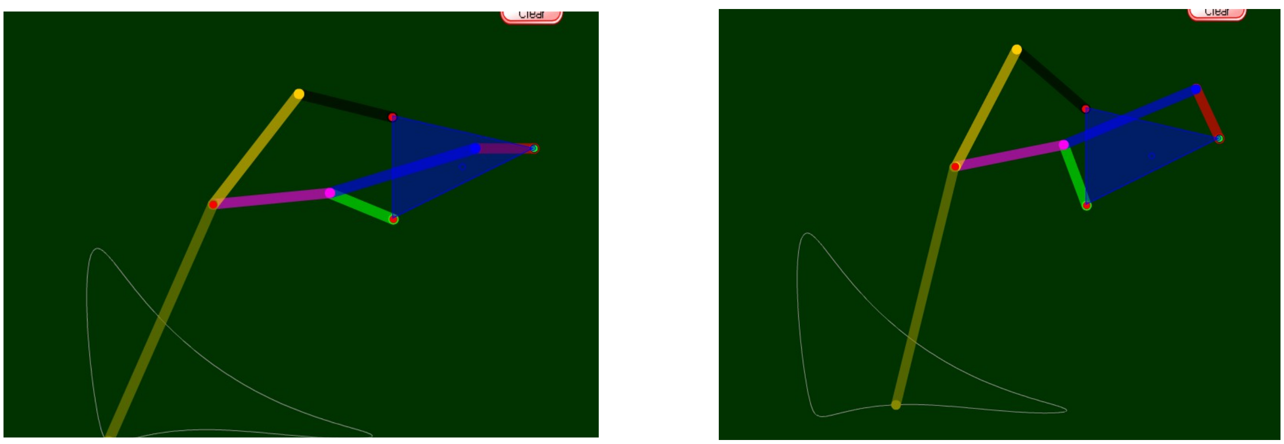


Stranbeest's *linkage system*, Tess Fenwick (2011) (Fenwick, Tess, *Progamme: Morphosis,* P. 32)

[300] Klann, Joe, *Op. Cit.* (05/03/2015)



Stranbeest's Theo Jansen (1990-XXXX) *linkage system flash animation,* courtesy of mekanizmalar.com (http://www.mekanizmalar.com/theo_jansen.html) (05/03/2015)



Mechanical spider's, Joe Klann (2010) *linkage system flash animation,* courtesy of mekanizmalar.com (http://www.mekanizmalar.com/mechanicalspider.html) (05/03/2015)

Next steps

"I think the next steps will be their brains. Now they have stomachs and can walk on air. But the brains are something, which they really need. Right now, I can only leave them alone for 5 minutes and if I want to extend that period they really must learn to think for themselves."[301]

The search for intelligence within kinetic systems, we can now state, is not just a caprice of architecture nor engineering, at least in Jansen's view, it is a logical step towards living artificial creations.

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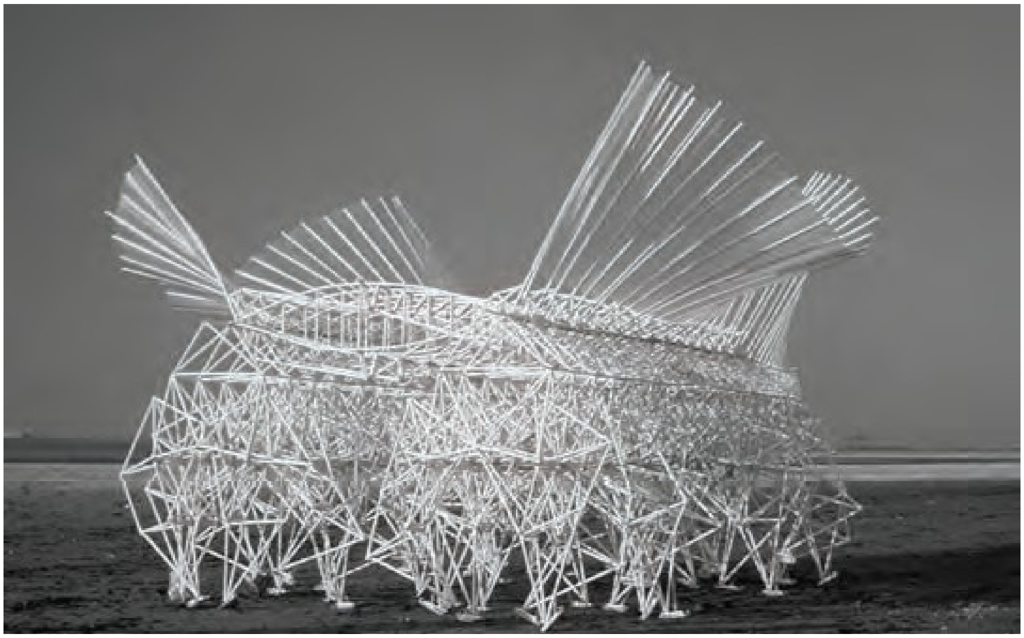
301 Jansen, Theo, *Interview with theo Jansen* by Artificial.dk (http://www.artificial.dk/articles/theojansen.htm)(27/03/2014)



(Fenwick, Tess, Progamme: Morphosis, P. 33)

4.5.4-MUSCLE: Trans-Ports Proactive Building Concept_

Architect: ONL (Oosterhuis & Lénard) (2003)

Programmable architecture:

MUSCLE was a prototypical kinetic interactive building project, it is one of the most representative attempts to solve the program accommodation via shape shifting environments in an intelligent, programmable manner. It *is a programmable building with six modes being: artmode, officemode, networkmode, infomode, commercial mode, and dancemode.*[302] This project was the culmination of a series of research cases within motion kinematics that started with *Tans-ports*(*2001), at the time "transports" represented an initial step towards the paradigm shift from frozen architecture to architecture in real-time ... transports" will be the first truly e-motive building.*[303]

What is relevant in this project's case is the interactive implementation, although not an SMS, having been made *up of pneumatic hydraulic space frames, which connect together with spherical joints allowing the space frame to move in three dimension*[304] as a basic structural frame, in that *the* [MUSCLE's] *space frame bars are adjustable in length and work together to morph in real-time,*

302 Fenwick, Tess, *Op. Cit.* (2011) P. 34

303 Oosterhuis, Kas, *2000 Trans-ports | Architecture Biennale Venice,* (http://www.oosterhuis.nl/quickstart/index.php?id=167) (27/03/2014).
As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 34

304 Fenwick, Tess, *Op. Cit.* (2011) P. 32

according to data received from the trans-ports game [305] which makes it a game changing project, as it deals with responsiveness and autonomy in a same setup based on the notion of KDG's ***Ubiquitous Responsive In-Direct Control*** (see section *kinetic control means*) and a built example of programmed structures.

"Varying air pressure can change the length, height and width of the MUSCLE to one third of its original size... The space frame of the body can relax, become flexible, supple and bendable, but it will resist extreme forces and become as hard and strong as any permanent construction."[306]

Material performance

"The interior and exterior material has to be truly flexible to follow the space frame structure. ONL developed a strong and elastic conceptual "3-d membrane, which expands and shrinks ... seamlessly cocooning the moving structure."[307]

This venture into material behavior + computer programmed responsiveness *eliminates the need for six static buildings, as the extremely flexible space alters for each individual mode.*[308] This alone makes this a very important contribution to the kinetic systems panorama. As Tess Fenwick remarks *the structure becomes programmable and never stops calculating*[309], making it a recursive loop informational structure *based upon spatial adaptability, technology, movement and* (that) *has an innovative aesthetic and form derived from the morphing of these aspects.*[310]

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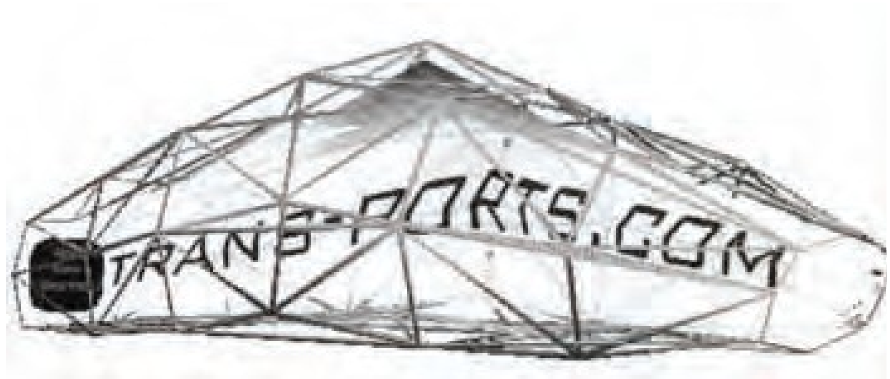
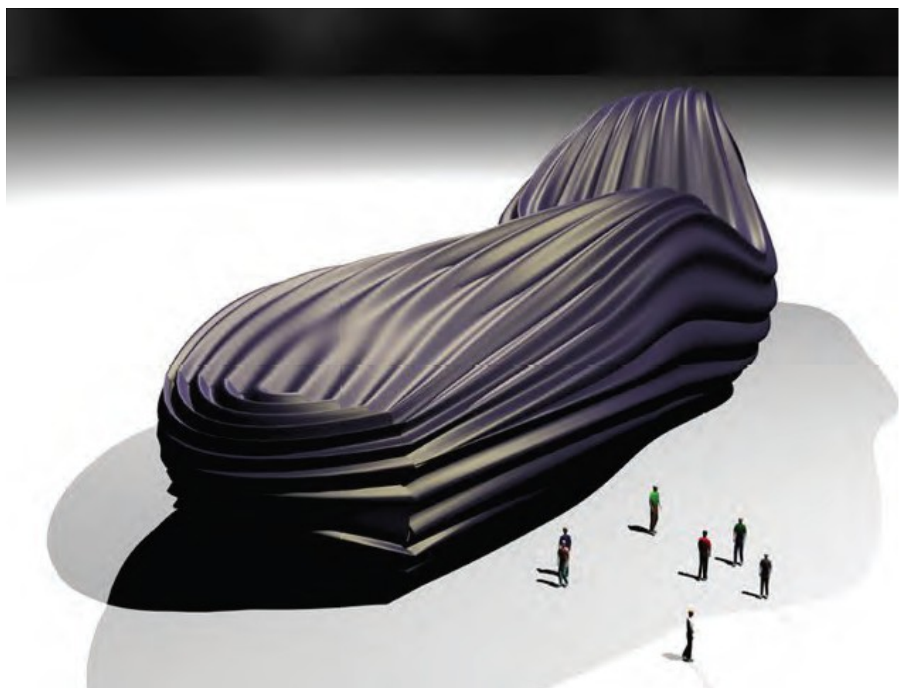
305 Ban , Alvin, *Trans-ports by Kas Oosterhuis,* (http://alvinban.blogspot.com/Oct 2007)
As quoted by: Fenwick, Tess, *Op. Cit.* (2011 P. 34
306 Oosterhuis, Kas, *2000 Trans-ports | Architecture Biennale Venice,* http://www.oosterhuis.nl/quickstart/index.php?id=167. (27/03/2014).
As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 34
307 Oosterhuis, Kas, *Architecture Goes Wild*, (https://books.google.fr/books?id=x2rbets9gWMC&pg=PA222&lpg=PA222&dq=transports+oosterhuis&source=bl&ots=bARGDQebDf&sig=zHd6-m5RIosaFwH7N-OVydlgxf8&hl=en&sa=X&ei=pYr4VIK9JYP3UpzfgdgM&ved=0CDgQ6AEwBA#v=onepage&q=shrinks&f=false) (2002), P. 96.
308 Fenwick, Tess, *Op. Cit.* (2011) P. 34
309 Idem.
310 Idem.



The adjustable MUSCLE space frame, ONL (2003) *(Fenwick, Tess, Progamme: Morphosis, P. 35)*



The MUSCLE, ONL (2003) *(Fenwick, Tess, Progamme: Morphosis, P. 35)*

*The MUSCLE prototype,*ONL (2003) *(Fenwick, Tess, Progamme: Morphosis, P. 35)*

4.5.5-Topotransegrity - Non-linear Responsive Environments_

Architect: Robert Neumayr. (2001)

Another example, this time a the urban scale through building design, sit he responsive project called *Topotransegrity*, carried out by architect Robert Neumayr, which *explores how the integration of an intelligent responsive architecture will impact on an urban space, and public life, essentially challenging architecture as a passive arrangement.*[311]

It is a kinetic concept scaled up to the urban scale that employs both KDG's control methods and ONL's aspirations in a larger influence sphere. *Topotransegrity connects users, spaces and real-time performance criteria, whilst continuously assessing its surroundings via ubiquitous technological devices.*[312] In this research, real-time connection (as in MUSCLE) and informational exchange and control via sensor technology (as in KDG's classification) become the grounding platform for an architectural whole that, *by adapting to isolated spatial requirements topotransegrity challenges the notion of a static architecture.*[313]

311 Fenwick, Tess, *Op. Cit.* (2011) P. 36
312 Neumayr, Robert *Topotransegrity.*
As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 36
313 Idem.

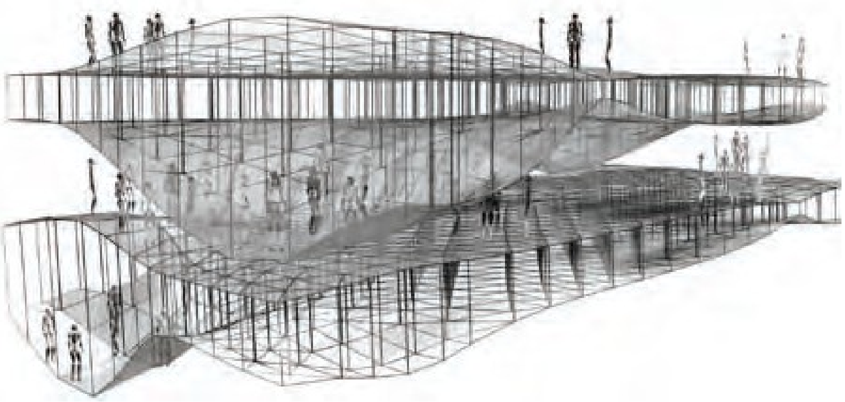
"Topotransegrity's ability to configure to isolated spatial requirements, whilst not necessarily affecting the rest of the surface, is critical. However, it appears that there is an element of unpredictability in controlling the surface as the three modes run simultaneously and the spatial configurations are user-dependent."[314]

Like all the other projects and researches cited in this section, it shares the issues of uncertainty (a recurrent topic within kinetic architecture), adaptability and control but, in this case, the actual prototype vehicle project is *a six level, static structure* (that) *contains an interlocking space frame system, ...which is powered by air driven pistons to drive re-configurations.*[315] (Placing it in the electro-pneumatic sub-category within our previous developed classification). *The ideas of spatial adaptability, the extent of the movement, and differing programme modes were particularly useful for this project.* [316] This notion of accommodation of plural programs in a single space is also consistent with ONL's work for MUSCLE, KDG's Kinetic Wall, and Folding Egg (see previous section for details), proving it a recurrent aim of kinetic architecture systems at large, not mattering its classification.

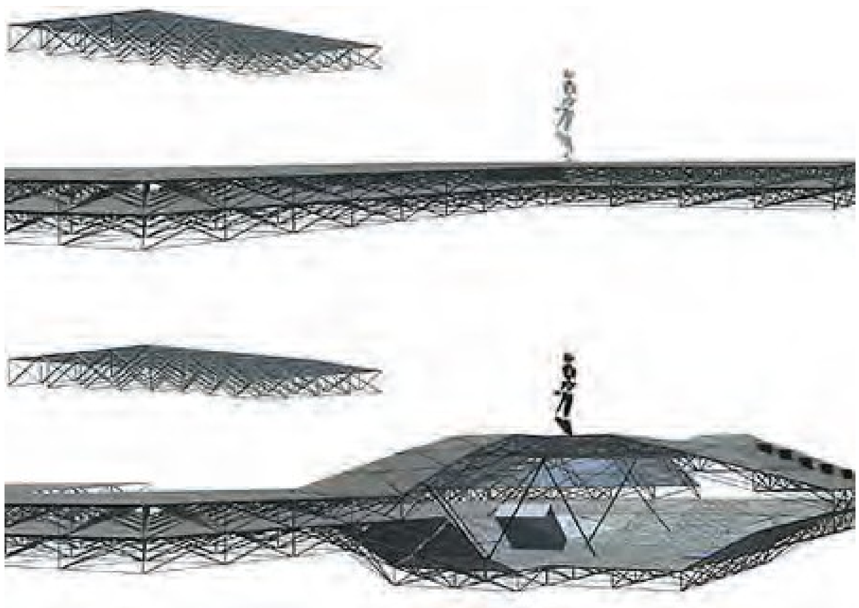
In terms of programme, *Topotransegrity* has three modes of being:

1. *Programme Mode – "automates the basic functions of the structure. Directly related to the specific event schedule of its environment it drives the generic transformations, initiating and locating the deformations that control the access and the circulation within the public spaces. It also generates small emergent temporary spaces, which host ancillary programmes related to ongoing events."*
2. *Crowd Mode – "responds in real time to the movements and behavioral patterns of the visitors within the structure. It influences the size, orientation and development of the temporary enclosures, previously established by the program mode."*
3. *Memory Mode – "records, on a long-term basis, the paths and motion patterns chosen by individual users, influencing the surface topography by indicating and levelling the most frequented parts."*[317]

[314] Oosterhuis, Kas- Feireiss , Lukas, *The Architecture Co-Laboratory,* 427.
As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 37
[315] Ibid. 432. As quoted by: Ibid. P. 36
[316] Idem.
[317] Olson, Marisa, *Topotransegrity Non-Linear Responsive Environments* (http://rhizome.org/editorial/2006/apr/12/topotransegrity-non-linear-responsive-environments/.) (Accessed April 6, 2011).



Topotransegrity's interlocking space frame, Robert Neumayr. (2006) *(Fenwick, Tess, Progamme: Morphosis, P. 37)*



Topotransegrity adapts to isolated spatial requirements, Robert Neumayr. (2006) *(Fenwick, Tess, Progamme: Morphosis, P. 37)*

"[The] *control of the surface, and in fact any moving building / building parts, with both appropriate parameters and the ability for the user to override the computer is vital for success. It appears that a parameter applied to the surface limits movement to approximately 180°. This essentially affects the extent of movement in the surface."*[318]

[318] Fenwick, Tess, *Op. Cit.* (2011) P. 37

All of these projects have been implemented and (in some cases) built with the aided assistance of CAD parameric models, it has become apparent that in practice there is a growing interest in the mathematical modeling within these computational environments on the account of time economy and material reduction as will be tested in chapters VII, VIII and IX.

4.5.6-Ambient Intelligence (AmI)_

Theorist: Socrates Yiannoudes (2012)

"Adaptive architecture is a term that usually refers to physical structures with mechanical properties and kinetic capacities able to adapt to changing needs and circumstances. These structures, ranging from Chuck Hoberman's and Buro Happold's transformable structures to Kas Oosterhuis' computationally enhanced "Hyperbodies", seem to be too inflexible for adaptation, due to the material limits and interrelations of their structural components. In this paper, we set out to explore the potential of ambient intelligence to augment architecture with adaptive capacities. In particular, we examined the so-called end-user driven intelligent environments implemented through tangible computing systems and artifacts, and discussed how these environments deal with indeterminacy and open-endedness, by empowering occupants to customize and personalize their domestic environments through improvisational engagement. We explained how these environments can be seen as "ecologies", assemblages of people, software and hardware, working in a conversational manner to achieve open, indeterminate, multiple and user-customized functionalities. To relate this approach with architecture we proposed the "digital" layer, in the order of the 5 layers in the organization of buildings according to Leupen's theory, which would constitute the changeable -adaptive- part. More importantly, we highlighted the fact that the functionalities emerging from this layer, have to do with the management of information and energy supply, the levels of comfort and environmental perception, rather than the physical transformation of the building or structure."[319]

Using **AmI** as a tool to integrate simulation for programmed architectural objects. To deal with the inflexibility of architecture and so called "adaptable architecture" in the face of user interaction and thus user influence in changeability within space functionality, Socrates Yiannoudes, a researcher at the

[319] Yiannoudes, Socrates, " Architecture in the Field of Ambient Intelligence: Towards a "Digital" Layer in Buildings" *International Conference: Scaleless – Seamless Performing a less fragmented architectural education and practice* (2012) P. 342

School of Architecture Technical University of Crete, Greece has come up with a vision that reacts to kinetic systems, as a critique, proposing digital layer systems instead of kinetic ones, to address adaptability, flexibility and uncertainty in the context of a building.

"Ambient intelligence (AmI) is a vision of the field of computer science aiming by definition at the creation of spaces, the so-called Intelligent Environments, able to respond to the presence and activities of people in an adaptive and proactive way by supporting and enhancing their life through smart devices. Although automatic buildings have been around since the 1950s and 1960s."[320] *...In the context of AmI, it refers to autonomously functioning systems able to provide automated services, assessing situations and human needs in order to optimize control and performance in architectural space.*[321] A concern that *Responsive Skylights* questions as also a functional aspect of information management's implementation within building performance. He goes on talking about embedded computation as in KDG's projects. *Such systems use environmental information acquired through activity recognition / detection- as feedback to obtain knowledge and experience, through learning, memory and proactive anticipation mechanisms, in order to adapt to personalized needs as well as changes of user habits.*[322] Both theories aim towards the fulfillment of personal (user) needs (see earlier section *Responsive Skylights*) so, in that sense, at least theoretically, there is still no distinction from KDG's perspective.

"Tangible computing systems, which are part of the wider field of intelligent environments applications, involve everyday environments, objects or devices enhanced with computational power, so that they will be able to become active agents, reacting to their environment and the activities of people, while knowing their location and their neighboring context. However, unlike traditional computational devices, such as mice, computer interfaces, keyboards etc, these systems interact with users through the affordances of everyday objects in 3-dimensional physical space."[323]

What he calls tangible computing systems are no more than gadgets or what is known as *ubiquitous computing* (arduino, smart-phones, sensors et al.) *a term used by Paul Dourish in the context of his embodied interaction theory which examines how meaning is produced, managed and perceived*

320 Yiannoudes, Socrates, *Op. Cit*. (2012) P. 335
321 Ibid. P. 336
322 Idem.
323 Idem.

through direct interaction with objects[324], that are put together or assembled to from complex digital integrated networks, a subject I have already explored in my earlier undergrad thesis research called *It's About time: Towards an architecture of Imaginary Multiconnections* (2005) (where it was argued that buildings should start behaving like computers: connecting us all to the global networks) and that I actually understand quite well, yet with a slight detour from his reach on augmented reality's implementation in building's: *In order to turn physical objects into tangible computing objects they must be augmented with hardware and software components which incorporate and determine their functionality.*[325] This proposition is not without sense, since interactive control is one of "the internet of things" basic propositions as interconnected cogs in the system configuration. *Digital information is thus embedded in physical form while manifesting itself through physical changes in the domestic environment: for instance, lighting patterns, sound signals or movement of furniture and architectural elements.*[326] In his vision, everything becomes a piece of the network and, by these standards, the separation between hardware parts and building blurs to the point of non recognition. *As far as hardware is concerned, tangible computing artifacts must have batteries, a processor, sensors and a wireless communication unit*[327], setting these requirements as minimum standards for becoming a network integrated gadget.

"According to Kameas et al., the points (properties and capacities) in which tangible computing artifacts differ from traditional objects are:

1. *• The artifacts possess information about their functionality, instructions for the execution of functions, and messages that can be sent to or received from other artifacts. Artifacts can process this information which appears in the digital space as data on what services the artifact can ofer or request from other artifacts.*
2. *• Artifacts can interact with their environment, understand the context of their use through sensors or by communicating with other artifacts, and respond to these stimuli using actuators.*
3. *• They also have the capacity for collaboration, i.e. they can exchange messages with other artifacts -from simple to complex data, such as programs and databases- through wireless communication.*

324 Dourish, P., Where the Action is: The Foundations of Embodied Interaction. London/Cambridge MA: MIT Press, 2001, p. 16.
As quoted by: Yiannoudes, Socrates, *Op. Cit.* (2012) P. 335
325 Ibid. P. 336
326 Ibid. P. 339
327 Ibid. P. 337

4. • *They can be combined with other objects, that is, they can be used as virtual building blocks of larger and more complicated systems. This can be achieved through their embedded communication unit and the capacity to publish their services to other objects.*
5. • *They also have the capacity to change or disconnect the digital services that they offer.*[328]

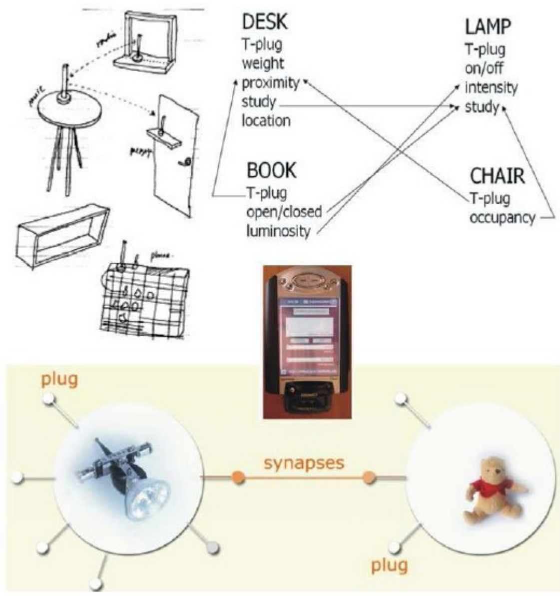


Fig. 2
e-Gadgets.

e-Gadgets, Socrates Yiannoudes (2012) ***(****International Conference: Scaleless – Seamless Performing a less fragmented architectural education and practice, chapter: Architecture in the Field of Ambient Intelligence: Towards a "Digital" Layer in Buildings, P. 338)*

After the gadget level, the next logical step is the definition of the network itself:

"In his book Frame and Generic Space, Leupen reviews a large number of mainly 20th century buildings analyzing their potential for flexibility and changeability through the exploration of the permanent rather than the temporary layer of their organization. [329]*This layer he calls "frame". To do this, methodologically he defines a system of 5 layers composing every building –structure, skin, scenery, services and access- which can acquire the role of the "frame" (the permanent layer) either alone or in combination with others."*[330]

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[328] Yiannoudes, Socrates, *Op. Cit.* (2012) P. 335
[329] Ibid. P. 339
[330] Ibid. P. 335

While he focuses on permanence (at first glance going backwards in the evolution of architectural systems as established in earlier in this chapter), he establishes a *layer* system (strangely enough, I called for the superposition of a *digital layer* to the existing constructive one in my undergrad thesis project) which is reminiscent enough of my earlier work and suggests a very important personal question: *is this framework just a necessary step towards understanding kinetic systems? Or is it actually the right path towards flexible architectural environments?*

Although for this research's ambitions, far more important issues arise from this plugin gadget position of a built environment:

1. *Discussions and debates circle around the concerns of computer scientists and engineers rather than architects. Is this because these two fields (architecture and ambient intelligence) are irreconcilable?*
2. This has been discussed in chapters I and II. and will be demonstrated within experimental proof in chapter IX.
3. *Or is it because we, as architects, have yet to develop a more open definition of architecture, extending our role and our form of practice?*
4. As will be demonstrated in chapter IX and has been theorized in chapter II, the practice of architecture is expanding towards IT at an ever-increasing rate.
5. *Should the profession of architecture engage a form of practice that no longer places the act of making buildings as the central and defining role of the architect?*
6. *Are we then witnessing a possible epistemological shift of the very identity of architecture, that is, a shift from the "hardware" of space -the built environment- to the immaterial architecture of "software" infrastructures and network configurations?*[331]
   (see chapter II)

In a number of visionary drawings, such as Holographic Scene Setter (1969), and Room of 1000 Delights (1970), architecture, no more the design of hardware, would dissolved into the "software", i.e. programs to enable diverse situations in a given space.[332] This was actually a question that my undergrad thesis also took on and got to the conclusion that architecture is indeed disappearing in the midst of speed and the instantaneity of the internet, challenging the definition of architecture itself.

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[331] Yiannoudes, Socrates, *Op. Cit.* (2012) P. 340
[332] Ibid. P. 341

Questioning the disciplinary limits of Architecture:

"Anticipating his (Reyner Banham) later book The Architecture of the Well-Tempered Environment, where he proposed an alternative architectural history seen through the lens of environmental control rather than through typology and form, Banham challenges the very identity of architecture shifting its definition from the monumental, the permanent and the enclosed to the environmentally sensitive system, the light, and the temporary."[333]

After thoughtful consideration, this research has come to the conclusion that, although Yiannoudes questionings about the limits of architecture are legitimate and represents a serious insight into the obstacles of kinetically embodied architecture and architecture at large in the face of the emergence of the internet of things, it is not conclusive enough in the sense that it does not demonstrate how this is achieved in experimental sets nor real world testing, no test project. It is a proposition (a very interesting one) that I myself have explored but that only states certain kinetic architecture example's limitations (which are non SMS based systems) as stated in the same paper:

"*Although this attempt to conciliate architecture with ambient intelligence applications in order to propose a more adaptive architectural environment is a theoretical one, the field is open for exploration by architects and researchers."*[334]

This research will prove that, in fact, what is needed is a theoretical and practical synthesis of the two approaches (echoing what Karl Chu states for molecular and developmental biology; and moprhodynamical and morphogenetic architectural approaches within contemporary architecture, see chapter II)

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333 Yiannoudes, Socrates, *Op. Cit.* (2012) P. 340
334 Idem.

*4.6-Conclusions_*

This chapter's conclusions have been done observing earlier theoretical approaches and classifications, and its has been established that these classifications can be carried out considering a number of “angles” or standpoints (e. g., Asefi's structural approach, Zuk's kineticism approach -or the way movement is generated-, Fox's “ways and means” approach -or how and where kinetic components are arranged and controlled and so on). This means that it is possible to find other manners on classifying kinetic components and structures. This thesis has demonstrated that there are multiple aspects to kinetic design and structural conception, that it can be seen as a concept (i. e., *kinesis* and its opposite -*stasis*-), a language, a system or as structure in the physical, althoug *dynamics oriented* sense. A different classification has been proposed to understand kinetic systems considering their actuation activation fashion.

1. Kinetic systems have been demonstrated to theoretically address, through “dynamic flexibility”, the problem of “change” and uncertainty”.

2. They have been also shown to give rise to emergent phenomena and that its definition stands as none other that of a dynamic system. As in Helen Castle's definition: “*emergence already surfaces as a model capable of sophisticated reflexive attributes exceeding any mechanistic or static notion of architectural form-one that could perhaps define new levels of interaction within natural* [and artificial] *ecosystems.”*[335]

3. A classification has been established that arranges kinetic systems according to their energy sources and divides them in three major groups: mechanically sourced, electrically sourced, passive systems. Among which our main focus is classified within the programmable matter systems subdivision.

4. It has been established that active shapes are a useful tool to model kinetic actuation from lower to higher level transfer yet it still might need automation and computational implementation to test material behavior driven actuation.

[335] Emergence and Design Group, *Op. Cit.* (2004) P.9

5. It has been theoretically argued that kinetic control systems can be generated in ways different than sensor driven, computer regulated, ubiquitous gadgetry assembled systems positing the possibility of programmable matter as a main source of kinetic actuation traits.

6. Ubiquitous computing, also known as ambient intelligence, is proposed by some as an alternative to flexibility than kinetic systems, yet no development is neither cited nor carried out thus remaining a theoretical proposal, nevertheless calling on researchers for its immediate investigation. Although full of potential, these assertions remain to be tested.

*5-Kinesis as a design method: Bottom-up vs. top-down_*

"There is a possibility that form will no longer follow function, but form will become function."[336]

- Amanda Parkes, Ivan Poupyrev, and Hiroshi Ishii-

Greg Lynn argues that the digital era has let architects implement, as standard and almost common practice, what scientists were researching and trying to achieve more than one hundred years ago. As a general definition, this condition is rather vague and it depends a lot on the particular architect at hand, everybody has his/her own method, even when sharing similar ideas and the same or similar digital tools, but one thing is certain, these creative design methods have common denominators. They all try to tie together the material's properties with forces acting upon it or around it (be them sometimes even situations or agents-as in computerized agent based modeling- playing in an associative relation model), affecting the way material behaves or making it react to certain external stimuli based on the material's physical properties, enter from-finding. In Gaudí and Otto's cases, it was more focused on gravity as a central axis for their prowess, still also now-a-days, *in architectural design and engineering, form finding is commonly used to develop structural form in response to gravity.*[337] But form-finding's function in the architecture world is defined by a duality that Michael Hensel thinks of as the central and basic from the theoretical and objective standpoint as *its two primary tasks are the generation of the form to be built and the full-scale construction of the desired form. These co-joined tasks lead to finite building solutions* [338] that were found to would be, through previous methodology, impossible or improbable, especially focusing in the "*how to build it"* aspects (in terms of construction), but that a change is needed in the way we understand the dynamic within them as *finite designs resulting from form-finding processes are at odds with understanding material systems as inherently dynamic*[339], they consider systems as static thus deriving in three-dimensional form-finding, *this understanding necessitates a dramatic shift in focus of the aim of architectural design*[340] narrowing the spectrum of both possibilities and probabilities in terms of result and process, accordingly, this

336 Amanda Parkes, Ivan Poupyrev, and Hiroshi Ishii, "Designing Kinetic Interactions for Organic User Interfaces," *Communications of the ACM* 51, no. 6 (2008): 64.
As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 143

337 Hensel, Michael, *Op. Cit.* (2004) P.27

338 Idem.

339 Idem.

340 Idem.

paradigm has to move *f*rom producing static and discrete objects to the generation of mobile material arrangements that are responsive to the environment. This is consistent with the paradigm shift (see chapter II) experimented by architecture compared to what was thought to be consistent with the XXth century restless dogma: *should form generate function or the other way around?* A gospel that would inundate architecture schools all around the globe and, with its successes and mistakes, would later provoke opposition by younger generations in the likes of post-modernists and de-constructivists but that, in a rather insistent way, was persevered in the background like an ceaseless hum which still generally dominates the practice but has begun to loose the academia. In the previous chapter (see section *Kinesis as a system*) an analysis of certain projects regarding their typology and control means was carried out, Michael Fox's classification was chosen to guide the selection of these kinetic applications in real design projects, yet they did not disclose any information on the steps towards achieving their kinetic traits, that is why they are not included in this chapter, here we analyze the methodologies that lead towards kinetic *operability.* After an extensive search for research projects which disclose their methods or, at least, show some of the steps they followed to arrive at their conclusions, this research has settled on two opposite approaches in design (each on one extreme of deductive and inductive reasoning spectrum) that echo the contemporary dichotomy within non kinetic architectural design as well. As Michael Hensel has, very logically has posited, *the question is then: How can we approach form finding if material form continuously transmutes in response to an equally dynamic force-context?*[341] We will observe two design approaches generated in the context of academic research and compare the two to approve, discard, use or derive conclusions concerning *how to construct movement and implement it in design.*

5.1-Top-down approach: "Program Morphosis" case_

In 2011, Tess Fenwick, a graduate student at UNITEC in Auckland, New Zealand wrote a masters degree thesis that focused on the design of a multi-functional "art-house" building utilizing kinetic characteristics to house a variety of distinct activities ([342]exhibition spaces, performance spaces, cafe / bar, art house movies, teaching / conference spaces, visual media spaces, workshops, outdoor air cinema) coupled and adapted to also very differentiated disciplines (choir, dance, theatre, live music, festivals). From a Top-Down approach, among other stimulus, we might have a series of questions that we would have to answer when addressing the issue of kinetic implementation into architectural

[341] Hensel, Michael, *Op. Cit.* (2004) P.27
[342] Fenwick, Tess, *Op. Cit.* (2011) P. 68

systems. For example, the question of defining a program, which may in turn enhance an environment or ambient in which we can implement a kinetic strategy or application.

"When considering a kinetic programme, aspects considered were often time-based.
• Is the programme permanent, or does it stay for a short duration?
• Does it come, leave and then reappear?
• Is there a combination of functions that complement and enhance each other?
• Does it change daily, nightly, weekly, monthly, seasonally and / or annually, or with the weather?
It is vital for the selected programme to provoke change and generate opportunities and alternatives for the project."[343]

5.1.1-Site analysis_

And while this specific analytic process was pretty much our standard *Context, Site limits, History, Climate and Car flow/ Circulation* type, it addressed fundamental basis in the kinetic architectural systems theory and aims. From then on, the initial conditions analysis goes on to standard and relatively correct assessments in information gathering and interpretation for project placement. We will just look at some of the extracts to understand the designer's point of view regarding topics such as landscape, climatology, territorial ordering, and circulation flux confronted with a kinetic building design. Also it is pertinent to remark that the process's ordering is rather confusing as it is simultaneously subdivided in *explorations* and *chapter numbering* with no apparent explanation for the division and makes the fluidity of it, at times, hard to grasp.

[343] Fenwick, Tess, *Op. Cit.* (2011) P. 67

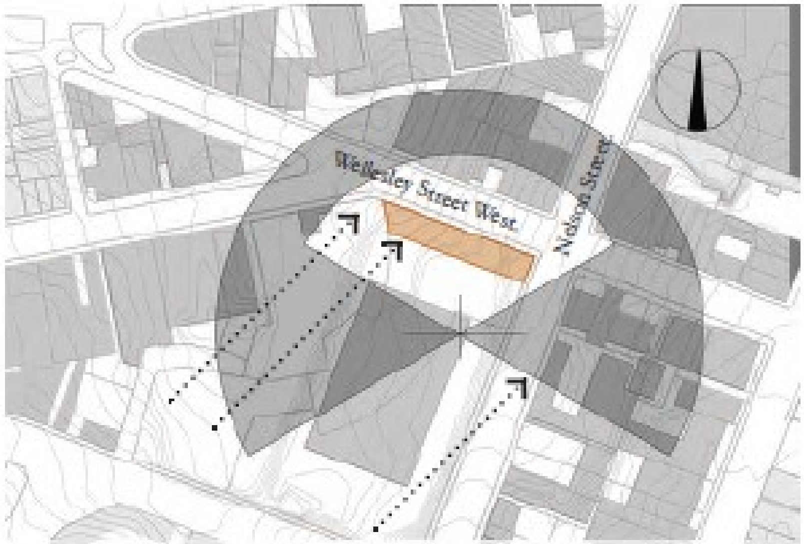


Figure 3.14 Site analysis - sun angles and south westerly winds.

Figure 3.15 Pedestrian movement in the vicinity.

(Fenwick, Tess, *Progamme: Morphosis*, P. 60)

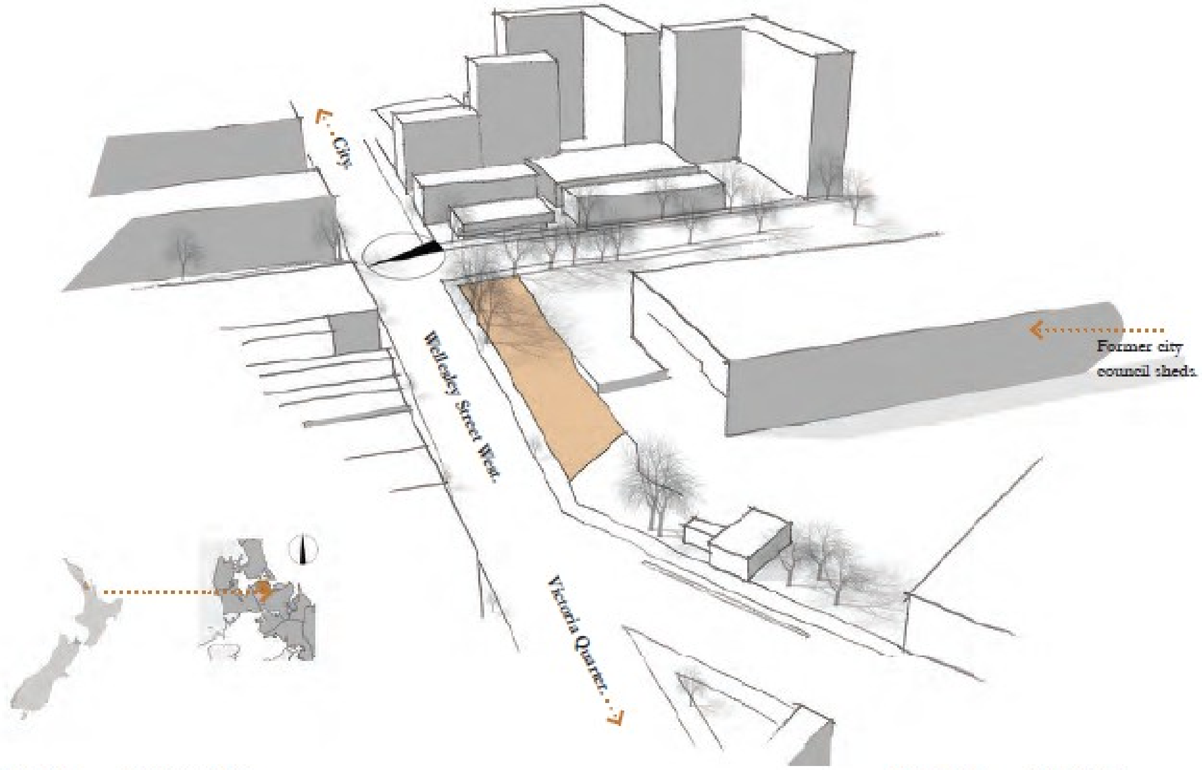


Figure 3.16 Site locator plan. Figure 3.17 Current site.

(Fenwick, Tess, *Progamme: Morphosis*, P. 61)

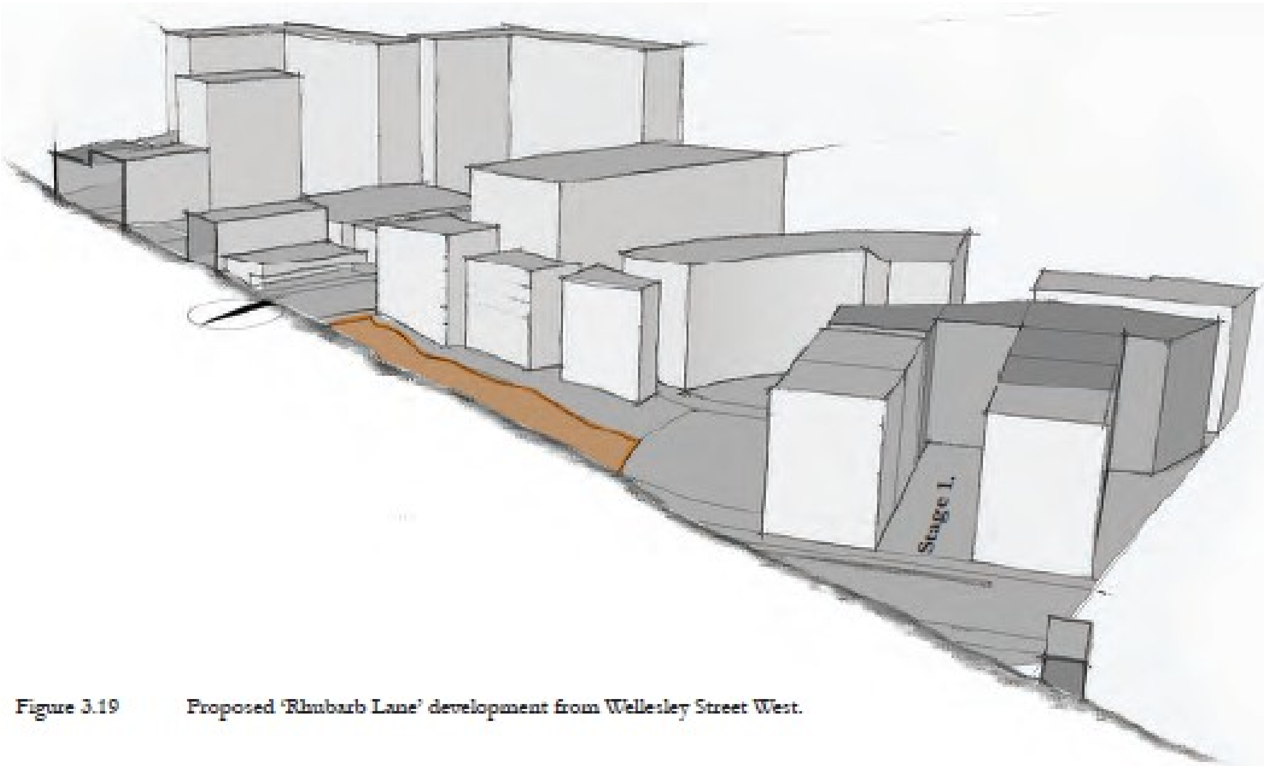


Figure 3.19 Proposed 'Rhubarb Lane' development from Wellesley Street West.

(Fenwick, Tess, *Progamme: Morphosis*, P. 63)

Figure 3.20 Traffic densities in the site vicinity.

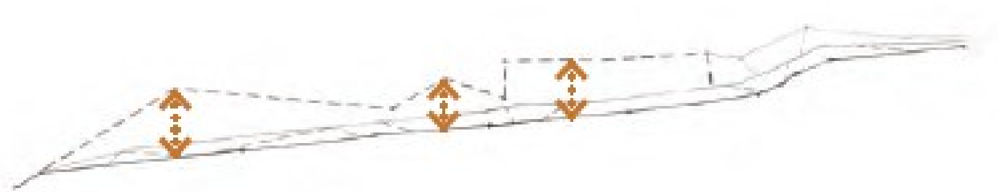
(Fenwick, Tess, *Progamme: Morphosis*, P. 65)

*5.1.2-Design Process_*

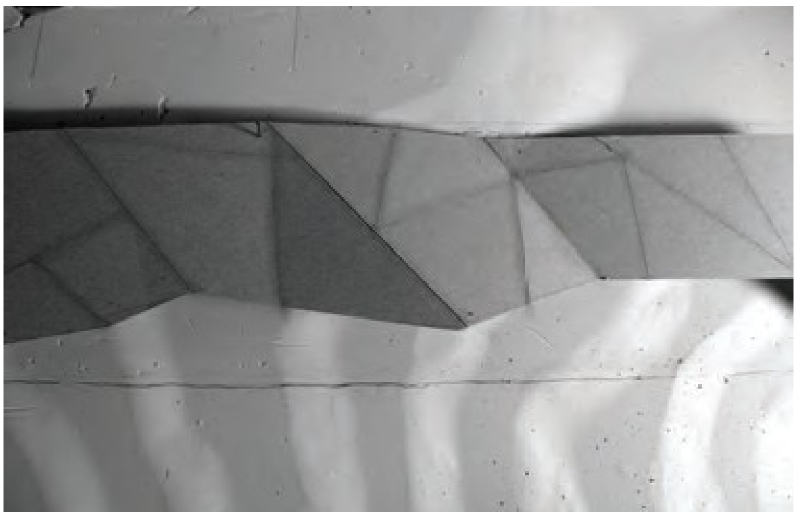
Fenwick carried out her design process in what she termed "explorations", in each of them defining a certain kinetic trait or motion, which is superimposed onto determined program requirements and in turn derived and synthesized into "outcomes", in themselves subdivided in "issues" and "positive aspects" as assessment criteria. This design process is based on a "deductive reasoning" method, itseld a logical process that draws conclusions from the concordance of multiple premises that are assumed to be true. This means that it is clearly defined in terms of what it wants to gain, in this case concerning qualitative data regarding the functionality of the chosen kinetic traits. Before going any further it is pertinent to alert that Fenwick does not formally define a *bottom-up* approach to the design process yet implies that this current part of the "explorations" is such an approach (specifically in exploration 5.1 -section 3.4) and it leads to confusion on which process she did use as guideline for the first part of her project development, this will be explained later in this section excerpt selected in this research to show it as an example. It is imperative to note that the designer's definition of the last phase of the process as "top-down" manifests certain misunderstandings about what a "top-down" approach is, wherein all of the previously carried out "explorations" were also "top-down", so the distinction comes across as not only unnecessary, but also confusing, at the very least. A "bottom-up" approach is, in its pure state, oriented to defining internal or lower level *interactive* configuration based on simple rules and aggregation (or in this case, mechanisms), which is itself defined by the internal morpho-genetic code, that in turn are adapted to higher level requirements or conditions which, as seen in the previous cases, is only managed in defining vague ideas of mechanisms which are basically constructed out of site interpretations as shown in this passage in the memory of the project:

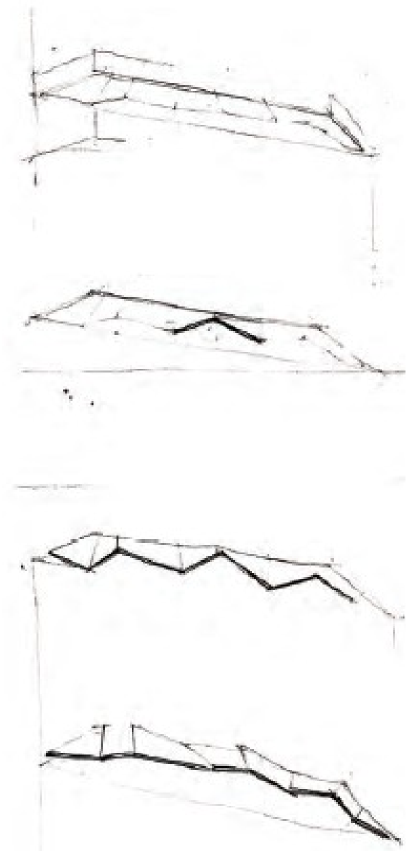
"The ground plane is divided into platforms, which can separately raise and lower on scissor lifts, breaking up the formation onto different levels. When the cubes are in the garage the platforms and landscape become interactive. "[344]

So, even though putting mechanism before general contextual conditions, it is "top-down" in genesis as it is the general zoning criteria that drives the decision making at a higher level. This is made evident by the fact that exploration 5.1 and 3.2 ("Continuous Folded Roof " and "Morphing Landscape") are conceptually and geometrically immensely similar, if not identical, the only difference between them residing in that the first is used as a roof and the second as a floor-roof thus confusing approach with application. Here the designer is clearly applying conventional readings of the territory and context, to discern, through comparison, which "kinetisisms" would better match the program's goals, this will proven to be time consuming and mistake generating.



[344] Fenwick, Tess, *Op. Cit.* (2011) P. 70





(Top) *Exploration 3.2*, Tess Fenwick (2011) (Fenwick, Tess, *Progamme: Morphosis*, P. 73)
(Bottom, bottom-right) *Exploration 5.1*, Tess Fenwick (2011) (Fenwick, Tess, *Progamme: Morphosis*, P. 79)
The similarities between these two “top*down” and “bottom-up” strategies are evidence that, in fact, they are both top-down approaches that just take different variables as departure but are in the same thought direction known as deductive reasoning.

As specified in *Exploration 3.0*, the designer here engaged in he construction of (very inexpensive) models and plan and section drawings (although just two oft them) which take time to make and they are, even though they generate somewhat reasonable assumptions about the kinetic mechanism's usefulness, not practical in any sense from a project development standpoint. Also, no qualitative and few geometric aspects of the proposed solution mechanism are addressed within this approach's outcomes (something that, in top-down approaches is not out of the ordinary as normally they are left for a later technical design phase and in this solution it is not mandatory because of its geometric simplicity). In the mentioned exploration, the design process starts showing some signs of geometric analysis towards kinetic motion, although not very detailed, its strictly interpretative way of describing the problems do not help much in the understanding of the solution's depth and effectiveness, so we are obligated to take the designer's word as our only means of validating if the implementations work or not. Exploration 3.3 can be affirmed as a repetition of exploration 3.1 (“24 Cube Garage”); which is something that, if done with an animation or simulation software program setup, would render it a totally unnecessary step in the design process as it may come up as an axiomatic discard from the very start because their similarities between them (“24 Cube Garage” and “Sliding Volumes”) would stand out almost instantly. The “Outcomes: Positive aspects and issues” analysis structure is kept by the designer until the end of the project, yet for its unnecessary length and, in some cases, obvious conclusions we will not show them in the remainder of this section, for more information on this project's details regarding the decision making process, please consult Fenwick's *Progamme: Morphosis, Master of Architecture Graduate Thesis* (Unitec Institute of Technology, Auckland, New Zealand,in requirements for the degree of Master of Architecture, 2011) or the appendixes at the end of this thesis. For further graphic information and contextual orientation, please see appendixes section or refer to Fenwick, Tess, *Progamme: Morphosis, Master of Architecture Graduate Thesis, Abstract,* Unitec Institute of Technology, Auckland, New Zealand,in requirements for the degree of Master of Architecture (2011)

5.1.3-Spatial adaptability and program_

Here the designer addresses important issues regarding the housing of the program and the building's adaptability guidelines that are relevant to kinetic architecture (see chapter V). This definition of activities and their interchange-ablility and simultaneity works as something relevant when designing multi-functional buildings and is a central engagement within the kinetic architectural discourse and justification, In its intention, this division in the program helps the mapping of the project in terms of how it approaches the aforementioned issues. During the whole process, these “discoveries”, although architecturally interesting, are aspects of the structure's potential that can be detected early in the design process, the method utilized, even though proven effective, is not efficient. This entire process of decision making could have been cut down to at least half the time, energy and model making employment.

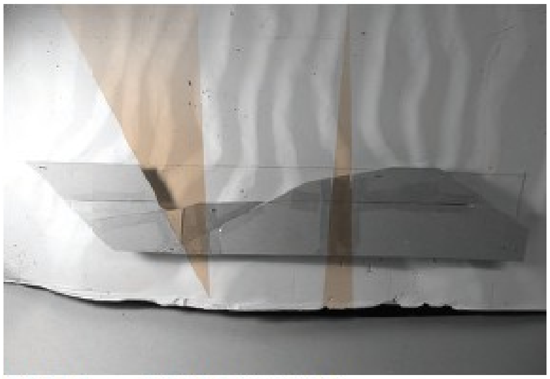


Figure 3.44 Potential short through paths.

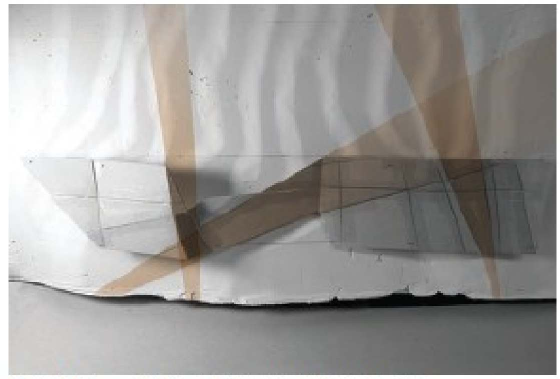


Figure 3.45 Potential short and long through paths.

(Fenwick, Tess, *Progamme: Morphosis*, P. 95)

Figure 3.46 The Rhubarb Lane circulation routes will be kept in approximately the same locations so the circulation will still work with the development.

Figure 3.47 Potential short and long through paths.

(Fenwick, Tess, *Progamme: Morphosis*, P. 95)

"The number of cuts around the paths have been increased, placed closer and sometimes cross over each other forming an 'intersection.' The through paths need to be relatively flexible, hence smaller planes with increased movements will be employed to visually define the route through. (Figure 3.49)"[345]

Until now (*Exploration 6.5: Roof Plane – Creating Habitable Exterior Spaces around Movement*), all points in the decision making process were, to a certain point, relevant and, to a certain point, quite clear and understandable, decisions that are based in kinetic analysis and purpose definitions regarding the different program's interchangeable traits which are valid concerns for a kinetic design (echoing MUSCLE, Torotransegrity, see chapter IV). But all the sudden, at this point in the process, it becomes difficult to follow the decision process cause of lack of visualization techniques to enhance the discourse (the claimed street side cannot be seen in these graphics and pictures) and the problematic which is described in the outcomes and considerations is not evident and requires too much explanation by be understood. Too much writing is involved necessarily to understand the structures behaviors and shape-shifting traits. There is no reference to the site specific features that the designer points out in its decision making process, the use of physical models help, but it is not enough to communicate ideas. When Fenwick states *"connect Wellesley Street West with the 6 metre wide pedestrian access-way*

[345] Fenwick, Tess, *Op. Cit.* (2011) P. 96

between Rhubarb Lane and the building."[346] It is difficult to pinpoint where or how exactly is it carried out in the plans and pictures, there is no reference to the site context-specific conditions and the graphic resources are weak as to help in this respect.

These either:

- Enclose the path. (Figure 3.60)
- Frame the path, or; (figures 3.61 and 3.62)
- Completely open up the path. (Figure 3.63)

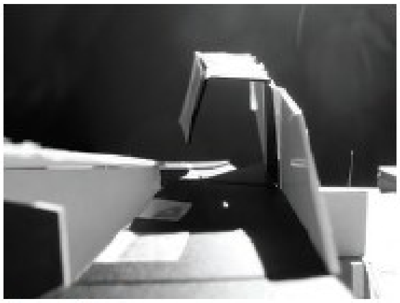


Figure 3.60

Figure 3.61

Figure 3.63

(Fenwick, Tess, *Progamme: Morphosis*, P. 106)

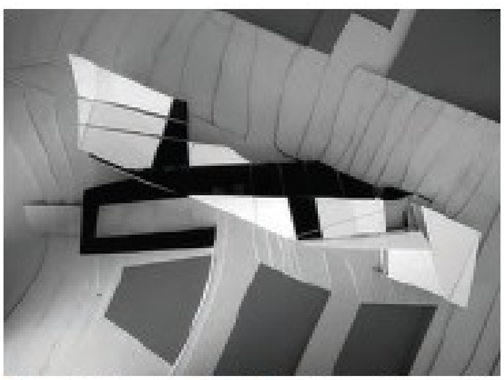


Figure 3.57 The black planes indicate the through paths.

Figure 3.62

(Fenwick, Tess, *Progamme: Morphosis*, P. 104-106)

[346] Fenwick, Tess, *Op. Cit.* (2011) P. 104

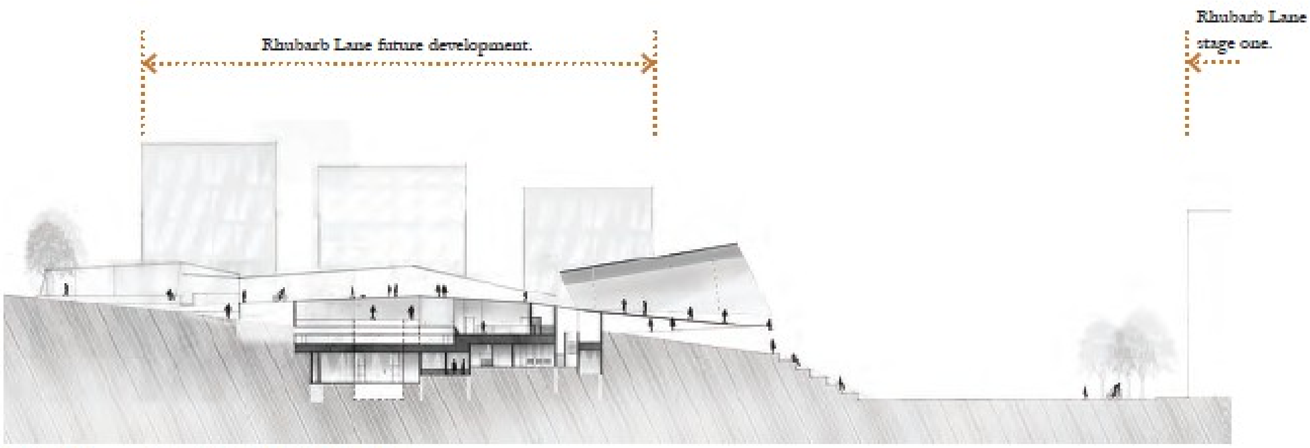


Figure 3.64 Section A - A. Long through path.
(Fenwick, Tess, *Progamme: Morphosis*, P. 107)

The hand drawn section, in terms of explaining movement or kinetics traits, barely makes it as an explanatory tool as it demands immense attention from the viewer to understand the discourse and corroborate that it is in fact true what the designer proposes.

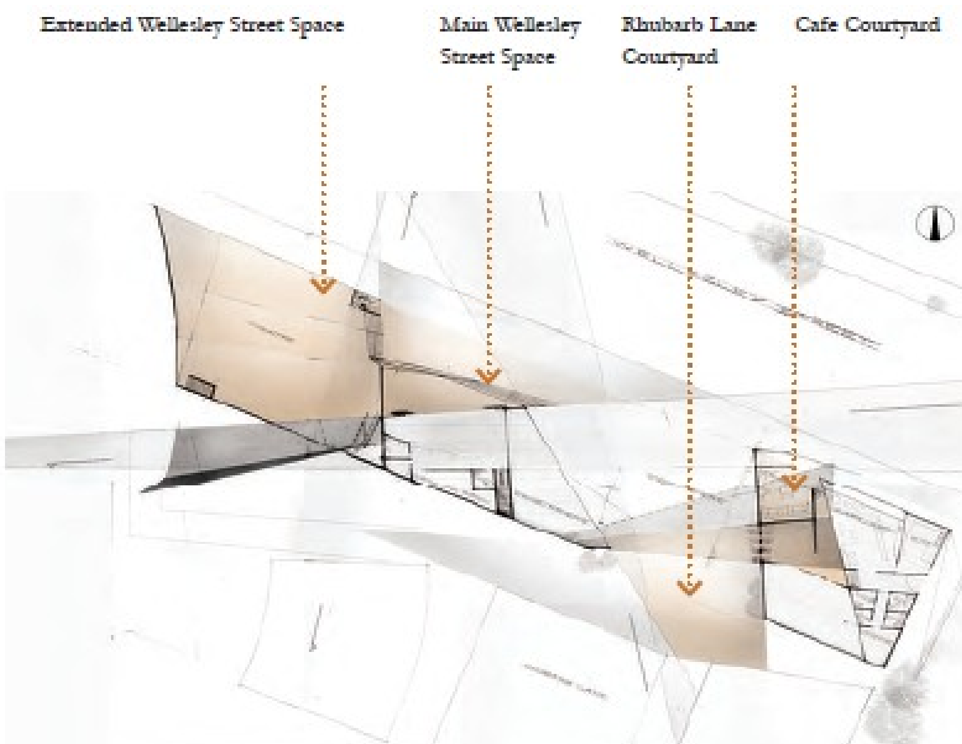


Figure 3.65 Solution 1 - Public spaces.

(Fenwick, Tess, *Progamme: Morphosis*, P. 108)

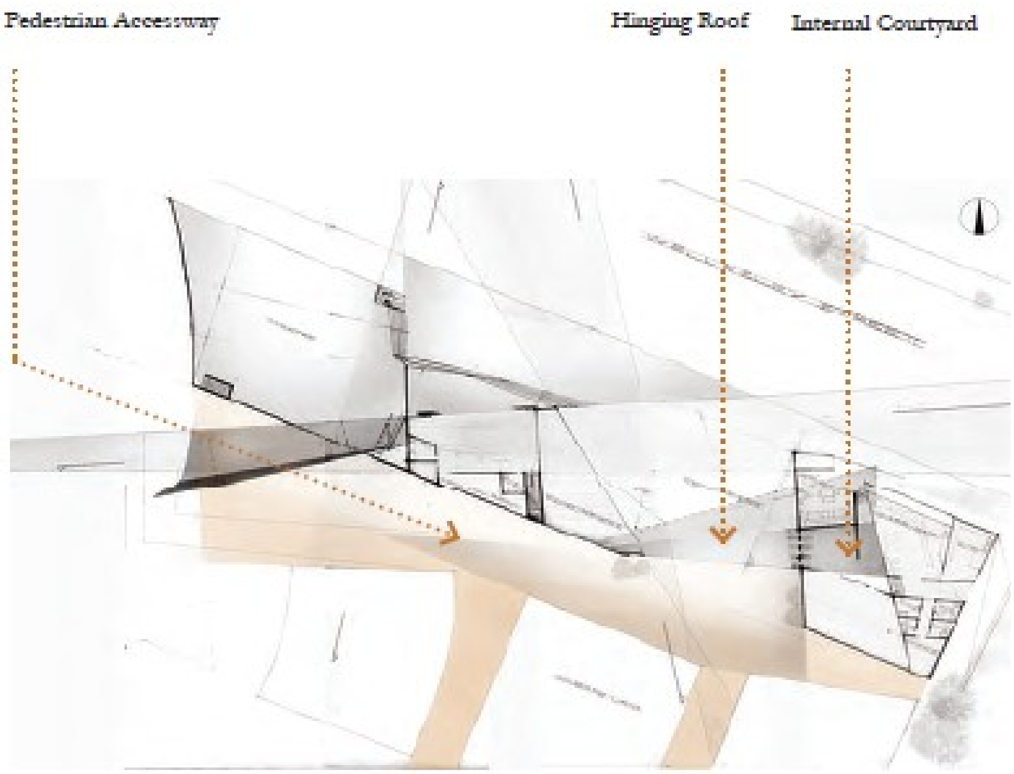


Figure 3.66 Solution 1 - Hinging roof.

(Fenwick, Tess, *Progamme: Morphosis*, P. 109)

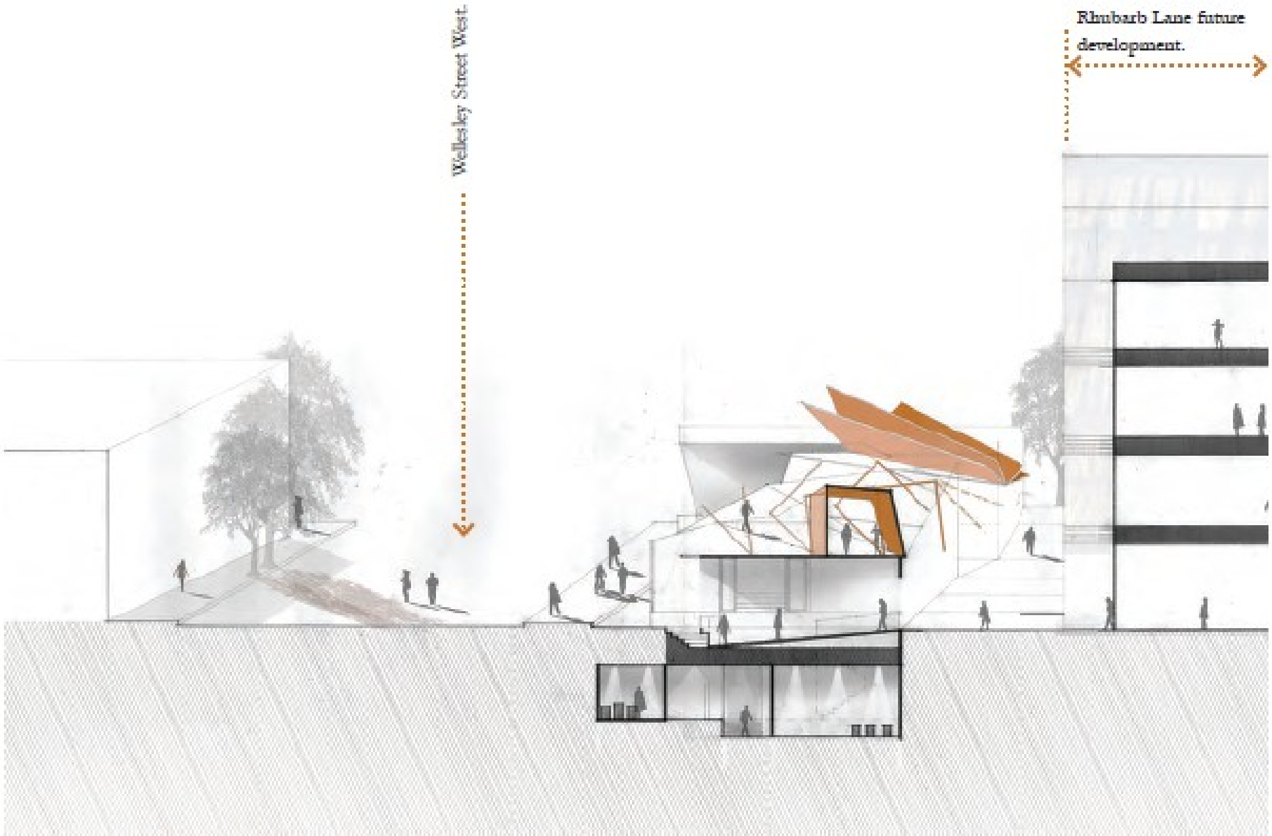


Figure 3.67 Section B - B.
(Fenwick, Tess, *Progamme: Morphosis*, P. 110)

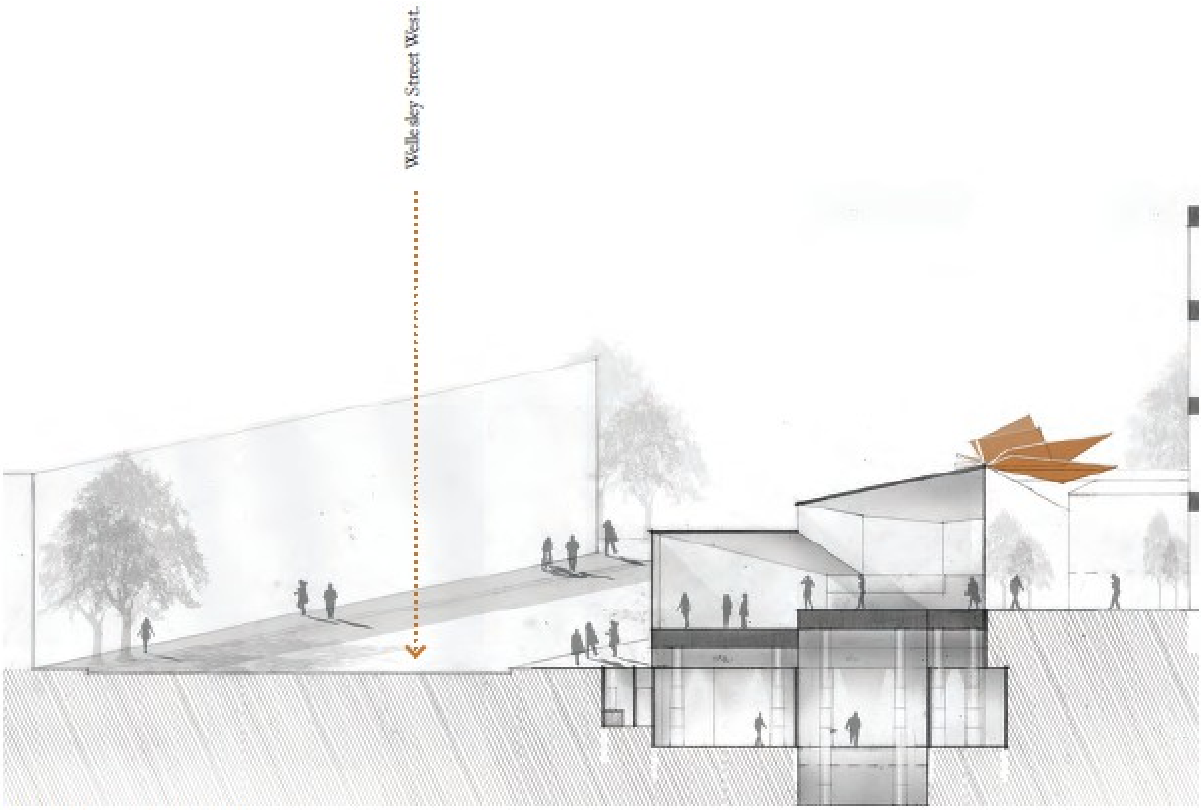
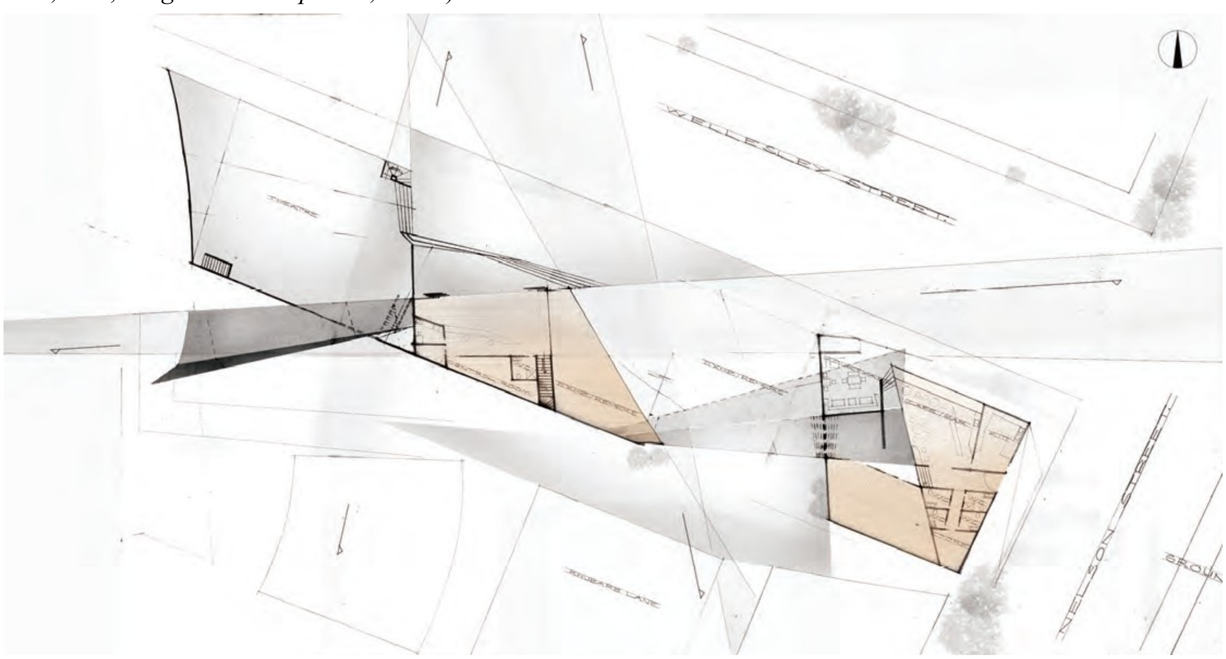


Figure 3.68 Section C - C.

(Fenwick, Tess, *Progamme: Morphosis*, P. 111)



(Fenwick, Tess, *Progamme: Morphosis*, P. 112)

In these previous last five graphics, the program logic is understandable yet their kinetic traits of interchangeable comparison is not even shown, it becomes difficult to follow the project's logic and basis for kinetic operability, basic meaning is lost.

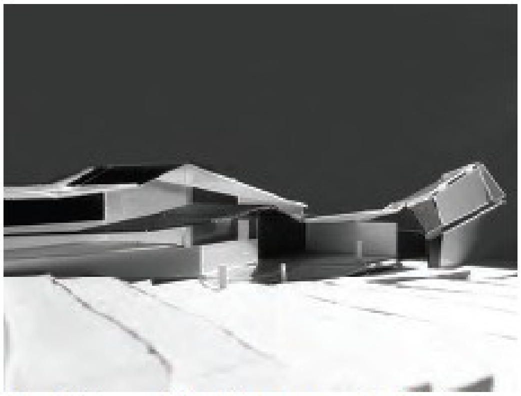


Figure 3.71 The public space created on Wellesley Street West. (Looking southwest)

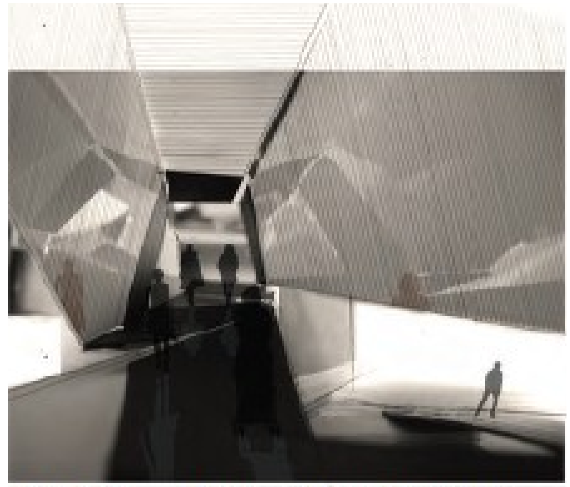


Figure 3.70 Long through ramp looking west.

(Fenwick, Tess, *Progamme: Morphosis*, P. 113)

The project has required an extensive research to determine that it is not viable; something that this research hypothesizes would be less time, energy consuming and mentally confusing if digital simulation techniques had accompanied its process of becoming.

Figure 3.75 Looking east - new spatial configurations for section four are formed by modifying cuts.

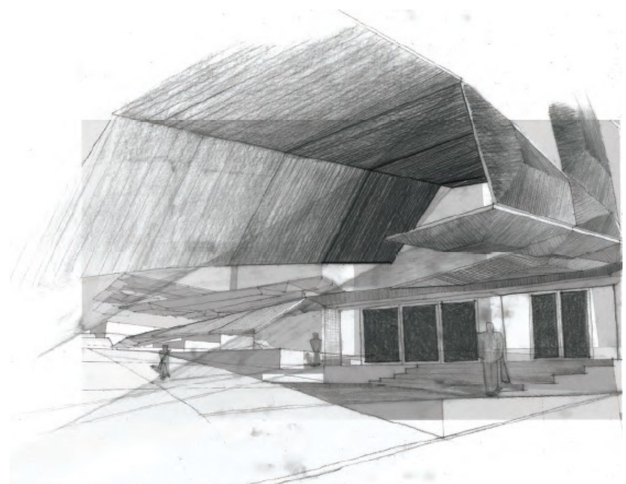


Figure 3.76 New spatial qualities over the main Wellesley Street West space.

(Fenwick, Tess, *Progamme: Morphosis*, P. 116-117)

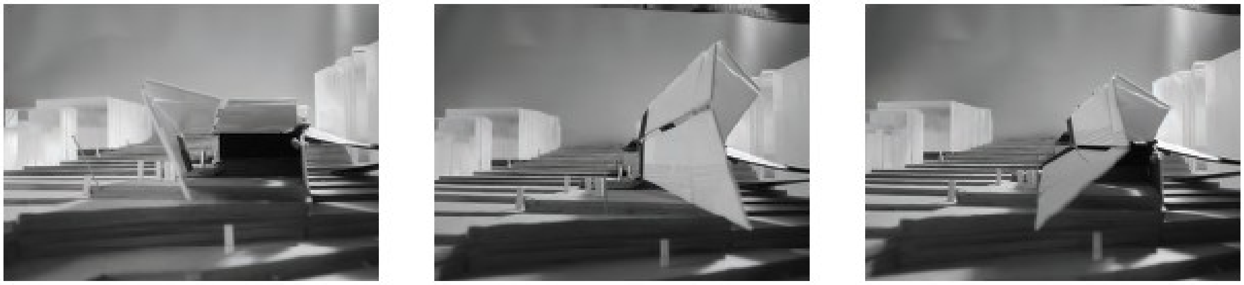


Figure 3.77 Section four - Selected spatial configurations.

(Fenwick, Tess, *Progamme: Morphosis*, P. 118)

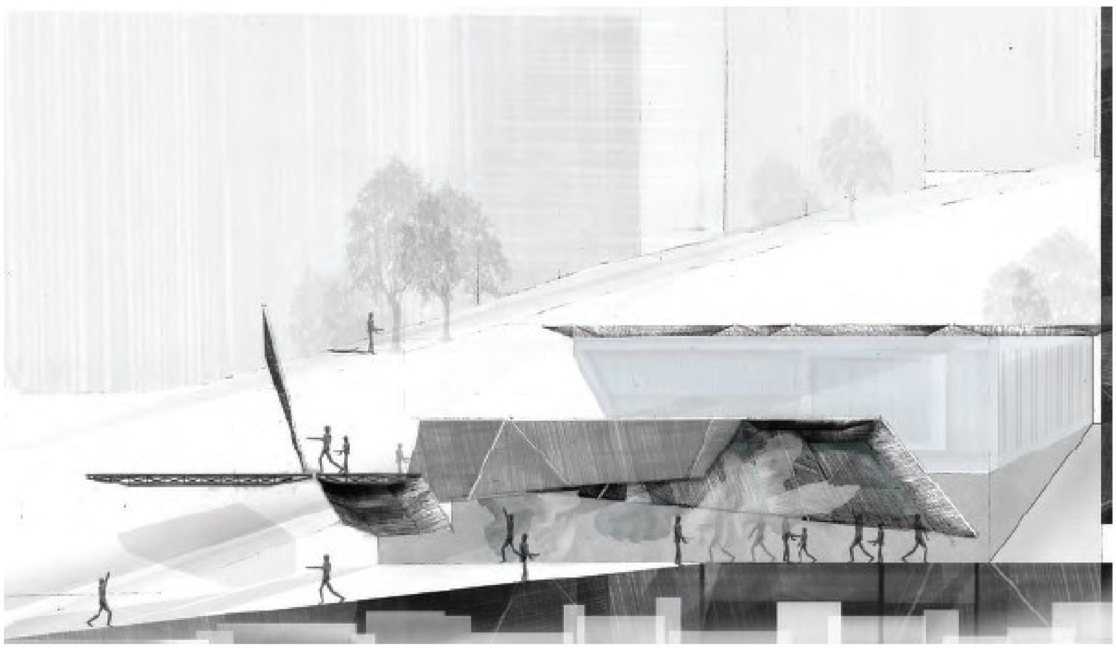


Figure 3.86 Solution 3 - Section A-A.

(Fenwick, Tess, *Progamme: Morphosis*, P. 123-124)

"Forming the walls and ceilings with the ability to hook back onto two, adjoining roof sections. Sections were used to test spatial adaptability which appeared to be highly improved by this change. (Figures 3.86 and 3.87) This exploration will need to be reinvestigated structurally. "[347]

[347] Fenwick, Tess, *Op. Cit.* (2011) P. 123

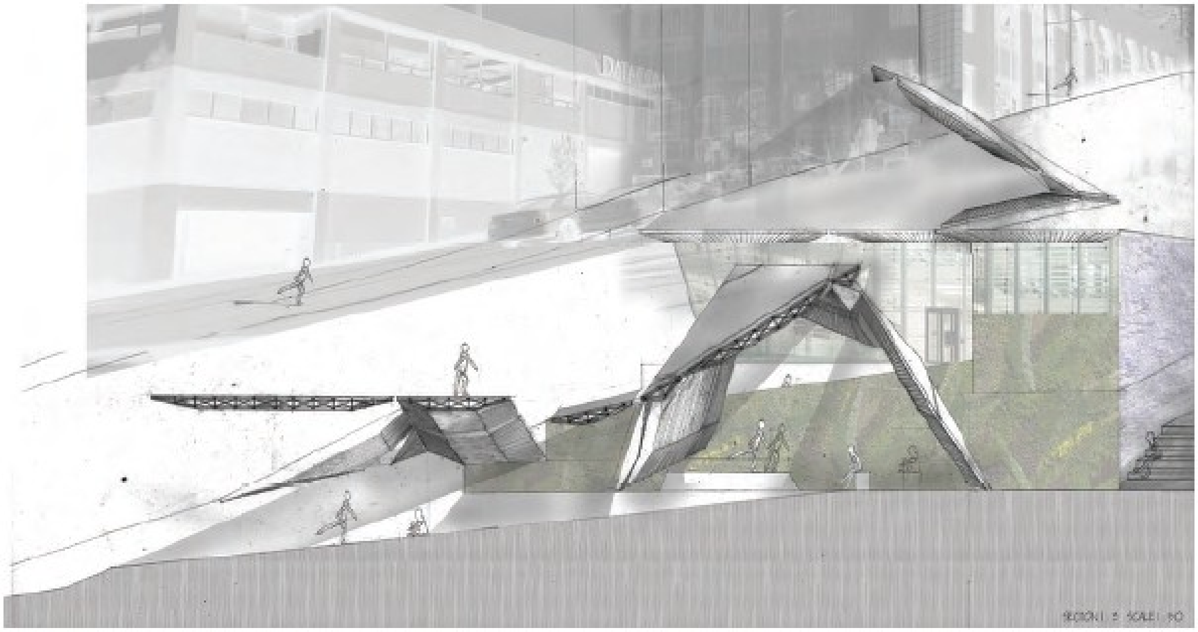


Figure 3.87 Solution 3 - Section A-A

(Fenwick, Tess, *Progamme: Morphosis*, P. 125)

Sensors:

"Relative to the time kinetics has been around in architecture, embedded computation (EC) is in a state of relative infancy. EC can be reduced to possessing a combination of both sensors (information gatherers) and processors (computational logic to interpret). EC is important not only in sensing change in the environment, but also in controlling the response to this change. The combination of embedded computation and kinetics is necessary to allow an environment to have the ability to reconfigure itself and automate physical change to respond, react, adapt, and be interactive."[348]

Concerning sensor technology, this aspect of the project was only theorized and, was not addressed extensively enough (this can be attributed to the exhausting amount of time dedicated to the form and "kinetisism" research); maybe except for a couple of pages in which it was vaguely described. Yet, in the project's advantage, it showed what looks like a correct conceptual framework for development.

[348] Fox, Michael, "Catching up with the Past: A Small Contribution to a Long History of Interactive Environments", *Footprint, Digitally Driven Architecture*, Spring, (2010) P. 10 (http://www.footprintjournal.org/issues/show/digitally-driven-architecture.) (30/04/2014)

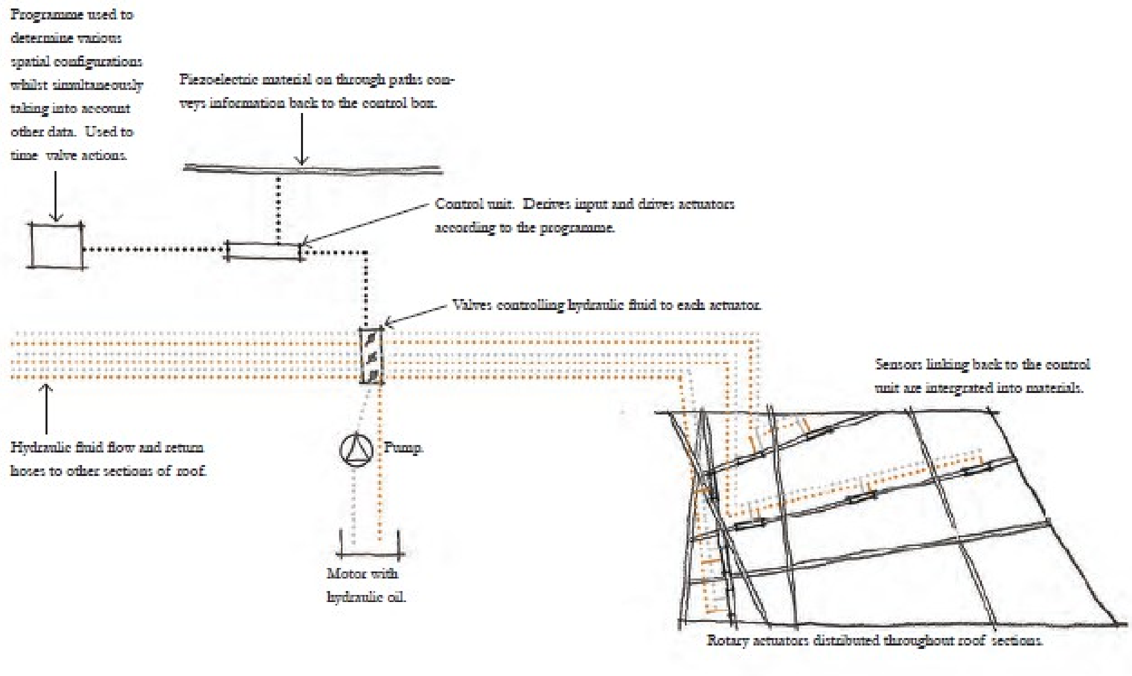
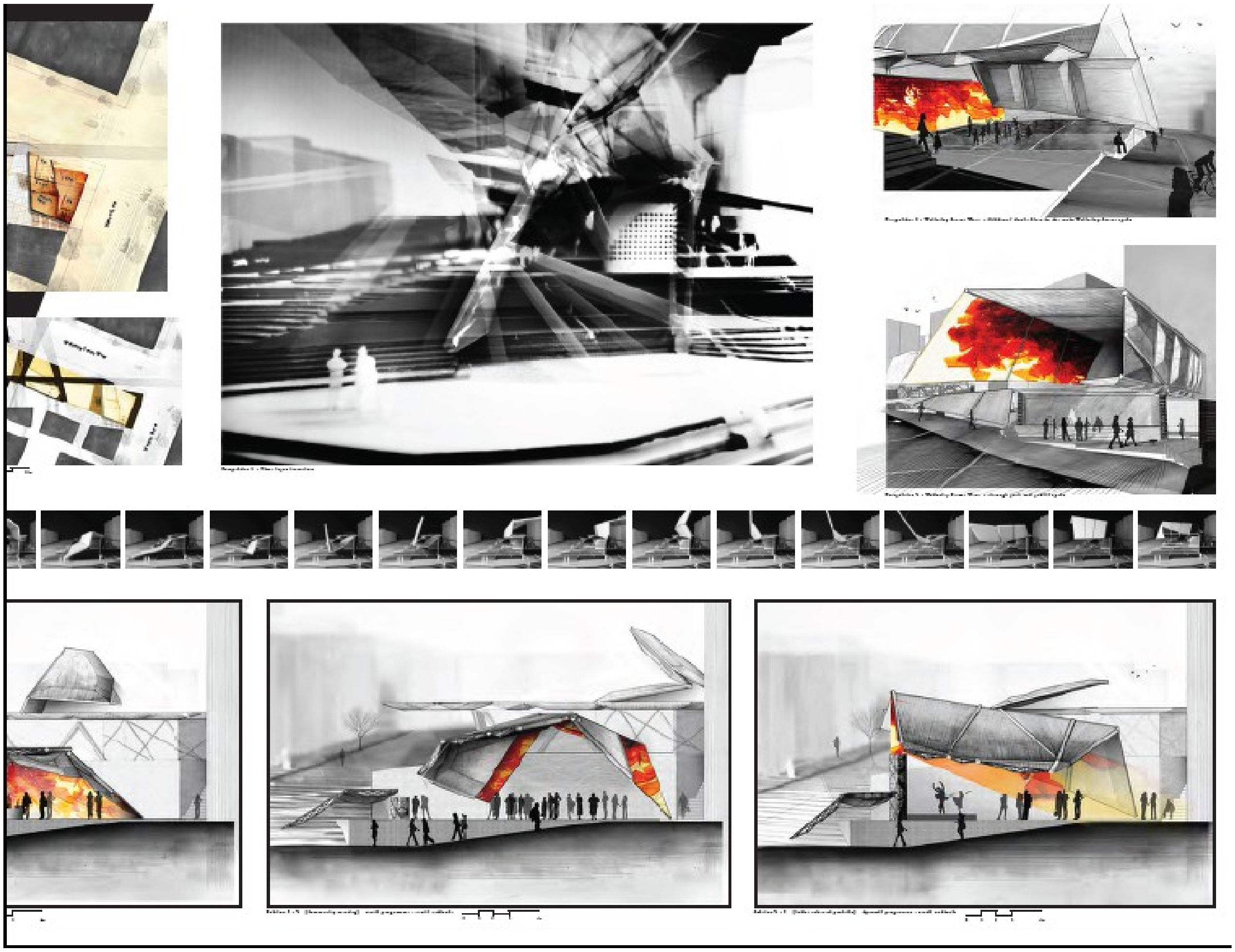


Figure 4.8 Schematic of the rotary actuator system.

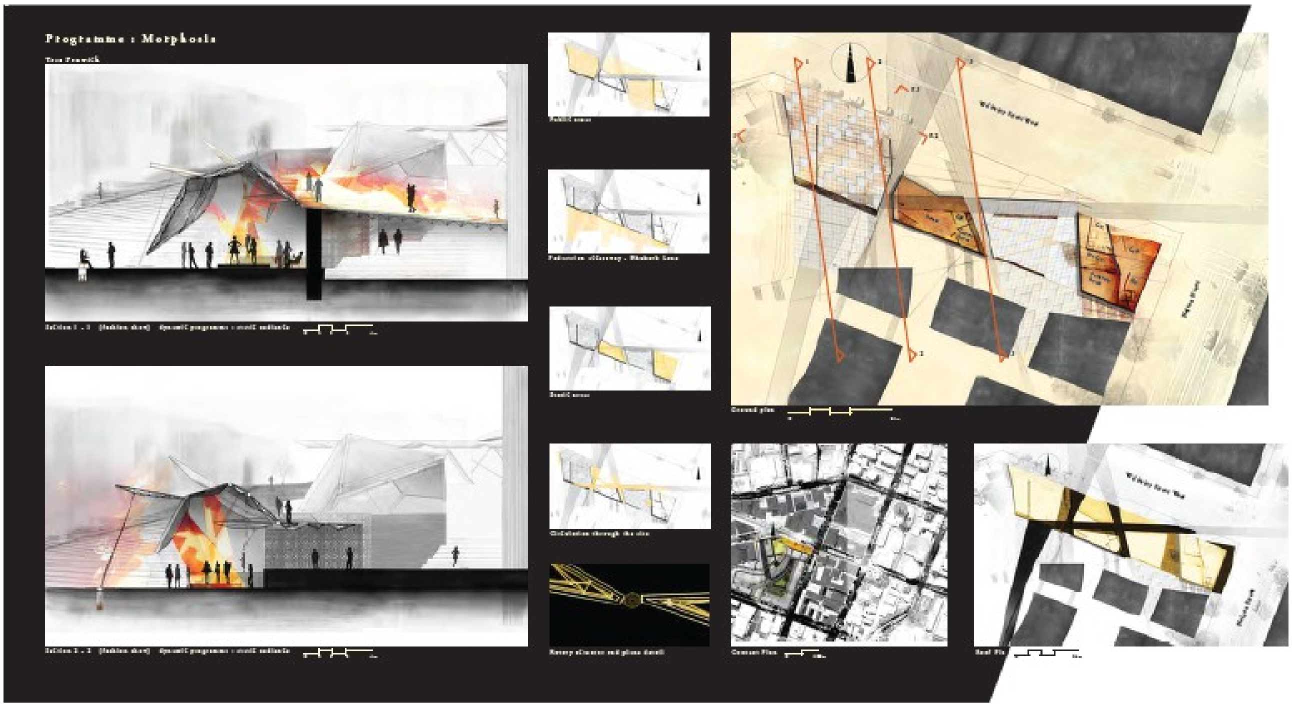
(Fenwick, Tess, *Progamme: Morphosis*, P. 139)

*5.1.4-Project results_*

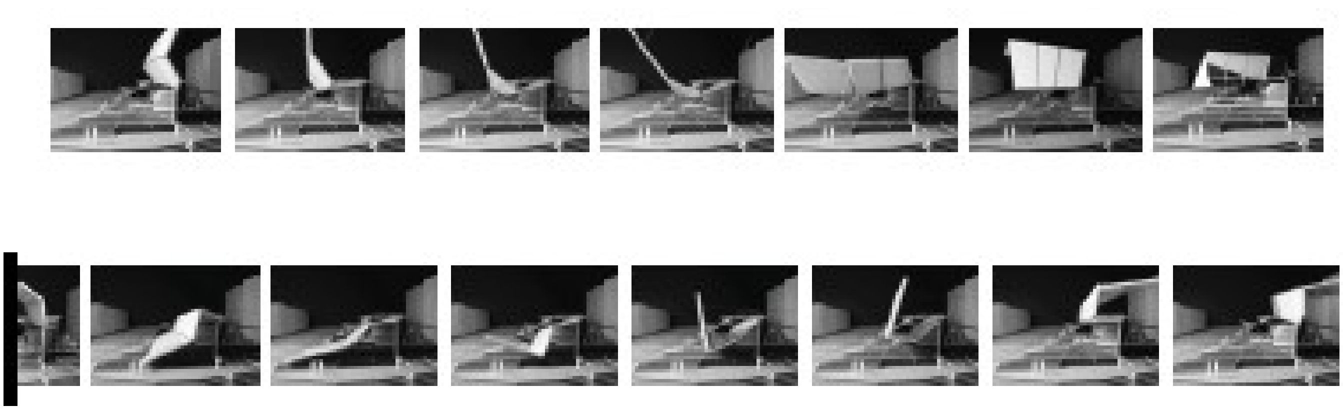
(Fenwick, Tess, *Progamme: Morphosis*, P. 178)



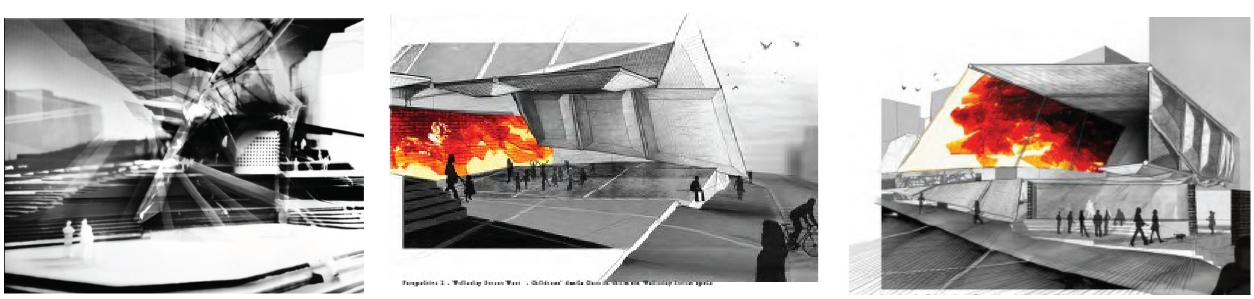
(Fenwick, Tess, *Progamme: Morphosis*, P. 179)



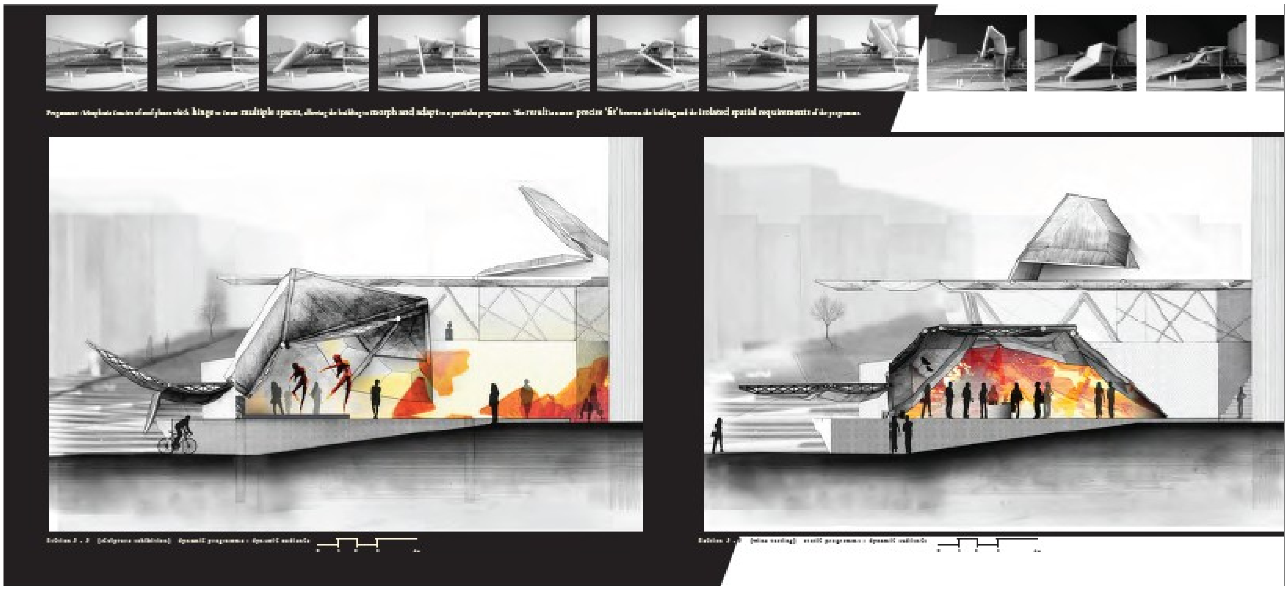
(Fenwick, Tess, *Progamme: Morphosis*, P. 179)



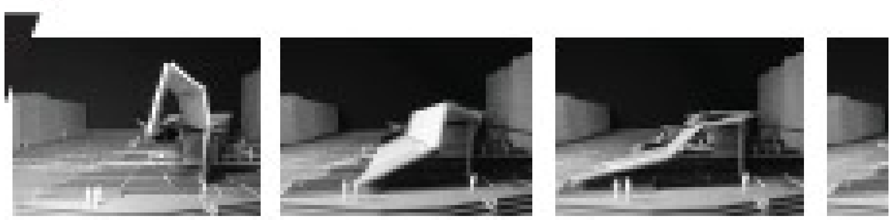
(Fenwick, Tess, *Progamme: Morphosis*, P. 180)



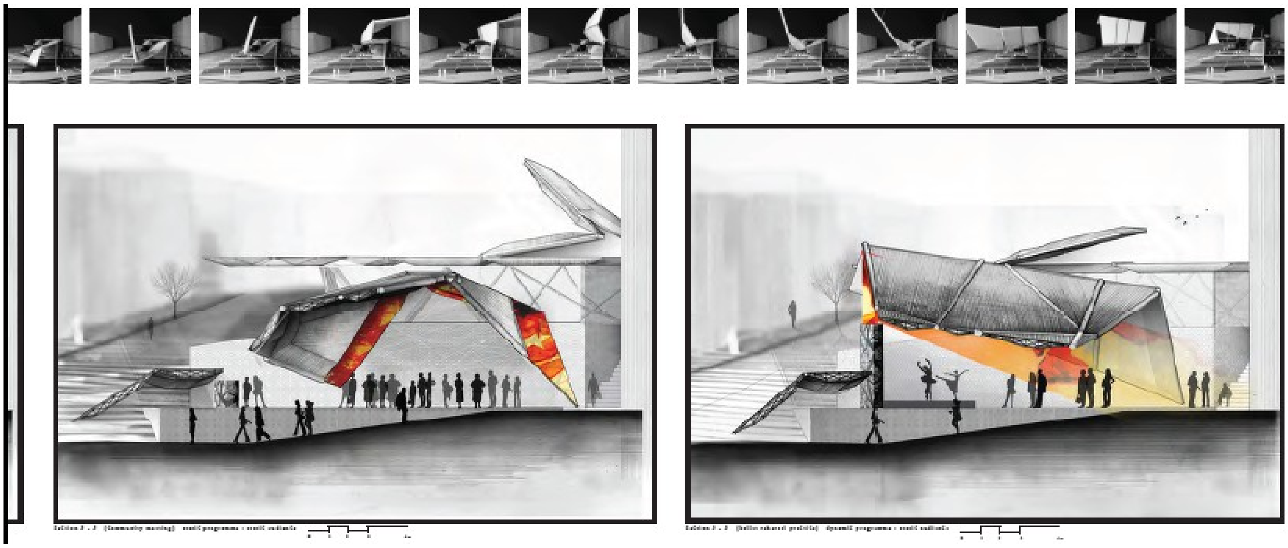
(Fenwick, Tess, *Progamme: Morphosis*, P. 181)



(Fenwick, Tess, *Progamme: Morphosis*, P. 182



(Fenwick, Tess, *Progamme: Morphosis*, P. 182)



(Fenwick, Tess, *Progamme: Morphosis*, P. 183)

(Fenwick, Tess, *Progamme: Morphosis*, P. 183)

In the final presentation, there are some still-frame series that help to understand and accentuate the projects kinetic operability yet, no geometric, transformational nor realistic means of expression is portrayed, rendering the project as full of potential yet not quite reaching the realistic levels that can assure the factual achievement of the project's discourse (even though it addresses structural, material and sensor technology issues, it does it entirely relying on assumptions; a higher and more precise level of analysis is needed regarding the actual -not interpreted- conditions). It would be very difficult to realize and carry out by a design team, basically it lacks specificity in its guidelines and it is not clear enough as a document in relation to its behavior under real conditions. Three claims stand out as relevant in this project's assumptions out of all the 125 pages worth of project development and design process (an insanely great amount of document space, considering the project's scope and scale)

"Outcomes:

Positive Aspects:

3. The interior spaces in section two have increased in flexibility, achieving the goal of spatial adaptability. (highly questionable)

Issues:

2. Size and power of rotary actuators need to be calculated. (obvious if its developed just out of scale models)

3. Weather tightness issues remain [this is highly questionable].*"*[349]

Two main challenges to this approach remain unanswered and yet to be determined by this research as Fenwick's research shows no sign of a viable alternative to exhausting all options prior to "finding" the right one or oversimplifying the design.

"The challenge of finding the 'best' route of approach, particularly at the conceptual stage, revealed an unexpected solution with the roof planes being able to provide numerous spatial variations of different qualities...

...This project tests and suggests how architecture may transform and adapt with the digital revolution. A new aesthetic and form was naturally required. The final architectural solution is a radical approach / prediction, and, as controversial as it is, movement in architecture seems to be the next logical step in the progression of the discipline. [yet it provides no clear solution to its design considerations]*"*[350]

Although we can agree that these claims have basis, it is difficult to asses how exactly it is that this project is implemented; its concerns are legitimate yet, as an application case, it lack descriptions. Actuators used as controllers are in charge of provoking the desired motions in the project, using energy and a lot of mechanical systems, which is suitable as a valid solution, non the less it is the very mechanical nature of it that this thesis is trying to surpass through its propositions and development project. In short, it was a tortuous (even Fenwick herself notes that *the process of testing each version bought up unexpected iterations and errors* [351]), unclear and dreamy project that cannot even be tested in terms of kinetic implementation in real building projects. *The reality of this project in the current era is not likely; however, once technology develops maybe the dream will become a reality* [352]*,* she writes in her thesis's *Future directions* chapter, it is the conclusion of this research that, even though it

[349] Fenwick, Tess, *Op. Cit.* (2011)) P. 129
[350] Ibid. P. 143
[351] Ibid. P. 93
[352] Ibid. P. 145

addresses fundamental concerns in interactive and kinetic architecture adaptability, this approach (top-down) lacks the appropriate paradigm and tools (both conceptual and craft oriented) to address the concerns of contemporary intelligent kinetic systems.

*5.2-Bottom-up approach: "Active Shapes" case_*

The other opposite in the spectrum of design approaches lies in the "bottom-up" fashion. In terms of method, as noted in the later section, it seeks to provide strong evidence for the truth of the coclusions as in probability based evidence. In architectural interpretation, it prioritizes local interaction as a catalyst for design intent and problem facing that can be influential on higher level systems conditions. In chapter IV we began looking at how kinetic structural systems that might as well be solved within Dina El-Zanfaly's case studies in *Active Shapes.* Dina El-Zanfaly's Active Shape design process depicts a very clear and simple bottom-up approach method to produce iterations within a grammar system for kinetic architecture. Her thesis experiments proposed multi-participants experiments and exchange results for further design exploration and application (six students in a workshop given by the thesis's researcher), it consisted of problems within the *A->t(A)* formula's output probabilities. El-Zanfaly organized a workshop with a group of students from the Design and Computation group at MIT to test, in experimental cases, the guidelines she had researched in the *Active Shapes* propositions followed by a self study on two projects of her own design, they divided the process in two parts: The *"students study"* and t*he "Self study"*. The process was outlined as follows:

*5.2.1-Workshops_*

The experiments consisted of a sequence of exercises that developed throughout four stages: two design stages and two reporting stages after each design stage. In the first stage the participants were asked to choose a single AS with one or two arrangements between a table and were allowed to utilize any representational tools like sketching or modeling. In the second stage (after reporting results from the first stage) they were asked to take a structure from their colleague and apply one of the transformations mentioned on the AS, from the original structure, and design a kinetic structure. Out of five problems to be solved, three made four stages and the remaining two just made it to the first one.

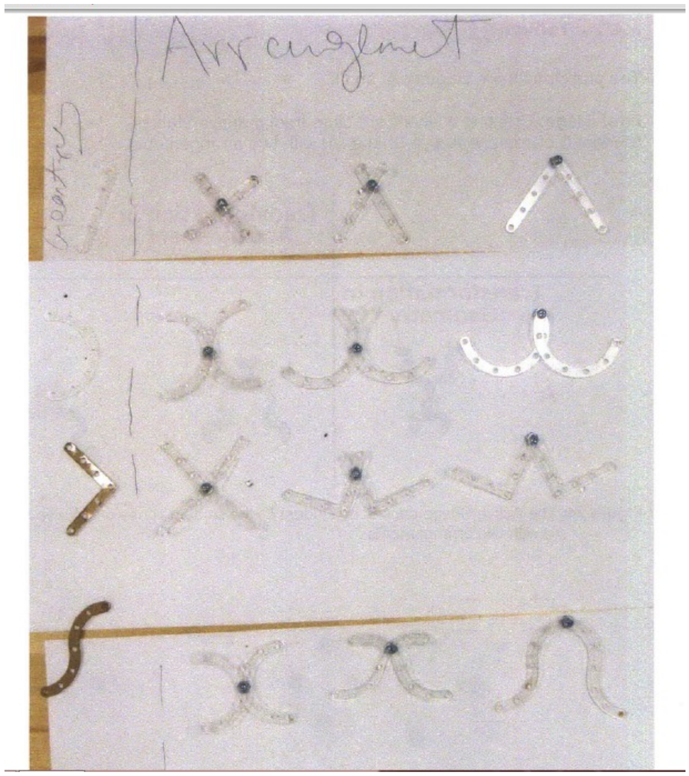


Table of *Active Shapes* to choose from, Dina El-Zanfaly (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 35)

*5.2.2-Problem I_*

"Participants are students C and E.

1st stage:

Creating a kinetic structure from the given tables. Student C chose and Active Shape (A) with two arrangements."[353]

[353] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 36

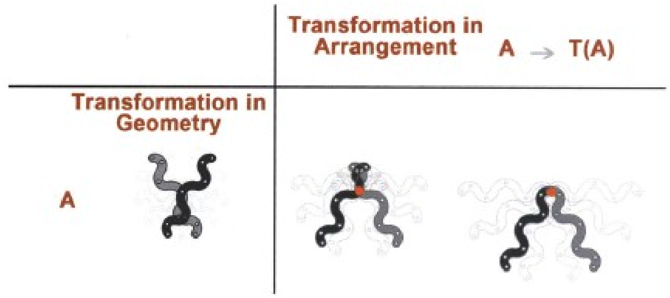


Figure 24: The Active Shape chosen by student C, the student chose one Active Shape *(A)* with two arrangements.

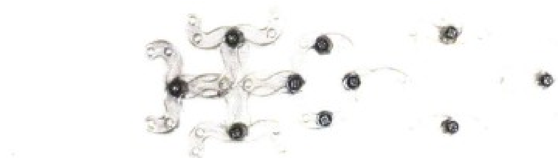


Figure 25: The kinetic structre created by student C by using one Active Shape ***(A)*** with two arrangements.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 36)

"2nd stage:

Student C reports the design stage.

He tried at first to create a symmetrical structure, so he fixed all the joints/pivot points at the sale place. He expected the structure to act like a scissor or a straight member, but he realized that it behaves a little bit different than he thought, and there is definitely another horizontal motion. He realized that by using the 2 arrangements he is getting a large motion from the structure he created by just using a small motion from the first part of the structure. He started thinking about multiplying the structure, which might result in larger motion in the structure with smaller created by him at the first member. The student said that he didn't have anything in mind while he was designing it; he was only thinking how to create an efficient deployable structure."[354]

[354] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 3

Figure 26: Student C reporting what he did in the first design stage: He realized that by using the 2 arrangements he is getting a large motion from the structure he created by just using a small motion from the first part of the structure.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 37)

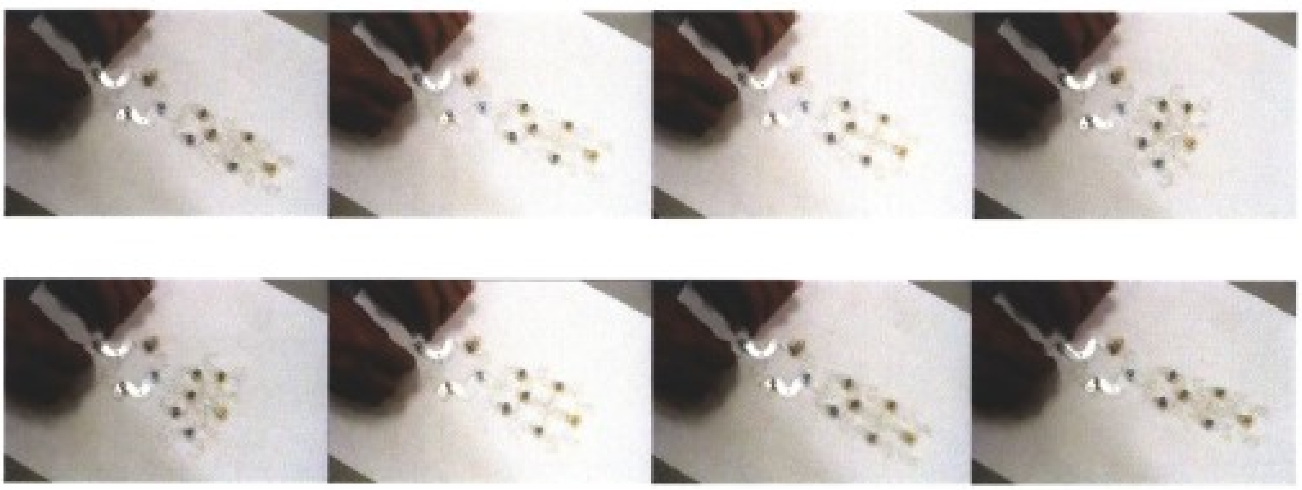


Figure 27: The kinetic structure created by student C.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 38)

"3rd Stage:

*Applying one of the transformations in the design produced in the first stage by another participant. Student E applies a transformation in geometry **t** in the Active Shape **(A)** chosen by student C on the first stage. He kept the same arrangement from the first stage."*[355]

[355] El-Zanfaly, Dina, *Op. Cit* (2011) P. 36-37

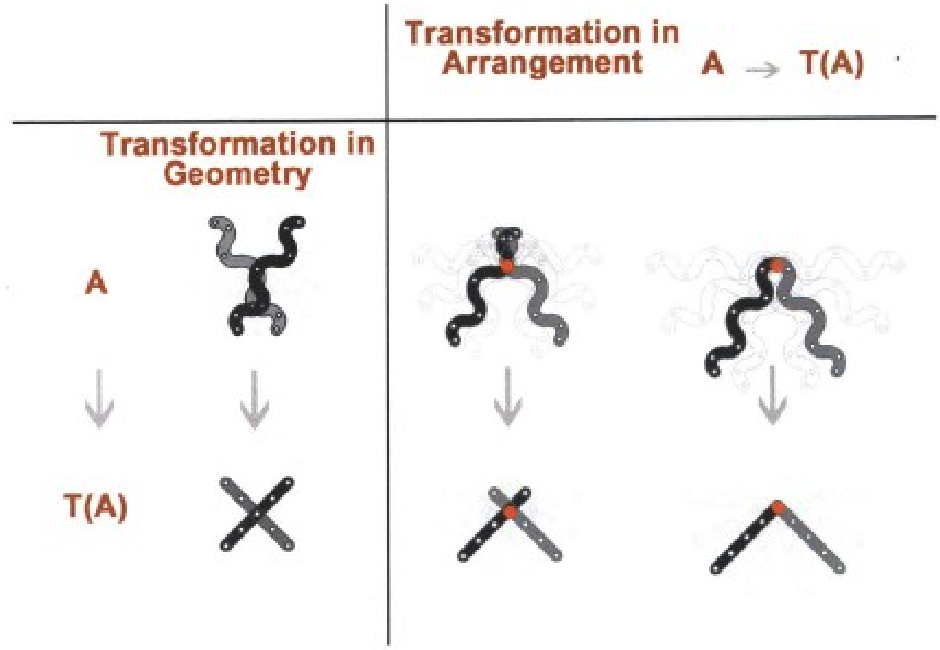


Figure 28: The Transformation in geometry *t* made by Student E on the Active Shape ***(A)*** chosen by student C in the first stage, the arrangement of the components of the Active shape are kept the same from the First Stage.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 39)

Figure 29: Opening state: A comparison between the original kinetic structure created by student C from stage one and the new kinetic structure created by student E created in stage 3 by applying a transformation *t* on the original Active Shape ***(A)*** from stage one.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 39)

Figure 30: Closing state: A comparison between the original kinetic structure created by student C from stage one and the new kinetic structure created by student E created in stage 3 by applying a transformation ***t*** on the original Active Shape ***(A)*** from stage one.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 40)

"4th Stage:

*Student reports design stage, where he applied a transformation in geometry **t** on the original Active Shape **(A)**. The student here used the transformation in geometry as descriptive method for the original structure. He wanted to see the motion in the original structure. He realized that by keeping the arrangement and changing the geometry of the components, interesting result is produced. The student commented on what he did as a way to describe a motion. He stated that because the components are curved and not on a straight mine, it produced an interesting motion."*[356]

[356] El-Zanfaly, Dina, *Op. Cit* (2011) P. 40

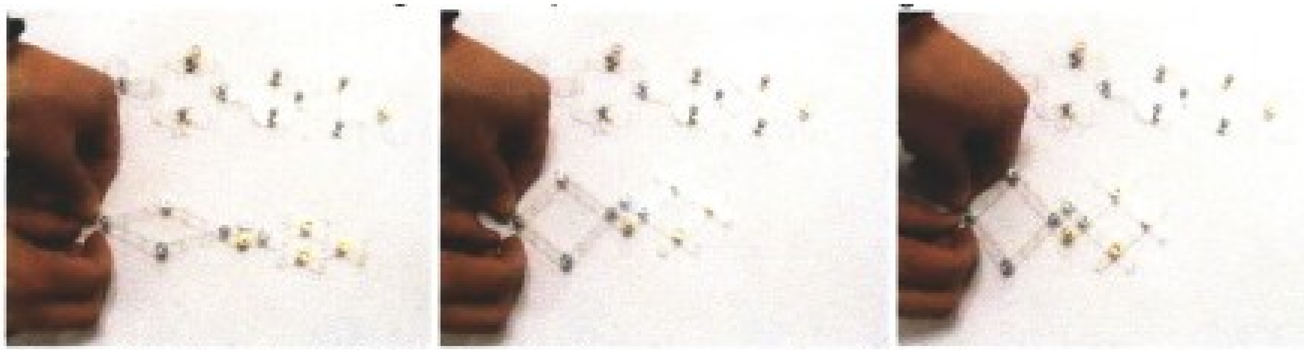


Figure 31: He realized that by keeping the arrangement and changing the geometry of the components, interesting result is produced.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 40)

*5.2.3-Problem II_*

"*The participants are students E and A.*

1st stage:Creating a kinetic structure from the given tables. Student E chose and Active Shape (A) with two arrangements."[357]

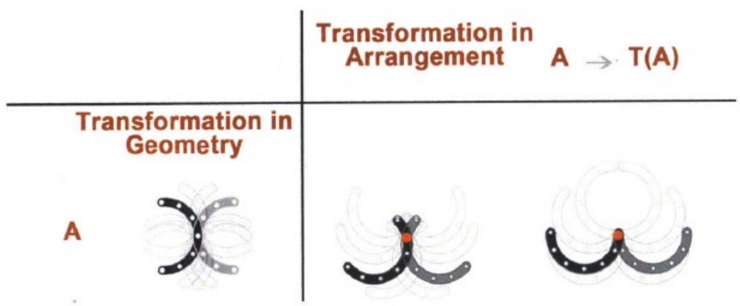


Figure 32: The Active Shape chosen by student E, the student chose one Active Shape *(A)* with two arrangements.

Figure 33: The Kinetic structre created by student C by Using one Active Shape ***(A)*** with

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 41)

[357] El-Zanfaly, Dina, *Op. Cit* (2011) P. 41-45

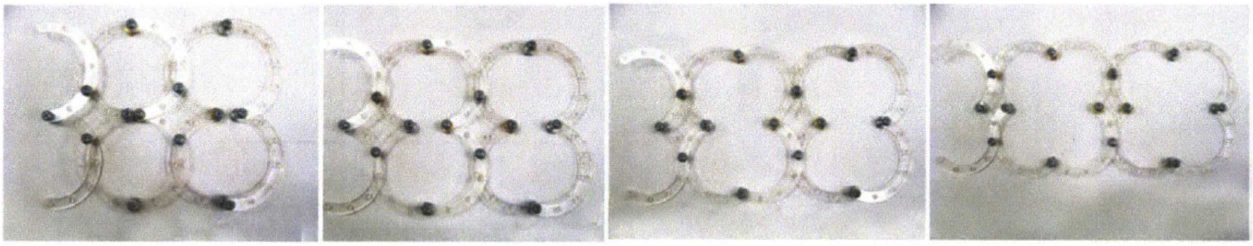
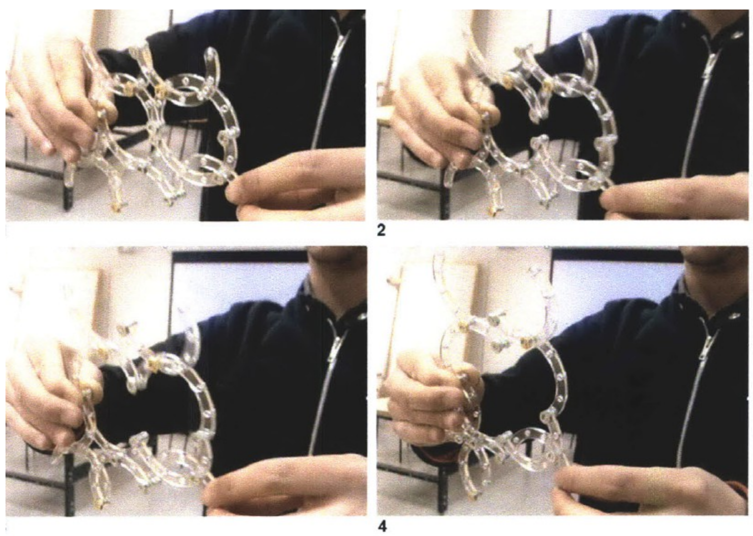


Figure 34: Stage one- Created by Student E.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 42)

"2nd stage:

Student E reports from the design stage. He described the structure as set of circles, but once it put in motion, it opens up and it will look like flowers. He described it as a wall that opens up with different windows."[358]



'igure 35: Student E describing his design.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 43)

"3rd stage:

*Applying one of the transformations on the design produced in the first stage by another participant. Student A applies a transformation in geometry **t** on the Active Shape (A) chosen by student E in the first stage. She kept the same arrangement from the first stage."*[359]

358 El-Zanfaly, Dina, *Op. Cit* (2011) P. 41-45

359 Idem.

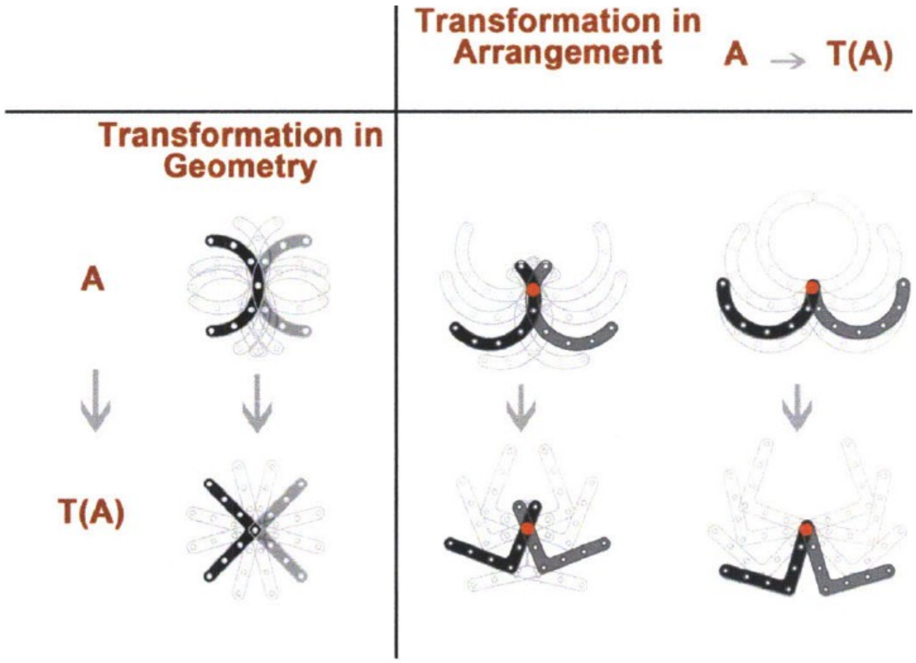


Figure 36: The transformation in geometry ***t*** made by Student A on the Active Shape ***(A)*** chosen by student E in the first stage, the arrangement of the components of the Active shape are kept the same from the First Stage.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 44)

Figure 37: Opening and closing states: A comparison between the original kinetic structure created by student E from stage one and the new kinetic structure created by student A created in stage 3 by applying a transformation *in geometry* ***t*** on the original Active Shape ***(A)*** from stage one.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 44)

"4th stage:

She replaced the half circle with a right angle; she described it as a diamond shape. She has added 2 (two) *more components than the original shape. She realized that the shapes are not affecting each other and creating the motion as the original structure. She described them as modules not affecting each other."*[360]

5.2.4-Problem III_

"*The participants are students A and B.*

1st stage:

Creating a kinetic structure from the given tables. Student C chose and Active Shape (A) with one arrangements. Student A chose one active shape (A) with one arrangement."[361]

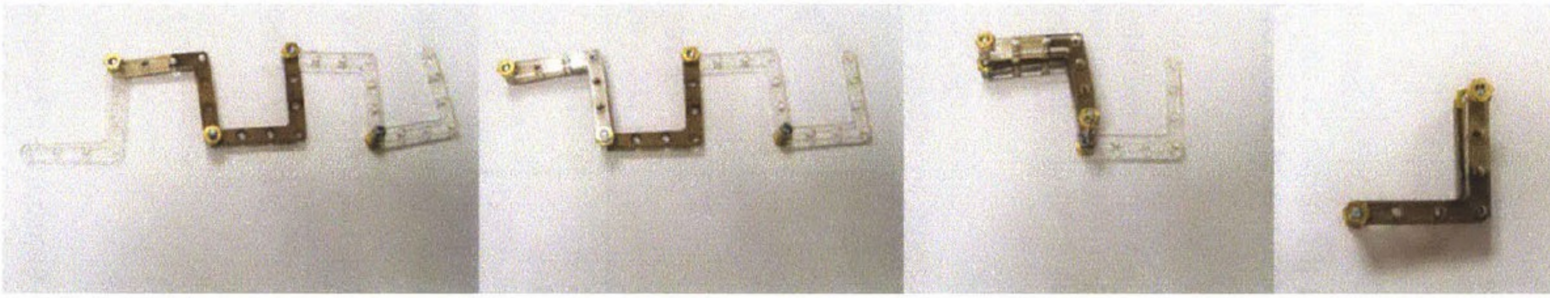
Figure 38: The Active Shape chosen by student A, the student chose one Active Shape *(A)* with two arrangements.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 45)

"2nd stage:

*The transformation in geometry **t** made by student A on the Active Shape (A) chosen by student E in the first stage, the arrangement of the components of the Active Shape are kept the same from the first stage. She wanted everything to collapse on itself, to save the space and take the least area initially. She would like to expand it to be a multiple use structure to form a table or a desk to save space."*[362]

360 El-Zanfaly, Dina, *Op. Cit.* (2011) P. 41-45
361 Ibid. P. 45-47
362 Idem.



(Infoline 2009)

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 46)

"3rd stage:

*Applying one of the transformations on the design produced in the first stage by another participant. Student B applies a transformation in geometry **t** on the Active Shape (A) chosen by student A in the first stage. He kept the same arrangement from the first stage."*[363]

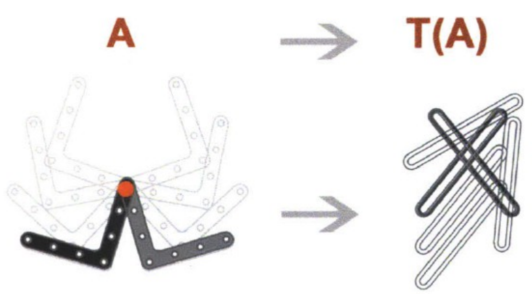
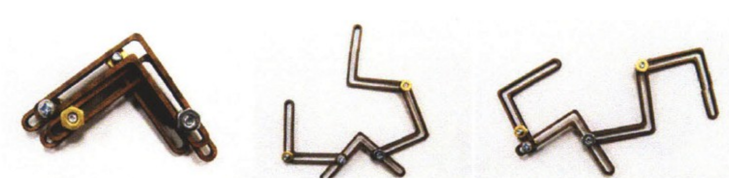


Figure 39: The Transformation in control mean ***t*** made by Student B on the Active Shape ***(A)*** chosen by student A in the first stage, the arrangement of the components of the Active shape are kept the same from the First Stage.



(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 47)

[363] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 45-47

"4th stage:

*Student B reports the design stage,where he applied a transformation in the control mean **t** on the original Active Shape and got a new Active Shape(A). He commented that by changing the control mean to a slider, the structure became loose, and now he is more inclined to introduce more constraints systematically by putting more connections."*[364]

*5.2.5-Problem IV_*

"*The participant is student B.*

1st stage:

Creating a kinetic structure from the given tables.

Student B chose one active shape (A) with one arrangement, one from the given table and one not from it."[365]

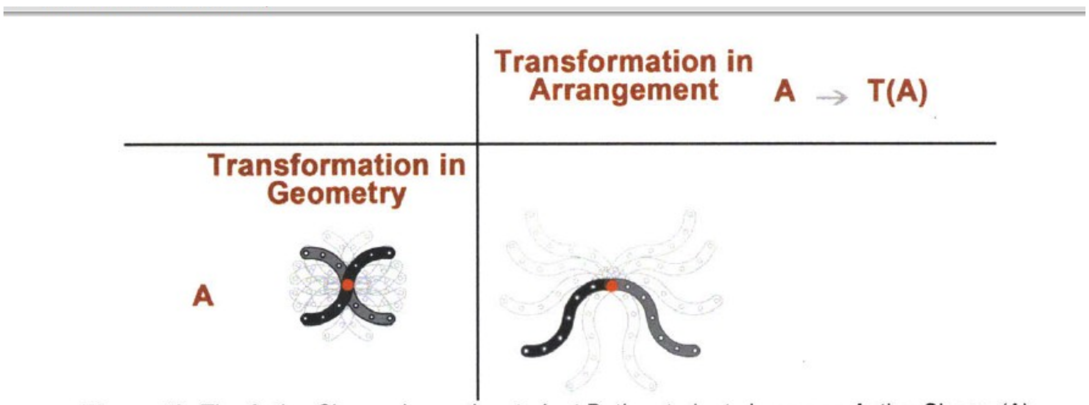


Figure 40: The Active Shape chosen by student B, the student chose one Active Shape *(A)* with two arrangements.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 48)

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[364] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 45-47

[365] Ibid. P. 48

"2nd stage:

Student B reports the design stage.

Advantage of the curve, hard time visualizing anymore that (than) *two pieces connected, can't simulate it in his head, it was a hands on work. He tried to make it asymmetric and continuous. "*[366]

*5.2.6-Problem V_*

"*The participant is student F.*

1st stage:

Creating a kinetic structure from the given tables. Student F chose one active shape (A) with two arrangements, but he also chose to [create one of his own]."[367]

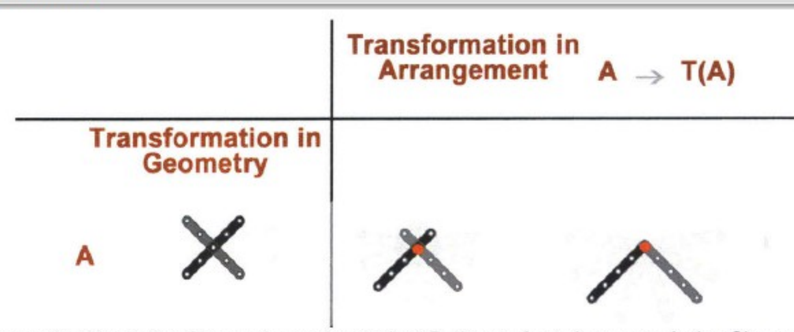

Figure 41: The Active Shape chosen by student B, the student chose one Active Shape *(A)* with two arrangements and sizes.

Figure 42: Stage one- Created by Student F

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 49)

[366] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 48

[367] Ibid. P. 49

"2nd stage:

Student B reports the design stage. He described it that it's like a computer which gives A and B states and locks it."[368]

Figure 43: Student B reporting his model.

(El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 50)

Workshop discussion:

When the mini-workshop was done, El-Zanfaly and the participants had some considerations that were relevant to this research as they established in hands-on exercises that, not only was it necessary to employ special software and according computational tools (answering a specific question in the outline of the thesis), but also that implementing shape grammars helps the motion setting process.

- "*Although it is difficult for the designer to predict the exact behavior of motion of a kinetic structure in the design process, the workshop has proved* (sic) *that once the designer follow* [s] *the presented guidelines, he/she gets* [a] *better idea of what would happen to the motion if he/she applied (sic) one or more of the transformations on the components of the Active Shape. The trial and error process will be still used to give an idea how a kinetic structure moves, but the introduced guidelines in this thesis proved to be more efficient, and give the designer the ability to produce novel kinetic structures* [as demonstrated by earlier by Fenwick's Morphosis process].

- *The guidelines also proved (sic) that they could be used as descriptive tools as seen in the third stage in problem one. This would help the designers to look at different kinetic motions and describe them with these tools and get an Active Shape. By applying transformations on the Active Shape (A) the designer gets a new Active Shape (A) that could fit to his design*

[368] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 49

problem."[369]

And this conclusion concerns and proves this research's initial speculation and question:

- *"Without simulation software or digital fabrication of the active shapes, its very hard to predict the exact motion or quantitate (sic)* [quantify] *information.*

- *Assembly of more than an Active Shape is very important here. As we seen in one of the examples, the student said that he can't imagine the kinetic motion of the structure, unless with the hands-on exercise."*[referring to populations][370]

5.2.7-Self study_

As denoted, El-Zanfaly's research carried on to analyze the facts derived from her initial theories (proven in the previous section) and submitting them to scrutiny on her own design projects for her Masters Degree dissertation.

5.2.8-1st project_

This project was an origami model called *Kelidocycle*, that is *a connected ring of tetrahedrons, which give specific rotational motion.* [371]

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[369] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 49
[370] Idem.
[371] Ibid. P. 53

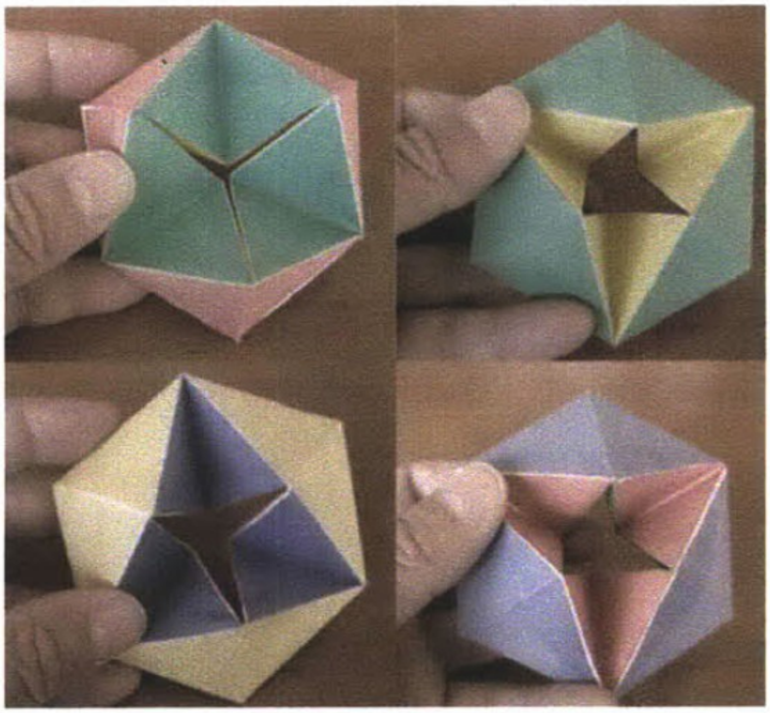


Figure 44: Kleidocycle in Action.

Kelidocycle, Tetrahedron study, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 53)

tetrahedrons connected together, and I studied their behavior.

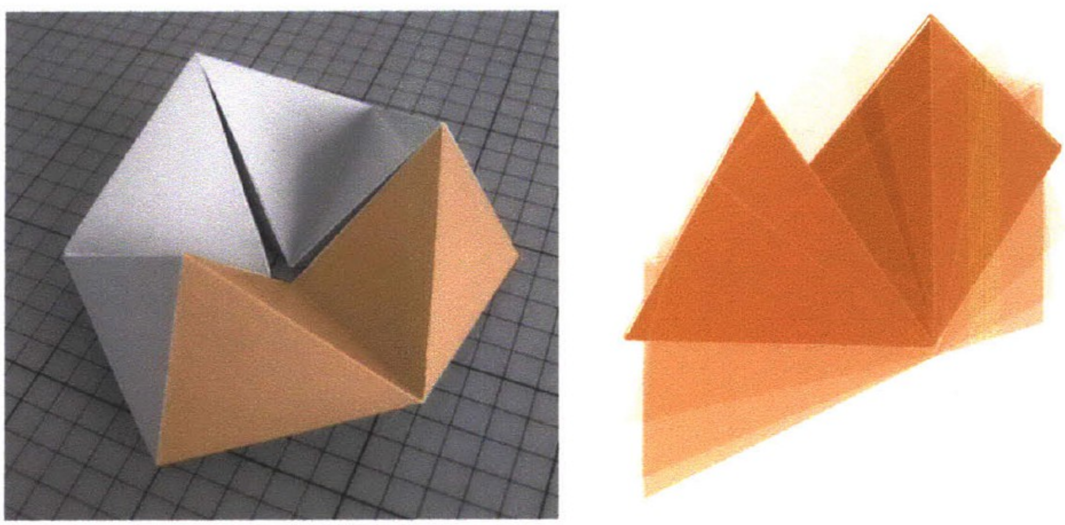


Figure 45: Choosing the active shape from the kleidocycle.

Kelidocycle, Tetrahedron study, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 53)

By observing the *Kelidocycle* in action, she chose the active shape as two tetrahedrons connected together studied their behavior.

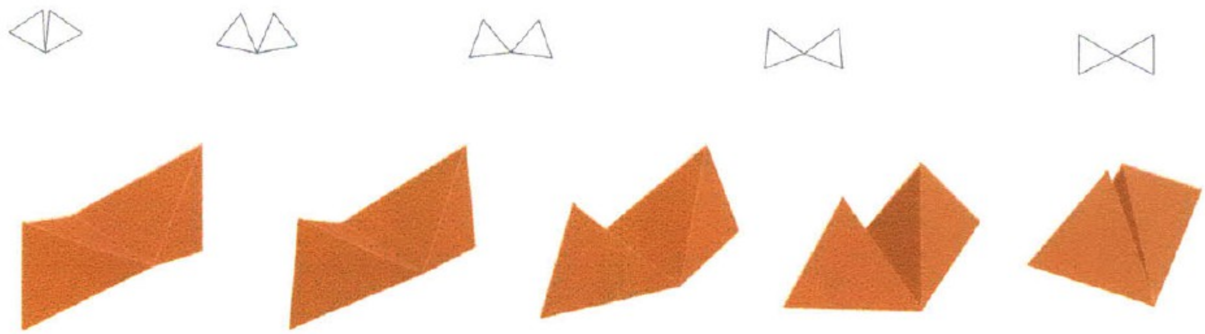


Figure 46: Caption for the movement of the Active Shape.

I chose a transformation in geometry *t* to be applied on the components of the original active shape, which I got from the kelidocycle.

Kelidocycle, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 54)

Then she chose a transformation in geometry *t* to be applied on the original active shape gotten from the kelidocycle.

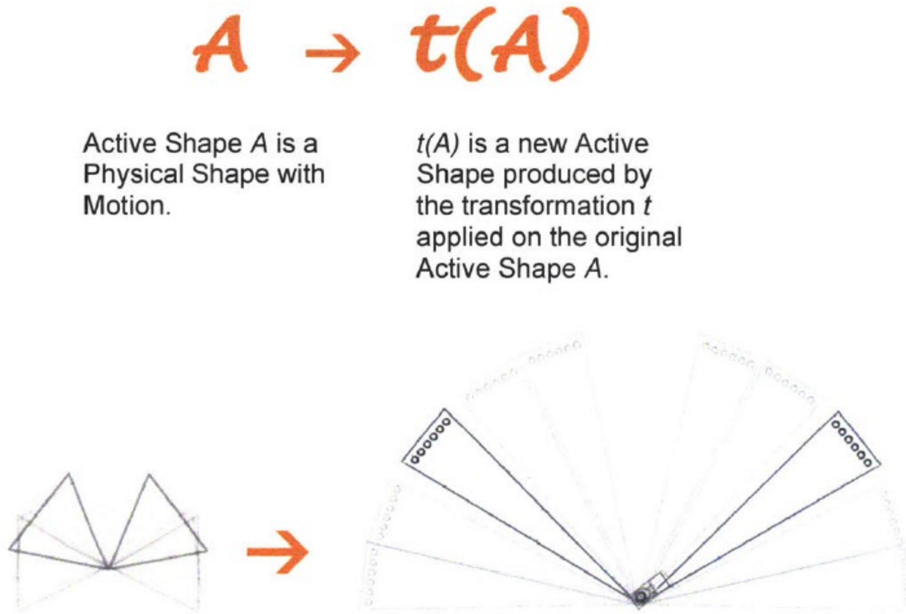


Figure 47

Kelidocycle, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 54)

Figure 48: Caption for the new movement of the Active Shape (A) .

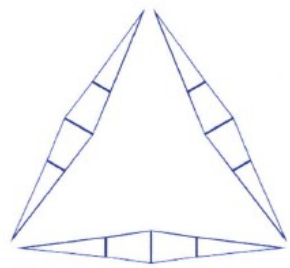


Figure 49

After Assembling 3 active shapes together, I got a Kleidocycle in which it has 2 separate motions. 1. Revolving, and 2. Folding

Kelidocycle, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 55)

Following she assembled three active shapes together deriving a kleidocycle with two separate motions:

1. ***Revolving***
2. ***Folding.***

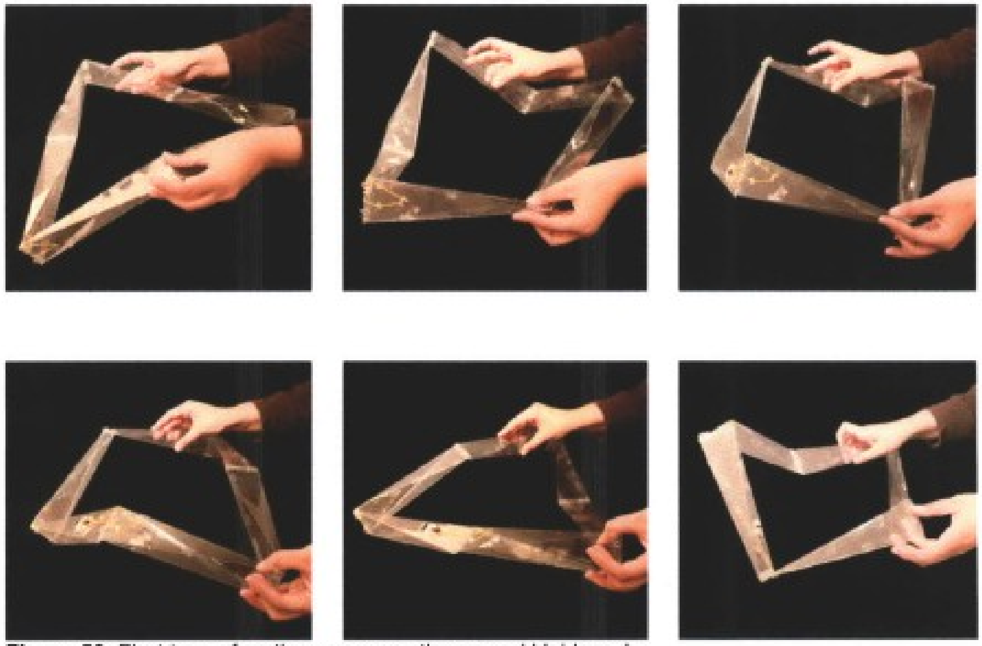


Figure 50: First type of motion , same as the normal kleidocycle.

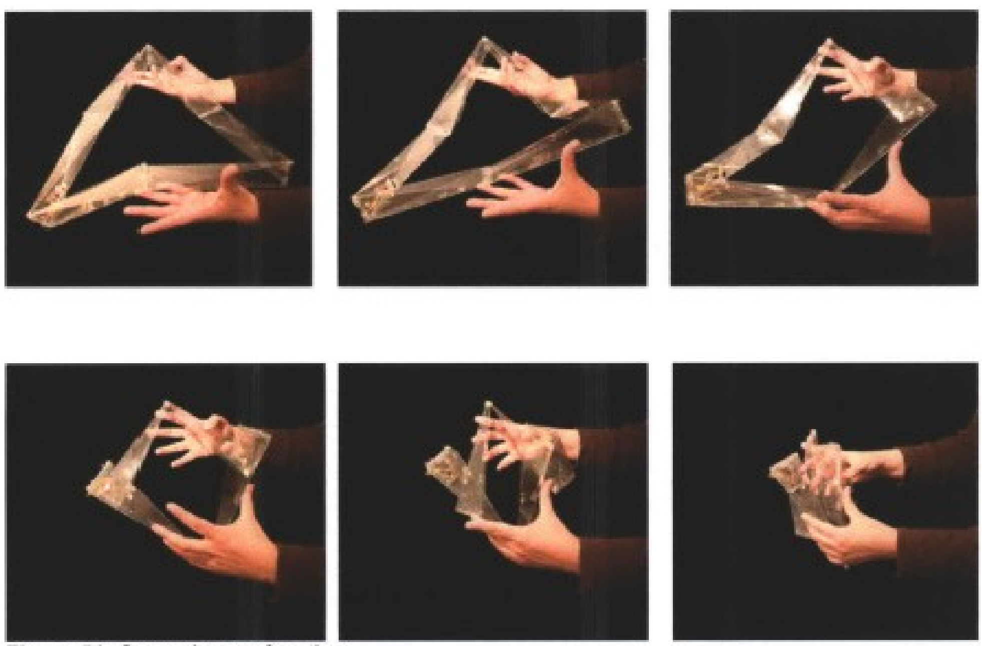


Figure 51: Second type of motion.

Kelidocycle, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 56)

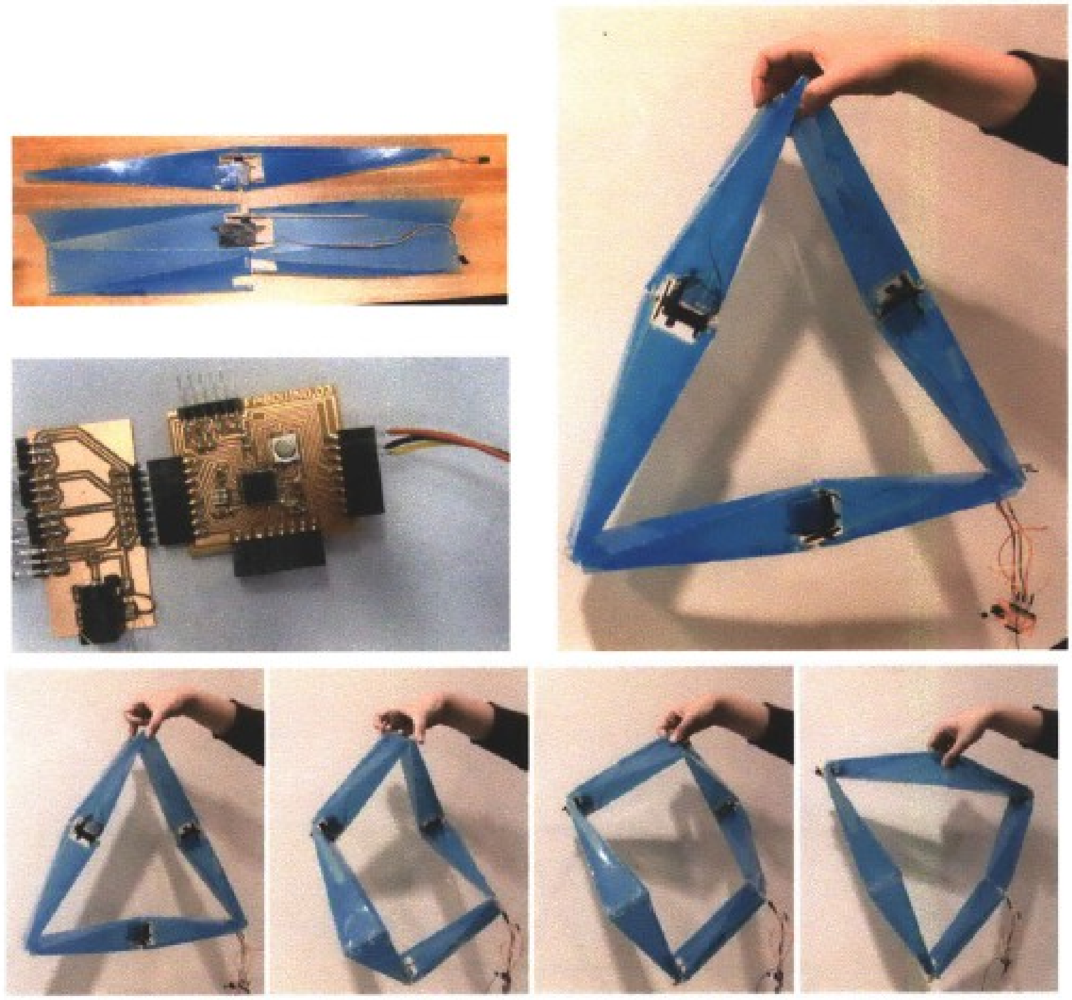


Figure 52: Embedding computation inside the kinetic unit to act as one unit in a shape shifting structure.

Kelidocycle, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 57)

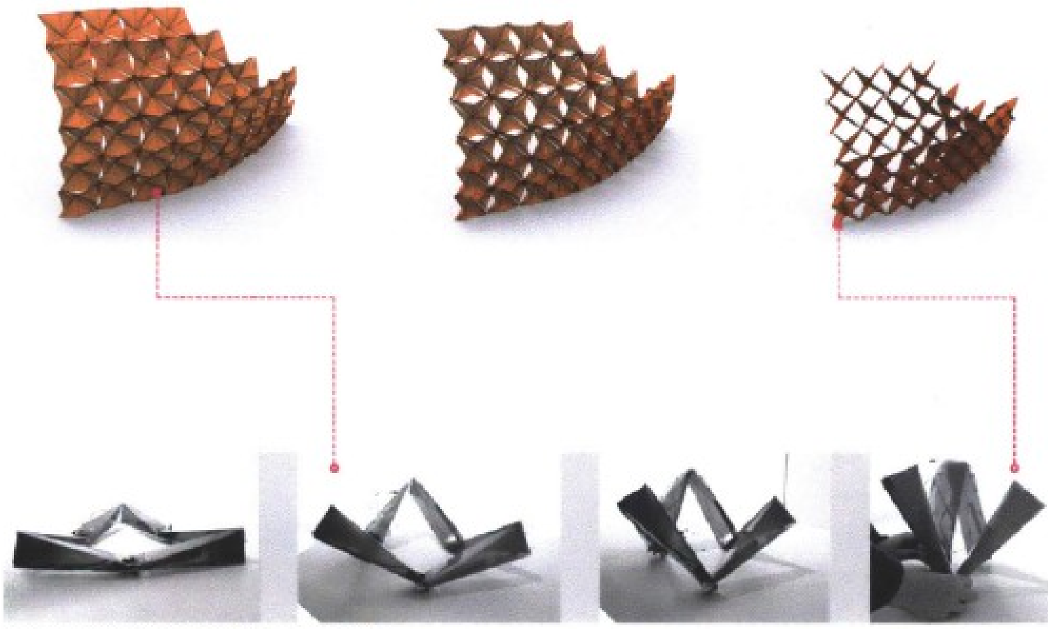


Figure 53: One unit in the structure.

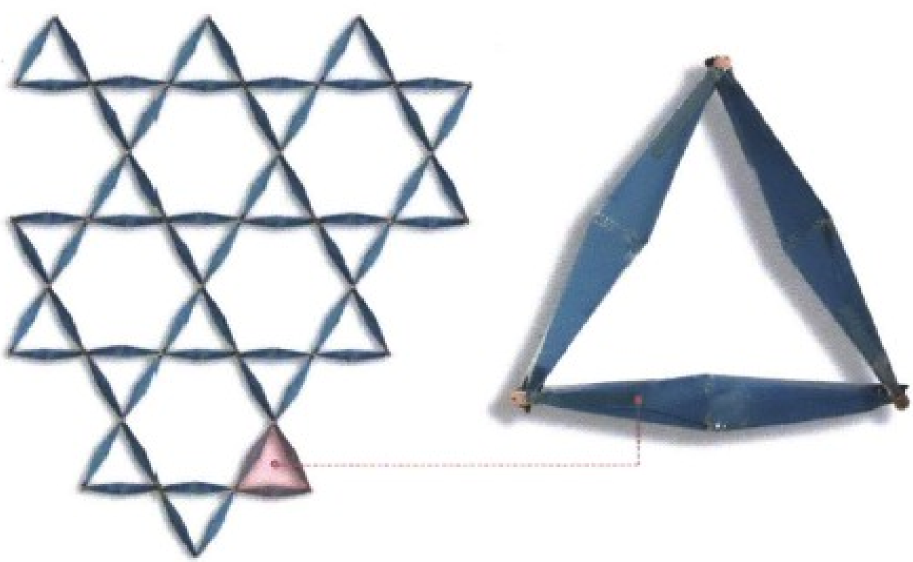


Figure 54: One unit in the structure.

Kelidocycle, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 58)

*5.2.9-2nd project_*

For the second project study case she studied the conceptual design and digital fabrication of scissor-pair transformable structures, creating a fold-able structure in two steps: 1) parametric modeling and 2) digital fabrication process (fabrication and mechanical implementation). Which was achieved via:

"*Arduino, a microcontroller, and a small motor together with a sensor to manipulate the structure's motion, this is used to mimic the change in the structure when it reacts to any contextual or environmental change in the reality."*[372]

This is a very important concern for this thesis as it outlines a problem that persists in kinetic architecture implementation: ***the paraphernalia of artifacts utilized to render a kinetic structure responsive, which will be addressed in chapter VII arguing programmable matter as a possible medium to avoid such complicated and ineffective methods.***

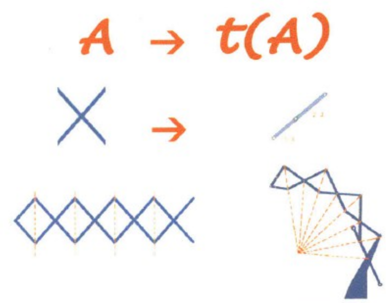


Figure 55: Applying a transformation in arrangement on a scissor par structure, resulting in a radial motion instead of a horizontal one.

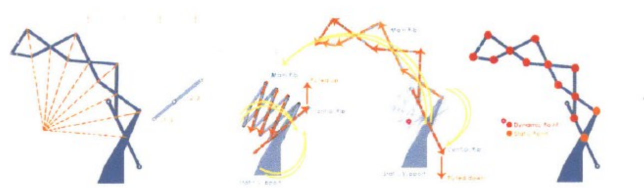
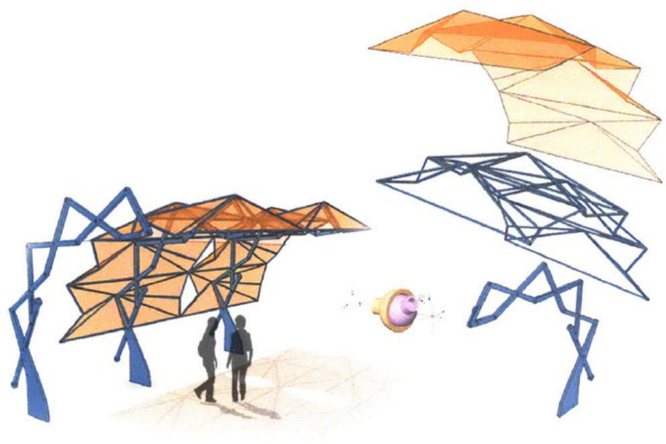


Figure 56: Diagrams showing the radial motion.

Scissor Pair Structure, comutational design, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 59)

[372] El-Zanfaly, Dina, *Op. Cit*. (2011) P. 59



Scissor Pair Structure, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 60)

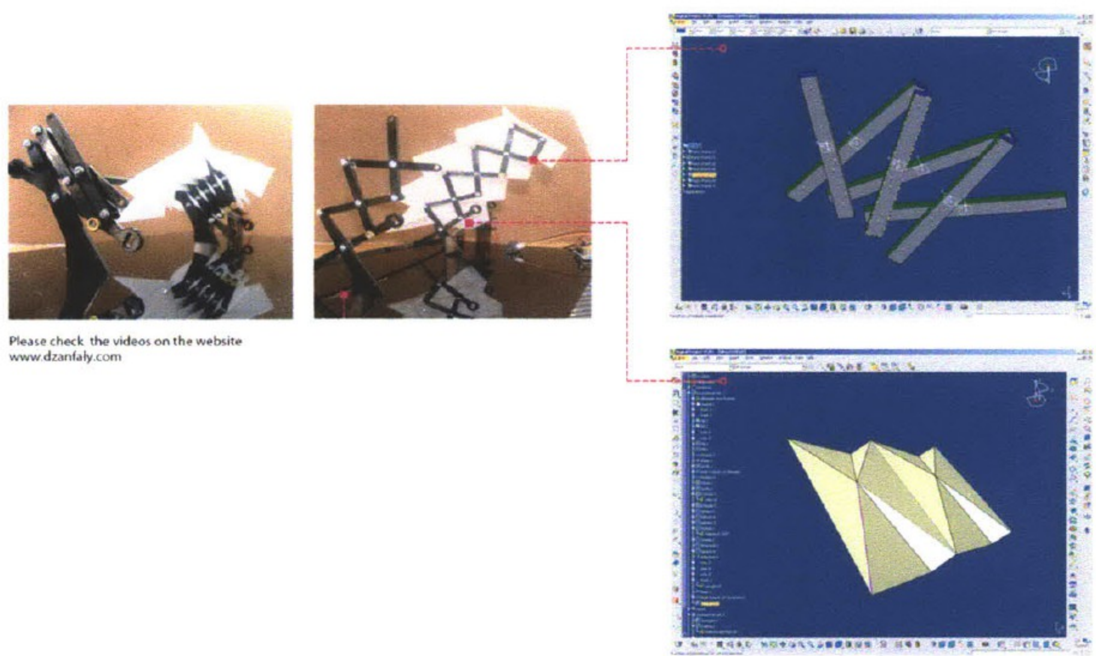


Figure 57: using Digital project and digital fabrication for simulation.

Scissor Pair Structure, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing* *kinetic architectural structures*, P. 60)

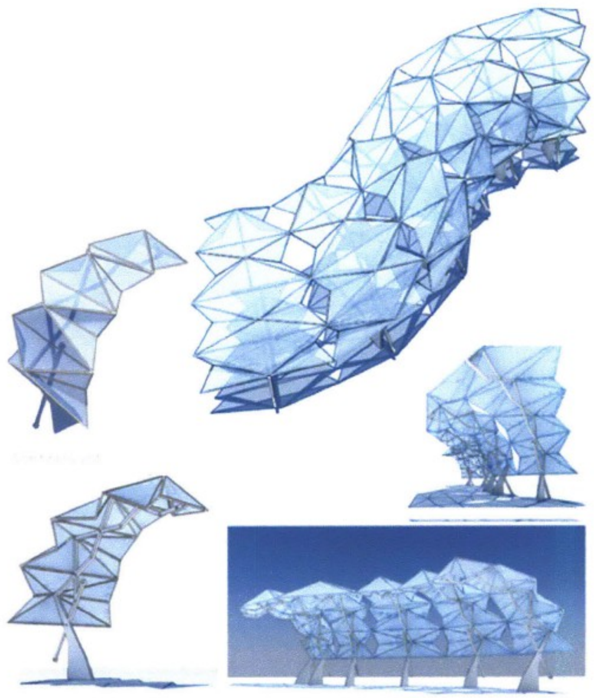


Figure 58: Implementation1: Arcades.

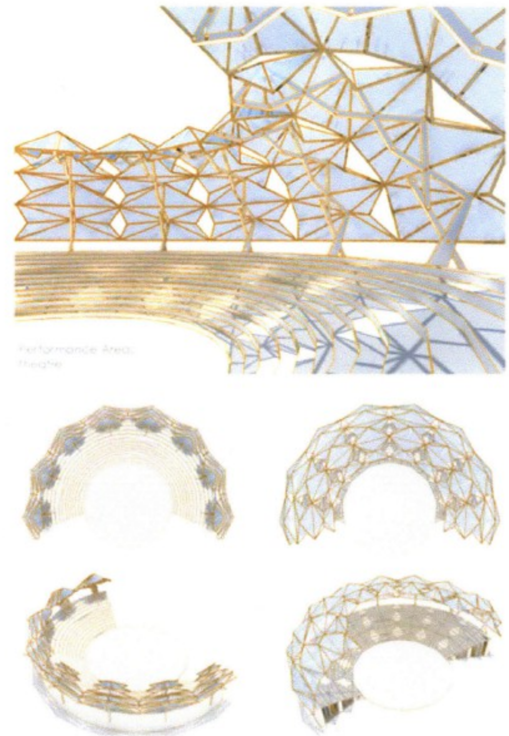
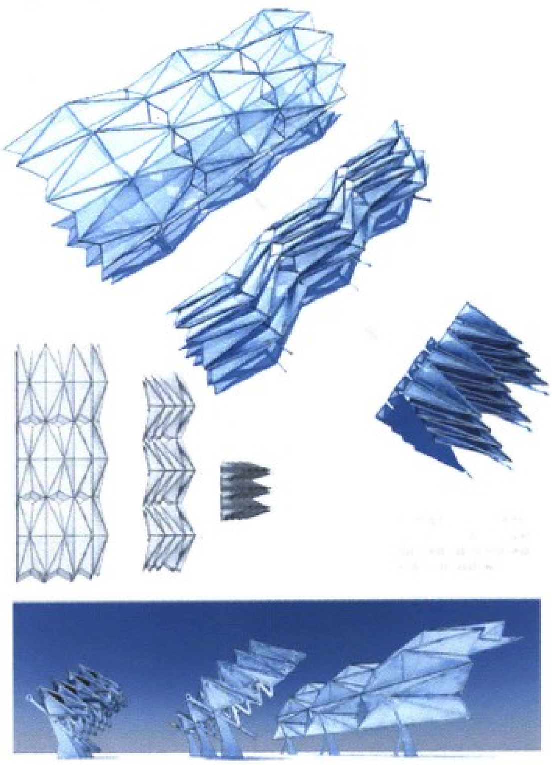


Figure 59: Implementation 2: Amphitheater

Scissor Pair Structure, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 61-62)



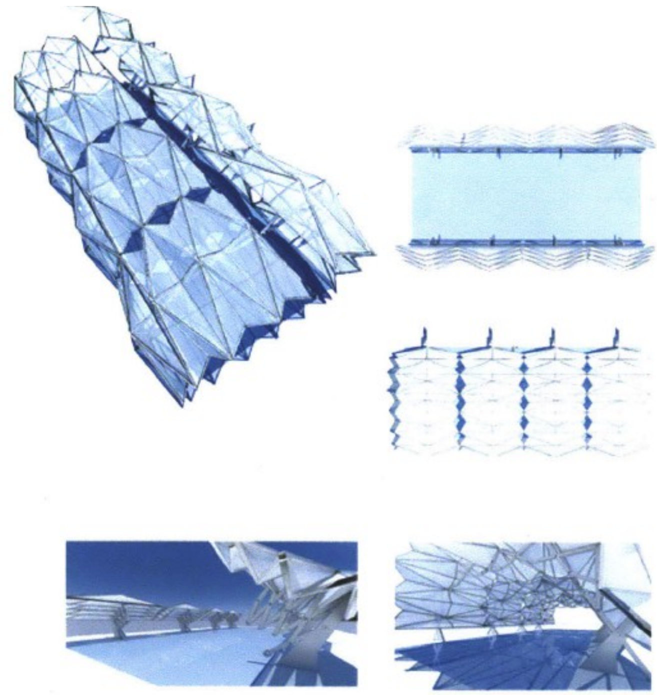


Figure 61: Implementation 4: Swimming pool.

Figure 60: Implementation 3: Emergency Housing.

Scissor Pair Structure, Dina El-Zanfaly (2011) (El-Zanfaly, Dina, *Active Shapes: Introducing guidelines for designing kinetic architectural structures*, P. 63-64)

*5.3-Conclusions_*

Out of all the conclusions that El-Zanfaly drew from her research, one question stood out as the main one to answer and it remained in consonance with this present research's aims:

"*How can designers design novel kinetic architectural structures?"*[373]

Her main concern at the end of her investigation was:

- *"The trial and error process* [as in Fenwick's inefficient "iteration" process in the previous section] *will be still used to give an idea* [of] *how a kinetic structure moves, but the introduced guidelines in this thesis proved to be more efficient, and give the designer the ability to produce novel kinetic structures.*

[373] El-Zanfaly, Dina, *Op. Cit*. (2011) P. 67

- *There are too many parameters, and too many areas in designing a whole kinetic structure has* [have] *to be explored and researched.*

- *The materiality should also be studied as a major transformation parameter in the active rules* [a concern that this research will address directly later in this chapter and is central to the development of this investigation's project]

- *In addition to exploring the rest of the possible transformations in the active rules, the presented guidelines should be put in a framework for designing the kinetic structures, which should also contain: The design mediums, which include the simulation softwares (sic) and physical prototyping* [of which this thesis will address the former -simulation software and computational techniques to achieve it- as the latter is out of the research scope of action].

- *Some of these elements should be also connected in a loop like the virtual design and the physical prototyping to maintain the connection of geometry and physics to materiality, mechanics and scalability.* [this is also another conclusion that ties up with the aims of this research in producing a software tool that models SMM behavior to continuously simulate them in the decision making process within design] "[374]

- *"Several stages should be introduced in the framework including:*
    1. *Motion types, whether it is continuous or discrete*
    2. *The motion speed*
    3. *The degrees of freedom* [This specific "stage" was investigated in 2007 by Angeliki Fotiadou and will be detailed thoroughly later in this thesis]
    4. *The material properties and* (a subject also addressed, discussed and implemented in this thesis project as it will be shown in chapters VII, VIII and IX)
    5. *The structure scalability"*[375]

These conclusions further prove the top-down approach rather inefficient and tortuous and also points

[374] El-Zanfaly, Dina, *Op. Cit*. (2011) P. 68
[375] Idem.

out that the bottom-up approach holds better chances (although not a complete victory is announced, for bottom-up still has a lot of uncertainty to deal with in real world applications) of successfully addressing kinetic architectural implementation under local interactions in lower levels. And Although it is difficult for the designer to predict the exact behavior of motion of a kinetic structure in the design process, after a certain complexity is reached as concluded in the prior case studies, it is this thesis's hypothesis that neither "top-down" nor "bottom-up" are completely advantageous on their own when engaging with fundamental to practical application in the context of kinetic systems (with a significant tendency favoring bottom-up approaches) therefore a synthesis between the two paradigms ("top-down" or "symbolic", and "bottom-up", this merger dubbed the "sub-symbolic" paradigm by Karl Chu) is needed to fully grasp the complexity that can be achieved and dealt with at different scales when designing and implementing intelligent kinetic systems design into the architectural environment. Programmable matter is proposed as a material definition, material design as a methodology and craft, and performance driven simulation as a design instrument. These will be thoroughly scrutinized and tested in digital experiments at the end of this thesis.

*6-The need for Performance Driven Simulation software_*

*6.1-Animation and simulation: a fundamental difference_*

"Simulation has already allowed architects to pursue novel approaches to a design problem which has led to a growing number of investigations where simulation is an integral part of the form finding process."[376]

Before going any further, it is imperative to draw the line between ***animation*** and ***simulation***, though they are rooted in the same conceptual, practice framework and background, there are some, non obvious, but fundamental differences that are imperative to sort out before moving on with this kinetic architecture analysis, as their confusion may pose problems if mistaken in the implementation and modeling practice, as not the same outputs may come from one as compared to the other and that may cause problems in the fabrication, assembly and construction processes. It is certain that using animation processes to produce design that lead to high quality processes skyrockets your capability to understand what it is that you are actually going to build in real time, as some kind of communication between the designer, object and even the environment, that it also lets you visualize, in a very intuitive way, how the object can possibly morph or shape shift in response to constraints because *a key phenomenon in animation is its ability to simulate metamorphosis and its digital progression, "the morph"*. [377] Animation processes portray a lot of opportunities and they are indeed a great leap in advance within architectural design methodology but, even if this will prove a fundamental basis in developing simulations for kinetic systems, at the same time, its limitations in terms of producing *close to real world properties replication*, *uncertainty*, *adaptability* and *parametric model reuse* (one of Daniel Davis main concerns in building parametric models in the practice of architecture) are, although not evident (just as the difference between animation and simulation), very important at when it is imperative to have specific, fluid input and output synergy in a highly intuitive yet highly precise process of design to fabrication that emphasizes in adaptation and transformation. Simulation does not just build virtual models, it tries to implement materiality and phenomenology within its computations, whereas *animation* could be equated to an *artist rendering*, simulation is a more scientific, data driven process of test and run loops, where a certain actuation model is run in an *interactive write-compile-*

376 Oxman, R: 2008, Performance-based design: current practices and research issues, *International journal of architectural computing*, Vol. 06, pp. 1-17
As Quoted by: Attar, Ramtin -Aish, Robert - Stam, Jos - Brinsmead, Duncan - Tessier, Alex - Glueck, Michael - Khan, Azam, *Op. Cit*. (2009) P.2.
377 Buchan, Suzanne, editor for Animation journal, personal communication to Dollens, Dennis, (12 October 2005)
In Dollens, Dennis, *Op. Cit*. (2006) P. 111(http://anm.sagepub.com/content/1/1/105) (12-11-2010)

execute-cycle[378], much like computer programming, with outputs being rendered based on actual material and context property data woven in a *recursive loop* opposite perceived interpretation in the case of *animation*.

"*Several objects designed with these methods appear blob-like and imprecise. However, the designer establishing and manipulating the parameters is in strict control of the deformations possible. Actual material properties are applied to the virtual model to test the construction feasibility.*"[379]

In Electra Mikelides, Valentina Sabatelli and Delphine Amman's research, this phrase is used to describe a property of *animation*, where in fact, they are describing *simulation.* This proves that, at least in their investigation, there is a confusion about the difference between the two terms. *Animation and simulation* can be both viewed as art forms and, sure, animation software and simulation software can both simulate then, in this context, this difference is highlighted, not so much as a software tool difference, but rather as a conceptual tool one. Ruth Thomas, an eLearning, Java and simulation expert, while working at *JeLSIM* partnership[*], wrote a paper back in 2003 titled *What Are Simulations? – The JeLSIM Perspective*, that concentrated on the definition of simulation and highlighted its propensity to misinterpretation. She defined animation as *a series of moving images or a dynamic visualisation.*[380] However, since an animation can be used to represent a system's output, it *can thus easily be confused with a simulation.*[381] Thomas clears out that the distinguishing criteria that tells the two apart (animation and simulation) are two key features that set aside simulation from other system representations:

1. *"There is a (sic) no model of a real or theoretical system behind the animation.*
   In this case, the animation is more like a cartoon, it will not be accurate as the speed and location of images is not calculated by a model. The animation cannot be altered to reflect a change in system conditions, only responds to preset values.

[378] Davis, Daniel, *Op. Cit*. (2013) P. 65.
[379] Mikelides, Electra - Sabatelli, Valentina -Amman, Delphine, *Op. Cit*. (2002) P. 6
[*] The JeLSIM partnership was set up in July 2002. Before setting up the partnership we worked together for several years at Heriot-Watt University and in MultiVerse Solutions Limited. Over time, we have developed a range of complementary skills in Java, eLearning and Simulation.
Thomas Ruth – Milligan , Colin, About us, *JelSIM webtsite*, (blog post comment thread) (http://www.jelsim.org/about.html) (27/05/2015)
[380] Thomas Ruth , *What Are Simulations? – The JeLSIM Perspective.*, Copyright ©JeLSIM (2003) P. 7 (http://www.jelsim.org/about.html) (27/05/2015)
[381] Idem.

2. *There is no possibility of experimentation: According to Laurillard, there has been terminological confusion when `simulation` is used to refer to a program that runs a model without any input from the user – the program generates its own input to the model, the user simply watches. This is certainly a simulation, but Laurillard contends that since the usual usage within education is "interactive simulation", it is reasonable to reserve the term simulation for those, and to relegate the non- interactive ones to the term "animation" or "demonstration" as they could equally well be shown on the non-interactive medium of video. When the full capabilities of a simulation are not used, then it is possible turn a simulation into an animation or even the equivalent of a video*."[382]

These two characteristics are to be used as a distinguishing standard from now on through this thesis's corpus. Video display and spatial navigation do not comprise simulation in the context of this thesis, therefore, animation does not either.

6.1.1-What is a Simulation?

Defining simulations is problematic, given the many perspectives of its users.[383] Thomas acknowledged that the term was (at the time and still today is) very ambiguous, to say the least. In the paper, she resorts to definitions of several experts coming from diverse disciplines, starting with the Oxford dictionary.

"A typical dictionary definition from The Oxford English Dictionary describes simulation as:

'The technique of imitating the behaviour of some situation or system (Economic, Mechanical etc.) by means of an analogous model, situation, or apparatus, either to gain information more conveniently or to train personnel."[384]

While this definition sounds like a very precise one at first, once we look at what an actual expert has to say about the term, its signification starts to shift off-course. If you take for example, computer

382 Thomas Ruth , *Op. Cit.* (2003) P. 7
383 Ibid. P. 1
384 The Oxford English Dictionary.
As quoted by: Thomas Ruth , *Op. Cit*. (2003) P. 1

simulations as a focus (like Thomas does in her paper and like it is focused in this thesis) Paul Fishwick, a simulation techniques specialist, in his 1995 book titled *Simulation model design and execution*, describes computer simulation as "*.. the discipline of designing a model of an actual or theoretical physical system, executing the model on a digital computer and analysing the execution output*."[385] Interestingly enough, they both use the words "system" and "model" yet in slightly distinct semantic contexts, in the dictionary definition, the simulation is an imitation; in Fishwick's, it is "designed", meaning that there is an extra dimension when implementing it: the simulation it's its own system, even when it is "imitating" another an actual "real" situation, it can run "physical" or "abstract" systems alike. And, of course, Fishwick's simulations have the finality of analyzing and running input in addition to the dictionary's end game which is to only "gain information" or "train personnel". On the educational front, Thomas cites Diana Laudrillard who, in a book titled *Rethinking University Teaching*, affirms that: *"A computer-based simulation is a program that embodies some aspect of the world, allows the user to make inputs to the model, and displays the results."* [386] Thomas then asserts that there seems to be an agreement among experts and educators that utilize these methods in their disciplines.

"*The key features of simulations* [according to Thomas] *are:*

1. There is a computer model of a real or theoretical system that contains information on how the system behaves.

2. Experimentation can take place. i.e. changing the input to the model affects the output."[387]

These are definitions which, in the context of the interest, objectives and aims of this thesis, certainly adhere to how simulations are going to built and tested in the experiments phase in chapter IX and therefore will be used as theoretical foundation on how case studies will be picked, defined and judged as such.

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385 Fishwick, Paul A., (1995), "Simulation Model Design and Execution". Prentice Hall Inc.
As quoted by: Thomas Ruth , *Op. Cit*. (2003) P. 1

386 Laurillard, Diana, (1993) , "Rethinking University Teaching a framework for effective use of educational technology". Routledge.
As quoted by: Thomas Ruth , *Op. Cit*. (2003) P. 1

387 Thomas Ruth , *Op. Cit*. (2003) P. 1-2

"From the educational perspective Laurillard would set a level below which a simulation ceases to be useful. She says:

'Simulations are useful in representing complex relations. There would be little point, for example, in simulating a model of an aspect of the economy, such as `increasing inflation leads to increasing unemployment` as the relationship is simple enough to understand from the description alone."[388]

Establishing complexity as simulation's main utilization context. Its uses may vary from field to field, but the end is always the same: to model profound and highly encrypted phenomena. The full understanding on what is and how is a simulation used, according to Thomas, *it is necessary to have a grasp of the processes and techniques used in producing and using a computer model of a system (simulation).* [389]

Ruth Thomas *What are Simulations?*

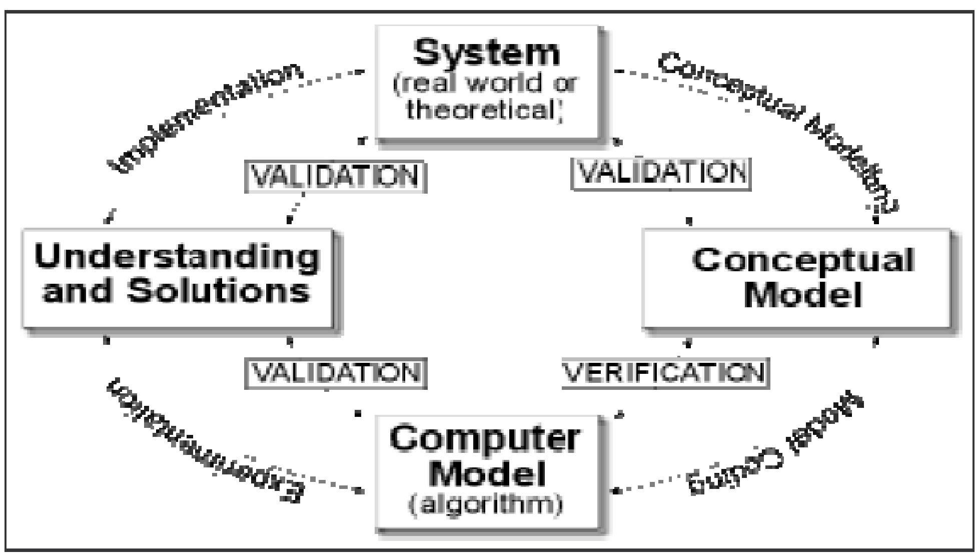

***Figure 1** The modelling and simulation process*

The modeling and simulation process, Ruth Thomas (2003) (Thomas Ruth , *What Are Simulations? – The JeLSIM Perspective.*, *Copyright ©JeLSIM 2003* P. 3)

The modeling process in simulation building is illustrated in a diagram of Thomas's own confection

[388] Thomas Ruth , *Op. Cit*. (2003) P. 2
[389] Idem.

that emphasizes the difference between "static" and "dynamic" simulations and its goals, in that the most important one is to predict and understand its behavior under different conditions, be them theoretical or real:

"The process illustrated in the diagram can be applied to any system either real or theoretical. The aim of the modelling process is to be able to predict and understand the behaviour of the system under a range of conditions. The system modelled may be dynamic and exhibit a behaviour that changes over time or be in a steady state that can be perturbed by changing the system parameters."[390]

In this light, our definition of simulation-based will adhere to any of these connotations.

6.1.2-Conceptual modeling_

The process of modeling is abstract at its core and what is important, rather than the actual running of the simulation, are the concepts that drive it. It is an iterative process on based on simplifying complexities in an abstract way. *Conceptual modelling is the process whereby the modeller defines a simplified representation of a system.*[391] For example, Thomas cites features like ignoring drag and rotation in a projectile motion simulation, as approximations or simplifications that *are introduced to reduce complexity, computational requirements or solutions time.* [392] And on modeling techniques and styles, she asserts that *the modeller will make the choice based on the needs of a particular project*[393], leaving the final decision to the model builder, basically every project will "ask" for specific techniques. *For some systems, there may be an analytic solution and a set of equations that define the model adequately, in others the computer must be used to approximate solution.*[394]

"Other considerations in choosing a modelling technique include:

Time span: *Models may be either:*

o dynamic, describing behaviours changing over time or

o static describing the system at a given instant of time and in an assumed state of equilibrium.

· ***Dynamic behaviour:*** *Changes in a system over time can be represented as:*

o Discrete Events where changes to the system take place in distinct

[390] Thomas Ruth , *Op. Cit*. (2003) P. 3
[391] Idem.
[392] Idem.
[393] Idem.
[394] Ibid. P. 3-4

steps or

o Continuous where the system evolves continuously.

· ***Randomness:***

o A deterministic model generates the response to a given input by one fixed law, for a given input, it always provides the same output. A chaotic model is a deterministic model whose output is unpredictable due to the sensitivity of the initial conditions (i.e. the starting state cannot be defined with sufficient accuracy).

o A Stochastic model picks up the response from a set of possible responses according to a fixed probability distribution and can thus simulate the behaviour of real systems under random conditions. (Techniques such as Monte Carlo are used for such models[*])"[395]

6.1.3-Model coding_

As we established earlier, the modeling process is abstract a its core, this meaning that the simplification process has to be reduced all the way down to fundamental mathematical relationships, which are to be tested and verified using a range of techniques.

"During coding the model is converted to an algorithm that can be executed on a computer. The computer algorithm must be verified to ensure it matches the model and validated to ensure the output reflects the behaviour of the system. This is an iterative process repeated until a sufficiently accurate model is obtained."[396]

To evaluate code correctness when modeling simulations, a number of techniques have been developed, yet according to Thomas. She asserted that in 2003, when she wrote her paper, there were already certain means that were adequate to construct them.

"The main ways of constructing computer models are [were, at the time]*:*

· ***Specialist Toolkits:*** *These are available for many different types of modelling e.g. Systems dynamics (Stella, PowerSim), Discrete event e.g. (Simul8, Arena)*

[*] Models which are based on computational algorithms that rely on repeated random sampling to obtain numerical results.

[395] Thomas Ruth , *Op. Cit*. (2003) P. 3-4

[396] Ibid. P. 4

· ***Programming Languages: (****e.g. Java, C++ etc.) In which models are constructed from scratch.*
· ***Spreadsheets:*** *These provide a simple general purpose tool which can be used for less complex systems."*[397]

*6.1.4-Experimentation_*

After the model is (provisionally) "finished", or at least exhibits working functionality, then *...the modeller experiments with the model to solve problems within the system and to obtain a better understanding of the system.* [398]. This understanding is acquired using a range of techniques or their combination in order to test the candidate to model a given project or system.
"Techniques used at this stage include:
· ***Sensitivity analysis:*** *This is used to test the robustness of a solution and to ascertain the effects of uncertain input data on the system outputs and behaviour.*
· ***Searching the solution space:*** *To search for an optimum solution or simulation state by repeatedly running a simulation is extremely time consuming and rarely practical. Techniques such as hill climbing and genetic algorithms* [about which we talked about in the context of genetic architecture in chapter II] *have been developed to assist in this.* [This relates to computational expenditure and code cleaning when making a simulation utilize the resources at hand in the least expensive way].
· ***Validation of accuracy of results****: It is important to check the validity of results obtained and to ensure that bias from poor sampling is not introduced.* [This thesis, although interested in fact checking digital results with laboratory ones, does not venture into the "real" experimental comparison due to non sufficient time and circumstances, therefore it will focus only in mathematical proofs and published laboratory work from other authors as accuracy validation. Future work within this thesis subject matter will include laboratory work on materials themselves.]"[399]

*6.1.5-Implementation_*

When implementing the "finished" model, the cycle of iteration of comparison with the real-world starts with modifying the system inputs and circumstances. *After obtaining an understanding of the system, decisions may be made and actions taken which affect the real world system. The cycle of modelling may then begin again, as the original system is changed by these interventions.*[400]

397 Thomas Ruth , *Op. Cit*. (2003) P. 4
398 Idem.
399 Idem.
400 Ibid. P. 4-5

6.1.6-Uses of computer simulation_

"Before the advent of graphics terminals, output from a simulation was usable only by the modeller and the discipline was very much the domain of the mathematically adept programmer. Once improved hardware provided better data visualisation, non-mathematicians (e.g. business mangers) were able to easily explore the solution space and the experimental stage of the simulation process became more generally accessible. Design and analysis using simulation was more widely used."[401]

With graphic techniques such as animation to prompt dynamic simulations that use more intuitive interfaces to communicate with users, this field has evolved into a series of applications that range from movie making to scientific, cosmological modeling to explain phenomena as complex as the origin of the universe. Simulation is so widely used that it s hard to sub-categorize all its applications yet it is possible to outline a brief of its main general uses, according to Thomas:

"Currently, most simulation use falls into the following categories:

1. Research

Research into simulations is important in exploring the accuracy and utility of novel analytic techniques that may prove of use in design and analysis; it involves the derivation and verification of models of systems. Simulations are used as research tools to establish trends, demonstrate relationships between system parameters or make predictions about the future.

2. Design

Designers use simulations to characterise or visualise a system that does not yet exist so as to achieve an optimum solution. For example, using simulation to model a manufacturing facility to experiment with layout of different capacity machines and storage bins, times for preparation and transfer of materials, so as to improve efficiency.

3. Analysis

Analysis refers to the process whereby simulation is used to determine the behaviour or capability of a system currently in operation or to verify its correctness. It may also be used to test real life systems

[401] Thomas Ruth , *Op. Cit*. (2003) P. 4-5

under extreme or even impossible conditions. Model behaviour is established by collection of data from the system. E.g. optimising the management of a hospital, by simulating the scheduling of doctors, staff, equipment and patients.

4. Training

Training simulations are used to recreate situations people face on the job and to allow trainees to practice a sequence of actions or to learn the correct response to an event. Training can allow learners to make potentially fatal mistakes without injury. A great range of training can be carried out using simulations, from the highly complex which uses bespoke hardware (e.g. flight simulators, or mock-ups of nuclear power plants) to the simpler training available on a desktop PC (e.g. IT or soft skills training).

5. Education

In education, learners don't just need to know "how" to do something; they need to know "why". Simulations represent an exploratory world where students can use models to conduct experimentation, to create and test hypotheses and construct their own understanding of a system. Simulations can provide tools for teachers to demonstrate and explain the behaviour of complex and dynamic systems. Potentially any simulation can be used in education at one level or another.

6. Entertainment

Computer entertainment such as arcade games, war games, and role-playing games require a consistent model of an imaginary world. Many make use of simulation techniques used in training, design and analysis (for example for optimisation and control). Strategy games often contain sophisticated computer models e.g. SimCity."[402]

This thesis is interested in the implications on the first three categories of use in Thomas's classification that are research, design and analysis. Other types of models that may be confused with simulations are emulations (EM), virtual reality (VR) and augmented reality (AR). An emulation can be defined as an *accurate simulation where no approximation has taken place and all features of the original are present in the emulation.*[403] Therefore it is not to be mistaken with simulation in that the latter is not

[402] Thomas Ruth , *Op. Cit*. (2003) P. 5
[403] Ibid. P. 6

aimed at exactly replicating the original system at hand. As for virtual reality, *some VR does include simulations but the simpler type such as wire frame and 3D models do not. The "model" in a simple 3D model, is spatial only, it does not include behaviour, and it doesn't react to perturbations.*[404] So it could be argued that, even though it overlaps with simulation in certain situations, it comprises a whole different domain within computer modeling. And last, augmented reality, which is part VR part data set due to the fact that:

"...the real world provides information that is difficult to duplicate in a computer. An augmented reality system generates a composite view for the user. It is a combination of the real scene viewed by the user and a virtual scene generated by the computer that augments the scene with additional information."[405] Ultimately, although also overlapping with VR, *This* [AR] *is not a simulation, but a sophisticated data display.*[406]

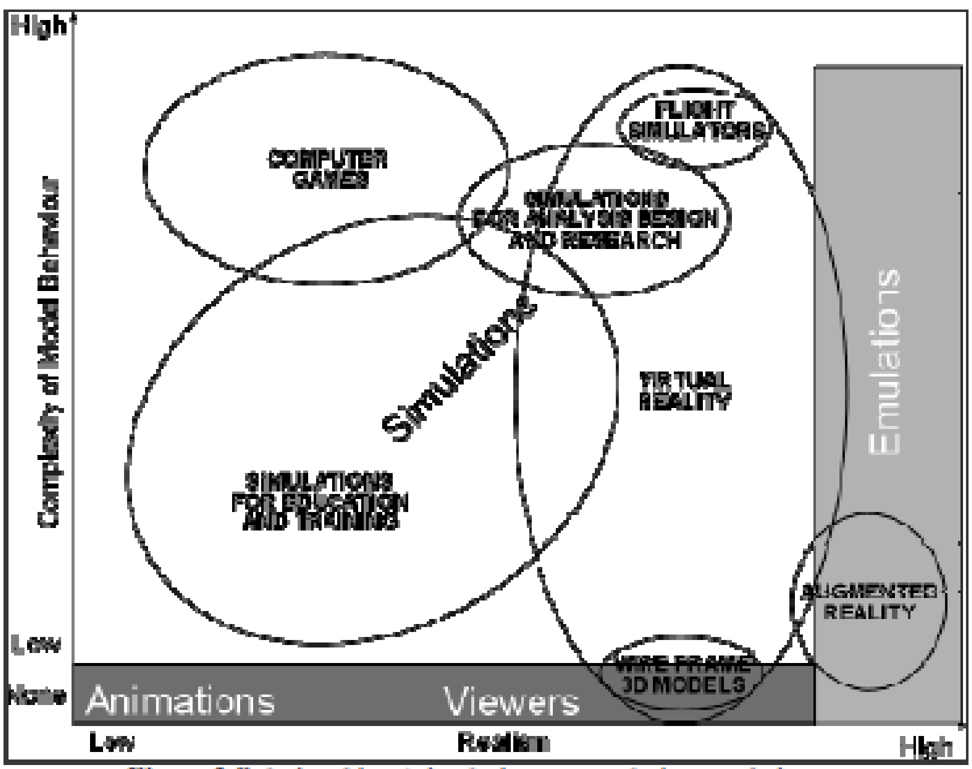

Figure 2 Relationship of simulations to emulations and viewers

[404] Thomas Ruth , *Op. Cit*. (2003) P. 7
[405] Ibid. P. 8
[406] Idem.

The relationship between simulation and simulation-like software, Ruth Thomas (2003) (Thomas Ruth , *What Are Simulations? – The JeLSIM Perspective.*, *Copyright ©JeLSIM 2003* P. 3)(Thomas Ruth , *What Are Simulations? – The JeLSIM Perspective.*, *Copyright ©JeLSIM 2003,* P. 9)

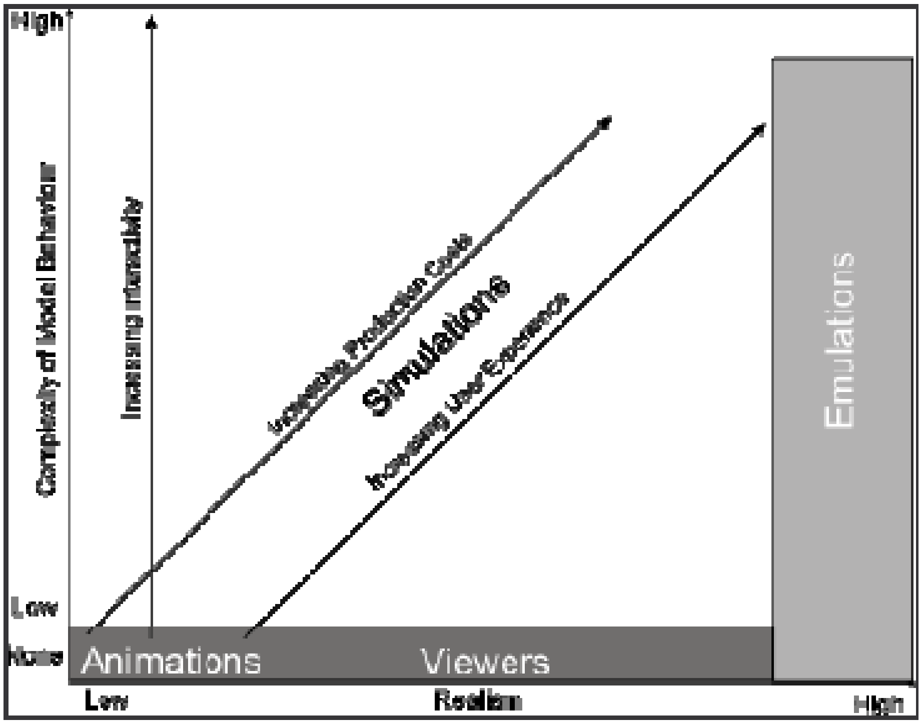

Figure 3 *Trends within simulation space*

Trends within simulation space, Ruth Thomas (2003) (Thomas Ruth , *What Are Simulations? – The JeLSIM Perspective.*, *Copyright ©JeLSIM 2003* P. 10)

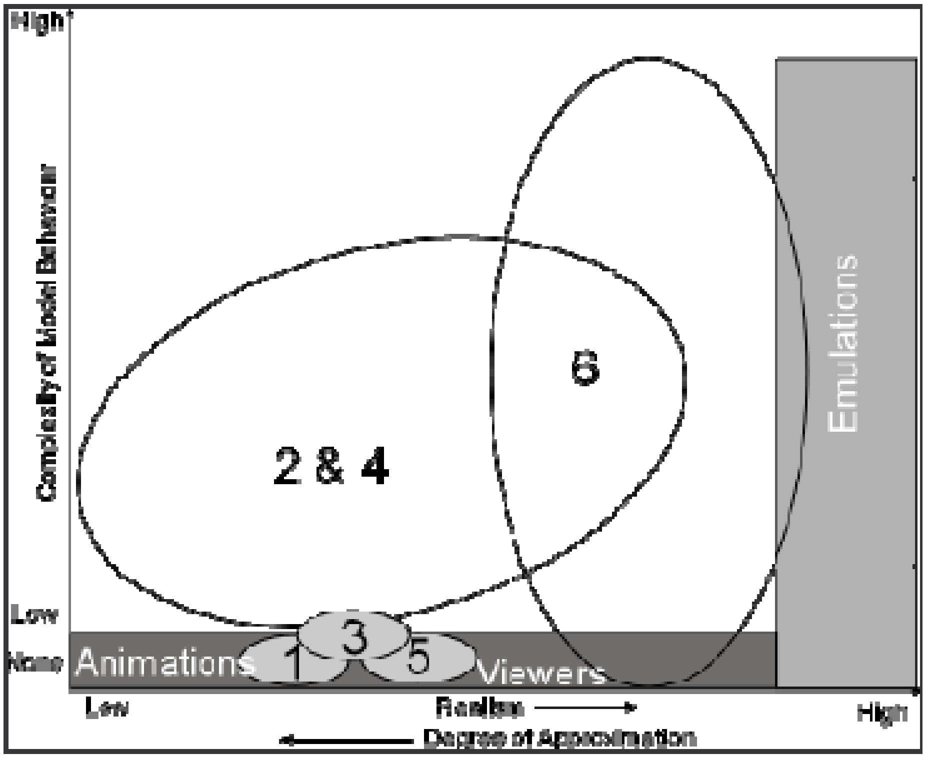

***Figure 4 Simulation** space occupied by Brandon Hall simulation categories*

Simulation space occupied by Brandon Hall simulation categories, Ruth Thomas (2003) based in Brandon Hall (2002) (Thomas Ruth , *What Are Simulations? – The JeLSIM Perspective.*, *Copyright ©JeLSIM 2003* P. 11)

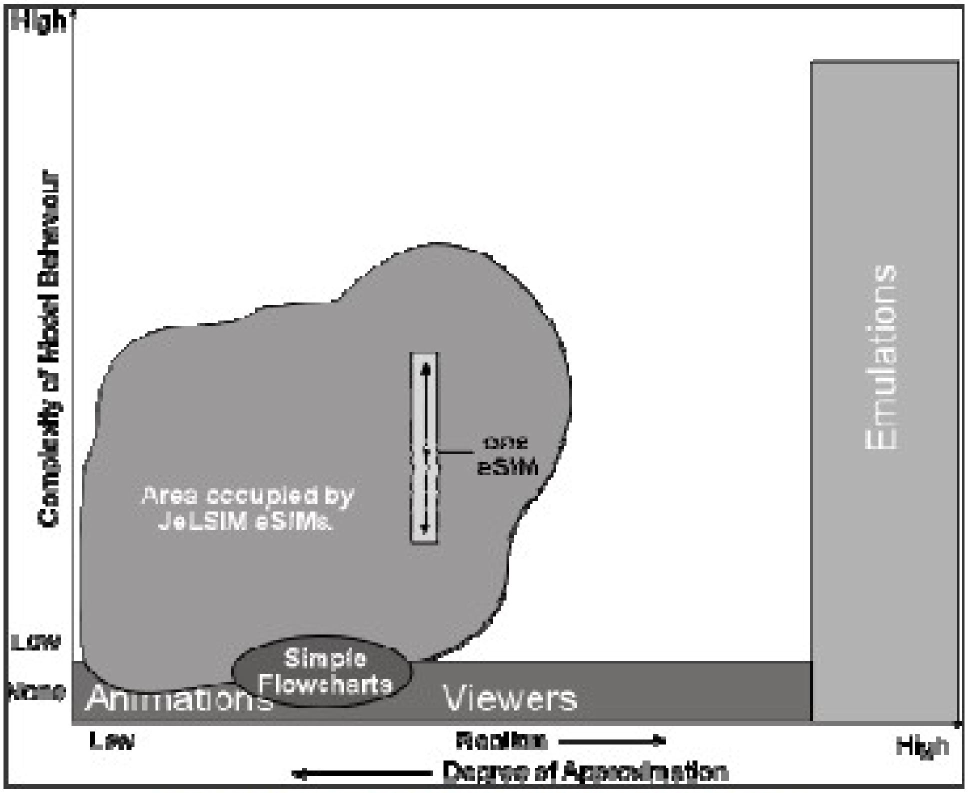

Figure 5 The simulation space occupied by JeLSIM eSims

Simulation space ocuppied by JeLSIM eSIMS, Ruth Thomas (2003) (Thomas Ruth , What Are Simulations? – The JeLSIM Perspective., Copyright ©JeLSIM 2003 P. 12)

Ultimately, this thesis will follow Thomas's criteria for the definition of simulation models, specifically those comprising computer generated simulation which, to be classified as a simulation, needs to meet to basic criteria:

1. *There is a computer model of a real or theoretical system that contains information on how the system behaves.*
2. *Experimentation can take place. i.e. changing the input to the model affects the output.*[407]

[407] Thomas Ruth , *Op. Cit*. (2003) P. 11-12

*6.2-Performance driven Simulation Software_*

This section addresses the predicament within a particular situation that, up to the last few years (as back as 2010), has only begun to be addressed by some like the 4D Printing Project (Skylar Tibbits @ SAL at MIT) and Project Cyborg (within the Autodesk research network Canada); and is the fact that we do not yet rely on practical and organized methods (or tools for that matter) to utilize when designing kinetic structures, specifically those powered by SMM, 4D printing or basic origami, in a fluid like work-flow. We still rely on mechanical analysis to predict possible situations and developments. Last chapter's conclusions showed convincingly that it is necessary to use computational methods to shorten and optimize time consuming procedures and produce reliable results reducing dead ends and somehow "predicting" motion as expressed by Dina El-Zanfaly's reseach on *Active Shapes* and evidenced b Tess Fenwick's *Morphosis* masters degree theses projects.

Dina El-zanfaly's utilization of "*the trial and error process"* [as in Fenwick's inefficient "iteration" process in the previous section] helped give an idea of how a kinetic structure might move, *but the introduced guidelines in this* [her] *thesis **proved to be more efficient***[408]. Designing a kinetic structure without computational means makes the process so tortuous that the designer cannot focus on desired functionality as *there are too many parameters, and too many areas in designing a whole kinetic structure.*[409] And although Fenwick's design method was un-successful in its implementation and final proposal (at the expense of vagueness- yet not in the Spuybroek sense of the term), she did carry out an extensive and thoughtful research, and did ask legitimate questions regarding the digital process applied to design: *Many projects of the digital revolution stay just that: digital. The design process often taking inspiration from computer based information and real-time data*[410], echoing Frei Otto"s concerns into digital imaging for design intentions, he states that *solving problems with software programs that are not specially written for the particular problem one is dealing with may lead to a lack of understanding of what is shown on the screen. Something may look perfect on the monitor, but that does not mean you understand it or that it is functioning in real size.*[411] This particular issue is related to, among other obstacles, something called *"change blindness"*, a psychological phenomenon that disguises change in images and *experiments* [when] *using a diverse range of methods and*

[408] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 67
[409] Idem.
[410] Fenwick, Tess, *Op. Cit.* (2011) P. 30
[411] Otto, Frei, *Op. Cit.* (2004) P. 24

displays[412] that makes them undetected by the human eye as *unless a change to a visual scene produces a localizable change or transient at a specific position on the retina, generally, people will not detect it.*[413] *This phenomenon can invalidate the using of animation tools to achieve simulation, even though they represent interesting ones from the design standpoint.* This is a situation that goes beyond a mere understanding of the geometric aspects of kinetic design and one in which material performance is a main, unattended aspect. *The materiality should also be studied as a major transformation parameter in the active rules*.[414] For an example, the design & research process in Dina El-Zanfaly's method is very "hands on" and physical by nature (which uses the material itself to compute the transformation, thus gaining the information only when applying the grammar to the piece directly) but, in a different case of kinetic research, this thesis asks the next question: *what happens when you need to test shape memory materials?*

Generally a laboratory is needed, that holds specific conditions to be met in order to work through the experiment phase successfully and provide accurate results. The laboratory set also needs the latter mentioned SMM material physically present in the process, we know that laboratories have a significant financial cost and, in order to be tested, SMM need to be formally and chemically designed (which also needs industrial foundry metallurgic cauldrons) and then, and only then, get tested. To eliminate set backs and delays, the use of more personnel and resources could be reduced in both dimensions if the kinetic design methodology integrates digital simulation processes into its concept and design developing. In problem 4 of Dina El-Zanfaly's conducted ones for her masters degree thesis, there is a situation in which I would like to concentrate for the development of this chapter and the most necessary need for the developing of a tool that can take the designer farther and faster than current manual laboratory practice can. In this exercise, the student tried to apply the Active Shape conditions to a curved shape and came short in visualizing and *simulating it in his head*.[415] This and other situations arose interest that in architecture would not be standard view until recent times, until the AEC's world to turn to material science for directions on how to embed intelligence in its buildings. For a structure to be intelligent, it must have some kind of embedded computation and autonomy, something that holds concept and construction together.

412 Simons, Daniel - Levin, Daniel, "Change Blindness." *Trends in Cognitive Sciences* 1 (7) (1997) 261–267. As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 44

413 Idem.

414 El-Zanfaly, Dina, *Op. Cit.* (2011) P. 67

415 Ibid. P.48

"Understanding, that until now, these two areas have not been combined, an opportunity is being created for the fulfilment of this knowledge gap...

...The information that this thesis is presenting can lead to this direction and can be considered as the base of information on which this software could be created."[416]

Some of these elements should be also connected in a loop like the virtual design and the physical prototyping to maintain the connection of geometry and physics to materiality, mechanics and scalability.[417] These additional guidelines "left to develop" suggest the intrinsic development of systematic logic tools that aid in the process of decision making to pave the way for reliable, structurally sound and intelligent buildings which, to El-Zanfaly, means that:

"*in addition to exploring the rest of the possible transformations in the active rules, the presented guidelines should be put in a framework for designing the kinetic structures, which should also contain: The design mediums, which are the simulation software and physical prototyping."*[418]

The former for speculatively helping in the understanding of motion patterns and also suggesting the possibility that material behavior can be integrated to the conceptual design process to fabrication (as demonstrated by both El-Zanfaly's student tests and self-study projects). So the project of producing a software tool that models material behavior to continuously simulate it in the decision making process within a design oriented environment is suggested as an imminent follow up agenda. In her conclusion, she also states some guidelines to the problematic to solve in the research for more optimized kinetic design tools :

- "*Several stages should be introduced in the framework including:*
    - *1)motion types, whether it is continuous or discrete*
    - *2) the motion speed*
    - *3) the degrees of freedom* [This specific stage was investigated in 2007 by Angeliki Fotiadou and will be detailed thoroughly later in this chapter]

[416] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 58
[417] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 67
[418] Idem.

- *4) the material properties and* [a subject also aimed at discussed and implemented in this thesis project as it will be showed in chapters VII, VIII and IX]
- *5) the structure scalability"* [419]

As of now, most of the simulation-based research for complex and kinetic architecture projects has been done with software tools from outside the discipline of architecture (which is actually the case with popular software tools like Maya by Autodesk that was originally made for movie making and animation and has spilled over to other domains including architecture), however there have been some earlier examples of design research conducted through animation processes and even though they are not the same (animation and simulation, see the beginning of this chapter) they share motion driven analysis and visualization techniques making animation a predecessor, in architecture, of simulation-based research (outside architecture, numerical simulations have been around for more time than a century). Some architects began searching for new architecture through novel expression methods and techniques, one of them is Dennis Dollens who, as discussed in chapter III, is one of the few who has dived into the animation tool's universe in the light of seeking potential to produce more accurate and, in his case, *alive* designs, to engender creativity. *There is no surprise in claiming that the potential for animation as a tool for architectural research, as a generator of ideas, as a medium for testing spatial and material relationships, is vastly underrated.* [420]

In 2006, he wrote a paper called *"The Cathedral Is Alive: Animating Biomimetic Architecture"*, which explained his interpretation, for architectural potential, of an animation called in turn *"The Cathedral"* [421] done by polish animation artist Tomek Baginski, asserting that its *artistic and technical ur-level is a landmark for animation as design research.* [422] In this masterful piece, the artist rendered the becoming of a blending symbiotic organism made from the merging of human and botanic in a single entity. *In **The Cathedral** we are confronted with a mysterious, even existential narrative, suggesting that architecture is a natural growth botanically rooted in the cosmos and literally seeded by human bodies or body parts* [423], nevertheless, this cosmic generative is reminiscent of a metaphor than a literal embodiment. *In fact, however, recent architecture (while its origins may be genetic) is a growth and*

[419] El-Zanfaly, Dina, *Op. Cit.* (2011) P. 67
[420] Dollens, Dennis, *Op. Cit.* (2006), P. 105
[421] Baginski, Tomek (2002) *The Cathedral, DVD.* Poland.
[422] Dollens, Dennis, *Op. Cit.* (2006) P. 107
[423] Ibid. P. 106.

expression of civilization[424]; the coming into being (see chapter II) of a symbiotic relationship of thought and nature, throughout the design to building process as a whole or, *more precisely of a particular zeitgeist filtered through an individual, a team of builders, a set of economics. If architecture is seeded, it is in thought: consciously and/s unconsciously.*[425] To deduce all this from an artistic animation arises several intrinsic questions for architecture:

- What are the limitations of design in an animation-based generative context?
- What are the realistic limitations of animation regarding design-to-production?
- What is the relationship between animation and architecture as an exploration tool?
- Is animation enough to replicate architectural embodiment in a reliable way?

Dollens, who is a leading figure in bio-mimicry, states that animation can replicate real settings they are not to be confused when addressing each others scope.

"While animation can simulate reality, architecture embodies and encases it – atmospheric pressure, heat, smell, cleanliness, and noise, all in addition to the designed visual substance of a building, are evidence of differences outweighing animation's particular abilities that might introduce the possibility of architectural dialogues." [426]

This distinction is made in the wake of symbiosis of a single all encompassing look at the way the can merge together as a means of producing better design methods as he affirms that it does *not to imply that one medium speaks to higher states of contemplation than the other, or that one is a finer expressive force than the other; it is simply to highlight architecture's difficulties in telling narrative and animation's showing without it*[427], which can in turn be interpreted as a preceding inquiry into what this thesis is asking: *how well can we approximate real conditions in the context of simulation?* And while no doubt about how the animation medium can aid in a design process, though nevertheless *its powerful rendering, conception, and action brazenly illustrate how effectively animation can articulate aspects of complex architectural transposition and visualization in cinematographic form*, the question

[424] Dollens, Dennis, *Op. Cit.* (2006) P. 106
[425] Idem.
[426] Idem.
[427] Idem.

is still left to be answered: *how accurately can it perform these traits and how much data can we output to its physical embodiment?* (this as a subset of the question about the realistic limitations of animation regarding design-to-production which will be addressed in the case study chapter IX at end of this thesis). Still, Dollens does have a point in asserting animation as a turning point in design when he states that:

*"By delineating plant growth evolving into architectural elements, and architectural elements evolving as hybrid tree-people, **The Cathedral** soars into conceptual, experimental spatial speculation that leaves the static realm of design behind."* [428]

The Cathedral, Tomek Baginski (2002) Stills progressing from human figure transforming into botanic growth; the botanic growth developing into an architectural pillar; and the pillar comprised in the cathedral. (Dollens, Dennis, *The Cathedral Is Alive: Animating Biomimetic Architecture*, P. 107)

This does mark the point when the design process of animated, kinetic structures (although he was referring actually to growth patterns which develop in bigger time scales thus not being inherently kinetic, however neither static) works as a servomechanism, a platform from which simulation methods can give rise to complex intelligent kinetic systems, leaving behind drawing as a central tool for approaching conception and development, documentation is still at large of this fundamental change, but it is industry related, architecture is ready to leave it behind too yet it is the AEC industry which has been somewhat reluctant to embrace it.

"The Cathedral could grow and illustrate a new breed of urban, environmentally active, semi- alive architecture that addresses some of today's sustainability issues as encountered in experimental

[428] Dollens, Dennis, *Op. Cit.* (2006) P. 107

architectural discourse: monitoring, even sequestering pollution or mitigating noise, etc. Poignantly, and more than anything else for my consideration, The Cathedral demonstrates that the low volume of architectural research, visualized and tested in animation, results from a lack of imagination in architects and design schools, not from animation's in-applicability or technical limitations.''[429]

With the advent of digital technology and its revolution, it has been proven in the popularity of CAD tools that, as design moves towards sustainability as a central gospel to strive by, its complexities can be visualized and represented in a pan-optical fashion with the aid of modeling. In this sense, *the Cathedral presents a direct mimetic model for studying and visualizing such developments* [430] and as a source of inspiration, as Dollens remarks, it can be attributed as a gateway to *visualize advances in materials and form as manifested in animation, simulating real-world conditions in order to stimulate and grow ideas that eventually lead to fabrication and building* [431], a subject matter that was cleared out, at least for software programs available in the market (like Maya, 3Dmax et al.), and will be analyzed in this same chapter. Bu what exactly does *visualization* mean, what is to *visualize?* Whereas in the *Merriam-Webster Dictionary* it is defined as:

"*noun vi·su·al·i·za·tion\ˌvi-zhə-wə-lə-ˈzā-shən,ˌvi-zhə-lə-,ˌvizh-wə-lə-\ (first know use:1883)*

1: formation of mental, visual images
2: the act or process of interpreting in visual terms or of putting into visible form.''[432]

For Dollens, it is a matter of manifesting complexity and relationships through visual outputs, on answering Janine Benyus's fundamental question regarding architectural representation: *How can I visualize nature's work in a digital context?*[433] He opens up a dialog which this thesis is trying to provide a practical answer to. His position is clear and blunt:

"I am absolutely persuaded that architects are not fully aware of the potential of animation or the

[429] Dollens, Dennis, *Op. Cit.* (2006) P. 108
[430] Ibid. P. 109
[431] Idem.
[432] "Stasis." Merriam-Webster, n.d., *Merriam-Webster.com*. (http://www.merriam-webster.com/dictionary/stasis) (04-02-2014)
[433] Benyus, Janine M., Biomimicry: Innovation Inspired by Nature. New York: William Morrow (1997).
As quoted by: Dollens, Dennis, *Op. Cit.* (2006) P. 108

complexities involved in the word 'visualization'."[434]

However his concern is totally on point and legitimate; there is some confusion (as established a the beginning of this chapter) regarding what animation and simulation are. In this same article, just for the sake of clearing things out, I would like to point out some differences. In the article, he starts speculating about how:

"with programmed, generative cellular and/or chaotic algorithms mediated in a software's test parameters, matrices could be generated as structure or infrastructure experiments – the research agenda, combining aspects of science, history, and design intention, could be suited perfectly to animation's abilities."[435]

This implicitly denotes that animation and simulation are exactly the same, but to be clear here, animation, even though it outputs behavioral visualization, does not output analytic information (if it does it is then simulation in a visual representation environment which is not the same as animation) and is unidirectional (meaning that it is the designer/operator that willingly sets how motion is to happen and it is not reacting to ongoing recursive re-computation in real time). However, this is not because he does not understand the difference, but because he is blending two mediums as one in the wake of design research tool combination as there is no sign in the paper of him confusing its utilitarian traits and seeing and exploiting its potential (something different from Fenwick's inaccuracy in deifining top-down and bottom-up approaches in chapter V concerning her not being able to generate concise output, therefore showing lack of understanding and confusion on certain aspects) this is evident in this passage :

"*Yet equally or more exciting is the pairing of digital animation with other software… Thus paired, animation then becomes a generative tool for researching complex geometries, spatial relationships, and environmental impact; it becomes a primary pathway for a designer's mind's eye visualization of built environmental forms."*[436]

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434 Dollens, Dennis, *Op. Cit.* (2006) P. 108
435 Ibid. P. 109
436 Idem.

Evidently, what is actually underlined here is the combination of various software and mediums as speculation and investigation as it is evident that visual mediums can aid in a more straight forward manner than analytic ones. *For my work, the hybrid digital plant files must then be exported from Xfrog and imported and transformed in 3D modeling or architectural software; for this development and articulation process I primarily use Rhinoceros*.[437] Nevertheless, what software swapping holds as a advantage is not merely visualizing the same thing under different filters but "testing" under different filters since each software is fundamentally similar yet inherently functionally distinct concerning its user experience (which defines the user's sensations, understanding, feeling and results when working on a certain platform, commonly noted as UX) and user interface (commonly noted as UI, which defines the conditions of the platform's interface and how its functionality communicates with the user) and this makes a case for swapping as a speculation tools, adding animation narrative to the process of simulation and vice-versa.

"Tests from environmental simulations reveal what happens to the quality of sunlight and shadow and to water run-off, it determines micro-climate behaviors such as intolerable wind gusts, it reveals visual impact on street, skyline, and natural views, as well as focusing basic, quality-of-life research data for decision making in both urban and wild contexts. Expecting different research results, architects could anticipate assistance, information, and visualizations from research animations." [438]

Sure, merging software is a practice that I myself carry out as standard practice, also exploiting its *architectural matrix*[439] potential (as in *The Cathedral is Alive*, according to Dollens) as building performance is directly proportional to material development (a subject that will be explained later in in chapter VIII) *and researching biological matrices is necessary if eventual biomimetic materials (and potential semi-live materials) are to be integrated into architecture, historic preservation, and urban design.*[440]

"In such a scenario, animation's inherent narrative would be submerged into the physical depiction of the mutating form and research visualizations. In this light, The Cathedral, an Academy Award nominee, may prove the most important production for architecture since Blade Runner's dystopic,

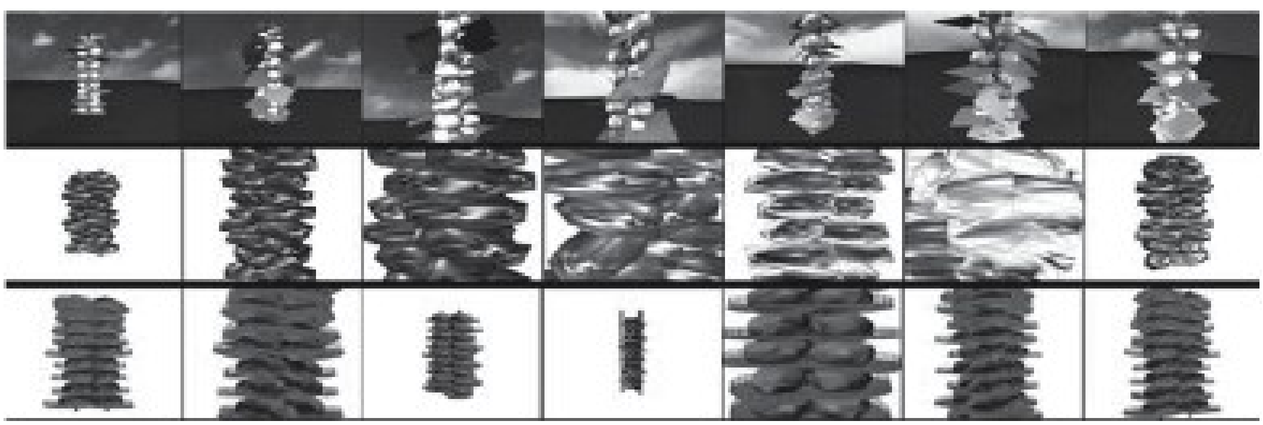
[437] Dollens, Dennis, *Op. Cit.* (2006) P. 116.
[438] Ibid P. 110.
[439] Ibid. P. 108-109
[440] Idem.

computer-generated, animated special effects of a future Los Angeles."[441]

His applications of this theoretical approach were displayed along a certain list of his own projects, from light tracking solar panels to bio-morphic bridges. According to Dollens, from the material study standpoint, the he used methods strove:

"to manipulate a seed stalk's clustering forms to study massing, or to grow trees and control their trunk and branch formations until they function as columns or structural trusses. Such digital growths are partially calculated in [*]*Xfrog's use of L-Systems, the algorithms developed to simulate natural biological growth."*[442]

And as he points out, operationally, these methods holds potential *for light and photo-voltaic installation, to study possible kinetic mobility, while always following aesthetic relationships.*[443]



Test Animation Group. Dennis Dollens (2006).

Top row: *Solar panels tracking and shading a core structure based on seedpods*.

Middle row: *Flower seedpods morphologically elongated. Bottom row: Stalk, leaves, and seedpod with leaves morphed into balconies, window inserted, and service core highlighted in red.*

441 Dollens, Dennis, *Op. Cit.* (2006) P. 108-109

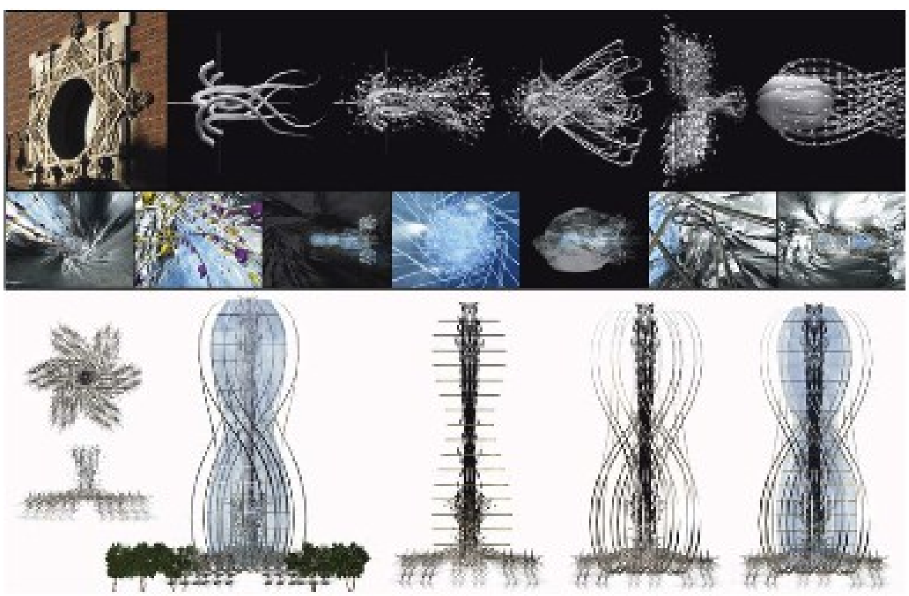
* Xfrog is a landscape-generating software from Greenworks, Germany [http://www.xfrog.com/]. It produces lifelike trees, plants, and flowers and can also be programmed, with its proprietary icon-based interface and underlying biological (L-Systems) modeling, to creatively transform or hybridize its digital growths into experimental, schematic files. In Dollens, Dennis, *Op. Cit.* (2006) P. 116

442 Ibid. P. 114

443 Idem.

In this passage, Dollens explains his process for designing in *Xfrog,* an algorithmic software for digitally testing 'a priori' phenomena such as photo-tropism as well as material relationships and environmental simulation, whistle the inception of simultaneity into the design process, a subject that eludes architectural thinking but is should be treated as central in a complex, ever changing society (see chapter II and IV) stating the implementation of [Certain] *animation articulated movement of solar panels tracking the sun while at the same time shading the building.* [444]

"These working animations provide a fast way to visualize and think about movement [echoing this research's own speculations on resource and time reduction in the design process as a practical, invaluable tool earlier in this chapter]*, relationships between materials, transitions between forms and massing, as well as ideas concerning light and shadow; and even if vague, these animations communicate a sense of the buildings as 3D environmental works. Working tools, these animation tests serve as a kind of environmental simulation."*[445]



Sullivan Inspired Group, Dennis Dollens (2006).
Top row: *Louis Sullivan's ornament; sequence of hypothetical digital growths seeded by his terra-cotta ornament.*
Middle row: *Animation cells from the study of the digitally grown forms. Bottom row: Digital growths evolved as a*

[444] Dollens, Dennis, *Op. Cit.* (2006) P. 115.
[445] Idem.

coincidental skyscraper.

Yet there is still an unanswered question that this thesis will address in the experiments phase in chapters VIII and IX: *Does a digital, all-encompassing, material behavior simulation tool exist? Or, if it does not, can it be created? And then how?*

Apparently Autodesk is on its trail to built just that kind of tool set as it works on a design platform that unites all scales and simulates nano to human scaling-up building systems called *Project Cyborg:*

"While a distinct pipeline of methods, from concept to construction, can work quite well, the proposed method may naturally draw other design stages into early iterations of a project. By starting with a simulation-based process, the framework is already in place for migrating design concepts into design development, analysis and even other types of simulation. To achieve this we need to transform the role of simulation beyond pure analysis or isolated design cases. A comprehensive extensible simulation framework that ties together the entire design-to-production process is proposed. A unified solver also provides us with new possibilities for creating a bidirectional relationship between the physics engine and scripting control, parametric systems, or embedded analyses. We strongly feel that simulation for design will be an enabling technology for advancing the future of computer aided architectural design."[446]

6.2.1-Analysis of Design Support for Kinetic Structures_

Academically, the first thesis that this research has found to focus on software implementation in the design of kinetic structures and, more specifically, their animation (other than only addressing it theoretically or speculatively) was carried out by Angeliki Fotiadou in 2007, entitled "*Analysis of Design Support for Kinetic Structures"* a masters degree requirement at the Technical University in Vienna (TU Vienna). The research focused on selecting one existing animation software among the most popular and respected of them and testing it within constrained situations in real, built project cases (the Kuwait Pavilion and the Alcoy Community Center Hall both by Santiago Calatrava and the Folding Egg by the Kinetic Design Group at MIT -lead by Michael Fox). Her motives for calling at

[446] Attar, Ramtin -Aish, Robert - Stam, Jos - Brinsmead, Duncan - Tessier, Alex - Glueck, Michael - Khan, Azam, *Op. Cit.* (2009) P. 231-244. Autodesk Research, Canada, P.13.

software visualization through animation lies in the imminent and almost mandatory characteristics of kinetic design which *especially in the field of the kinetics, where everything depends on the movement:* ***design not only requires, but demands for visualization***.[447] She basically wanted to test the limitations (which were known but not before measured in quantitative manners and that she showed in a group of graphics that will be shown later in this section). It is evident that *representation of kinetic structures by means of the existing ordinary software sources is possible*[448] yet their implementation into the design process *lacks of different important features and functions and results eventually in the total absence of a real model of the construction.* [449] For this selection, according to Angeliki Fotiadou, in order to choose the right software to perform video animations for kinetic design & construction it was *appropriate to perform a research for the kind of existing software in the area of architectural design and animation nowadays, their special features and their ability in a structure animation.*[450] While I agree with this last statement in that it is necessary to look at existing tools in order to broaden them or envision other new ones, at the time of her research, the parametric software bundle *Grasshopper* was not yet in the market, so it is understandable that it is not included in her thesis, nevertheless, as we will see in the next section, most of the issues regarding her research have been overcome by this particular parametric modeling editor, others remain at large: the ones that we will tackle during the experiment phase in chapter IX. All this said, in animation software, which still dominate simulation-based design and representation ***the common characteristic of the existing software is that they are basically created for the performance of character animation and not architectural constructions***[451], thus making it difficult, not only to communicate fluently with the software from a building profession vocabulary stand point, but furthermore from a kinetic design and construction one; *in order to create the kinetic structure animation into this software, the purposes for which the functions are used in the character animation must be interpreted in correspondence to serve the animation of structure.*[452] Each software package has its own vocabulary and way of communicating or interpreting a the modeler's orders or design intentions. *All the software follow approximately the same* [utilizing] *procedure* [yet not the same mathematical processes]*, differing in the terms that they use to define the different elements and functions*[453], usually following a similar, if not same, procedure which is basically: *The*

447 Fotiadou, Angeliki, *Op. Cit.* (2007) P. 1
448 Idem.
449 Idem.
450 Ibid. P. 14
451 Idem.
452 Idem.
453 Idem.

design process, the creation of the necessary joins and articulations together with the bones to create a skeleton and lastly, the animation are briefly some of these common operations.[454] Which themselves are based on character design terminology as in the practice of character animation for films and video games the likes of which are biologically conceived, functionally setup and named, and within which *the term "character animation" it is meant the animation which is implied on objects or models designed to resemble as creatures, such as humans, monsters, animals etc, resulting with their 3d natural or a human like representation of movement.*[455] These animation representations are modeled as bio mechanical structures that *can be described as skeleton construction, with bones and joints, which can be outer covered by a mesh, named as "skin"*[456] in consonance, direct relation and proportional principles as the human body.

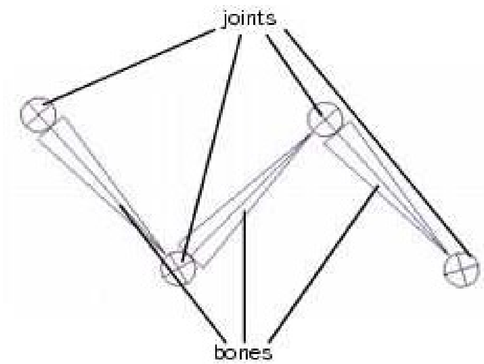
6.2.2-Character design and construction design_

Skeleton construction in these software packages are pretty much defined as ***hierarchical, articulated structures that let*** *you pose and animate bound models.*[457] Which, as stated before, are *just like in the human body* [and in this wake of functionality design] *the location of joints and the number of joints you add to a skeleton determine how the skeleton's bound model or `body' moves.*[458] This construction orientation is fundamental to all animation software, what this research is suggesting is that it is necessary to develop design-to-production simulation-based software tools that map this problematic across different scales. The fact that all these software solutions just focus in joint, skin and bones arrangements as means to produce articulation and motion is limiting (The joints are *"the building blocks of skeletons and their points of articulation. Articulations are the state of a skeleton's joints, including position, rotation, and scaling*[459]) at the very least, because it bounds the designer to follow a narrow path of motion control (this point is proven imperative to overcome in chapter IV -see Dina El-Zanfaly's research in Active Shapes) and constraints designs to *behaving in the software program exactly as a wrist or the elbow of a human body.*[460]

Skeleton structure showing bones and joints system, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design*

[454] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 14
[455] Idem.
[456] Idem.
[457] Idem.
[458] Idem.
[459] Ibid. P. 15
[460] Idem.

Figure 3-1. The skeleton structure showing the bones and joints system (Maya Help)



Support for Kinetic Structures, P. 15*)*

This all leads to a representational mode of simulation which look real-world isomorphic but it is not even approximately close. *What the animation can do is just give an overall representation of the kinetic movement, but when a simulation for this field of construction is needed, the software seems to be missing functions.* [461] And concerning kinetic architectural systems, the scope is very narrow, at the time of her thesis (this has changed as of today, as we will further address in this chapter) *no design tool or generally an animation software which could support the formation or study of this specific architecture has* [had] *been found* [462], there were neither specific rules or criteria by which to speculate on the matter at hand *since there is no evidence of which rules exactly this architecture follows, there can be no easy recognition of the needs that it has over an animation software.*[463] Another issue with kinetic architecture's previous research was the fact that almost everybody that did study them (Zuk, Fox et al. -Fox wrote a lot about embedded computation in kinetic systems but never published anything about its software implementation in this direction) had not before attempted to investigate animation software's possibilities in this scenario, sure Dollens (as established earlier in this section) had speculated about it and conducted animations towards design research, but never actually published anything on kinetic structures. As a result and Fotiadou's motivation for her thesis explains:

"Even researches that have been performed do not seem to be equivalent with the attempt to combine the ***kinetic architecture with the animation software****. Most of them relate to one of the two subjects and not to the combination."*[464]

461 Fotiadou, Angeliki, *Op. Cit* (2007) P. 6
462 Idem.
463 Idem.
464 Idem.

This research can corroborate on the fact that this situation has not changed since the time of Fotiadou's thesis as after approximately four years of researching literature, Fotiadou's thesis *Analysis of Design Support for Kinetic Structures* is the first academic document to directly address the issue of how to digitally model already built, and therefore proven, kinetic constructions (most of the other researchers focused on kinetic architecture itself and not on how is it digitally modeled) addressing also which tools to use, thus focusing on the tools more than the result they provide. After which very few followed the same line between software design and configuration for kinetic animation. The problem with animation software, according to her and as expressed in this chapter, lies in that *different functions in them seem to be missing, those that will provide the user of the programs, always to the direction of kinetics, with a real model of the construction.*[465] But this is the least of the problems regarding this particular angle, animation's most important and huge problem s in the fact that *the software that exists today has the ability of representing a structure and its kinetic movement, by creating an animation*[466] yet it is evident even before testing them that, in most cases, unless the designer is very skilled in material, mechanical and bio mechanical physics or engineering *however, this animation does not correspond* [generally] *to reality or cannot give realistic results when other parameters such as forces, or material properties, have to interfere with the construction.*[467] I say "generally" because software like Maya or 3dmax are know to be able to carry out realistic "*visual"* simulations but they do not output analytic data necessary for construction and building analysis nor they do so in *real-time*, it is basically input based and does only output video data. Therefore while animation and simulation are not the same, animation programs can render simulations. Consequently, as a methodology, Fotiadou followed a simple yet reliable set of steps that helped clear apart the inconsistencies of most of the available tools, in that time and even still today, which had little or no significant changes in their work criteria towards kinetic architecture besides the ability to produce "artistic" yet not realistic animations.

"Investing, therefore, in further knowledge over kinetic structures with the creation of a software is nothing but a gain. And that because not only this investment concern a developing issue, which is kinetic architecture, but also relates to a subject which in the future will be included even more than

465 Fotiadou, Angeliki, *Op. Cit* (2007) P. 6
466 Idem.
467 Idem.

today in our daily life, the use of computer. Understanding, that until now, these two areas have not been combined, an opportunity is being created for the fulfillment of this knowledge gap."[468]

This situation makes evident the opportunity at hand, to unite the design-to-production strategies that undertake the computational tool's virtuosity and precision (as stated in chapter II) as a gap closer between the conception and realization of kinetic structures. One thing stands out about her thesis project: her assertion that her work would further be taken on by others in order to overcome this gap between the two fields (kinetic architecture and animation), this is something that marked this research's motivations and gave it all the more reasons to continue her path not only for its invaluable contribution to this research's discussion, but also for displaying humbleness necessary to carry out scientific work: *"The results of the thesis will be used in the future as the basic knowledge in the creation of software for simulation of kinetic architecture."*[469] This is one of the central aspects that this research aims to introduce and implement as an accessible method/tool to model kinetic intelligent systems and, as stated in the objectives and agreeing with Fotiadou, that is to be *an application which will be used as a tool to provide the architect with the ability to create simulation of the kinetic movement based on the calculation of the thermal, solar etc. analysis, can be thought as a useful step for the further development of kinetic architecture.* [470] With this guideline in mind, this research is firmly on the right course of action. *Using the foundings (sic) of the thesis over the malfunctions of the software and discovering a way to overcome and even further develop them*[471] is therefore the strategy chosen to face the situation regarding the design and testing of intelligent kinetic systems. To categorize her study, Fotadiou chose (from Michael Fox's classfication) to specifically study embedded kinetic stuctures which *can be sub-categorized as Mobile, Transformable and Incremental kinetic systems.*[472] As for this research, it will try to take on all three of Fox's Kinetic Intelligent Kinetic Systems (Embedded, Deployable and Dynamic), she classifies the motion schemes in what she calls ***"degrees of freedom"***, which are just directions or *rotation constrictions that can be given for a desired pose*[473], of which she chose structures which exhibit no more than two degrees of freedom, this research hypothesizes that today it is possible to accomplish kinetic simulations but first re-configuring and developing certain functionality (which will be properly investigated in chapter IX) in currently

468 Fotiadou, Angeliki, *Op. Cit* (2007) P. 58
469 Ibid. P. 1
470 Ibid. P. 58
471 Idem.
472 Ibid. P. 7
473 Ibid. P. 15

existing software. Rhinoceros + grasshopper +Kangaroo is a definitive choice to develop further as it permits, in an declarative visual programming environment, to set up parametric models in which to carry out reliable approximations in material behavior within physical simulations, specifically those of PM systems and SMM. This will be tested in chapter IX.   This thesis hypothesizes that the tool we need to develop right now can, at last, take on the whole three categories that Fox stated in his Intelligent Kinetic Systems papers (Embedded, Deployable and Dynamic kinetics systems).

*6.2.3-Software evaluation_*

Before getting into the present research's propositions, first we look at Fotiadou's method, which has been very helpful for this thesis purposes, because it laid the way for development, as she went through and did what we can call the “leg-work” of testing dead ends and setting the mark on the metrics to measure animation and simulation software functionality in a kinetic structure design context. After defining which kind of structure, specific projects and how they were to be classified, she set a set of criteria to compare the different packages that were in the market and were worthy competition to be chosen for testing. The first of them being *the correspondence between the software and the structural language for kinetic architecture*[474] (in which, from now on, we will replace with the word language [software or construction] for the word terminology, not to confuse it with scripting or programming language). It is axiomatic to say that:

“By realizing how the parts of a structure can be interpreted into the software, it will be easier to recognise (sic) the functions and the different structural parts that are missing but they are necessary for the representation of the kinetic structures in order to recognize in real time its possibilities and weaknesses.”v

This means that the software has to be accorded with construction language, or at least be translatable o it, to be able to serve as a testing device through which permeate what is there to fix and further develop. Then *with the help of the computer and the scripting language examples will be given towards the creation and overcome of the malfunctions. Future possibilities and usage of the program will also be described.*[475] This thesis's hypothesis in this regard is that by implementing algorithmic visual scripting (which will be further disclosed in chapter IX) which, for now, we will define as ways to input

474 Fotiadou, Angeliki, *Op. Cit* (2007) P. 15
475 Ibid. P. 12

programming data into a software or parametric model for its execution, it is possible to produce SMM material behavior simulation and thus efficiently approximations of kinetic systems simulations.

6.2.4-Kinetic structures in animation applications_

The software terminology's anatomic inclinations *already form a link between nature's terms such as "skin", "bones" etc, with software's terms.*[476] These are fixed, non changeable command names that, according to Fotiadou, work well in getting the user to familiarize him/herself with the software's environment.

"By importing in their language exactly the same names of different elements or terms existing in nature to correspond to elements or functions created into their environment, they help the user understand the way of the function operation and make easier the interaction."[477]

And she underlines this aspect as one that further needs to be "connected"[478] with the construction terminology universe, as of today, this has been overcome by software like Grasshopper, which allows the designer to name each of the inputs, parameters and groups of aforementioned instances, giving the user complete independence in this specific respect, only preserving the most basic mathematical operations non re-nameable (which has other kinds of problems as consequence of it, like information sharing and collaboration difficulties, as we will see proven and resolved in Daniel Davis work on how to structure parametric models importing programming techniques from software engineering in the next chapter).

476 Fotiadou, Angeliki, *Op. Cit* (2007) P. 16
477 Idem.
478 Idem.

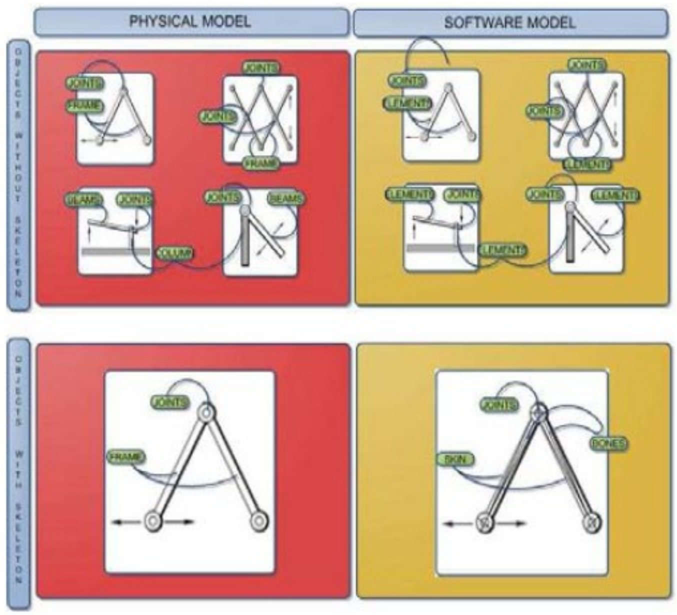


Table 3-1. Correspondence between mechanical model and model implemented into an animation software

Graph showing differences between animation software's language and actual construction language, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P.16*)*

To overcome this in her case studies, other methods were tried as alternatives within the animation setup, as bones and skin is not precisely analog to beam and columns, lets say:

"by implying a skeleton inside the skin, which in this case resembles the columns and the beams, gives more possibilities of creating the representation of the movement of the kinetic structure...

...The analysis and the correspondence of the elements from physical to virtual, has been performed by decomposing different kinetic structures to their primitive elements." [479]

This turns the designer into a translator so, aside from the modeling and animating work, he/she is brought behind by this additional task which takes sometimes years to get used to.

*6.2.5-Evaluation criteria to choose the software_*

The choosing criteria was defined by a certain important group of concerns when engaging with the very act of modeling and animating the structure types.

[479] Fotiadou, Angeliki, *Op. Cit* (2007) P. 16

"By classifying these criteria, we could say that these are the following:

• Possibility of creating proportional design

• Modification of spatial arrangement

• Possibility of creating parametric elements

• Elements/Objects Definition

• Joints Definition

• Control time function

• Existence of scripting language

• Types of import /export files"[480]

The first three criteria [possibility of creating proportional design, modification of spatial arrangement, possibility of creating parametric elements] *refer to the design process into a 3d modelling software*[481] as they are very general functionalities found in almost every commercial package available. After this the is a list of obviously important functionality that is needed to have any successful design software yet one in the list is immensely important for this research: ***creating parametric elements.***

"Regarding the parametric elements, the ability of changing the geometric forms of the objects is easily understandable, as for each structure and regarding its original drawing, elements of different proportions and use are going to exist."[482]

Which at the same time can create metric data prompting which in architectural design, *the existence of functions for creating a real metric representation of a building or a structure is absolutely necessary to, in turn, shorten the approximation to the architects original creation idea and the software would not provide after all to the user realistic results*[483]. This aspect is the very center of physical simulation and will be addressed in chapter IX.

Another basic concern is *the possibility of importing different kind of files in the software is necessary*

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480 Fotiadou, Angeliki, *Op. Cit* (2007) P. 17

481 Idem.

482 Idem.

483 Idem.

[484] (more software compatible, more cooperation with other platforms = more possibilities for better work) Rhino has very little problems in this regard, having a broad interchange format list.
This is a very important aspect about the environment to develop design and simulation in real time, the fact that the given software has to be able to import each object and recognize them in full functionality which holds as a problem in Grasshopper when referring to the physics-based analysis and parametric definition, although not with the geometry after it is baked into Rhinoceros. Because the joins are *the key to the movement there is highlighted importance in defining their rotation angle, their degrees of freedom but also their constrains* [which] *is easily understandable.*[485] And one of the most important aspects, if not the most important to prove this thesis hypotheses is *the possibility of using a scripting language in the software... only by this way it will be possible to modify the chosen software and create new functions that there might be needed.*[486] This is also (in Rhinoceros) offered in two ways: imperative (Rhinoscript -Python or VB) and declarative programming (Grasshopper visual programming + kangaroo physics engine) so this issue is very much well handled by the mentioned platform as will be demonstrated in chapter IX.

*6.2.6-Program comparison_*

Fotaidou's internet search kept drawing her to the same software names, as sime were more known than others but, regarding their proning to utilization for animation purposes, she devised a list of programs that met, some way or another, her criteria for comparison and further selection, these were the following:

"• 3DS Max
• Blender
• Cinema 4D
• Houdini
• LightWave 3D
• Maya
• XSI"[487]

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484 Fotiadou, Angeliki, *Op. Cit* (2007) P. 17
485 Ibid. P. 18
486 Idem.
487 Idem.

She proceeded to build a table comparing their capabilities, showing very similar characteristics and that *the differences between them focus more on the scripting language and the types of files that can be imported or exported..* [488] As here seen in the table 3-2.

COMPARISON OF ANIMATION SOFTWARE								
Package	**Animation and Simulation**		**Extension Language**	**Import/Export type of Files**				
	Object	**Character**		**DWG**	**OBJ**	**3DS**	**DXF**	**FBX**
3ds Max	Yes	Yes	MAXScript	Yes	Yes	Yes	Yes	Yes
Blender	Yes	Yes	C, Python	No	Yes	Yes	Yes	No
Cinema4D	Yes	Yes	COFFEE	Via Plugin	Yes	Yes	Yes	Yes
Houdini	Yes	Yes	HScript, VEX, Python	No	?	?	?	?
LightWave 3D	Yes	Yes	LScript	No	Yes	Yes	Yes	Via Plugin
Maya	Yes	Yes	MEL	Via Plugin	Yes	Via Plugin	Yes	Yes
XSI	Yes	Yes	VB Script, JScript, Python	Via Plugin	Yes	Via Plugin	Via Plugin	Via Plugin

Table 3-2. Comparison of Design Software

Comparison of animation software, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 19*)*

Physics processing is indispensable when attempting a realistic simulation that will later be used in actual construction, as in the case of kinetic structures, it is imperative *that the program proves as functions and that can be implied to the character or the object in order through the animation procedure to have a more natural result.*[489]

*6.2.7-UI/UX Analysis_*

After shortening the number of programs to two (3dmax and Maya) as they seem to *provide with more possibilities over the animation part, to be the most well-known and used software, with a wide field of*

488 Fotiadou, Angeliki, *Op. Cit* (2007) P. 18
489 Ibid. P. 19

tutorials and user instructions[490], out if which became evident that Maya is very complicated to master compared to 3dmax, although it has abundantly more capabilities than the other among other issues listed as follows:

"For a new user, the environment and the documentation in the user help is difficult to understand and handle and functions seem to be differently organized in comparison to usual programs. Maya though it supports the .dxf file, it doesn't do the same for a .dwg, an important factor when someone wants to import a drawing. On the other hand, 3DMax has the possibility to import a .dwg file and it is easier to use. Therefore, 3DMax is chosen as the more appropriate software that would be used for the study of kinetic structures."[491]

All these issues made Fotiadou choose 3dmax as the most interchangeable and at the same time powerful program out of her initial options.

*6.2.8-On Complexity and Animation_*

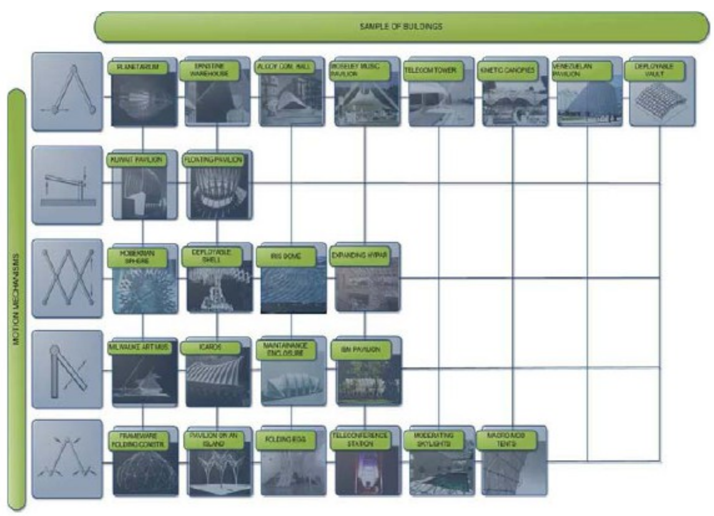

Table 1-1. Buildings categorisation to motion mechanisms

Sample chart for kinetic buildings, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 11)

The mechanisms and, therefore, the buildings, presented in the matrix seem to have an increasing difficulty concerning the creation of the movement animation into the software.[492]

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[490] Fotiadou, Angeliki, *Op. Cit* (2007) P. 20
[491] Idem.
[492] Ibid. P. 22

From this I derived an axiom within her table of building types:

"that the more elements and freedom in movement that the kinetic elements seem to have, the more complex and difficult is their representation over the software."[493]

From this matrix, Fotaidou selected three (3) project to act as case studies: Kuwait Pavilion, the Alcoy Community Center and the Folding Egg.

*6.2.9-Steps towards creating a Kinetic Structure_*

Before starting with the case studies she defined a *general way of creating the different structures into an animation software and implying on them the necessary functions for the simulation of their movement* [494], as shown in the following graphic:

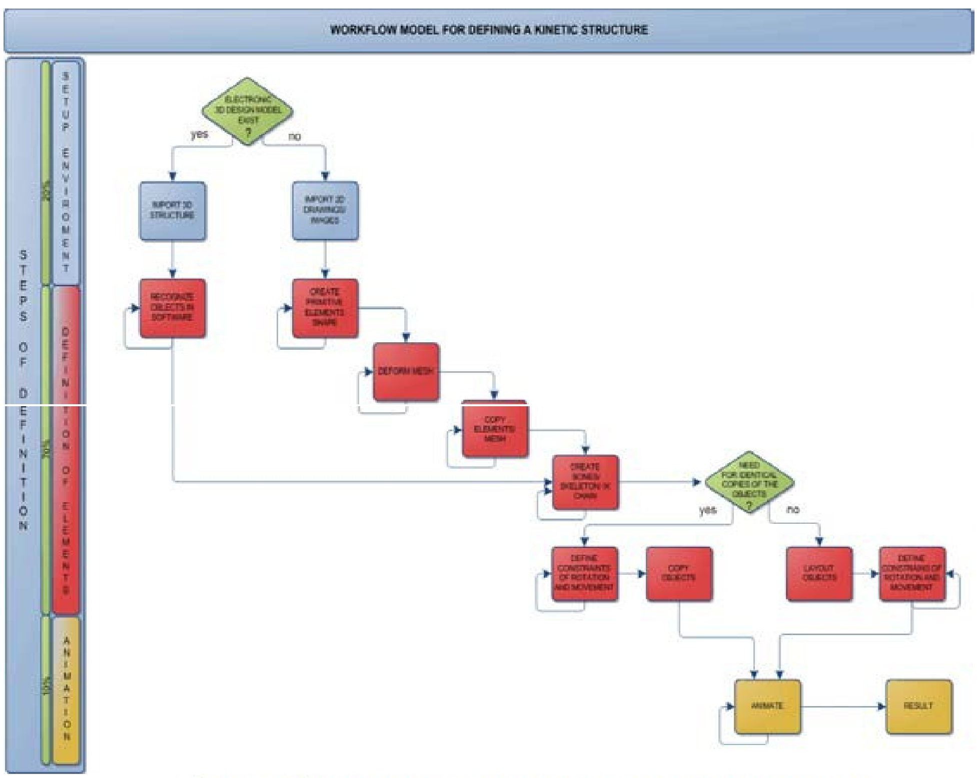

Table 4-1. Graphic representation of the definition of a kinetic structure into an animation software

Work-flow model for defining a kinetic structure, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 23*)*

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493 Fotiadou, Angeliki, *Op. Cit* (2007) P. 22
494 Idem.

from which subsequently was deducted that *the whole process can be divided into three major categories,* ***the setup environment, the definition of the elements and the animation.***[495] This will be proven in chapter IX no to be the case when implementing parametric modeling or customized software solutions or their combination. And as shown in the graphic, *The first part* [setting up the environment-importing 2D/3D information] *covers almost 20% of the overall time, the* second [defining the elements-geometry], *which is the most time consuming, 70%, whereas the third part* [setting up and running the animation]*, though expected to be of longer duration, only the 10%.*[496]

6.2.10-Modeling the case studies_

When modeling in a software package like 3dmax, it is imperative that you get trained and familiar with it at all scales and operationally, having had some experience with it at school, I can corroborate that all of Fotiadou's claims are realistic (in her case for version 2006) although the software has changed especially since it was bought by Autodesk in 2005, it still works very much lik it did in its *Discreet Soft* days. To model in 3dmax is very intuitive but at the same time a bit restricted, you can sculpt but you need to do it in the program's own way from primitives (almost like any other software package on the market, *the elements that construct the objects of the structure (as defined as above and shown in Figure 4-1) should be created, but in a draft way, using an appropriate approximate primitive shape like a scare (sic*) [square], *sphere, pyramid, etc. which can contain the overall desirable shape of the element.* Fotiadou proceeded with a "sculpting" approach towards each element in the structures. *Figure 4-2. This basic shape is the one whose mesh will be deformed in order to give the shape of the element of the structure Figure 4-3.*[497] Distinguishing between two approaches in using the commands: motion definition + modeling + copying each element -vs- Modeling each element one by one + motion definition of individual elements.

For example, in the first case *in Figure 4-1, the elements are not identical and should be created separately.*[498]

[495] Fotiadou, Angeliki, *Op. Cit* (2007) P. 22
[496] Idem.
[497] Ibid. P. 24
[498] Idem.

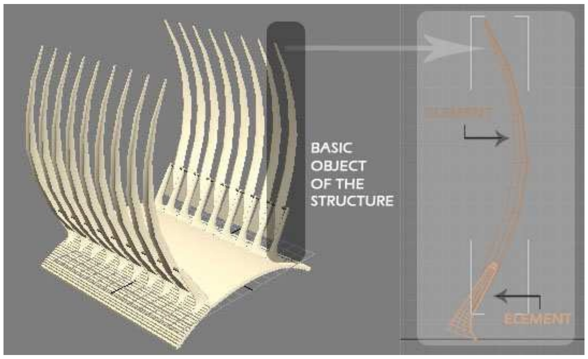


Figure 4-1. Elements and basic objects of structure.

Kuwait pavilion 3dmax model method, elements and basic objects of structure, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 24*)*

And as we see in this image, Figure 4-4. *In the second case, an interpretation of the character design has been performed to adjust with the needs of the structure.*[499]

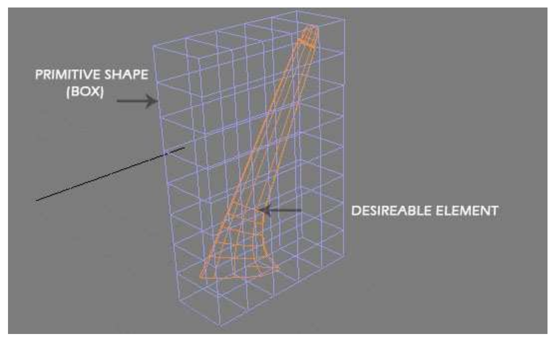


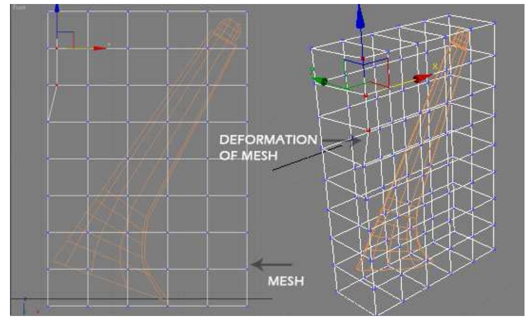
Figure 4-2. Primitive shape for an element's creation

Kuwait pavilion 3dmax model method, primitive shape for an element's creation, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 24*)*

Which of the two methods is going to be used during the creation of a construction into the software depends on the complication and the needs of function for the implementation of movement in each case.[500] And while this method could be useful for certain kinds of structures, as it will be shown in this section, it will also prove to be not useful for more complex ones, accentuating the need for more specialized and specific functionality.

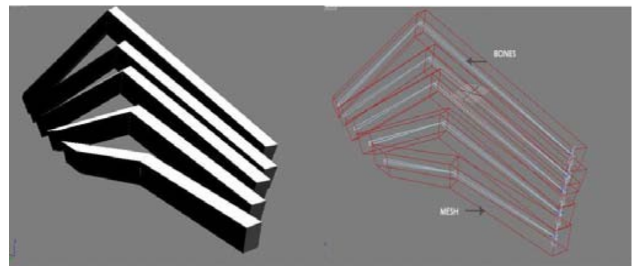
[499] Fotiadou, Angeliki, *Op. Cit* (2007) P. 24
[500] Ibid. P. 25

Figure 4-3. Deformation of the primitive element



Kuwait pavilion 3dmax model method, deformation of the primitive element, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 25*)*

Figure 4-4. The bone structure and skin(mesh) into an kinetic construction



Alcoy community hall 3dmax model method, the bone structure and skin (mesh) into a kinetic construction, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 25*)*

There is also significant difficulty in regard to automation where, in some cases, when it is needed to set up multiple, identical elements, you need to first apply the motions onto the basic element which then has to be multiplied to achieve the whole. *This is done because once the constrains are set, there is no possibility of modification of the objects and their elements*.[501] I am not sure that this is still the case in the more recent versions nor it is this research's intent to re-do Fotiadou's investigation all over again, but to highlight the fact that most software on the market relates like this to kinetics is quite accurate, and I can also certify firsthand that Maya is even more complicated to learn, even though it is not as restrained (in Maya there is a command called “interactive playback” that lets you toy around with material like behavior in real time, not based on time-line manipulation). *Lastly, after the settlement of the whole structure, the animation parameters have to be adjusted for the representation of the kinetic movement. Depending on the automation of the functions (commands or tools) will the animation be difficult or not..*[502]

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501 Fotiadou, Angeliki, *Op. Cit* (2007) P. 25-26
502 Ibid. P. 26

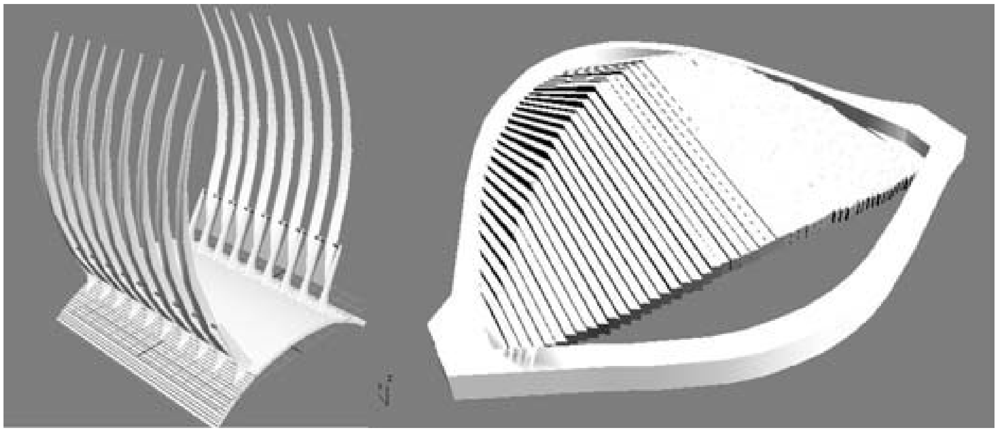


Figure 4-5. a) Structure with identical objects, b) structure with different proportional objects

Kuwait pavilion and Alcoy community hall 3dmax models showing identical and different proportional objects, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 26*)*

The main difference between parametric modeling the motion controls (therefore setting up one's own customized commands) and setting up "by hand" animation models in a software like 3dmax is that by setting *the motion of the structure to be linked and follow the position of one single object, it is easy to move the actual construction just by moving this object into eligible locations and by setting in the timeline, keyframes to represent these locations* [503], but with this method there is a problem, it is very difficult (although not impossible) to render realistic motion in a kinetic structure, but all the calculation has to be done outside the software (this could be overcome with a script that calls material properties -i. e. structural- and apply them to the model) and it is not real-time (according to Daniel Davis, *for a model to feel interactive, research suggests that the latency should ideally be less than a tenth of a second and certainly not much more than one second*[504]) visualized, leaving the output most likely to be an "artist rendition" as in cases:

"where no automation exists, all the objects should be arranged individually into different locations and poses for every different key frame that will be created, in such a way so that the whole movement will have a logical progress... In order to be understandable, the way of creating the animation appears similar with the different frames in a film of a movie...

[503] Fotiadou, Angeliki, *Op. Cit* (2007) P. 26
[504] Cross, Nigel. 2006. *Designerly Ways of Knowing*. London: Springer-Verlag (2011) *Design Thinking: Understanding How Designers Think and Work*. Oxford: Berg.
As quoted by: Davis, Daniel, *Op. Cit* (2013) P. 76

...The software itself creates afterwards the middle steps of the movement, giving as a result a complete movie of the whole kinesis."[505]

It is reasonable to conclude that, in 3dmax, modeling in general is significantly unrealistic and non interactive, unless the designer has an innate or intuitive physics functioning psyche which becomes difficult to make accurate, even to experts, as Daniel Davis and Nigel Cross agree that *designing, it seems, is difficult to conduct by purely internal mental processes*[506], this becomes especially true with kinetic design processes. As we are about to detail, this kind of process and tool requires of the designer a capability to model the behavior or motion in his/her mind to the very detail therefore suggesting limitations about form-finding and creative usefulness, this will be tackled in chapter IX.

Case study 1: kuwait Pavilion_

The Kuwait Pavilion, designed by Santiago Calatrava, was commissioned for the 1992 World's Fair in Sevilla, Spain and has a parallel, two row, tapered, 25 meter long "finger" elements, made vault that opened on top of a 525 square feet piazza and opened as two hands unfolding.

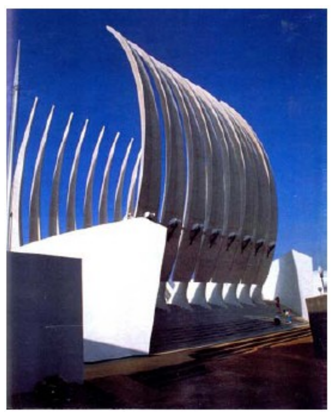


Figure 4-6.
Kuwait pavilion
(A. Tzonis)

Kuwait pavilion, Santiago Calatrava (1992) photo by Alexander Tzonis (1999) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 28*)*

505 Fotiadou, Angeliki, *Op. Cit* (2007) P. 26

506 Cross, Nigel. 2006. *Designerly Ways of Knowing*. London: Springer-Verlag (2011) *Design Thinking: Understanding How Designers Think and Work*. Oxford: Berg.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 61

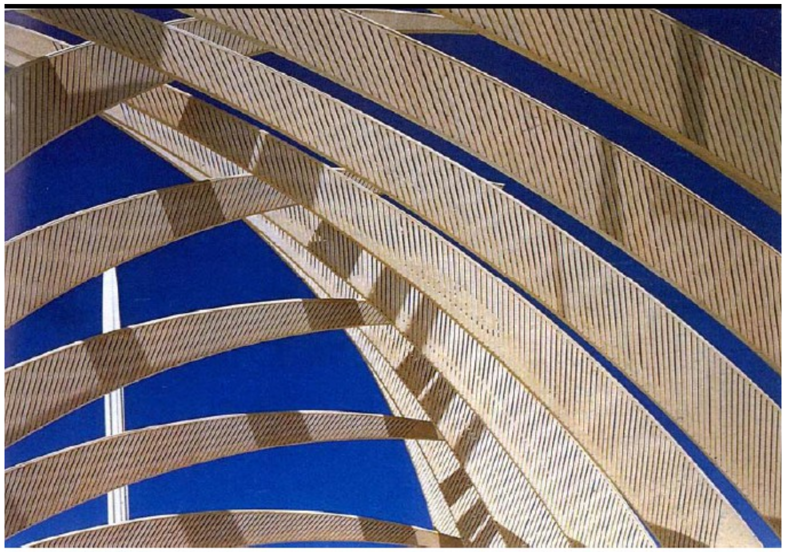


Figure 4-7. Detail of the "fingers". (A. Tzonis)

Kuwait pavilion, Santiago Calatrava (1992) photo by Alexander Tzonis (1999) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 29*)*

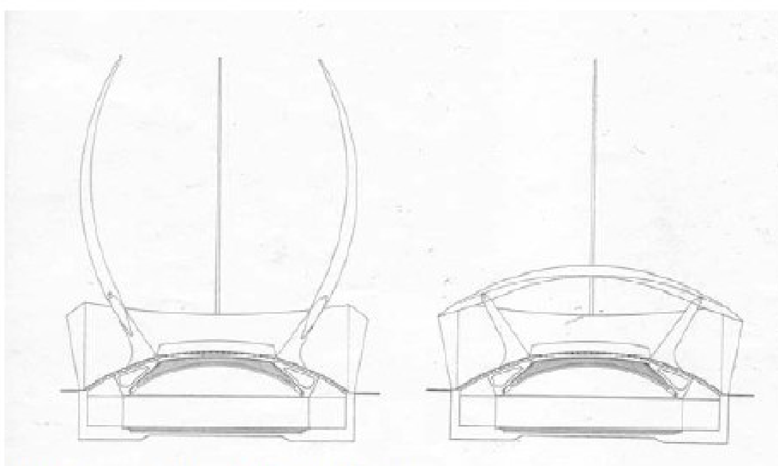


Figure 4-8. Drawings from Kuwait Pavilion (A. Tzonis)

Kuwait pavilion drawings, Santiago Calatrava (1992) photo by Alexander Tzonis (1999) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 29*)*

This process was relatively easy and simple to execute, yet it raises questions about timing both in creating the model and its own motion timing, how was it derived or from which documentation is not clear and accentuates the fact that it requires the designer to function as an artist and not a scientist, further making the gap between animation and simulation evident, this is not a simulation.

"The existence of many constraining functions but also the various possibilities of applying one, created confusion over the choice of the most appropriate for the needs of this construction. This caused the constant repeat of the stage until the proper constrain was found, leading to time lose."[507]

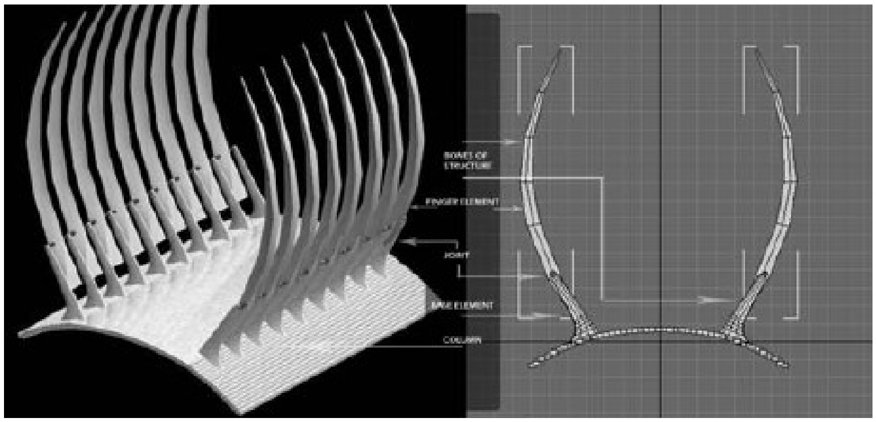


Figure 4-9. Terminology of real and virtual structure

Technology of real and virtual structure, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 30*)*

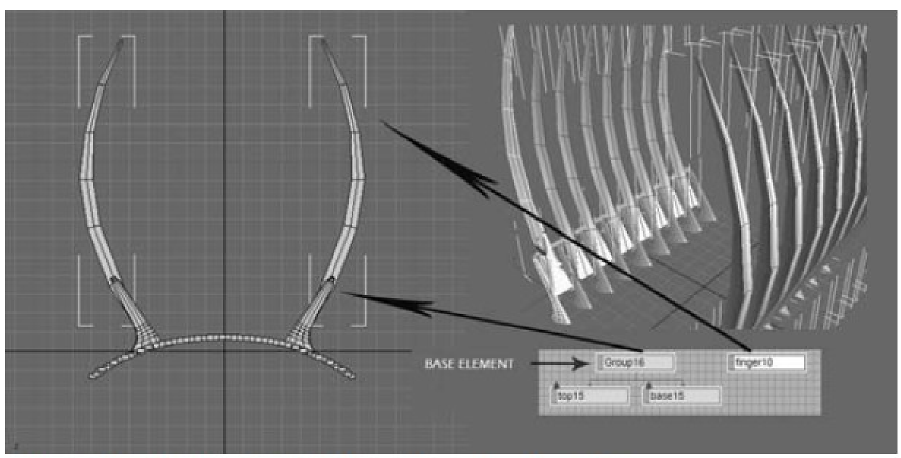
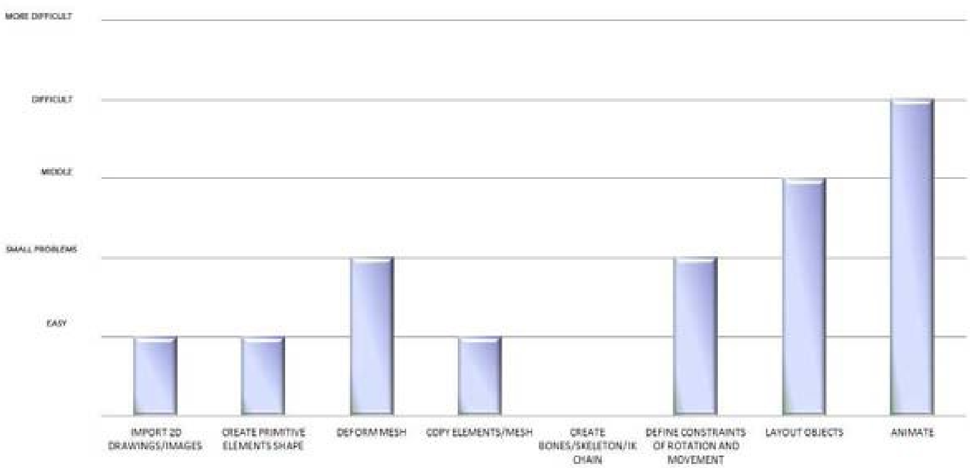


Figure 4-10. The hierarchy of the basic object. The selected elements are presented with different colour both in hierarchy graph and in scene

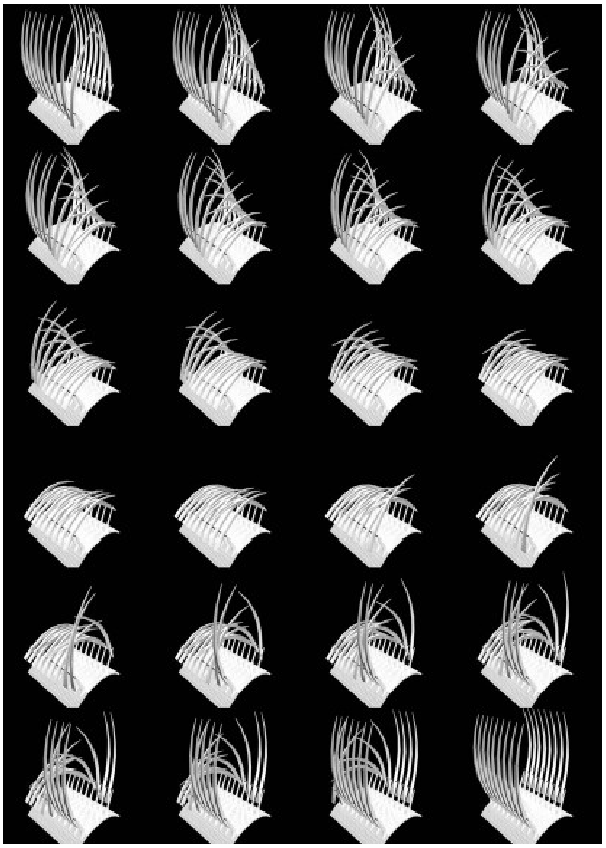
Hierarchy of the basic object. The selected items are presented with different colour both in hierarchy and in scene, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 31*)*

[507] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 31

Table 4-2. Evaluation of each stage of the Kuwait's Pavilion structure definition according to the level of settlement's difficulty



Evaluation of each stage of the Kuwait pavilion's structure definition according to the level of settlement's difficulty, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 31*)*



Kuwait pavilion final key frame sequence animation, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 33*)*

Case study 2: Alcoy Community Hall_

Alcoy Community center was designed and built by Santiago Calatrava (1995).

"The hall is situated in the heart of the town's Plaza Espana, site of festival of St. George and other community events. To preserve historical nature site, Calatrava created a subterranean multiuse civic hall with capacity of six hundred, ideal for civil weddings and exhibitions. Translucent glass floor panels attached to stain less-steel frames let light into the hall by day and emit a diffuse, mind glow by night that illuminates the plaza above. Above ground, a fountain, lights and an enclosed entrance break the continuity of the plaza surface to announce the presence of the underground space. Both the fountain and the entrance employ moving rod and joint mechanisms that produce the effect of veil or drape, a variation of Ernsting Warehouse and on the "eyelid" of the planetarium in Valencia. Building on the previous cases, the movement produced here is surprising, strange and in this fountain even eerie. As with the doors of the Ernsting Warehouse, Calatrava draws on both the technological principles of his Ph.D. dissertation and on the motor-spatial investigations of his sculptural experiments. The Hypnotic movement of stainless-steel door, which reveals an entrance cavity and stairs, as well as the folding cover of the spring-fed circular pool, at the opposite end of the plaza, offer a provocative prelude to the puzzles and marvels under the pavement of the plaza."[508]

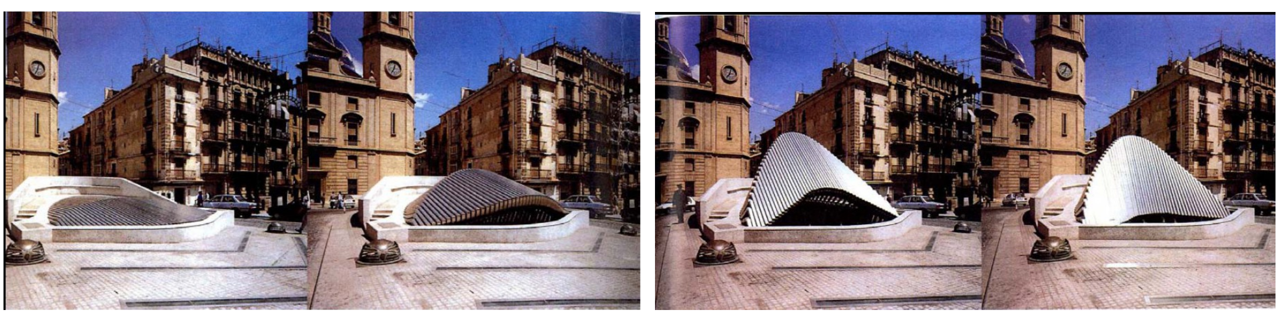


Figure 4-11. Phases of the movement (A. Tzonis)

Alcoy Community center, Santiago Calatrava (1995) photo by Alexander Tzonis (1999) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 35*)*

[508] Tzonis Alexander, "Santiago Calatrava, The Poetics of Movement", Thames & Hudson Ltd, London (1999) As quoted by: Fotiadou, Angeliki, *Op. Cit.* (2007) P. 34

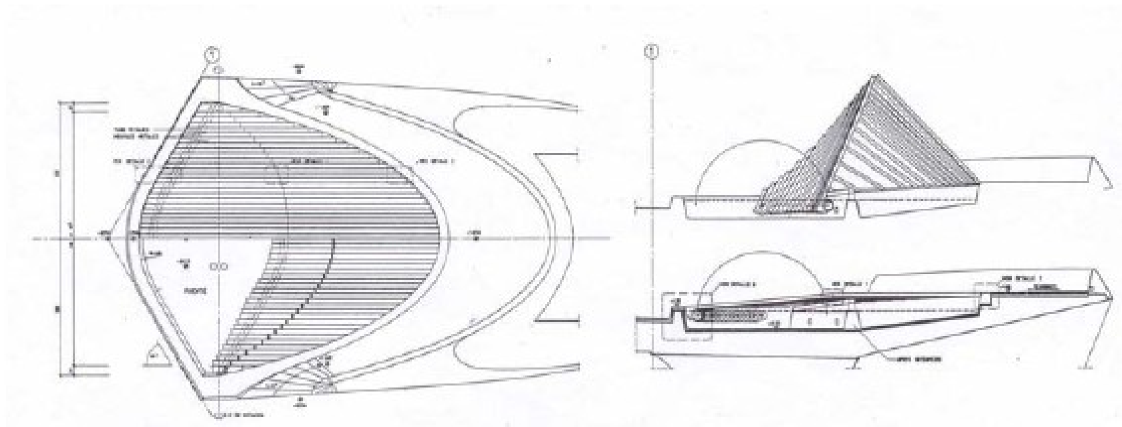


Figure 4-12. Drawings of the entrance(A. Tzonis)

Alcoy Community center drawings, Santiago Calatrava (1995) photo by Alexander Tzonis (1999) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 35*)*

In the second study case, the terminology starts to break apart, *the steel frames are called box elements into software language whereas the rest use the same terminology*[509], marking a significant, yet still not critical starting point of divergence between building and software ontology.

The correspondences between the constructive language and the software can be seen in ***Picture 4-13.***[510]

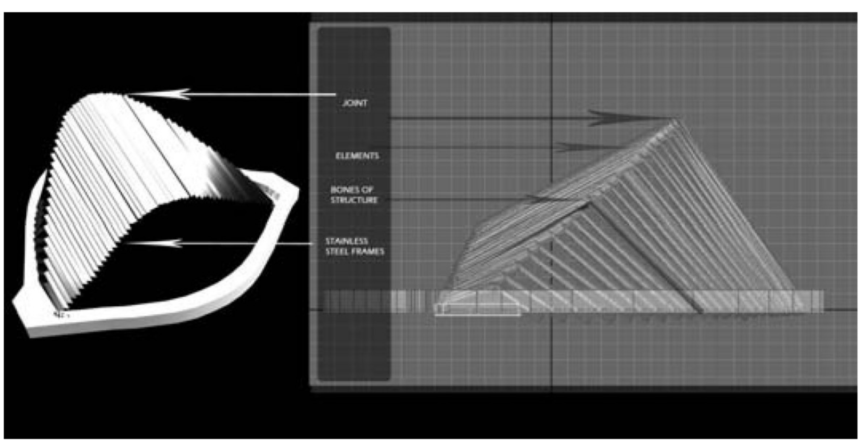


Figure 4-13. Terminology of real and virtual structure

Technology of real and virtual structure, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for*

[509] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 36
[510] Idem.

Kinetic Structures, P. 36*)*

This model brought to light 2 major issues with 3dmax as a kinetic architecture modeling environment and even as a complete design tool, making it clear that without further development it can only work for character design.

1. Major problem I: 3dmax only recognizes 1 pivot point per element (at its extremes) then multiple elements all connect at the same point. This problem is not even considered if using parametric editors such as Grasshopper or Generative Components because in them the designer sets up connections as he sees it fit and almost as if creating commands from scratch.

2. Possible solution: To introduce a function that inserts different pivot points for a single element (in this case "bone").

3. Major Problem II: Big problem with the 3dmax setup related to parent child relationships that end up in unwanted results.

4. Possible solution: This problem may arise in no matter which software tool but the fact that it interrlates with interactivity in that if the model is interactive by nature the designer can visualize the result almost instantly as remarked by Daniel Davis and Nigel Cross observations and my own experience with the software.

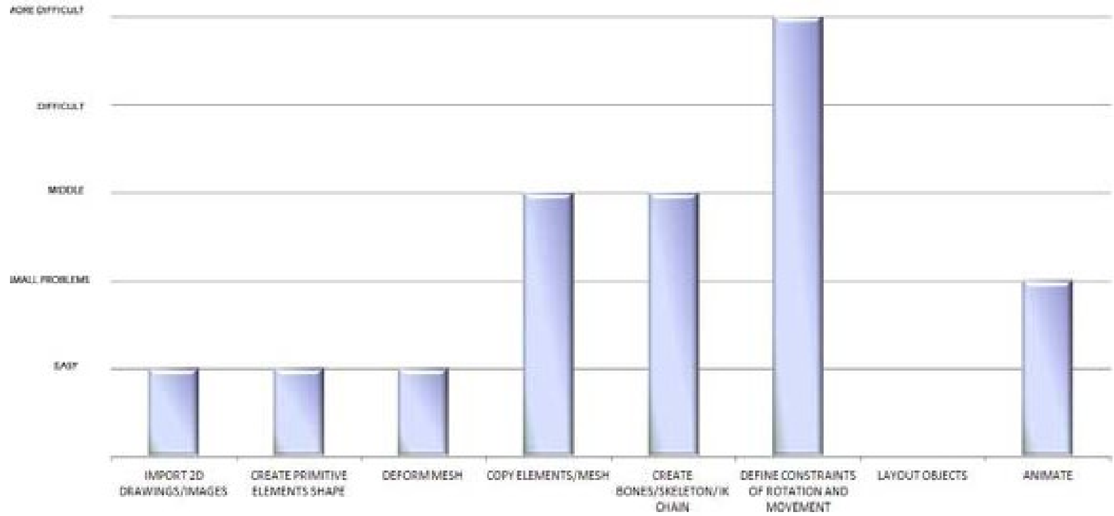


Table 4-3. Evaluation of each stage of the Alcoy's Community Center structure definition according to the level of settlement's difficulty

Evaluation of each stage of the Alcoy Community center structure definition according to the level of settlement's difficulty, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 37*)*

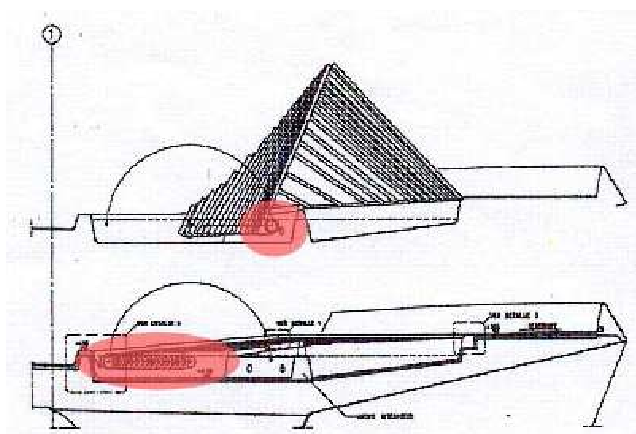


Figure 4-14. Position of the bent rod where all the objects are articulated

Alcoy Community center drawings showing the rod and objects articulation, Santiago Calatrava (1995) photo by Alexander Tzonis (1999) re-touched by Angeliki Fotiadou (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 37*)*

To overcome this problem, Fotiadou went through two modeling strategies, the first involved modeling box elements and connecting them with two bones. *The boxes were attached afterwards to the bones as skin to the skeleton..*[511] Then utilized function called IK solver (a kind of physics engine that works like a bio-mechanical prosthesis would) yet this did not work:

[511] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 38

"For their movement, in order to be restricted in the angle of rotation and to resemble to the physical movement of a human leg (including the thigh, knee, shin), the IK Solver, a function was used, which has as a result the appearance of a rope in scene and it is not rentable(IK Chain). The same procedure was done for every pair of metal frames."[512]

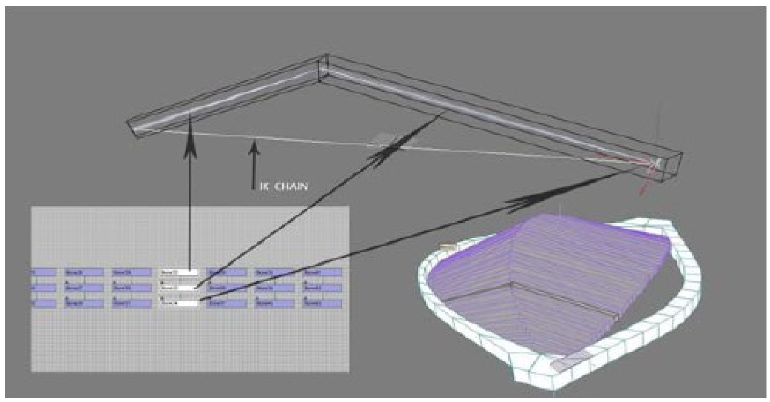


Figure 4-15. Hierarchy of the basic object

Hierarchy of the basic object, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 38*)*

The second strategy involved the modeling of a rod element that was built out of *"bones in a continuous hierarchy as shown in Figure 4-16*[513]

"...Each bone has a dimension equal to the vertical distance of one IK Chain to the other between two objects and follows at the same time the shape of the bent rod. (Figure 4-17)...

...Lastly, all the IK Chains, which manipulate the movement of the joined frames, were constrained in position to the corresponding bone of the rod skeleton structure (Figure 4-18) enabling, during the rotation of the parent root of the rod, the whole structure to simulate the real movement of the Alcoy entrance." [514]

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[512] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 38
[513] Idem.
[514] Idem.

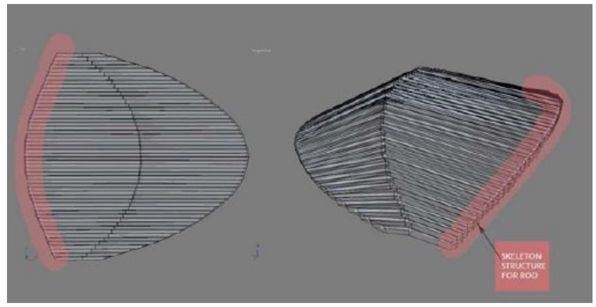


Figure 4-16. Position of the skeleton rod

Position of the skeleton rod, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 39*)*

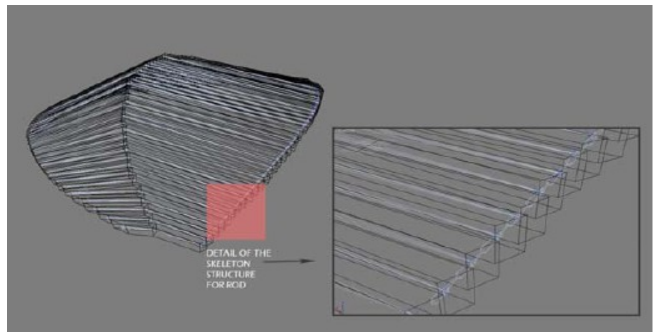


Figure 4-17. Detail of the connection between the rod and frame skeleton structure

Skeleton structure for rod, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 39)

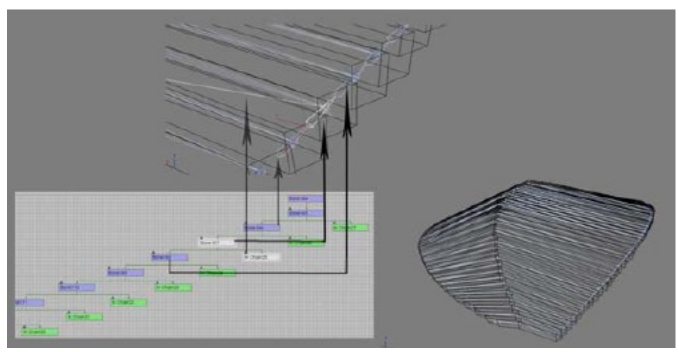
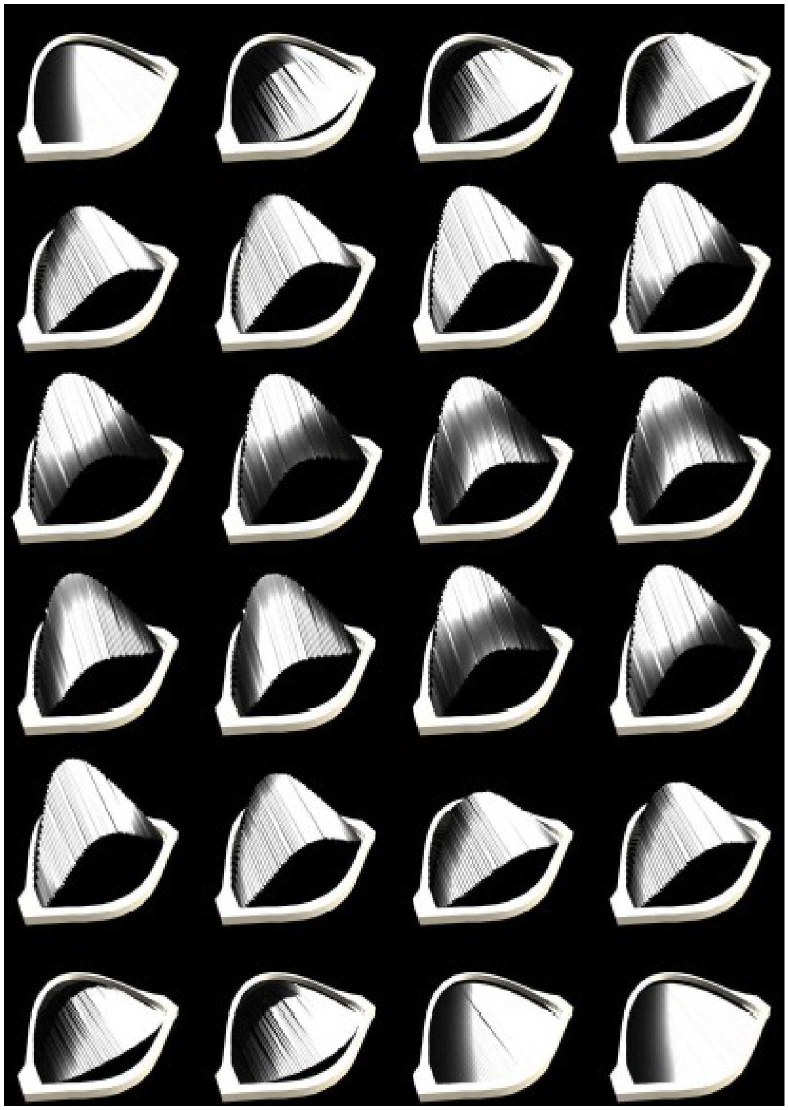


Figure 4-18. The hierarchy of the rod. The selected elements are presented with different colour

Hierarchy of the rod. The elements are presented with different colour, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 40)



Alcoy Community center final key frame sequence animation, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 41)

This structure was possible (yet not very time effective) to accomplish but, the fact that it was **not possible to anticipate its behavior before setting up the entire structure and only then being able to run it**, makes it a handicap that is very difficult to overcome without some serious software development that goes beyond what scripting can solve, it is evident that this is a critical point in which to concentrate when programming a kinetic modeling software application.

Case study 3: Folding Egg_

Definition_

The Folding Egg is a prototype kinetic folding sheet designed and built by the Kinetic Design Group at the Massachusetts Institute of Technology which was lead by Michael Fox at the time of its production (as mentioned in chapter III). *This structure is made by low-cost recyclable material and is essentially a collapsible three dimensional truss structure. It has a structural stability and many possible configurations.(Figure 4-19)*[515] it shows similarities with the Hoberman and Pérez Piñero's deployable structures structures (see chapter III for more on Pérez Piñero's transportable pavilion the Hoberman Arch and deployable structures) *however, the Folding Egg differs from these structures* [in this sense it is closer to Pérez Piñero and farther from Hoberman] *as additionally it has the ability to reconfigure itself through kinetic movement.*[516]

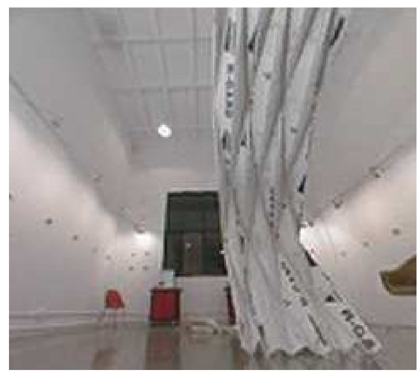


Figure 4-19. Different views of Folding Egg(Internet)

Folding Egg Sectional prototype, Michael Fox and KDG (2001) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 42)

This is were animation software begins to really break down when it comes to kinetic representation, for this case, Fotiadou reduced the model's complexity to its basic elements compared to the real prototype and still was not possible to carry out with 3dmax 9's functionality:

"In order to be designed, the structure had been simplified to the representation inside the software only of the main truss that supports the whole construction without including the panels and only for a

[515] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 42
[516] Idem.

segment, the one which could be considered as the basic object of the structure Figure 4-22."[517]

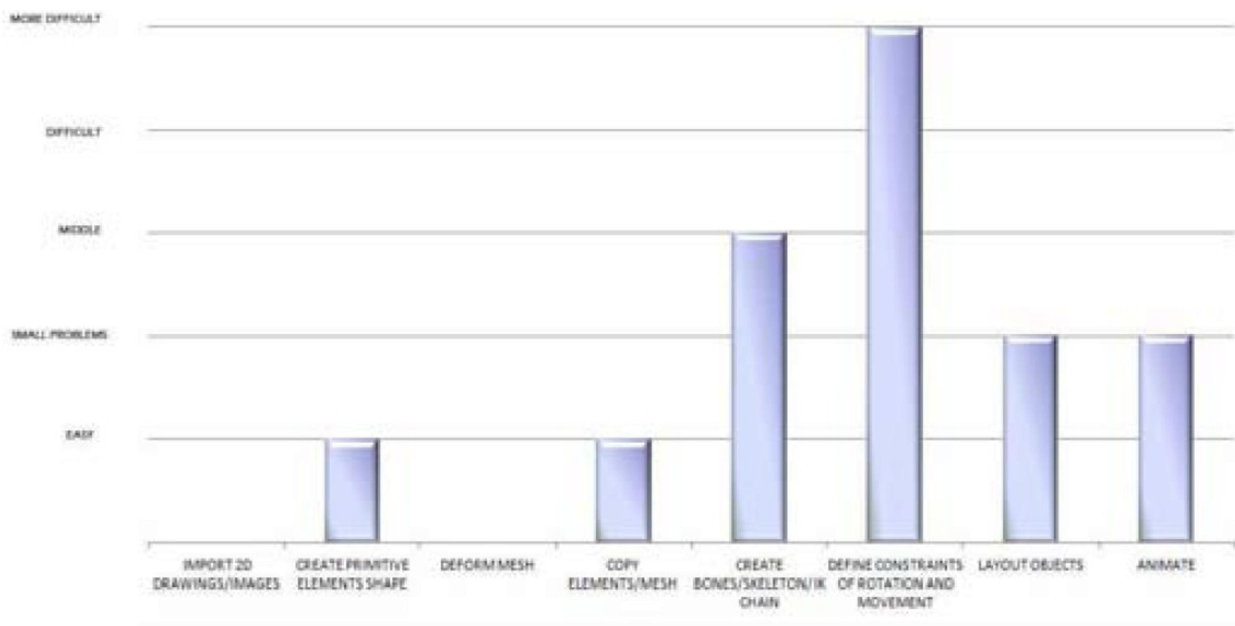


Table 4-4. Evaluation of each stage of the Folding's Egg structure definition according to the level of settlement's difficulty

Evaluation of each stage of the Folding Egg structure definition according to the level of settlement's difficulty, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 44)

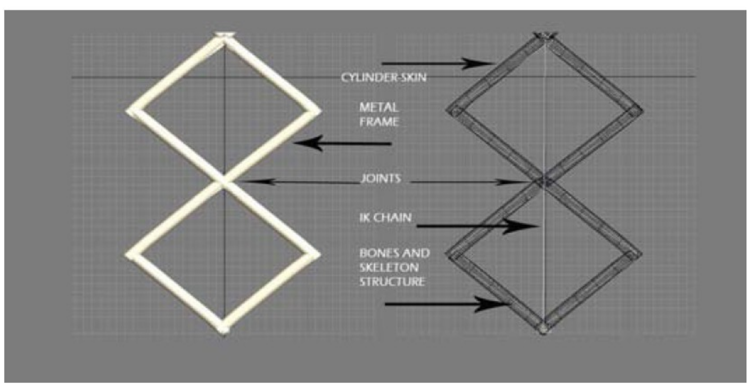


Figure 4-24. Correspondence of terminology

Correspondence of terminology, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 46)

She tried two different approaches in which the first *was each part of the basic object to be designed in such a way that the deformation and the movement will be done due to an horizontal set of forces.*[518] After multiple attempts it rendered no favorable results as the *The restrictions in rotation and in position were difficult to be preformed; every set of elements had to be constrained in position and*

[517] Fotiadou, Angeliki, *Op. Cit* (2007) P. 44
[518] Idem.

rotation and then again, as one object, to be restricted with the rest of the analogical objects.[519]

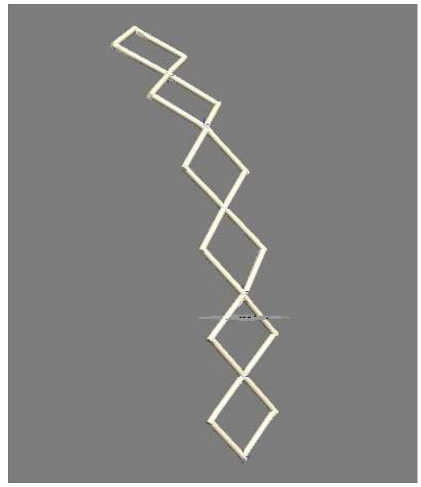


Figure 4-22. Basic Object

Folding Egg 3dmax model's basic object, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 45)

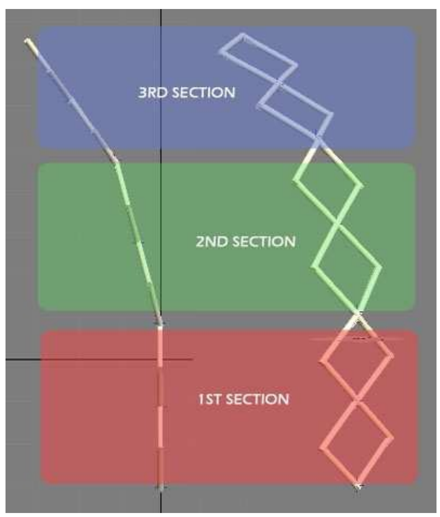


Figure 4-23. The three parts

Folding Egg structure 3dmax model section's subdivision, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 45)

Her conclusion after setting up the forces on an horizontal axis was the it was not possible unless the designer does not model every element's motion one by one:

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[519] Fotiadou, Angeliki, *Op. Cit* (2007) P. 44

"The animation into two directions could not be performed with the existing functions, without the interference of the user to transfer the elements in the right position for the different key frames of the animation during the stretching of the object...

...Therefore, the whole construction was created from scratch with respect to the vertical axis."[520]

2nd procedure:

"In this case, the three parts could move, with a small declination to their analogical distances and the real movement, without separating, into the three different directions Figure 4-26, 4-28. [521]*when an attempt was made to multiply the basic object, it had the same result as with the previous case, the objects were keeping distances between them Figure 4-27. Nevertheless also in this case, the real movement of the structure could not be performed."*[522]

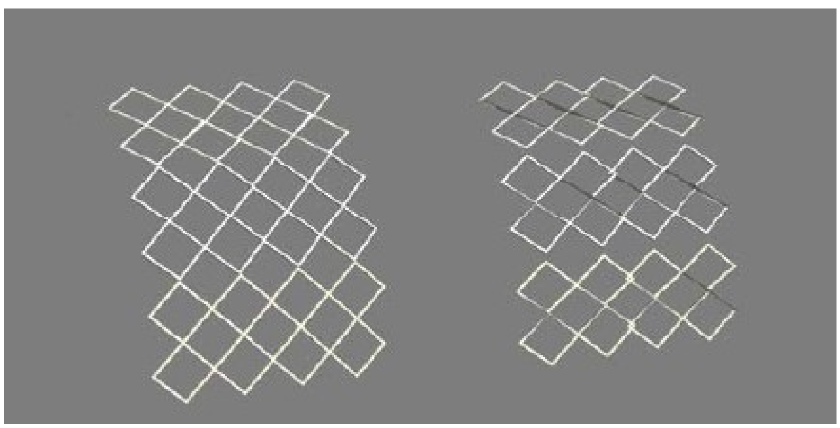


Figure 4-25. Distances between the three parts

Folding Egg structure 3dmax model section distances between three parts of the whole structure, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 46)

520 Fotiadou, Angeliki, *Op. Cit.* (2007) P. 46
521 Idem.
522 Idem.

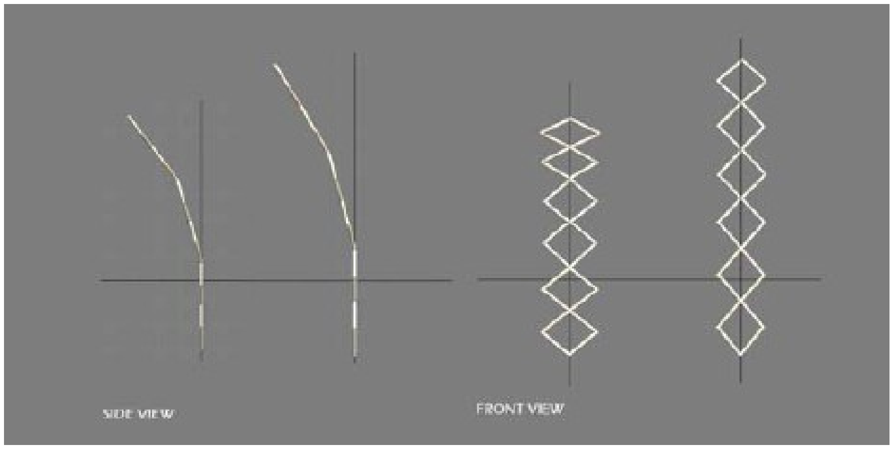


Figure 4-26. Movement of the basic object

Folding Egg structure 3dmax model section's basic object movement, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 47)

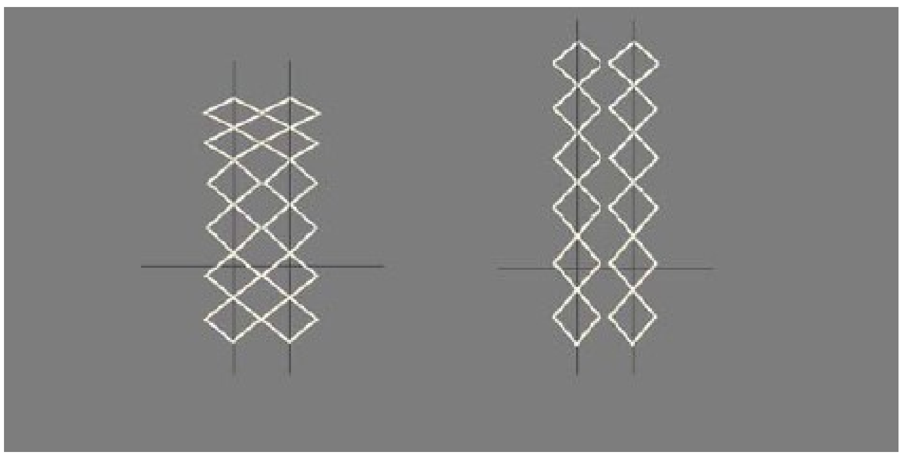
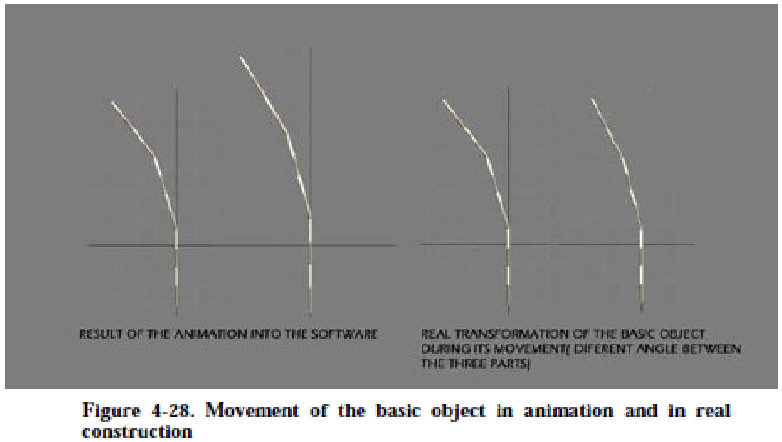


Figure 4-27. Distances between the two parts

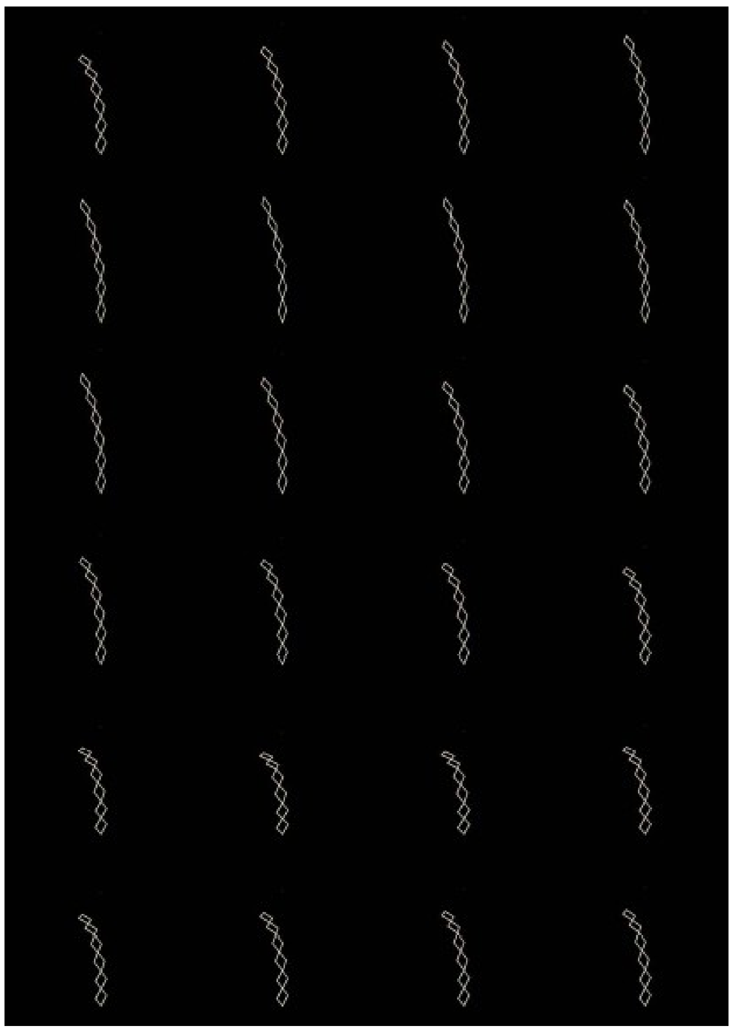
Folding Egg structure 3dmax model section distances between two parts of the whole structure, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 47)

Concluding that *this could not be simulated into the software with automation but with the interference of the user for each key frame, as again the movement of the structure in two different axes at the same time had to be represented.*[523]

[523] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 47



Folding Egg structure 3dmax model movement of the basic object in animation and in real construction, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 48)



Folding Egg final key frame sequence animation, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 49)

*6.2.11-Benefits and limitations_*

Found issues:

The lack of automation made a constantly repeating procedure to be performed for many similar objects where the same definitions were needed, consuming this way useful time.[524]

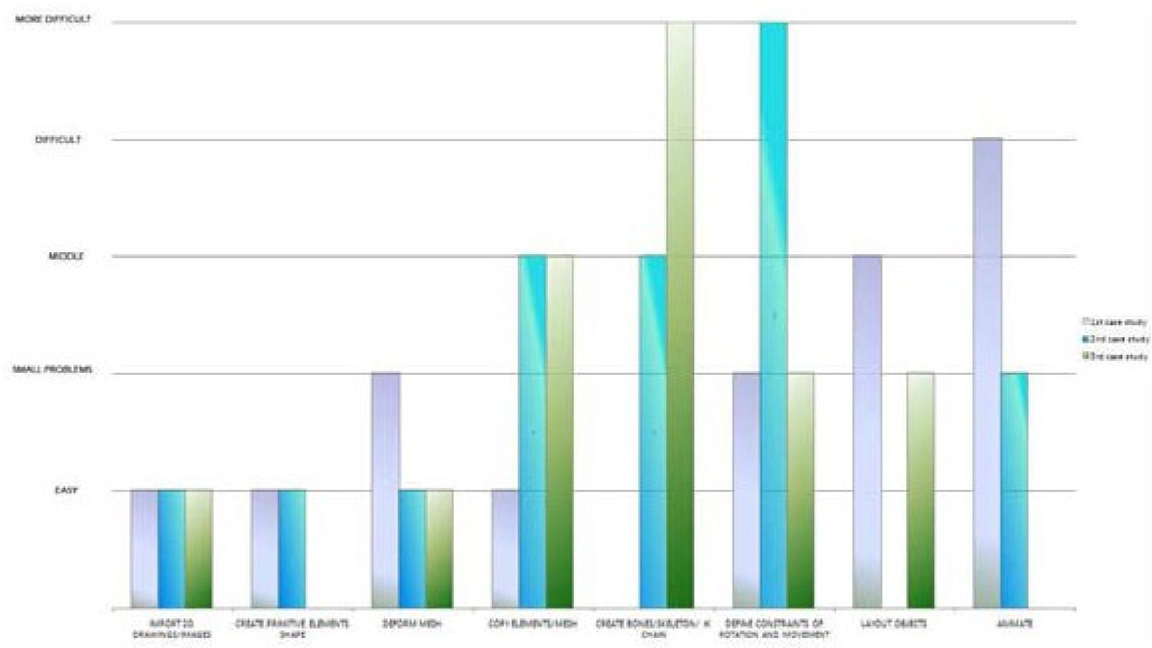


Table 5-1. Comparison and evaluation of the case studies of each stage of the structures definition according to the level of settlement's difficulty

Comparison and evaluation of the case studies of each stage of the structures definition according to the level of the settlement's difficulty, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, Analysis of Design Support for Kinetic Structures, P. 50)

the main problems that 3dmax shows toward the representation of kinetic structures are:

• Spatial arrangement in combination with the naming that the software provides

• Difficulty in changing common parameters for a selection of many elements of the same category

• Lack of automation in various functions

[524] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 50

• Problem in attaching elements or primitive objects between them -connection possible only in the pivot

• Problem in the hierarchy in child to child connection

• Difficult in arranging the constrains in complex structures - complicated connections must be formed

• Difficult in manipulating the animation into 2 or more axes at the same time with automation- can be performed only manually

• Difficult in manipulating the animation into 2 or more axes at the same time with automation or not when also the complex system of elements belong to different orientation and axes[525]

It is understandable that the software can not predict in which cases this automation is needed...However, for a fast construction of structure where similar elements exist the existence of cybernation[*] *in same cases could be useful.*[526]

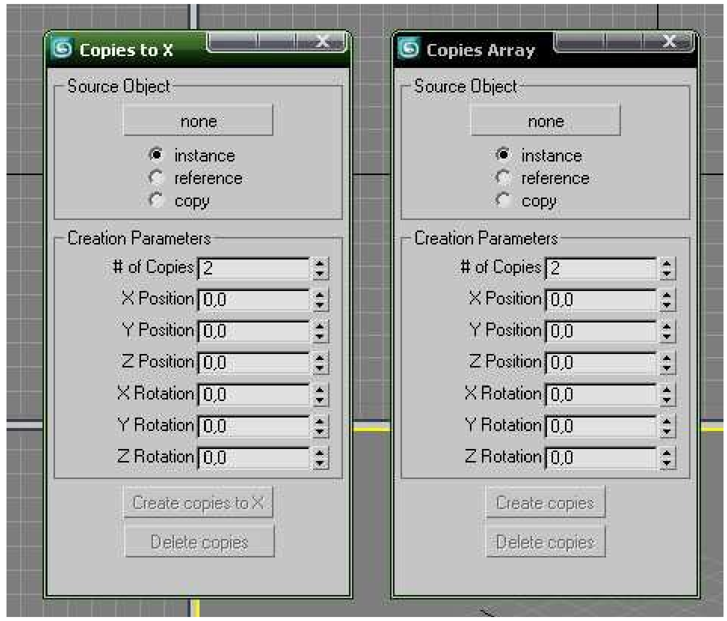
The only non expected function, which proved to be very useful and fundamental in the creation of the animation, was the implementation of the IK solvers and consequently the creation of the IK chains.[527]

6.2.12-Enhancements_

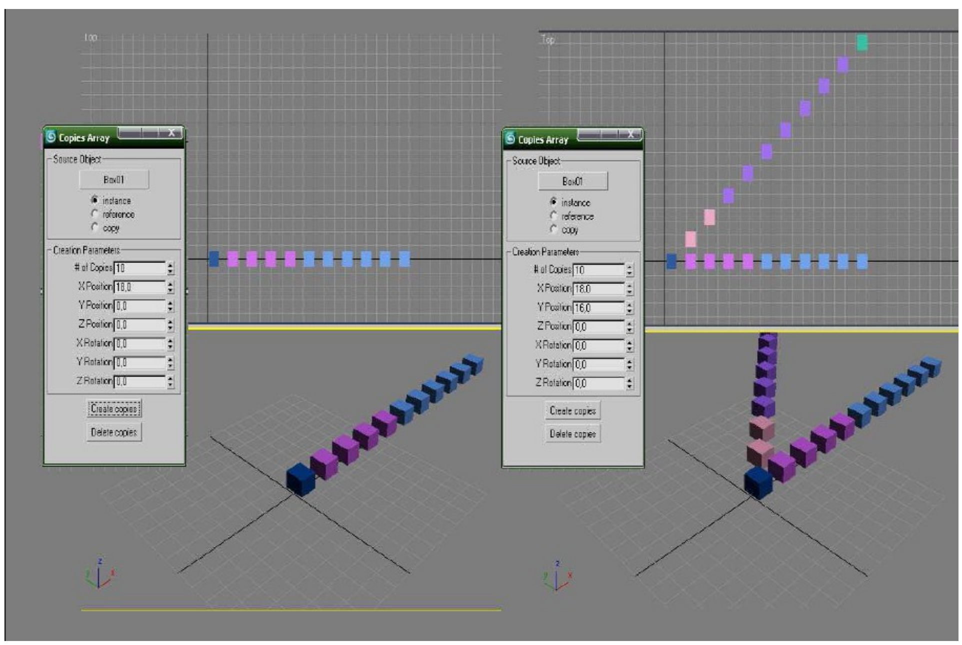
She even went to develop two new toolbars that solved a basic yet not resolved issue with the commands copy+array, the problem being that it is not possible to use them in combination. *The most important is that all the copies preserve an order during their creation, no matter how many in number*[528]*,* so this solution comes in handy yet it does not tackled the more systemic problems described in the previous section.

[525] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 50
[*] Cybernation: the automatic control of a process or operation (as in manufacturing) by means of computers. (http://www.merriam-webster.com/dictionary/cybernation)21/05/2014)
[526] Fotiadou, Angeliki, *Op. Cit.* (2007) P. 52
[527] Idem.
[528] Ibid. P. 53

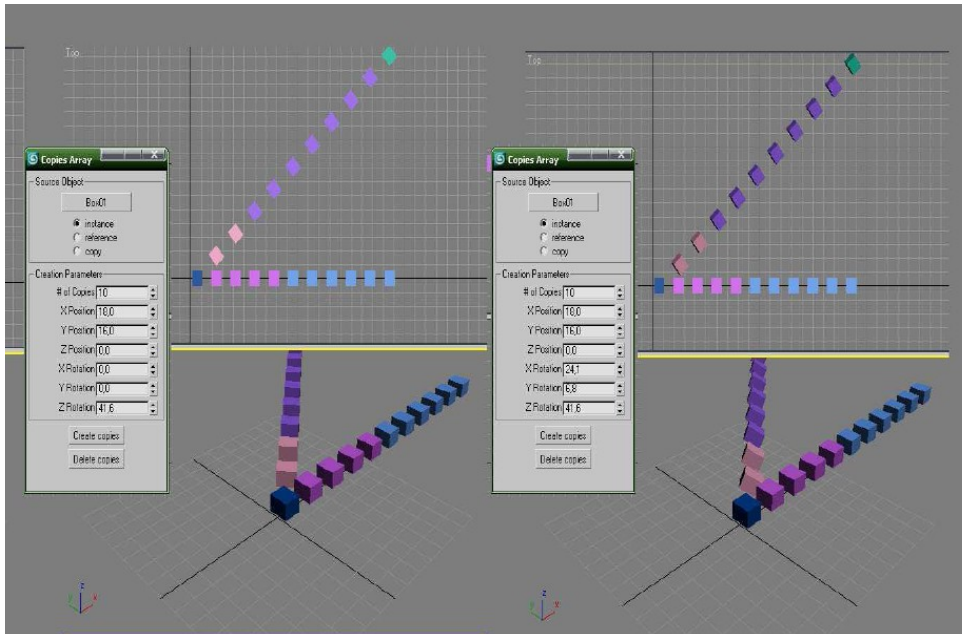
Figure 5-1. The two toolbars



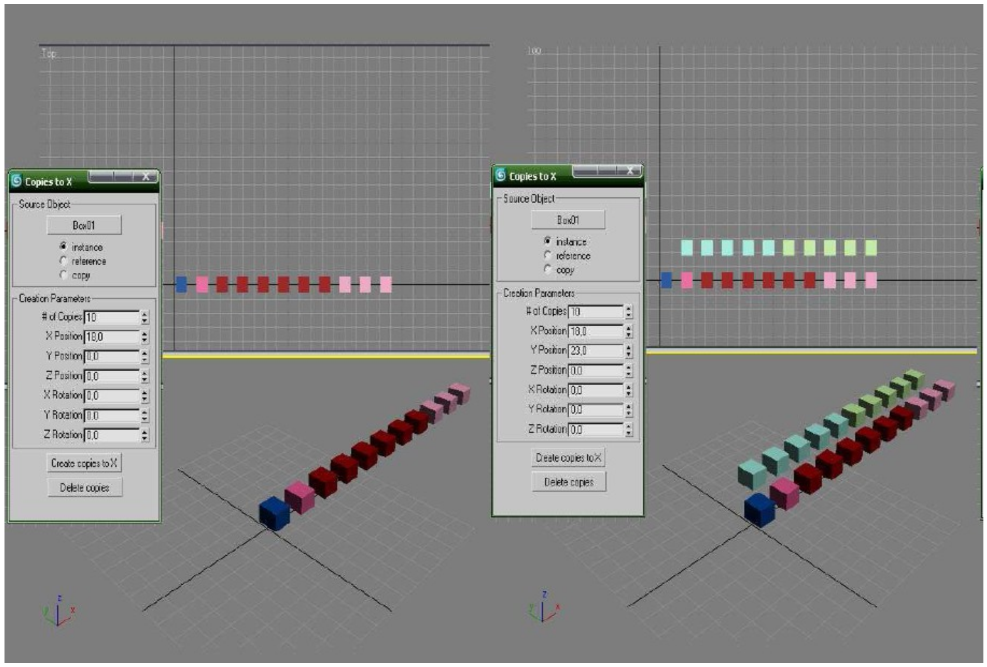
New "array" + "copy" toolbars in 3dmax, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 53)



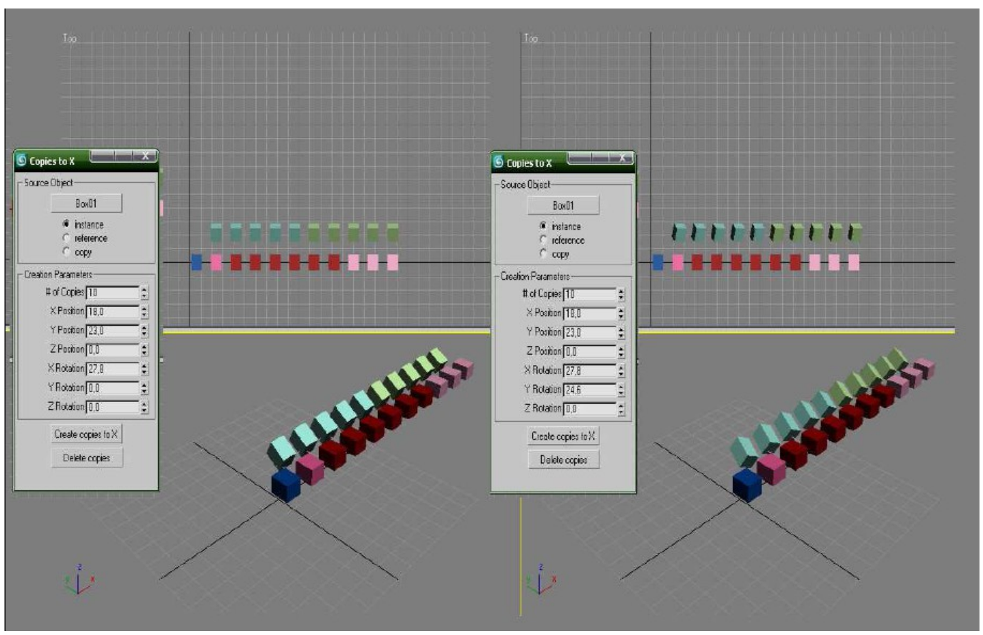
New "array" + "copy" toolbars in 3dmax, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 54)



New "array" + "copy" toolbars in 3dmax, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 54)



New "array" + "copy" toolbars in 3dmax, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for*



Kinetic Structures, P. 55)

New "array" + "copy" toolbars in 3dmax, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 55)

*6.2.13-Suggestions for further development_*

Problems like the automation in different functions or changing common parameters for a selection of many elements of the same category could be as well solved with the use of scripting language [which in the case of maxscript belongs to the imperative programming paradigm, as we will see in the next section]. *A new toolbar could be created that could imply instantly all the desirable changes or functions on the elements causing the automation in both cases*[529]

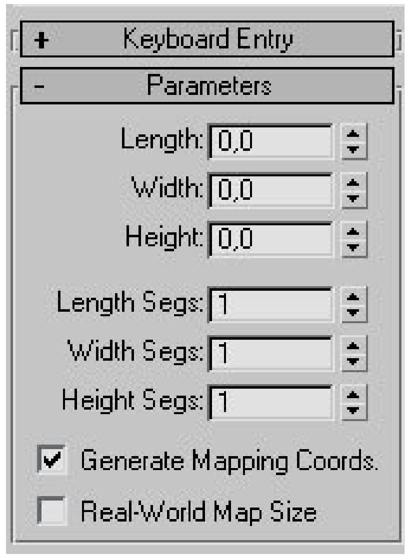


Figure 5-2. The parameters of the elements dimensions

New element dimension parameters menu box, Angeliki Fotiadou (2007) (Fotiadou, Angeliki, *Analysis of Design Support for Kinetic Structures,* P. 56)

*6.4-Conclusions_*

Fotiadou's research conclusions rise some the questions that this research is trying to answer and develop, in red are the ones that this research will continue researching in its experiments and project phase in chapter IX, the rest I left out of the scope of this research for practical and non future reasons.

"Seeing in the future and in detail the possibilities of this software it is thought that it could include:

- *Necessary tools for the detailed construction of the building (column, beams etc. as AutoCAD, Archicad) in 3D*

- *Necessary tools for the detailed instructions of movement of the elements that will be used in the kinetic architecture*

[529] Fotiadou, Angeliki, *Op. Cit* (2007) P. 56

- *Necessary tools for the calculation of the different analysis (i.e. Ecotect)*

- *Library of materials*

- *Library of elements*

- *Necessary tools for the detailed construction of the kinetic mechanism"*[530]

Basically, out of her conclusions this research, given its scope, will develop in more detail the following performance software functionality_

- *"The result of the simulation will be associated also with the kinds of material that the user will chose from the existing library, as they will include specific characteristics according to their type,*

- *e.g. for a fabric there will be the parameter of elasticity included into the material definition and therefore recognized by the software.*[531]

This will our definition of what performance is in the context of simulation-based modeling, the experiments will test design possibilities based on geometry, form and forces, all these in relation to material behavioral performance parameters.

This investigation concludes that pursuing the simulation of kinetic structures in animation software is not only not viable, it is not an adequate design exploration tool, therefore not suited for form-finding nor emergent behavior envisioning, making it a very "closed end" tool, yet we will continue trying to develop the conceptual guidelines in Fotiadou's conclusions, graphs and line of questioning, given that her quantitative method for measuring difficulty and time expenditure has demonstrated effective as means to arrive at concrete conclusions, using them as a map in which to set the path to follow but, her "by hand" modeling procedures proved being time consuming and leading to too many dead ends, this

[530] Fotiadou, Angeliki, *Op. Cit* (2007) P. 58-59
[531] Idem.

research will be implementing another method that has proven (specifically in the case of Dina El-Zanfaly, see chapters IV and V) to be very effective and useful when facing visualization, performance and geometric complexity issues while modeling: ***parametric modeling.*** Context specific forces, internal and external, both determine the relation between the material and the environment and, in between that relationship, we have ***performance***, which dictates the efficiency with which design is measured and understood, for this, Michael Hensel has argued the creation of a tool set that could address the form finding dilemma with a direct relation to performance within the material but in multilateral and multidimensional ways:

"Evolutionary form-finding software usually incorporates an environment-specific random factor as well as genome mutation that, together, constitute sources of contingent influence. Indeed we are at the threshold of having multi-parametric digital tools that generate and analyze combined geometric, structural, material, spatial and habitational characteristics and capacities. In combination with computer aided manufacturing tools such as rapid prototyping, physical models of selected transition states can be produced and tested in actual or simulated environments and the test data can be fed back into the generative process in the digital environment. An inclusive generative feedback-based and evolving tool would therefore constitute the next major step in the evolution of form-finding methods."[532]

This precisely the kind of software tool that this thesis is aiming at using and developing further or, in its defection, create. However we will only concentrate, until future research will be conducted, on strictly *geometric, structural, material and spatial* Qualities in programmable matter based kinetic design. Therefore it is definitely an accurate assumption that *Rhinoceros + grasshopper +Kangaroo* is a definitive choice to develop further as it permits, in an declarative visual programming environment, to set up parametric models in which to carry out reliable approximations in material behavior within physical simulations, specifically those of SM systems and SMM.

[532] Hensel, Michael, *Op. Cit.* (2004) P. 31

*7-Programmable Matter: Material Design & Programming as a vehicle for Architectural Design_*

"The next revolution after 3D printing will be the transition from analog to digital materials."[533]

-Hod Lipson & Melba Kurman -

Future directions for a kinetic architecture will require the chemical and mechanical development of materials and devices using micro and nanotechnology. For clearance purposes we will define nanotechnology, even though it is not the primary focus of this research, it does hand over significant conceptual and practical contributions to the development of programmable matter (PM), 4D printing (4DP) and kinetic architecture (KA) as it will be shown that it was among the initial catalysts that spawned the current PM frenzy, interest and its current development. According to the National Nanotechnology Initiative website, on its Nanotechnology 101 section

"Nanotechnology is science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers." Nanoscience and nanotechnology are the study and application of extremely small things and can be used across all the other science fields, such as chemistry, biology, physics, materials science, and engineering."[534]

Historically, it all appears to have started with Richard Feynman and a talk he gave the American Physical Society:

"The ideas and concepts behind nanoscience and nanotechnology started with a talk entitled "There's Plenty of Room at the Bottom" by physicist Richard Feynman at an American Physical Society meeting at the California Institute of Technology (CalTech) on December 29, 1959, long before the term nanotechnology was used. In his talk, Feynman described a process in which scientists would be able to manipulate and control individual atoms and molecules. Over a decade later, in his explorations of ultraprecision machining, Professor Norio Taniguchi coined the term nanotechnology. It wasn't until

533 Lipson, Hod - Kurman, Melba,Fabricated: The New World of 3D Printing Indianapolis: Indiana: John Wiley & Sons, (2013) P. 279 (http://books.google.fr/books?id=MpLXWHp-srIC&q=3d#v=onepage&q=The%20next%20revolution%20after%203D%20printing%20will%20be%20the%20transition%20from%20analog%20to%20digital%20materials&f=false) (28/03/2015)

534 National Nanotechnology Initiative, *What is Nanotechnology?*, Nanotechnology 101 section official website. (http://www.nano.gov/nanotech-101/what/definition)

1981, with the development of the scanning tunneling microscope that could "see" individual atoms, that modern nanotechnology began."[535]

Michael Fox states that *kinetic systems with embedded intelligence will expose new programmes and forms as this technology is incorporated into our everyday lives* [536]. Tess Fenwick's call for the development of ***Unobtanium*** materials (materials that do not yet exist but are needed yo fulfill specific building needs) is to wait until *other fields will develop material*[537]*,* as architecture's needs now a days are to be determined by other disciplines, relying on material science to come up with the solutions that address these predicaments *and when the properties match and the situation* [is] *suitable they will subsequently be applied to architecture* [538]. But that is all starting to change, the lines that divide data and matter are being blurred by digital tools that are being developed to suit this problematic and address , as Fenwick also states, that:

"...architecture is becoming, to an extent, the coexistence of experimental investigation, computer robotics, and redefining of spatial paradigms. It is almost as if we are seeing what could potentially be the next 'built movement', by exploring it thoroughly prior to building."[539]

Fenwick also suggests that there is certain preoccupation with the "over- theoretical" approach to the kinetic architecture paradigm remarking that *...it appears that a movement is currently occurring, -known as the "digital revolution", which explores kinetic architecture through digital technologies as purely theoretical paradigms.*[540] This is most probably because of the research focus into kinetic applications based more so in the "mechanical paradigm" (see chapter IV) and not so in the "plastic paradigm", judging from her master thesis project, which is a position that can lead to the definition of kinetic architecture as an arrangement and programming of discrete parts leaving out possibilities of material matrices and fluid configurations that can enable less complicated material arrangements but allowing for complex traits to emerge in the design process. But what if that intelligence would be embedded and programmed into the material? that it came along and within with matter itself? This is where programmable materials come in. This research suggests that, with the application of such

535 National Nanotechnology Initiative, *Op. Cit.*
536 Fox, Michael, *Op. Cit.* (2001) *(b)* P. 4
537 Fenwick, Tess, *Op. Cit.* (2011) P. 145
538 Idem.
539 Ibid. P. 28
540 Ibid. P. 28

materials in the development of kinetic design and production, not only do we open up a whole new territory to explore in terms of design, but also will make possible and realizable, many configurations and ideas that were not possible before, both in therms of form, geometry and actuation, provoking the construction of design methods that address a more ample scope within what can be built in physical reality, and as a result, building digital simulations may become, in certain aspects, significantly simpler. There is also the possibility of a change in philosophy of architecture altogether.

"Imagine a world in which solid material objects can morph into new shapes or change properties at the command of an individual or in pre-programmed response to changing external conditions like temperature, pressure, wind, or rain. That world— in which things are not quite what they seem—is on the horizon."[541]

*7.1-Background: Programmable Matter at DARPA_*

Programmable Matter (PM) is a project developed, originally commissioned by the Defense Advanced Research Projects Agency, led by Thomas Campbell and continued by Skylar Tibbits at the Self Assembly Laboratory within the Massachusetts Institute of Technology (MIT). The project is a multiple-institutional and trans-disciplinary effort between MIT (and inhouse institutes as the Center for Bits and Atoms among others), Autodesk, King Innovation, Procter and Gamble, Carbitex, Steelcase, Airbus and Seed Media Group, among other occasional contributors.

Grounded on the fact that *Objects created today, including by 3D printing, are primarily designed to be stable and static— that is, they are unable to change their form or function after fabrication*[*].[542] *The Defense Advanced Research Projects Agency (DARPA) ran the"Programmable Matter" program in 2007.*[543] Its original commission was to try to come up with certain answers to nanotechnology's problematic questions concerning scalability and application, utilizing robotics as a conceptual framework to solve the functional and scale-dependent practicality issues within the definition and

[541] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *The Next Wave: 4D Printing and Programming the Material World* , Atlantic Council, Washington, DC, USA (2014) P. 1

[*] A traditional solution toward enhanced capabilities is that of robotics, even micro-robotics—see box below for DARPA program description . While certainly promising in initial research, there are drawbacks and fundamental limitations that researchers encountered with micro-robotics, including fabrication expense, component failure, challenges in fabricating motors and batteries at the microscale, difficulty in interacting with micro-components for new programming and repair, and overall weight of fully assembled systems with numerous micro-robots.

[542] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 4

[543] Ibid. P. 3

tenets of nanotechnology itself. Where *the goal of creating PM by shrinking robotics and thereby enabling new functionality at the millimeter scale, e.g., the width of a pencil.* The emphasis was on scaling up the phenomenons and properties to have them serve for further military applications, DARPA *...laid out a multi*[-]*year plan for designing and constructing micro-scale robotics systems that could morph into larger military systems.*[544]

*"An example achievement is the "**milli-motein**" (mechanical-protein) designed and built by MIT. Millimeter-sized components and a motorized design inspired by proteins created a system that can naturally fold itself into complex shapes."*[545]

DARPA and MIT are not the only (although they are the most supportive of all) institutions that address the digital material (PM-SA) development and implementation within the USA educational systems. *A group at Cornell also developed a self-replicating reconfigurable robotic system.*[546] *Micro-robotic systems (M-bricks) were created that have the ability to move independently and relocate within a larger assembly.*[547] The same is yet to be coordinated at an institutional level in Europe, with a just some schools like The Bartlett School of Architecture in London (with its Biotechnology and Architecture Lab -BiotA-)[548], The Architectural Association (and its Emergent Technologies and Design program -EMTECH-) and the Institute for Computational Design (ICD) at the *Stuttgart Universität* in Germany -with its "Biomimetic Responsive Surface Structures"[549]- among others not less important institutions like the Institute for Advanced Architecture of Catalonia (IAAC) or the European Network of Heads of Schools of Architecture (ENHSA) which supported, in 2014, the editing by Maria Voyatzaki of a various author book called "*What's the Matter? Materiality and Materialism at the Age of Computation"* in which the IAAC published one of their projects called *"Intelligent construction systems for responsive buildings"* [550] investigating, among other topics, "Adaptive Building Structures" utilizing shape-memory polymers. And which have ventured with supported pilot projects and/or

544 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 3
545 Idem.
546 Idem.
547 Idem.
548 The Bartlett School of Architecture website (http://www.bartlett.ucl.ac.uk/architecture/programmes/postgraduate/labs/march-architectural-design/biota)
549 Correa, D., Krieg, O., Menges, A., Reichert, S., Rinderspacher, K. (2013). HygroSkin is a "prototype project for the development of a constructional and climate responsive architectural system based on the elastic and hygroscopic properties of wood."
550 Markopoulou, Areti - Dubor, Alexandre -Voyatzaki , Maria (ed), *What's the Matter? Materiality and Materialism at the Age of Computation*, Copyright c 2014 by the authors and ENHSA (2013) P. 116–121

tenured programs inscribed in this emerging field, yet the rest of the "important" European schools remain shy when it comes to PM or SAL. Although *this technology has attracted substantial press attention around its potential for manufacturing.*[551]

7.2-What is programmable matter?_

"PM adds the capability of programming the fundamental materials used in 3D printing and is thus a logical complement and extension of 3D printing. [552] Campbell Thomas says that it can influence anything that relies "*...on practical applications like furniture and eventually aerospace and construction — any field where you might want to change the object after it's in use. A car could adapt to rain, or a coffee cup could adapt to the relative heat of its contents."*[553] Formally speaking, the concept of programmable matter comes from material science within the spectrum of Science, Technology, Engineering and Mathematics(STEM); Campbell Thomas et al. define it as follows:

***"**Programmable matter (PM) is the science, engineering, and design of physical matter that has the ability to change form and/or function (shape, density, moduli, conductivity, color, etc.) in an intentional, programmable fashion."*[554]

4D Printing: Self-Folding Protein, Skylar Tibbits in collaboration with Shelly Linor, Daniel Dikovsky and Shai Hirsch at Stratasys and Carlos Olguin of Autodesk. (2013) (SJET website: http://www.sjet.us/MIT_4D%20PRINTING.html) (04/04/2015)

551 Tibbits, Skylar, *Op. Cit.* (2014) P. 116–121

Breeden II, John, "3D printing is yesterday's news—time for 4D?," (http://gcn.com/ blogs/emerging-tech/2013/04/4d-printing.aspx;) (28/03/2015)

Petterson, Robert, "What is 4D Printing?," http://quartsoft. com/blog/201304/what-is-4d-printing; "4D Printing: Multi-Material Shape-Change," (http://additivemanufacturing.com/2013/04/07/4d-printing-multi-material-shape-change/) (28/03/2015)

552 Tate, Ryan, *Op. Cit.* (2013)

553 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 3

554 Ibid. P. 2

And it may come in at least two forms:

"*(1) Objects made of pre-connected elements that are 4D printed* or otherwise assembled as one complete structure for self-transformation. (2) Unconnected voxels that can come together or break apart autonomously to form larger programmable structures."*[555]

Where a voxel is a kind of in-between of the digital and physical realms Thomas Campbell et al. Define it as *a volumetric pixel, often used to define the fundamental unit of digital space and Programmable Matter. Voxels can be both digital and physical.*[556]. Where it can be thought of as a unit, like workspace units in CAD software, they define the most basic unit in digital material construction. *Digital voxels are computational representations in 3D models. Physical voxels may be comprised of materials as diverse as basic raw materials (e.g., titanium), nanomaterials, integrated circuits, biological materials, and micro-robotics, among others.*[557] Yet, even though this research focuses on only shape-memory and shape shifting material simulation, PM does not confine itself to the realm of the shapeshifting. It *encompasses, yet goes beyond, a range of technological capabilities—including 3D printing, micro-robotics, smart materials, nanotechnology, and micro-electromechanical systems (MEMS), to name a few.*[558]

"PM would allow changes in material properties (e.g., flexibility, porosity, conductivity, optical properties, magnetic properties), and it would create objects that could be assembled, disassembled, and then reassembled to form macroscale objects of desired shape and multifunctionality."[559]

*7.3-Self assembly_*

All this is characteristic of PM's first category, the second one is defined as Self-assembly (SA) which, in words of the Self-Assembly Lab, can be also defined as *a process by which disordered parts build an ordered structure through local interaction.* [560] And is a property that is suggested to be scale-independent and which key ingredients are *a simple set of responsive building blocks, energy and*

555 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 2
556 Iem.
557 Idem.
558 Idem.
559 Ibid. P. 4
560 Tibbits, Skylar, *Self-Assembly Laboratory website,* (**http://www.selfassemblylab.com/**) (29/04/2014)

interactions that can be designed within nearly every material and machining process available.[561]. This statement echoes Zuk's concept of *reversibility* in which: *"Materials ... must be so joined that they can easily be dis-joined. This latter feature is known as reversibility. ... Foundations too would have this capability of reversibility".*[562] This means that, according to Zuk and Tibbits et al., in theory this process is able to go on up and down all scales. At the SAL they are very confident that it is a technology that will shape the future of the AEC industry altogether and reshape construction, fabrication and operation as we know it. "*Self-assembly promises to enable breakthroughs across every applications of biology, material science, software, robotics, manufacturing, transportation, infrastructure, construction, the arts, and even space exploration"*[563] is stated on their (SAL's) website in an almost irrefutable manner. They have also broken down the process in 4 "axes" or characteristics which are, basically these:

"Self-Assembly:
+Decoded assembly sequence
+Programmability of parts
+Energy of actuation
+Error correction"[564]

Although SA is an inherent part of the new methods that PM brings to the table of design disciplines, architecture and engineering at large, this research will not go, in its experiments and case studies chapters and its subsequent conclusions, further into it and will let other researches (possibly by the author of this work) to fathom into it in a technical fashion.

*7.4-Material design_*

In conventional material science, materials are calculated and utilized according to differential properties and volume and/or state changes, where "*important material properties include ductility,*

561 Tibbits, Skylar, *Self-Assembly Laboratory website.*
562 Zuk, William, "Kinetic Planning – A New Approach for Minimized Entropic Perturbations in Constructed Environments", *Modulus*, no. 8 (1972): 7.
As quoted by: Fenwick, Tess, *Op. Cit.* (2011) P. 23
563 Tibbits, Skylar, *Op. Cit.* (29/04/2014)
564 Tibbits, Skylar, *Can_we_make_things_that_make_themselves? TED talk* (https://www.ted.com/talks/skylar_tibbits_can_we_make_things_that_make_themselves?language=sr#t-94834) (29-01-2014)

malleability, density, strength, elasticity, durability and weather resistance. ”*[565] Which groups materials in a cataloged and operational manner, in other words, its classifies materials according to what there are conventionally used for, to what they are “good” for. In this manner, “*industrial and natural are two broad groupings for these materials. There are four major families of industrial materials: metals, polymers, ceramics and composites.”* [566] Material design (MD) is, as this research defines it, within material science, the process of configuration, reconfiguration or modification, through programming or other methods like physical form finding, of any material to meet a certain set of criteria ranging from macroscopic manifestation to behavior properties, thus enhancing its capabilities to meet a specific set of design needs, all together from the molecular scale, chemically designing purpose oriented matter and thus developing *Unobtanium* Materials or material matrices that own up to such objectives. Fox Seems to agree with nanotechnology as a bridge to get these tasks under control and develop a fringe science. On whether or not nanotechnology is suitable to address kinetic architecture's aspirations, he states the following:

“Smart materials are inherently tied to a function of scale. Nanotechnology is a new area of research based on the control of matter on a scale smaller than one micrometer, as well as the fabrication of devices on this same scale.”[567]

And while Emilio Castro Otero, a researcher at the Department of Condensed Matter Physics at the University of *Santiago de Compostela* and who's work focuses on the study of the properties of Linear and Multiblock Co-polymers (LCP & MBCP, respectively) agrees that “*the development of new materials is leaving obsolete traditional classifications (eg followed by the National Materials Program) materials in ceramics, metals, polymers, composites, biomaterials, semiconductors, superconductors, magnetic materials and catalysts. The future is in the mixing.”* **[568]** Numerous authors

* Ductility refers to the ease of a material to be drawn into a wire of flattened into a sheet. Malleable materials are easily workable. Density is measured in weight per volume, and consequently provides a relative measure of weight. Strength is typically assessed by a measure of how much a material can deform elastically, or in other words, deform without permanently deforming.

From: Chai, Shutsu, *The Design and Construction of Interactive Architectural Environments: The Digital Mile, Zaragoza, Spain*, Bachelor of Science Undergraduate Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, requierements for the degree of Bachelor of Science (2006) P.14.

565 Idem.

566 Idem.

567 Fox, Michael and Kemp, Miles, *Interactive Architecture*, 227.
As quoted by:.Fenwick, Tess, *Op. Cit.* (2011) P. 29

568 Castro Otero, Emilio, *"Los nuevos materiales del futuro serán nano, inteligentes y biomiméticos"*- , Interview for *Pagina Digital* online magazine's editorial piece (2005). (09/04/2014) Translated by Nelson Montás

(Hensel, Menges, Tibbits, Raviv, Costoya, Otero, Fox et al.) seem to agree on the fact that this "procedural"[569] way, as some have called it, of designing architectural components straight from the properties of materials and addressing design from their inner structures *provides a new field of work whose unpredictable results mark a new stage of man's relationship with nature*[570]. Shifting the result driven methodologies of the past (e.g. modernism) to a process based articulation of actuating and programmed properties, giving place to uncertain, yet very precise, phenomenons. *The implications of this way of conceiving architecture radically alter not only the end result of the design process , but the very process itself.*[571] Of course affecting its multiple possible (and probable) results.

"This way, new materials with which we will live in our daily lives during the twenty-first century will be developed from ordinary materials (ceramics, metals, polymers, composites and biomaterials) and they will have three main adjectives: they will be nanomaterials, smart materials and biomimetic materials."[572]

Meaning that this revolution on material programming will be possible, in terms of accessibility, for just about anyone. This is all provided by the ability to design custom materials at the architects disposition, but it comes with a cost, the research needed required for all these traits to emerge is enormous and in its beginnings, firstly, conventionally architects lack the material development knowledge, which encompass physics, chemistry, mathematics, mechanics, biology just to understand the phenomenons that produce the behaviors emerging from theses material matrices, which are basic procedures within other disciplines that can an do help in the design and configuration of programmable materials:

"The ability to design custom materials for architectural project requires double duty. For one, a job macro scale study and definition of the behaviors and due to the materials used features ; in this sense, as pointed out above, nature is presented as an endless catalog of processes and systems to be incorporated architecture. On the other hand, micro and nano[-]*work that allows the modification of the internal configuration of the material for the macro -scale features defined scale."*

(http://www.paginadigital.com.ar/articulos/2004/2004quint/tecnologia3/nanotecnologia-27105.asp)

569 Costoya Carro, Manuel, *Una nueva materialidad contemporánea*, Detail digital magazine, section: Arquitectura | Temas, (09/04/2014) Translated by Nelson Montás (http://es.detail-online.com/arquitectura/temas/una-nueva-materialidad-contemporanea-008646.html)

570 Idem.

571 Idem.

572 Castro Otero, Emilio, *Op. Cit.*. (2005)

And, of course, whenever there is change, it means that we the actors need to change our methods and, ultimately, our theory:

"This way of dealing with the architectural project requires the integration of knowledge of many specialized disciplines in the study of the environment, so you can imagine multidisciplinary project teams comprised of architects , ecologists, biologists and genetic engineers, radically changing the working methods own traditional architecture."[573]

But what exactly does "multidisciplinarity" mean in this context? In the context of PM and MD, multidisciplinarity is a central feature in its discourse and a *rosetta stone* to its conceptual scaffolding, yet there are some ideas that are even more critical to its individual comprehensive cognition and epistemological development and which are being left out to some degree: *Transdisciplinarity and interdisciplinarity.*

As mentioned in the introduction of this thesis, Bernard C. K. Choi and Anita W. P. Pak agree that:

"Multidisciplinarity draws on knowledge from different disciplines but stays within the boundaries of those fields. Interdisciplinarity analyzes, synthesizes and harmonizes links between disciplines into a coordinated and coherent whole. Transdisciplinarity integrates the natural, social and health sciences in a humanities context, and in doing so transcends each of their traditional boundaries."[574]

Although there is a bit of each term in what is observed in the development of PM and SA, this research hypothesizes that *interdisciplinarity* (as remarked in this research's introduction) is a more accurate term to describe what goes on within the development of PM and AS in its *research stage*. After the knowledge is acquired and standardized, when it becomes a conventional agreement, then the term multidisciplinarity serves as a more precise descriptive tool. Within PM, AS and SMM, the main common science domains are: structural engineering, material science, adaptable architecture and computer science, these are the four sciences that inform the computer simulation-based modeling and material testing that precede the design, fabrication and/or construction stages in the making of PM.

573 Costoya Carro, Manuel, *Op. Cit.* (09/04/2014)
574 Choi, B. C. K. - Pak , A. W. P., *Op. Cit.* (2006) P. 351–364

Accentuating its cross-disciplinary nature and making it a very difficult and, as such, a very unpopular research field to dive into.

"And while these new mechanisms of material research are largely contingent on technological prowess, they are also profoundly invested in the procedure of technological knowledge transfer – a cross-disciplinary exchange of often unrelated fields."[575]

Yet the discipline of architecture's diving into this novel way of working is so recent therefore not yet fully understood and that, as a consequence, we are still not able to figure out a clear and concise methodology that would be able to synthesize all the aforementioned fields of knowledge into a full-blown and comprehensive body of knowledge. So we focus on technical aspects to be able to develop the expertise needed to achieve artistry within this partially mastered paradigm. *Immersed in a surge of hyper-materialism, we find ourselves vacillating between our commitments to ultra-performance and environmental responsibility*[576], making it an obstacle in the making of an architectural language or code to start writing the narrative needed to achieve this expertise and be ethically consistent, maintaining then artistic integrity. A consistent obstacle in the synthesis and further development of the PM paradigm and the fulfillment of KA's aspirations is the fact that the discipline itself es not very prone to changes, it takes long for architecture to adapt to new technological advances, the last great technological advancement in architectural design was the introduction of structural steel framing to build higher buildings and longer cantilevers. But this influence, that came mostly from civil engineering, placed disciplinary boundaries in certain ways that are currently and in rapport to PM, SA and SMM development, not suitable. "*new delineations and new ways of interrelating data in order to further dissolve the limitations created by conventional disciplinary boundaries."*[577] In the 2011 book *Material Design Informing Architecture by Materiality,* Liat Margolis dove into this question, addressing it as an endemic characteristic of the AEC industry and putting that establishment into questioning:

"*How do we organize a unified physical archive of contemporary material specimens that may originate in fashion, civil engineering, automotive and biomedical design? How do we inter-relate*

575 Margolis, Liat, "Encoding Digital & Analogue Taxonavigation", *Material Design Informing Architecture by Materiality*, various authors, Birkhäuser GmbH, Basel (2011) P. 148
576 Idem.
577 Idem.

taxonomy distinct to metallurgy, polymer science, and botany, such that it can generate cross-pollination among disciplines? And what is the relevance of material classification to the process of design as well as pedagogy?"[578]

This research will address these two answers in the thesis conclusions, while directly work hands on with the first one (design process) while starting to develop an understanding of the second one in chapter VIII with the definition of SMM and their application in architecture as well as other design fields. In most cases, architectural standardization at best blocks and at worst altogether stops the train of thought and disjoints knowledge, information and experience that, as some kind of "mix", is exactly what produces both the precisely desired, previewed and the contingent outcomes in these developmental processes within design disciplines. Many cases can be presented as case to affirm this, *such as the Construction Specification Institute (CSI), whose underlying code is dominated by predetermined architectural applications*[579]. This both separates domains and places functional "tags" if you will on "architectural" components, limiting its vocabulary to predetermined formulas that, repeated over and over again, run the risk of becoming dogmas and thus hinder the coming of age and maturation in its methods and consequently its kind, quantity and typology production; ending flexibility. *The CSI Master Format has prevailed as the standard* (European Committee for Standardization -CEN- is the European equivalent as *"CEN supports standardization activities in relation to a wide range of fields and sectors including: air and space, chemicals, **construction**, consumer products, defenc[s]e and security, energy, the environment, food and feed, health and safety, healthcare, ICT, machinery, materials, pressure equipment, services, smart living, transport and packaging"*[580]**).** ***"****It* [the CSI MF] *organizes materials hierarchically, according to firstly, generic materials groupings such as paint, laminate, and concrete, and secondly, according to components or system.* [581]*Properties are solely considered in the context of codes and requirements for preconceived applications."*[582] These are all based on appointed applications, not necessarily on material on characteristics.

"According to Michelle Addington and Daniel Schodek these categories are not material- or performance-specific – such that the category of windows, for instance, includes multiple materials

578 Margolis, Liat, *Op. Cit.* (2011) P. 148
579 Idem.
580 CEN website, *Home>Who we are,* (https://www.cen.eu/about/Pages/default.aspx) (25/03/2015)
581 Margolis, Liat, *Op. Cit.* (2011) P. 154
582 Idem.

(e.g. wood, vinyl, aluminum, or steel)– thus giving primacy to applications and common uses.”[583]

Therefore architects learn tradition based knowledge that starts where technical domains stop and stops right where scientific ones start, leaving the its actors in a disadvantage when it comes to re-contextualizing utilization and reinterpreting applications scenarios, where *doors are organized according to their suitability for security, fire protection, egress, or by the distinction between commercial or residential use*[584] *...they are practical templates for communication between architects, contractors, fabricators, and suppliers.*[585] An affirmation that suggests that this approach literally kills creativity in a discipline that praises itself to be one of the most creative in history. *Addington and Schodek assert that conventional architectural codes are not intended to engender innovation.*[586] And at the same time hindering flexibility by over specifying applications. *Materials are relegated strictly to specifications at the end of the design process rather than utilizing material investigations as an iterative and generative process to design development* [587] *...[The] consequences of a specification-driven system generally are the exclusion of new and unusual material technologies due to an emphasis on liability and known entities*[588] *...“For many uses, codes and standards explicitly or implicitly identify acceptable materials, leaving the architect only to select between brands.”*[589] What all this means for architectural research and development in a PM context is that basically we are currently yet on a linear material choice system, one that focuses on what is “certified as valid” and that does not leave space for mutability or deviation and thus only serve within well known and familiar situations and contexts.

“If design innovation is reliant in part on hyperchoice and technology transfer, then material classification necessitates a flexible indexing structure that would link their intrinsic properties to a diversity of applications and hence transcend the “classificatory pigeonholes” of architectural

583 Margolis, Liat, *Op. Cit.* (2011) P. 154
584 Addington, Michelle, and Daniel Schodek. *Smart Materials and New Technologies for the Architecture and Design Professions*. Oxford: Architectural Press (2005) P. 25-26
As quoted by: Margolis, Liat, *Op. Cit.* (2011) P. 154
585 Ibid. P. 155
586 Margolis, Liat, *Op. Cit.* (2011) P. 155
587 Idem.
588 Idem.
589 Addington, Michelle, and Daniel Schodek. *Smart Materials and New Technologies for the Architecture and Design Professions*. Oxford: Architectural Press (2005) P. 25
As quoted by: Margolis, Liat, *Op. Cit.* (2011) P. 154

conventions."[590]

Daniel Kula and Élodie Ternaux, who belong to matériO, a community of material geeks based in Paris, France that define themselves as *above all a technology watch service, selecting specific, atypical and innovative materials.* [That] *It is dedicated to architects, designers and any creative professionals*[*]**.** In their 2008 publication *Reflections on Hyperchoice* in the book *Materiology: The Creative Industry's Guide to Materials and Technologies*, they clear out some concerns with the definition of material itself:

"*One of the main difficulties in understanding the concept of matter is that it requires many tools which do not all employ the same level of language and approach… Matter can be experienced through sensory perception, technical description, scientific theory, or a philosophical approach – so many possibilities which inextricably overlap elements of different definition."*[591]
Therefore, "materiality" is not only synonymous with structural and aesthetic categories, but is also aligned with evolving theoretical positions on the perceived or potential role of materials in contemporary culture.[592] Culturally speaking, contemporary materials develop certain feelings such as cultural attachments, themes and policies that go on to integrate the discourses within society which are *implicit in the advent of technological agility... such as softness, transparency, ultra-lightweight, optical elusiveness, and biodegradability, to name a few.*[593] All this suggesting that the very definition of matter, contained within that of material, needs and should be subject to constant revision. And *although scientists and engineers insist on the objectivity of material facts, it is evident that the reverse holds true; the mutability of material meaning and relevance lies in recontextualization*[594] and in this context of *sensorial, ideological (e.g. sustainability), structural, performative (e.g. bioremediation, self-repair), economically viable, new or outmoded, material meaning is* [thus] *mutable*[595]**,** that actually means, in drastic circumstances, redefinition. To escape from preconceived, age old cataloging leads to an openness that in turn allows for creative novelty. *Once we enable a deviation from architectural*

[590] Margolis, Liat, *Op. Cit.* (2011) P. 148.
[*] MateriO website, *Who We Are*. (http://www.materio.com/en/innovative-materials)(07/10/2015)
[591] Kula, Daniel - Ternaux , Élodie, (matériO), *Reflections,* P. 326.
As quoted by: Margolis, Liat, *Op. Cit.* (2011) P. 148-152.
[592] Margolis, Liat, *Op. Cit.* (2011) P. 152.
[593] Ibid. P. 154.
[594] Daston, Lorraine, *Speechless*, P. 17.
As quoted by: Margolis, Liat, *Op. Cit.* (2011) P. 154.
[595] Ibid. P. 152.

classifications, new considerations arise, new testing parameters and qualitative performances are identified, and design language expands. Recontextualization is the material collector's recipe to incite innovation.[596] In agreement with Margolis, Ternaux, Kula et al., this research proposes a joining of fields that inform architecture and design disciplines, which do not focus mainly in these areas of science, but attached to theses fields that foster potential material knowledge to further produce contingency and architectural innovation. According to Margolis, **[597]***...such a speculative platform presents the potential for further affiliations with engineering and material science faculties in order to perform proper testing and patent new products.* The focus seems to be aimed, for the moment, at material properties, it is the search for meaning in performance to work our way up from there to the socio-cultural sphere of meaning. *The clinical (detailed yet detached) dissection of material properties allows for a focus on the specific singularities (properties) and idiosyncratic nature of materials, while at the same time allowing for a* [598] *"de specialization" of matter in terms of its prescribed applications; the result of which produces unpredictable solutions.*[599] *The taxonomical indexing, to which they refer as a recipe for programmatic computer code, delineates a procedural thinking for the properties of their geometries.*[600]

Taxonomical indexing, or *taxonavigation,* a concept that Margolis has been working on at the Hardvard GSD as faculty and researcher, which had started with *Material ConneXion Inc. (MC), which in 1996 established an unprecedented material library and consulting service*[*] [601] as some kind of *hybrid structure of "library" and "lab,"*[602]*,* is proposed (and in agreement with the aforementioned authors) as an alternative narrative and reference to existing building codes (e.g., CSI and CEN codes).

596 Margolis, Liat, *Op. Cit.* (2011) P. 154.
597 Ibid. P. 160
598 Ibid. P. 161
599 Kula, Daniel - Ternaux , Élodie, (matériO), *Reflections,* P. 313.
As quoted by: Margolis, Liat, *Op. Cit.* (2011) P. 161.
600 Margolis, Liat, *Op. Cit.* (2011) P. 161-163
*The context to MC was Ezio Manzini's 1986 book *The Material of Invention*, as well as two seminal exhibitions – "Mondo Materialis," organized by MC's founder George Beylerian for the Steelcase Design Partnership in 1990,12 and "Mutant Materials," curated by MoMA's Paula Antonelli in 1994. MC was the first attempt to break away from the standard CSI system and develop a new database model for material classification based in properties and processes. For more information on the historical aspects and further details about Taxonavigation, which will not be addressed on this research, please refer to: Margolis, Liat, "Encoding Digital & Analogue Taxonavigation", *Material Design Informing Architecture by Materiality*, various authors, Birkhäuser GmbH (2011)
601 Margolis, Liat, *Op. Cit.* (2011) P. 155
602 Ibid. P. 160

Taxonavigation suggests a model whereby the agency of materialism relies upon the premise of speculation rather than specification[603]*,* accentuating matter's own “will” on the contingency and agency within design application. Sanford Kwinter, in the introduction to Jesse Reiser and Nanako Umemoto’s 2006 book *Atlas of Novel Tectonics*, defines the difference between looking at the same “construction element” from a more conventional optic and from on emanating from the material's internal properties and capacities, not its application:

“When a tree is configured to function as a wood column or beam, it is one set of properties of cellulose that is selected for expression; or more properly, it is the geometry of vascular bundling that selects the properties of cellulose and conveys their felicitous rigidities and flexibilities to the macroscopic scale of the building itself. On the other hand, when a tree is configured into a log for burning, it is the fire itself – that exists already inside of the wood, only dormant or infinitely slowed – that is selected for expression or release. These two forms of expression, chemical and tectonic, are of exactly the same order of physical reality. It is a testimony to the diagram’s action that such diverse properties can be called up and released. And it is no small revolution in design to have apprehended this simple but critical fraternity.”[604]

And Benjamin Aranda and Chris Lasch, in their 2006 book *Tooling,* assert that geometry can even be a trait of the material rather than an imposed characteristic or application, since a spiral can be perceived as a kind of force (as demonstrated in chapter II, matter and energy can be defined as one and the same thing, viewed from different sides). *Spiraling produces a shape unlike any other because it is seldom experienced as geometry, but rather as energy.*[605]

“ The distinction of the form/shape of a spiral from its emergence – “the evidence of a shape in formation” – allows for yet another definition of materiality, a becoming of form onto itself through processes of fabrication”.[606]

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603 Margolis, Liat, *Op. Cit.* (2011) P. 163

604 Kwinter, Sanford. “The Judo of Cold Combustion” in *Atlas of novel tectonics,* edited by Reiser, Jesse and Umemoto*,* Nanako-New York: Princeton Architectural Press (2006). P. 13.
As quoted by: Margolis, Liat, *Op. Cit.* (2011) P. 160

605 Margolis, Liat, *Op. Cit.* (2011) P. 163

606 Aranda, Benjamin, and Chris Lasch. *Tooling,* Foreword by Balmond, Cecil; afterword by Kwinter, Sanford. New York: Princeton Architectural Press (2006) P. 10-12
As quoted by: Margolis, Liat, *Op. Cit.* (2011) P. 161

The impulse to dwell into the mysterious yet fascinating *"Pandora's Box"* realm of materiality has the potential to tap into emergent and open-ended design processes and methods that can redefine, for the better, the core of architectural, computational and parametric design convergence within and between practice and research, and which this research aims to exploit to generate a more fluent design-fabrication-simulation decision making process in the modeling of kinetic architecture (as speculated and hypothesized in chapter II and developed in chapter IX) making it more fluid, feasible and intuitive, placing responsive nano-tectonics and autonomous buildings within current architectural practice's reach and it can literally change KA from the ground up.

"Equally paramount is the ambition to generate distinct and prolific scholarship concerning materialism, such that it can interchange between its technical and theoretical constructs and consequently provoke invention. It is therefore essential to frame materialism as inherent to the design process, and as such employ open-ended tools that can elaborate upon this particular relationship and likewise, elicit latent ones."[607]

To have an account of what the practice of "material design" already is, Margolis shares an academic/practice anecdote from two graduate students turned *Panelite* company founders Emmanuelle Bourlier and Christian Mittman; who patented a kind of material matrix that was their own creation from two more "conventional" materials:

"While graduate students at Columbia University, ... [they] *sought a translucent, structural yet ultra-lightweight panel material they could use as a pivoting wall for a residential pool house. At MC, they found honeycomb panels, which are typically used for the construction of the airplane wing. This composite honeycomb core interlayer, sandwiched between two metal sheets, answered their need for a high-strength-to-weight ratio, but did not comply with their vision of translucency. During the same search in the library, they also came across a translucent fiberglass panel and decided to "material design" their own panel by taking only the honeycomb core and developing a now patented adhesive technology to laminate translucent sheets. Shortly after, Panelite was formed not only as the manufacturer of honeycomb panels, but also as a material designer who works with architectural firms to research and develop new materials."*[608]

[607] Margolis, Liat, *Op. Cit.* (2011) P. 163
[608] Ibid. P. 158-159

This story not just lets us know how "not so difficult" it would be to design your own materials, but also how important it is to do so for architecture and the AEC industry at large, investigations and sought out "happy accidents" such as these can change, not just people's lives, but the research, practice and business context altogether and in one single blow. But what happened if material design was used to form a design method? Not just an approach, but an actual new paradigm for design, fabrication and building? How do you achieve such a contribution?

*7.5-4D Printing_*

"4D printing, where the fourth dimension entails a change in form or function after 3D printing, is one recent example of PM that allows objects to be 3D printed and then self-transform in shape and material property when exposed to a predetermined stimulus, such as being submerged in water or exposed to heat, pressure, current, ultraviolet light, or other energy source."[609]

Very few institutional, permanently held, research projects are developing the technology and knowledge to build up the PM application context, most projects limit themselves to either doing one or another domain, but scientists at the Self-assembly Laboratory at MIT are converging several technologies and domains to achieve what they call *4D Printing* (4DP), which combines additive manufacturing (AM), PM, MD and computational design to achieve evolving structures, materializing kinetic design and looking into the design-fabrication-simulation process with the objective to reshape it into a more accurate and open-ended process in itself, potentially putting autonomous buildings within architecture's grasp as outlined and speculated in chapter II.

"This challenge, of streamlining the process of production for programmable and adaptive materials, has led to the collaboration with Stratasys Ltd, an industry leader in multi-material printing, and the development of 4D Printing, aimed at offering streamlined multifunctional printed material systems."[610]

In a 2014 article for Architectural Design magazine, its director Skylar Tibbits, describes the laboratory's theoretical background, its activities and some of the projects which appear in this thesis as

609 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 2
610 Tibbits, Skylar, *Op. Cit.* (2014) P. 119

analytic and theoretical examples as base literature for the development of the experiments research phase (chapter IX). Given that the SAL *has as its focus the development of self-assembly, programmable materials and adaptive technologies for industrial applications in the built environment.*[611] Therefore it is axiomatically deducible that it works within the same material paradigm as this research hence it is accurate to state that it also shares the same concerns regarding PM, SA and their "synthesis into a coherent whole".

"*These phenomena are viewed by the Lab as one of the most important processes in both natural and synthetic systems, and a principle that crosses nearly every discipline, offering a new opportunity for making smarter materials and better techniques for construction."*[612]

And even though he does not mention kinetic -nor KA for that matter- in the article, by the definition in chapter IV, it can be deduced that they do develop kinetic systems and, in our favor, he does mention "responsive" when referring to materials and, in that context, he thus refer to responsive architecture, which is classified under the "Electrically sourced" category in chapter IV's classification table and as we can deduce from this brief but concise definition about what the fourth dimension in 4DP.

"The fourth dimension is described here as the transformation over time, emphasising that printed structures are no longer simply static, dead objects; rather, they are programmably active and can transform independently."[613]

Their project show what seems to be a common scientific optic and design sensibility to that of KA and has a central common problematic: bringing these systems up to the architectural scale. *A number of self-assembling, self-reconfiguring and programmable material prototypes have therefore been developed, emphasising the scalability of such principles across materials, fabrication technologies and external energy sources.* [614] This research focuses specifically in the SMM domain within PM. While at SAL, *however, many of these prototypes have required an additional production step of embedding 'programmability' and the potential energy for transformation; for example, magnets,*

611 Tibbits, Skylar, *Op. Cit.* (2014) P. 119
612 Idem.
613 Idem.
614 Idem.

elastic strands, Nitinol wires, rachetting mechanisms and many others.[615]

*7.5.1-4D printing Background_*

In 1984, Charles Hull *invented stereolithography* [commonly known as 3D printing] *as a new process for viewing and testing designs before investing in full production.*[616] And as a consequence founding *3D Systems* in 1986 to comercialize his patented technology. *Additive manufacturing and rapid prototyping have developed at exceptional rates and gained wide acceptance since their invention in 1984*[617] The ability to mass-produce customised components without substantial increases in time, material or inefficiency has been coined as one of the revolutionary advantages of additive manufacturing.[618] However, Skylar Tibbits and Michael Hayes seem to agree that there is a lot of road yet to navigate in terms of 3D printing and/or AM. Ass, according to both of them, *our current capabilities are far behind our expectations and visions for additive manufacturing technologies. Further, masscustomisation ignores the time and energy needed after custom parts have been printed, requiring excessive sorting and labour-intensive assembly.*[619] Tibbits recalls an event where Hayes pointed this out and other concerns and opportunities that lie ahead for developing, Tibbits states:

"At the 2013 US Manufacturing Competitiveness Initiative Dialogue on Additive Manufacturing, Boeing's Michael Hayes highlighted this issue by outlining the main hurdles that lie ahead for additive manufacturing, including: a larger build-envelope and increased scale for printing applications; structural materials that can be used in functional and high performance settings; and multi-functional and smart/responsive materials."[620]

These concerns echoe some shared concerns in the contexts of both PM and KA (as scalanlity and embedded autonomy and intelligence), which makes them all to pertinent to analyze in the context of this research, encompassing PM and AM as means to create a yet to be developed different kind or KA or intelligent kinetic systems, the kind of which have built in intelligence within their material configuration and that can actuate as programmed matter within contingency domains, both as self organizing systems (SO) and/or SA systems, all this including scaling up, a major problem in the KA

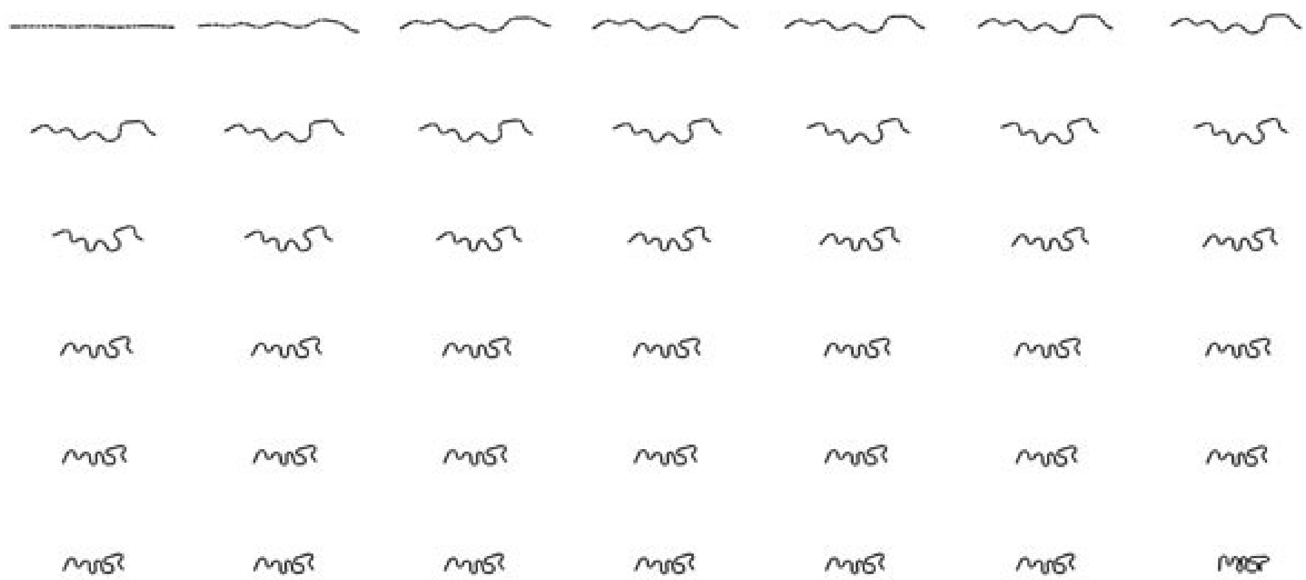
615 Tibbits, Skylar, *Op. Cit.* (2014) P. 119
616 Ibid. P. 118
617 Idem.
618 Idem.
619 Idem.
620 Idem.

paradigm. [621]*Each of these hurdles will need to be addressed and likely combined in order to truly demonstrate the scalability of additive manufacturing to rival existing manufacturing efficiencies.*

*7.5.2-The technique_*

While this new technology certainly qualifies the often-quoted quip that "any sufficiently advanced technology is indistinguishable from magic,"[622] this cross-disciplinary research profile is actually developed in the most practical way available. *It entails multi-material prints with the capability to transform over time, or a customised material system that can change from one shape to another, directly off the print bed.*[623]*I* Setting an almost direct pathway between idea and product, [624]*This technique offers a streamlined path from idea to reality with performance-driven functionality built directly into the material*s. The possible applications of this technique are numerous and will require years to develop into different contexts and domains and, maybe, it will spawn a new domain altogether. Its toolbox of combination and matrix oriented servo-mechanism material designing allows the higher level design to be able to shape-shift or "morph" from virtually any shape into another totally different one, including significant dimensional changes:

[621] Tibbits, Skylar, *Op. Cit.* (2014) P. 119
[622] Arthur C. Clarke, *Profiles of the Future*, (New York: Harper & Row, 1962)
As quoted by: Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 4
[623] Tibbits, Skylar, *Op. Cit.* (2014) P. 119
[624] Idem.



4D Printing: Self-Folding Strand into "MIT" Sequence (2), Skylar Tibbits in collaboration with Shelly Linor, Daniel Dikovsky and Shai Hirsch at Stratasys and Carlos Olguin of Autodesk. (2013) SJET website (http://www.sjet.us/MIT_4D%20PRINTING.html) (04/04/2015)

"With Connex printing capabilities and 4D Printed materials, a single print, with multi-material features, can transform any one-dimensional strand into a three-dimensional shape, any twodimensional surface into a three-dimensional shape, or morph from one three-dimensional shape into another."[625]

(The likes of which are to be studied in detail in the experiments phase on chapter IX.)

In chapters IV and V it was established that, within KA, the conception and analysis phases alone are extremely time consuming and difficult, with (animation software applications in *Analysis of Design Support for Kinetic Structures by* Angeliki Fotiadou and non specified parametric modeling in *Active Shapes: Introducing guidelines for designing kinetic architectural structures* by Dina El-Zanfaly) or without specialized digital software (no digital process whatsoever in *Progamme: Morphosis* by Tess Fenwick). The few number of projects exhibiting KA traits even in within *Embedded kinetic systems* examples; making it conclusive that also its cost, be it intellectual or material, far outdoes its

625 Tibbits, Skylar, *Op. Cit.* (2014) P. 119

implementation rate. In other words, it is expensive and hard to build KA at the building scale. Yet 4DP promises to get over that gap putting at architecture's grasp *adaptive and dynamic responses for structures and products... without adding time, cost or extra components to make systems 'smarter'*[626]. Integrating responsive logic and reaction causation laying the way for designing objects that evolve over time or *respond to user needs or environmental changes* [627], a major concern of all interactive architecture's subset disciplines, including adaptive, responsive and kinetic architecture.

7.5.3-The three main criteria behind 4D printing_

At the core of this technique are three main tenets or principles that give rise to the subsequent unleashing of possibilities which are: *"the machine, the material and the geometric 'programme'.*[628]

"1)Stratasys's Connex machine offers multi-material PolyJet printing with a variety of material properties from rigid to soft plastics and transparent materials, and high-resolution control over dot deposition.

2)*The dynamic material was developed with the Stratasys material research group and is a hydrophilic polymer that expands 150 per cent(%) when it encounters water. The printer deposits a rigid polymer material simultaneously with the expanding 'active' material to give both structure and potential energy.*

3)*The final component important for the viability of 4D Printing is the design and placement of the geometric programme that embeds the capability for statechange directly into the materials themselves."*[629]

To address KA within this framework, the only practial difference with KA is that this specific material is a hydrophilic polymer that can be printed specially developed for this multi-material printing technique, but this conceptual scaffold can be adapted to SMM (as they are, hydrophilic polymers and SMM, both subsets to PM) or other shape shifting material, including biological material and so on as it will be shown later in this chapter. In that sense, if we try to equate these tenets with Fox's KA

626 Tibbits, Skylar, *Op. Cit.* (2014) P. 119
627 Idem.
628 Idem.
629 Idem.

principles, we can see that according these, *intelligent kinetic systems arise from the isomorphic convergence of three key elements: structural engineering, sensor technology and adaptable Architecture*[630]. Although applicable to KA, the 4DP paradigm dissolves structural engineering and sensor technology into *"the material"* and adaptable architecture into *"the geometric 'programme'"*, adding one crucial factor: fabrication as *"the machine"*. This dilutes the mechanical paradigm's material and production dichotomy into a more fluid "plastic" coherent whole, enabling direct energy transfer and material assembly.

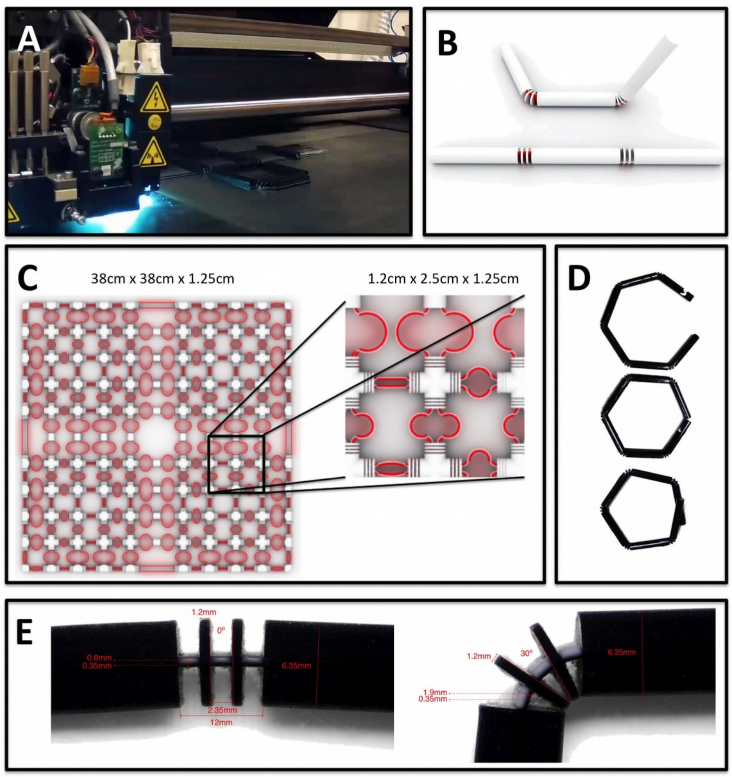


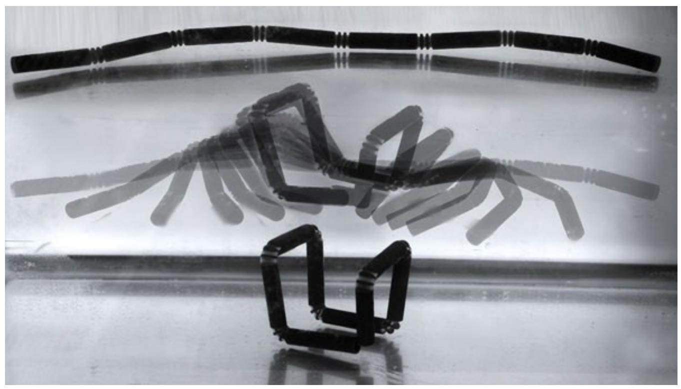
Figure 2 | (A) Stratasys Connex 500 Multi-Material 3D Printer. (B) Folding primitive in R3 requires two degrees of freedom. One angle is achieved by changing the spaces between the inner disks, which provides a physical stop once the end angle is reached. The second angle is maintained by changing the angles in between two neighboring bars. One can consider it as a rotational shift that changes the plane in which the bars fold. (C) A complete example embedding dynamic primitives of stretching and folding on a grid. This grid can accommodate a self-evolving deformation into a complex structure with both convex and concave parts. (D) Calibration of the folding joints is performed by repeated experiments on a planar hexagon. See Table 1 and Table 2 for angular and temporal measurements. (E) True fabrication measurements of bending elements, Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits (2014) (Raviv, Dan et al. , *Active*

[630] Fox, Michael - Yeh, Bryant, *Op. Cit.* (2001) *(a)* P.1

Printed Materials for Complex Self-Evolving Deformations, Scientific Reports, Nature, P. 3*)*

*7.5.4-Multidimensional shape-shifting printing processes_*

In his 2014 article , Tibbits described the nature and procedures of some of the showcased projects within the SAL research program, together with Stratasys*. A series of one-dimensional strands that transform into three-dimensional structures *that fold into the letters 'MIT' and complex selffolding Hilbert curves, each demonstrating transformation from one- imensional and twodimensional flexible shapes into rigid structures.*[631]



4D Printing: Self-Folding Strand into 3D Cube, Skylar Tibbits in collaboration with Shelly Linor, Daniel Dikovsky and Shai Hirsch at Stratasys and Carlos Olguin of Autodesk. (2013) (Tibbits, Skylar, "4D PRINTING: MULTI-MATERIAL SHAPE CHANGE*", Special Issue: High Definition: Zero Tolerance in Design and Production, Architectural Design,* P. 118*)*

4D Printing: Self-Folding Strand into "MIT" Sequence (1), Skylar Tibbits in collaboration with Shelly Linor, Daniel Dikovsky and Shai Hirsch at Stratasys and Carlos Olguin of Autodesk. (2013) SJET website (http://www.sjet.us/MIT_4D%20PRINTING.html) (04/04/2015)

* Stratasys is based in Minnesota, a partner with SAL and is the second largest 3D printing developer and producer in the world.

631 Tibbits, Skylar, *Op. Cit.* (2014) P. 120

The first experiment is a single strand (30 cm long) made of rigid and active material which, when dipped in water, transformed into the letters “MIT” *demonstrating a 1D to 2D shapechange*[632]. Thes second one was also a single strand yet this time one which shape-shifted into a *rigid wireframe 3D cube*[633]. The mechanical aspect of the experiments are not disclosed to their full extent for obvious industrial protection purposes, but the verbal explanation is quite clear and delineates very simple yet effective proof of concept methodological approach. Similar to the one we will use in chapter IX. On the 3D strand-made cube, the process goes as follows:

“At each of the joints, two rigid discs were printed that acted as angle limiters, which when folded and touching one another forced the strand to stop at 90-degree angles[634] and which is, in short, a Hilbert cube, meaning that a single line is drawn through all eight points of a cube without overlapping or intersecting[635].

The second one described in the article was a flat sheet made that turns into a 3D cube:

“In this case, a two-dimensional flat plane was printed, with both rigid and active materials. This flat plane represents the six unfolded surfaces of a cube. At each of the joints a long strip of active and rigid materials was printed that describes a 90-degree angle limiter that stops the surface from folding when it reaches the final-state condition. When submerged in water, the surface folds into a closed-surface cube with filleted edges. A wide range of other 1D, 2D and 3D transformations are also possible including self-folding origami, self-healing structures where holes close after encountering water, and other global geometric reconfigurations.”[636]

632 Tibbits, Skylar, *Op. Cit.* (2014) P. 120
633 Idem.
634 Idem.
635 Idem.
636 Idem.

4D Printing: Self-Folding Surface Cube, Skylar Tibbits in collaboration with Shelly Linor, Daniel Dikovsky and Shai Hirsch at Stratasys and Carlos Olguin of Autodesk. (2013) (Tibbits, Skylar, "4D PRINTING: MULTI-MATERIAL SHAPE CHANGE*", Special Issue: High Definition: Zero Tolerance in Design and Production, Architectural Design,* P. 120*)*

Material matrices play a significant role in the actuation and, as mentioned before, it is the combination with the rigid material and the geometric physical and spatial relation with its rigid neighbors that stops the folding and gives rise to the final shape. In Tibbits own words:

"The rigid material gives the structure and angle limiters for folding.[637] *When the part is printed it has an initial position, then after encountering water the active material swells, forcing the rigid material to bend...*
…When the rigid material hits neighbouring elements, it is forced to stop folding and thus has reached the final-state configuration...
...The placement and volume of the rigid and active materials encompasses an embedded geometric programme and the activation energy to transform."[638] *from one shape to another, completely independently.*

7.5.6-New physical simulation tool: Autodesk's Project Cyborg_

SAL, in collaboration with Autodesk, has come up with a software application specially developed to simulate PM behavior and *a priori* design evaluation called Project Cyborg(PC). *Project Cyborg is a design platform spanning applications from the nano scale to the human scale.*[639] This also meant building a modified version of PC *to simulate the dynamics of 4D printed objects and their material optimization.*[640] Among other simulation modeling and design visualization services, PC also *offers simulation for self-assembly and programmable materials as well as optimisation for design*

637 Tibbits, Skylar, *Op. Cit.* (2014) P. 120
638 Idem.
639 Ibid. P. 121
640 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 4

constraints and joint folding.[641] Its inception in the world of 4DP, is an effort to cut down the design-to-production gap and drastically improve error-correction in the embodiment of the products and architectural components or, as Tibbits puts it, *to tightly couple this new cross-disciplinary and crossscalar design tool with the real-world material transformation of 4D Printing.*[642] Yet the most important potentiality within this software advancement for this thesis and, insofar as the experiments phase in chapter IX, the case studies are concerned, is the promise of a major change in the work-flow itself. *The coupled software and hardware tools will eliminate the traditional paradigms of simulating then building, or building then adjusting the simulation.* [643] In a conventional design setup and situation, the process goes more or less like this: design, fabrication then simulation.

Design:
Propose a computational approach for designing self-evolving structures that vary over time due to environmental interaction.

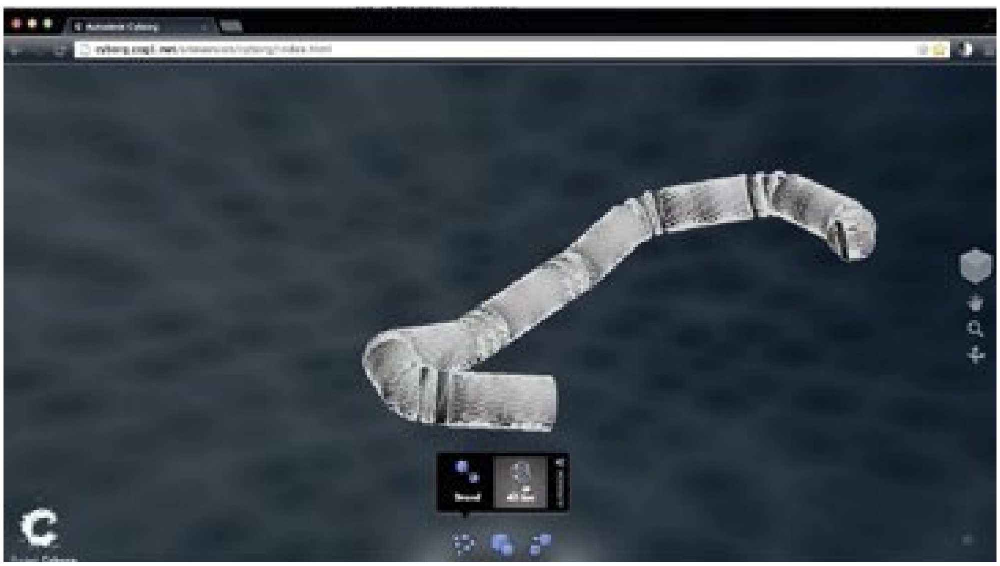
Fabrication:
Provide an implementable framework by specifying readily printable self-evolving elements that pair with computational models.

Simulation:
Realistically imitate the deformation of the materials for enhancing design capabilities.[644]

Currently, this is the only reliable and available way of working with 4DP and PM in a comprehensive and scientifically proof generating manner. The problem with this work-flow is that, it works backwards, meaning that, after the designer defines the component, he/she has to fabricate it in order to observe if his/hers original observations are accurate or even true regarding the desired outcome and how the process actually works in reality. This thesis is trying to prove that, within the literature concerning PM, 4DP and KA , we already have enough knowledge to draw upon to invert the last two

641 Tibbits, Skylar, *Op. Cit.* (2014) P. 121
642 Idem.
643 Idem.
644 Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, "Active Printed Materials for Complex Self-Evolving Deformations", Scientific Reports, *Nature* (2014) P. 1, 2. (http://www.nature.com/srep/2014/141211/srep07422/full/srep07422.html) (03/02/2015)

stages (fabrication and simulation) and start building *design, simulation, fabrication* work-flows (which will be detailed in chapter IX) that *create simulations that adjust physical performance and materials that promote new simulated possibilities, offering top-down and bottom-up evolution of design possibilities both physically and digitally.*[645] A feat that will be attempted to be proven true in chapter IX, drawn from already developed knowledge in previous literature (mainly in a 2014 article written by authors Dan Raviv, Wei Zhao, Carrie Mcknelly, Athina Papadopoulou, Achuta Kadami, Boxin Shi, Shai Hirsch Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar and Skylar Tibbits paper in the web formatted *Nature.com*) and which has not been yet published by any author in the field, being the most significant scientific contribution of this research to architecture and 4DP and PM.



Project Cyborg cube strand simulation, screenshot, Skylar Tibbits in collaboration with Shelly Linor, Daniel Dikovsky and Shai Hirsch at Stratasys and Carlos Olguin of Autodesk. (2013) (Tibbits, Skylar, "4D PRINTING: MULTI-MATERIAL SHAPE CHANGE*", Special Issue: High Definition: Zero Tolerance in Design and Production, Architectural Design,* P. 121*)*

The material's will to be_

In this paradigm is scaffolding, material becomes not only alive, but *willingly* so. The rise of autonomy in material performance and behavior can, if not re-write the industry, at best reshape the worlds around us, even the far and away. In this context, change many aspects of life, traveling and the relationship between objects and people, customizing almost every appliance and device in our environment. *Personal and responsive products will adapt to users' demands, biometric information, body*

[645] Tibbits, Skylar, *Op. Cit.* (2014) P. 121

temperature, sweat and internal pressures.[646] While at the same time addressing efficiency in an all encompassing grasp and responsiveness then changes its meaning to suggest that *products can now become far more resilient and highly tuned to environmental changes including moisture content, temperature, pressure, altitude or sound.*[647] Not just conflating the senses and our perception in one only flux, but setting the basis for an age in which *will be manufactured in completely new ways where materials are activated through ambient energies to come together on their own, reconfigure, mutate and replicate*[648], departing from monumentality (echoing concerns outlined in chapter IV about stasis and kinesis) to enter an era of real building autonomy, surpassing our current status of building automation.

"4D printing, where the fourth dimension entails a change in form or function after 3D printing, is one recent example of PM that allows objects to be 3D printed and then self-transform in shape and material property when exposed to a predetermined stimulus, such as being submerged in water or exposed to heat, pressure, current, ultraviolet light, or other energy source."[649]

*7.6-Sustainable applications of PM_*

PM's repercussions in our daily lives is not yet very evident, but its suggestions about infrastructure and logistics, especially transportation and garbage disposal are some of its immediate applicable forefronts, securing its integration into, not just the product world, but also at the heart of the productive world.

"Volume constraints in shipping will be dramatically reduced with flat-pack materials that are activated on delivery to full volume and functionality...

...shipping materials themselves will have non-Newtonian-like properties and respond in custom ways to resist forces and reconfigure space-filling containers for auto-distributed loads...

...All of these future programmable products will not just be thrown away when they fail; rather, they will error-correct and self-repair to meet new demands...

646 Tibbits, Skylar, *Op. Cit.* (2014) P. 121
647 Idem.
648 Idem.
649 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 2

...when they become obsolete, they can self-disassemble for pure recyclability, breaking themselves down to their fundamental components to be reconstituted as new products with lifelike capabilities in the future."[650]

In short, PM and 4DP will change the whole spectrum of how things work in almost every world making domain and, as ac consequence, also KA, responsive and adaptive architectural applications. *Transformative, multi-state, additive manufacturing will likely expand to become a palette of many materials with an almost limitless response to external forces.*[651] Providing for the first time in history a conceptual landscape in which sustainability and efficiency can be conjugated in the same sentence and actually make sense, where computation and material science can effectively program at will outside a CAD environment and in which CAD applications and material reality inform each other in fluent fashion.

*7.7-4D printing as a disruptive technology_*

In a 2014 report called *The Next Wave: 4D Printing and Programming the Material World* , a security oriented publication written by the Atlantic Council, in Washington, DC, co-authored by Thomas Campbell, Skylar Tibbits and Garrett Banning, was the first scientific report that, not only analyzed the pros (like any other writing found up to this one) regarding PM and 4DP, but also the potential dangers and problems surrounding them; something that, until the cited paper's publishing, this research had not yet encountered anywhere in the literature about the topic or in any related field, at the moment of writing this thesis. As the publication affirms, this kind of technological impact is not at all new, yet this time it appears to be far more in depth than ever before:

"History is replete with examples of new technologies disrupting global commerce and geopolitics (e.g., the telegraph and the Internet). 3D printing is already having such effects. PM/4DP will likely be more transformative as it enables 3D printed objects to not only be custom-tailored for their application, but also to be programmable for post-fabrication changes in shape and function—including adapting to changing environments—and then to be recycled, repaired, or reconfigured when

[650] Tibbits, Skylar, *Op. Cit.* (2014) P. 121
[651] Idem.

no longer of use."[652]

Its a technology that goes far beyond its predecessor (3D printing) with an extra immanence dimension to it as it [653]*...has the economic, environmental, geopolitical, and strategic implications of 3D printing while providing new and unprecedented capabilities in transforming digital information of the virtual world into physical objects of the material world.*

The subject matter was addressed using PM and 4DP definitions interchangeably, even though the authors recognized *that some PM can be made without 4D printing, but we have conflated the terms PM and 4DP toward the goal of readability.*[654] An ambiguity that, for the time being, serves its purpose and that in the context of this chapter we will also utilize int the same manner, one such that we will abandon in chapter IX. The quoted report's contributions to PM/4DP literature, which are mostly a sort of balance between 3DP and 4DP and the pros and cons of this step in digital fabrication and material design, will be dissected into two main "pros and cons" lists, derived from the article in question and with the aim of concisely and precisely defining the positive and potentially negative aspects, mostly security related of PM/4DP.

Pros:

"...[PM and 4DP] *allows objects to be 3D printed and then self-transform in shape and material property when exposed to a predetermined stimulus, such as being submerged in water or exposed to heat* [such as SMM]*, pressure, current, ultraviolet light, or other energy source...*[655]

...[It also provides] the *ability for material objects to change form and function after they are produced, thereby providing additional capabilities and performance-driven applications...*[656]

...from airplane wings that change form in flight to furniture and even buildings that self-assemble and reassemble for different functions."[657]

"[It enables a cleaner version of recycling] *not by saving some of the materials such as plastic to be*

652 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 9
653 Ibid. P. 1
654 Idem.
655 Ibid. P. 2
656 Idem.
657 Idem.

melted down and reused, but by commanding the object to decompose into programmable particles or components that then can be reused to form new objects and perform new functions...

...[Therefore]*The long-term potential of PM/4DP thus could be a more environmentally sustainable world in which fewer resources are necessary to provide products and services to a growing world population and rapidly expanding global middle class."*[658]

"4D printing, where the fourth dimension entails a change in form or function after 3D printing, is one recent example of PM that allows objects to be 3D printed and then self-transform in shape and material property when exposed to a predetermined stimulus, such as being submerged in water or exposed to heat, pressure, current, ultraviolet light, or other energy source."[659]

Cons:

PM's "upsides" we already have displayed out, now on its "downsides" the concerns are majorly security related, specifically in the realm of government and national security. Basically, politicians and officials do not understand the technology yet and must do so, according to Thomas et al., to prevent unforeseen problems arising unannounced. Affirming that *while PM could have significant benefits for nations as well as businesses and individuals, it could also create new uncertainties and even insecurities, especially for policymakers.* [660] And indeed, this type of world changing technology probably can and will take its toll current policies and legal framework, just *imagine a material world that can change in ways that are unpredictable by governments and potentially threatening to national security.*[661] Its applications, since they could arise virtually everywhere and at any time, are very hard to preview and thus be object to planning side by side with policy, our legal framework is not prepared for shape-changing and even nature-changing objects. *Intellectual property (IP) rights could also become more complex, as products are able to morph from one form to another, thus directly challenging patent rights for multiple product lines.*[662] This is a prone to speculation technology, similar to finance or software developing, very little people actually get it, and *policymakers need to understand the basics of this emerging technology and to get ahead of the curve on PM, as it offers both significant*

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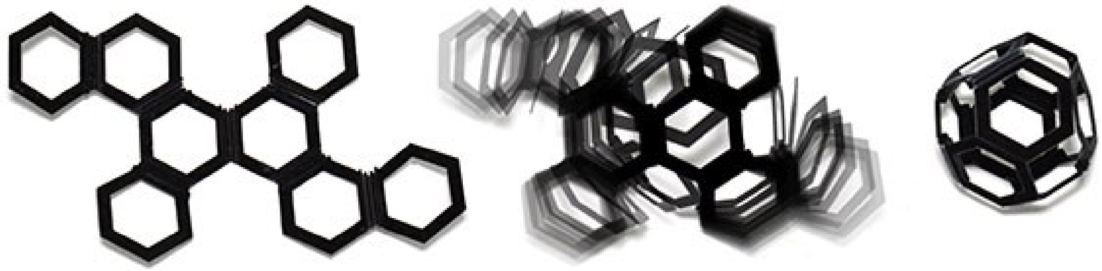
[658] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 1
[659] Ibid. P. 2
[660] Ibid. P. 1
[661] Idem.
[662] Ibid. P. 2

opportunities and unprecedented [as underlined before] *dangers* [663]. There is also a probability that terrorism and law-braking, security dangers may arise if not understood promptly. *Morphable wings could be hacked to crash airplanes while buildings could be commanded to "disassemble" with you inside. Anticipating such dangers, however, should enable protective measures to be "baked-in" to PM rather than recognized only after the fact.*[664] Therefore further time and resources (i. e., researchers, manufacturing and measurement equipment, funding, etc.[665]) will be in order to fully realize its (PM's) full potential.

*7.7.1-Insertion in the real world and AEC industry_*

Although PM is in its infancy, we could say, it is clear that its potentialities and promises make it one of the most emergent and emerging new science fields and, very soon, AEC territorries. *In the meantime, there have already been successful prototypes proving PM's viability, and it is likely that PM will begin to appear in real-world applications in the next few years.*[666] The causes for this sudden, rushed impromptu are varied and allover, insofar as applicable envisioning is concerned. Markets and previously set in motion information networks which are in the social of process "democratizing" the access to communication technologies have allowed for a current state of availability, accessibility and affordability within material, fabrication processes, and computational technical knowledge that were not probable to have, all around the globe, lets say...ten years ago. *Smart materials are similarly getting better and more affordable, while computing and electronics continue to become smaller and cheaper.*[667] And its underlined streaming of possibilities, provided by its predecessor 3DP, keeps it at center stage. *3D printing builds objects layer-by-layer, thereby enabling the fabrication of virtually any geometry, including objects that are impossible to create using any other manufacturing means.*[668] Also, anisotropic properties and efficient material behavior promise a landscape that potentially give rise to new robotics. In other words: *Introducing programmable capabilities into 3D-printed materials could enable robot-like capabilities embedded directly into the materials, without the need for energy-intensive and failure-prone electro-mechanical devices.*[669]

[663] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 2
[664] Idem.
[665] Idem.
[666] Idem.
[667] Ibid. P. 3
[668] Campbell, Thomas – Williams, Christopher B. - Ivanova , Olga S. - Garrett , Banning , *Could 3D Printing Change the World? Technologies, Potential and Implications of Additive Manufacturing*, Strategic Foresight Report No. 1, (2011) P. 2 (http://www.atlanticcouncil.org/images/files/publication_pdfs/403/101711_ACUS_3DPrinting.PDF.) (28/03/2015)
As quoted by: Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 2-3
[669] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 3



4D Printing: Self-Folding Truncated Octahedron, Skylar Tibbits in collaboration with Shelly Linor, Daniel Dikovsky and Shai Hirsch at Stratasys and Carlos Olguin of Autodesk. (2013) (Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *The Next Wave: 4D Printing and Programming the Material World,* P. 4)

4D Printing: Curved-Crease Origami, Skylar Tibbits in collaboration with Shelly Linor, Daniel Dikovsky and Shai Hirsch at Stratasys and Carlos Olguin of Autodesk. (2013) (Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *The Next Wave: 4D Printing and Programming the Material World,* P. 4)

*7.8-Other forms of 4DP and PM_*

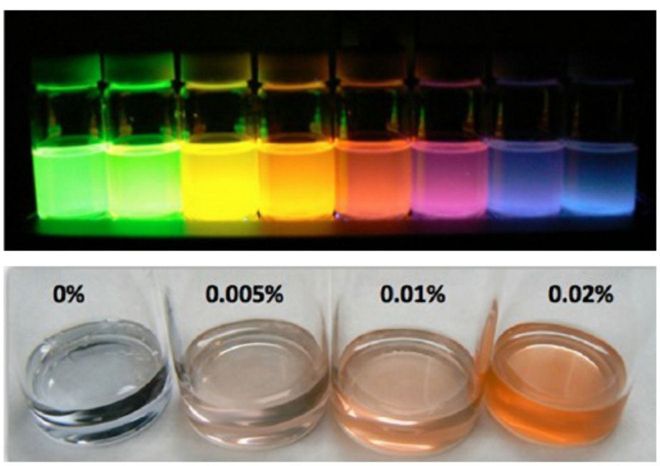
There are different forms of PM other than hydrophilic polymer printing, some of them touch metallurgy and others combine it with 4DP. *Other 4D printing approaches include composite materials that can morph into several different, complicated shapes based on a different physical mechanism and heat activation*[670] such as SMM muscle wiring*,* which can be combined with other materials to achieve programmed shape-change by:

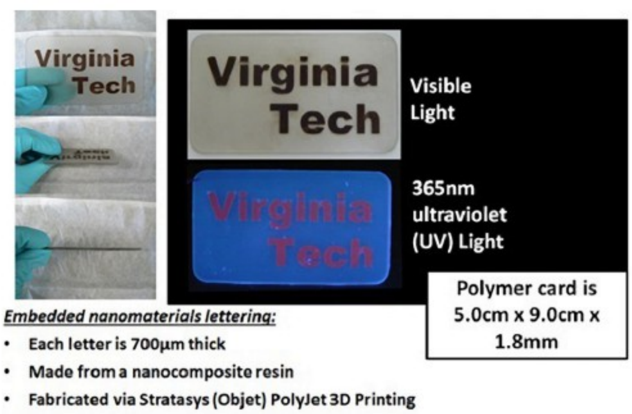
[670] Liu , Ying - Boyles, Julie K. - Genzer, Jan- Dickey, Michael D. , “Self-folding of polymer sheets using local light absorption,” *Soft Matter*, 2012, 8, 1764-1769 (http://www.rsc.org/suppdata/sm/c1/c1sm06564e/c1sm06564e.pdf) (28/03/2015)
As quoted by: Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 5

"...embedding wiring or conducting parts into special compliant components during the 3D printing job. After the object is printed, the parts can be activated by an external signal to trigger full assembly actuation."[671]

*7.8.1-Replacing sensor technology with sensing matter_*

Stimulation can come from a myriad of sources, almost anything you can think of can be turned into a on/off switch. *The insertion of nanomaterials into 3D printed objects can create multifunctional nanocomposites that can change in properties in response to electromagnetic waves—e.g., visible light and ultraviolet light*[672] , among other stimuli that, while directly changing the mechanisms behind each different application, still hold the same tenets and principles as it is still PM. The goal is still the same: to fabricate evolving objects. The *Cadmiun selenide quantum dots* research project at Virginia Tech *shows an example of what can be done with nanomaterials and a typical 3D printing resin*[*]*... ...When lit by visible light, the letters are gray, but when lit by ultraviolet light, the letters glow red.*[673]





Cadmium selenide quantum dots (CdSe QDs) *synthesized at Virginia Tech and suspended in toluene. Each vial contains a different size of QD (ranging from diameters of ~2.5 nanometers, dark green, to ~15.0 nanometers, dark blue), and thus*

[671] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) (2014) P. 4-5
[672] Campbell, Thomas – Williams, Christopher B. - Ivanova , Olga S. "3D printing of Multifunctional Nanocomposites," *Nano Today,* Volume 8 (2013) P.119-120 (http://www.sciencedirect.com/science/article/pii/S1748013212001399) (28/03/2015)
As quoted by: Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 6
[*] Cadmium selenide (CdSe) quantum dots are prepared synthetically via colloidal chemistry and embedded into a three-dimensional, business card sized, 3D printed object. Considered 'artificial atoms' as an assembly semiconducting material, quantum dots have the characteristic that their fluorescence is both light wavelength and size dependent. As shown in the top image in this page, the same CdSe material, at different size scales, fluoresces in different visible wavelengths when lit by an infrared light source. This enables significant freedom in sensing capability
[673] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 6

emits a different color when under ultraviolet light. MIDDLE–As prepared nanosuspensions of photopolymer/CdSe QDs with different QD loadings (by weight percentage as listed); QDs in each vial are the same size. BOTTOM–Embedded quantum dot nanocomposites in a 3D printed part. The same part is shown under visible and ultraviolet (UV) lighting. Thomas A. Campbell in collaboration with Dr. Christopher B. Williams of Virginia Tech. (Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, The Next Wave: 4D Printing and Programming the Material World, P. 4)

In this state of affairs, *sensors could be embedded into medical devices to test for extremes in blood pressure, insulin levels, and other important medical metrics.* [674] The applications could be virtually omnipresent, you name it, bio-medical, bio-mechanical, transportation, engineering and so on, the world is staring at an abyss through this technology. *More complex assemblies, different nanomaterials and raw materials, and different activation energies (water, heat, light, etc.) could theoretically be utilized to create a potpourri of novel applications for PM.*[675] But, according to Campbell et al., the research must be set in motion in order to profit fro these almost "magical" possibilities. [676]*Much like one can build more complex structures with a variety of LegoTM bricks—see Figure 6—only by having a wide collection of PM will a diverse set of capabilities for changing form and function be feasible... ...One vision of the future is PM/4DP with a suite of multiple voxels with different forms and functions that are custom-designed, easily deposited, and then programmed for specific applications.* [677]

*7.8.2-Genetic architectural implications_*

Future development in the realm of PM and 4DP and consequently KA will most likely be the embedding of biological mimetic methodology or perhaps even genetic engineering methods unifying computational design and material performance. In chapter II, this thesis outlined the importance and implications of genetic architecture (GA) and its relationship with KA, Campbell et al. seem to agree with the fact that providing PM (and kinetic systems at large) with the potentialities and emergent properties of the genetic paradigm can give rise to autonomous systems that can develop their own "will", as Karl Chu puts it, their own "will to be"**.** *The potential can be better understood by reference to DNA-driven biological systems*[678]*...In the same way a pixel is a building block of an image, a bit is a unit of information, and an amino acid is a building block of biological matter, a voxel is a volumetric*

[674] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 6
[675] Ibid. P. 7
[676] Idem.
[677] Idem.
[678] Idem.

pixel (hence its name).[679] To illustrate this, Campbell et al. use a metaphorical analogy taking biological life and its prolific generation of species through its own iterative combinatorial process to explain how probability can lead to possibility within material construction and combination.

"Biological life is composed of twenty-two building blocks—amino acids— that arrange themselves in different permutations to give rise to a myriad of proteins and eventually life forms….This makes it possible for biological life forms to repair themselves."[680]

Campbell et al. describe the relationships between how natural elements come together to produce intricate and complex compounds which servo higher level material properties.

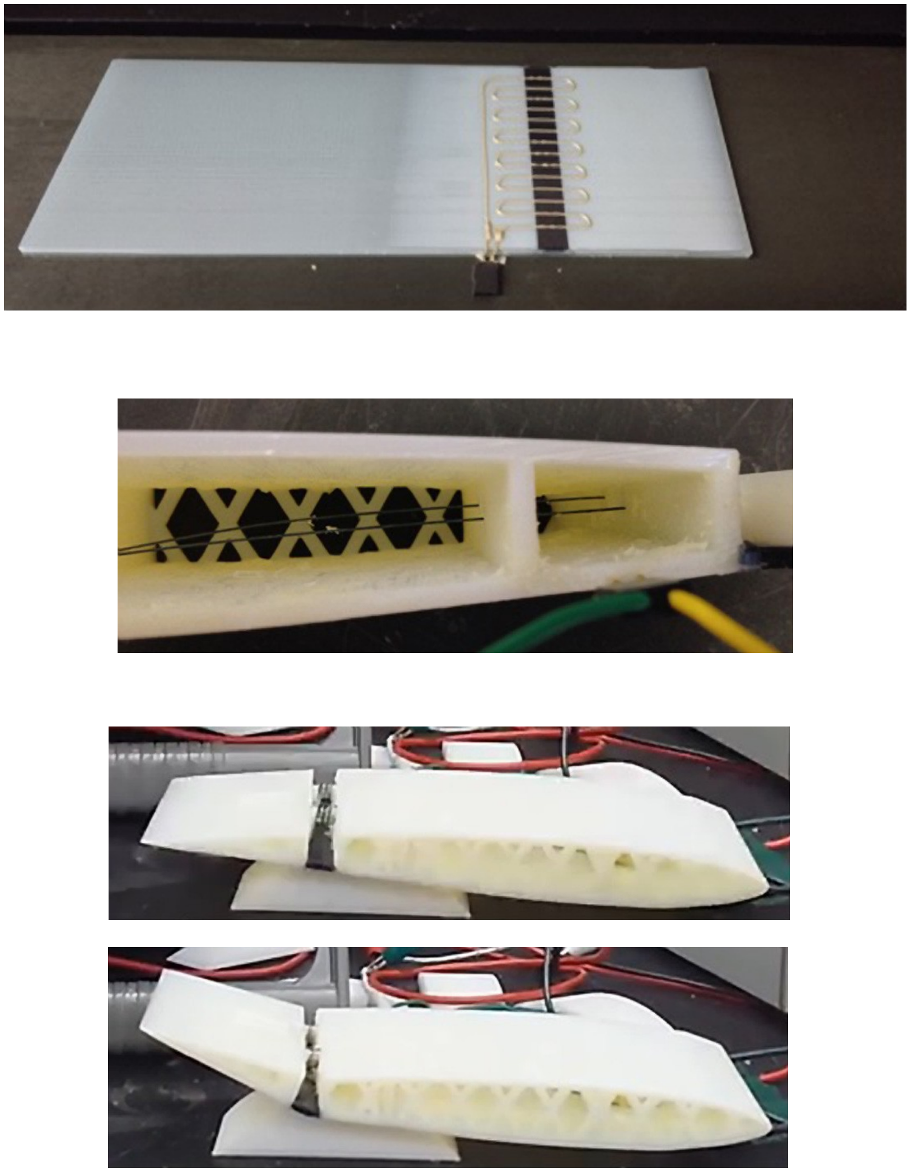
"If fewer than two dozen element types give rise to all biological life, a few basic voxel types can also open a large range of possibilities...

... let's combine rigid voxels and soft voxels. Using just those two types of voxels, it's possible to make hard and soft materials. Add conductive voxels, to make wiring...

...Add resistor, capacitor, inductor and transistor voxels, to make electric circuits. Add actuator and sensor voxels and you have robots."[681]

Robotic finger designed and created via in situ embedding with an additive manufacturing process: a) computer-aided design (CAD) representation, b) finger as-built (with embedded monofilament fiber), and c) finger actuated via a sliding joint, Justin L. Stiltner, Amelia M. Elliott, and Christopher B. Williams, "A Method for Creating Actuated Joints via Fiber Embedding in a Polyjet 3D Printing Process," 22nd Annual International Solid Freeform Fabrication Symposium (2011) (Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *The Next Wave: 4D Printing and Programming the Material World,* P. 5)

679 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 7
680 Idem.
681 Lipson, Hod - Kurman, Melba,*Fabricated: The New World of 3D Printing* Indianapolis: Indiana: John Wiley & Sons, (2013) P. 277



*Integrated sensing and actuating wing flap manufactured via a materials jetting process: (a) Embedding plane and geometry of directly written conductor shown on build tray during the mid-print deposition step (DuPont 5021 conductive silver ink; conducting lines are 700 µm wide and 32 µm tall); (b) Detailed view of embedded, actuating shape memory alloy wire within final printed geometry; (c) Integrated sensing and actuating wing flap (i) before, and (ii) after electrical current application. Wing is 7" long, 2.5" deep, and 0.75" tall at its widest point***, Dr. Christopher B. Williams, DREAMS Laboratory, Virginia Tech (http://www.dreams. me.vt.edu.)*** (Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *The Next Wave: 4D Printing and Programming the Material World,* P. 5)

*7.9-Digital Reality: digitizing physical reality_*

Neil Gershenfeld seems to agree with this conceptual approach when, in an interview given to

Edge.org, he describes the process of *digitizing physical reality* [682] as that of equating a kid building a *Lego* model and a ribosome, which according to him do much the same thing if you compare it to a 3D printer concerning metrology, error-correction and re-usability:

"What all of that [talking about 3D printing] *misses is, it's analog. The design is digital, but the process is smooshing material. You might cut it or you might squirt it but it's smooshing material. The real invention is 4 billion years old, that's the evolutionary age of the ribosome. To understand the ribosome, think about a child playing with Lego bricks and compare it to a state-of-the-art 3D printer. The child and the ribosome do much the same thing...*

...When the child assembles Lego bricks, the first attribute is metrology that comes from the parts. When you snap the bricks together, you don't need a ruler to play Lego; the geometry comes from the parts. What it means is that a child can make a Lego structure bigger than themself. The same way in the ribosome—the Lego bricks are amino acids, and the ribosome assembles aminoacids to elongate a protein. You can make an elephant one amino acid at a time because the geometry comes from the parts. In a 3D printer today, what you can make is limited by the size of the machine. The geometry is external...

...The second difference—now we come to the Shannon part—is the Lego tower is more accurate than the child because the constraint of assembling the bricks lets you detect and correct errors. The tower is more accurate than the motor control of the child...

...In a lab when you mix chemicals the yield is maybe a part per 100. In the ribosome, making proteins, the error rate is a part in 104, and when you replicate DNA there's an extra step of error correction and the error rate is 1 in 108. That 1 in 108 is the exponential. That's the exponential scaling for working reliably with unreliable parts. Because the parts have a discrete state, it means in joining them you can detect and correct errors. That threshold property may sound like a technicality but it's exactly the difference between an analog telephone and the Internet, or a differential analyzer and a PC. The second difference is you can detect and correct state to correct errors to get an exponential reduction in error, which gives you an exponential increase in complexity...

...The next one is you can join Lego bricks made out of dissimilar materials. In the ribosome there's twenty amino acids that represent the basic properties of life. It's very hard to 3D-print a conductor and an insulator and a semiconductor through the same process...

...The last one is when you're done with Lego you don't put it in the trash; you take it apart and reuse it

[682] Gershenfeld, Neil, "Digital Reality: A Conversation with Neil Gershenfeld", on *Edge.org* website (http://edge.org/conversation/neil_gershenfeld-digital-reality)

because there's state in the materials. In a forest there's no trash; you die and your parts get disassembled and you're made into new stuff. When you make a 3D print or laser cut, when you're done there's recycling attempts but there's no real notion of reusing the parts...
...The metrology coming from the parts, detecting and correcting errors, joining dissimilar materials, disconnecting, reusing the components—those are all the things Shannon and von Neumann taught us. They're digital fabrication. But the crucial distinction is that the code isn't in the computer, it's in the materials themselves. It's digitizing physical reality. There's an exact historical alignment between going from analog to digital in communication and analog to digital in computation, and now analog to digital in fabrication. That's the research revolution: digitizing fabrication, coding construction."[683]

In this extract, Gershenfeld clearly states that the road to digitization is that of *discreet metrology* and that, in turn, error correction and, because of the nature and repeated usefulness of the building-blocks, also re-usability derives from that metric property. This suggests that digital materiality has an inherent nature to it that produces diversification and emergent self-assembly properties embedded within the concept and that it is observable in every application of the digital that we have developed, specifically meaning digital communication, computing and fabrication. Also in agreement with Campbell et al., this potential building scenario could mean the total shaking of the AEC industry.

***"**Buildings or structures that takes on life-like qualities. Instead of casting brick or pouring concrete, we instead pour a building-size volume of PM into a foundation, and then program the PM elements to 'grow' into a full building with all the accoutrements of embedded electricity, plumbing, and information technology."*[684]

We have drawn upon this concept to build up a connection between material and digital system logic following Gershenfeld's idea of digital material; as in computation of the material in order to program it from within. This will be illustrated in more detail in chapter VIII.

683 Gershenfeld, Neil, "Digital Reality: A Conversation with Neil Gershenfeld", on *Edge.org* website (http://edge.org/conversation/neil_gershenfeld-digital-reality)
684 Michio Kaku, *Physics of the Future: How Science Will Shape Human Destiny and Our Daily Lives by the Year 2100*, New York: Doubleday (2011)

Arkenburg, Chris, "Cities of the Future: Built by Drones, Bacteria, and 3D Printers," (http://www.fastcoexist.com/1681891/cities-of-the-future-built-by-drones-bacteria-and-3-d-printers.)
As quoted by: Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 9-10

*7.10-Still Ahead_*

In their paper *The Next Wave: 4D Printing and Programming the Material World*, Campbell et al. balance 4DP's (in this context, equated to PM) challenges and obstacles for the future, which we will look to in the same order as presented by the authors, yet focusing, for the purpose of experimental development and simulation models, on *design, energy, programming and adaptability to different environments*[685] which have been taken in this thesis as a basis for framing the lines of action during the experiments phase in chapter IX. Meaning that in the aforementioned chapter we will show modeling processes and result regarding the aforementioned categories within Campbell et al's inventory of objectives to achieve concerning 4DP. Next, here are their concerns and priority list :

- *"**Design**—How do we program future CAD software to encompass PM with multi-scale, multi-element and dynamic components?"*[*686]

This is the main objective of this research, echoing the objectives table at the beginning of the thesis, through the application of computational concepts and parametric modeling, this research hypothesizes that it is possible to extract the right algorithms to subsequently build a more adequate software simulation solution than currently available, exploring *Kangaroo*, on the *Rhinoceros 5.0 + Grasshopper* nurbs modeling design platform with the intention to add functionality to accurately simulate SMM material behavior, which would be useful in the design-to-production workflow and decision making process, theoretically cutting it down in length and making it more fluid. Envisioning a future application that can simulate multi-scalar, multi-material assemblies and compounds.

- "**Materials**—How do we create materials with multifunctional properties and embedded logic capabilities?"[687]

Materials are being developed by architects in collaboration with scientists at some research programs around the world, yet this research does not dwell into the developing of these materials mostly because of lack of time and resources to do so. Therefore it limits itself to implement in a parametric simulation model its computational equivalent or approximate. There are enough papers and books written about PM, especially SMM, that have served as information sources to build the simulations exhibited in chapter IX.

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685 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 8

* Thomas A. Campbell and Skylar Tibbits recently (shortly before May 2014) attended a meeting to provide guidance to DARPA on "Rethinking CAD," which has the goal to advance software design and thus enable more complex, multimaterial, multifunctional 3D object fabrication

686 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 8

687 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 8

- “**Adhesions between voxels**—How can we ensure that adhesion among voxels is comparable to normally fabricated systems, while simultaneously allowing reconfigurability or recyclability after use?”[688]

This is a category that some of the experiments will make suggestions to, but will not be one of the main focuses, as most of the experiments will be built to simulate certain aspects of bigger systems or, in some cases, individual components that can be circumscribed into larger assemblies and that, to the extent of what is shown in the analyzed and referenced literature on SMM, are prone to re-usability and re-composition when in the design process.

- “**Energy—**How can we generate, store, and use passive and abundant energy sources to activate individual voxels and PM?”[689]

This is one of the main *leitmotifs* of this thesis, outlined int the objectives and contributions at the start of this Ph. D. dissertation: *can we build passive kinetic systems? And if so... how?* This thesis proposes PM as a mean to achieve passive and self-organizing KA, a feat that has not been achieved by KA to this date. To my knowledge, only the *Hyposurface* project by Decoi Architects has successfully set up a built kinetic wall that can be programmed and responds to a computer's orders. And Jordi Turco and Sylvia Felipe's *Hybgrid* project that successfully built a series of roof drape-like covers as prototypes for the same computer driven kinetic design. Yet non of these are self-assemblies nor self-organizing systems.

- “**Electronics—**How do we efficiently and effectively embed controllable electronics (or electronic-like capabilities) at the submillimeter scale?”[690]

These proposed traits, although an immensely interesting and suggesting one, will not be covered in depth in this thesis, this research will only argue certain theoretical scenarios in which these would be possible and useful. Arguing that it is a very wide and specific field (semiconductors, superconductors and mirco-electronics) which scale separates it from the practical implications of this thesis objectives and that is touched mildly in the material science investigation next in this chapter.

- *“**Programming**—How do we program and communicate with individual voxels both physically and digitally? How do we program variable state-changes (3+ physical states)?”*[691]

In the context of PM, programmability is the most important aspect at hand, therefore, it is one of, if not, the most significant standpoint from which to observe the experiments at hand and the theoretical

[688] Idem.
[689] Idem.
[690] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 8
[691] Idem.

implications within the larger context of KA. In chapter IX we will develop, program and implement algorithms that will in turn build PM models simulation that, int turn, could be adaptable to different situations and different materials, in some cases, the models will be able to simulate *unobtaniums* or non-existing materials while some of them will simulate specific physical scenarios and materials taken from the referenced authors work in material science. The usefulness of these models will lie in the theoretical, yet mathematically proven, development of digital and programmable materials and their testing before the fact in a computer environment which thus can lead to he development of a specific software package much like *Autodesk's Cyborg.*

- "**Adaptability to different environments**—How do we program and design environmentally responsive voxels?"[692]

This research also will experiment on the possibilities of KA that adapts to environmentally constrained scenarios. And in that line, will analyze the application of already developed models by different authors which address an ecologically friendly focus. Nick Senske's *Sunlight parametrics* models will be used as case studies which this research has replicated and applied in different places to observe outcomes and draw conclusions from.

- *"**Assembly**—What external forces would be needed to cause macro-scale self-assembly of voxels."*[693]

Riccardo Majewski's GH model Origami water bomb simulation, among other self conceived models, will be used to illustrate certain aspects of self-assembly and similar or co-influencing phenomena. This will be explored thoroughly in chapter IX.

- ***"Standardization**—Can standards (e.g., as produced by ISO) be created to ensure seamless interaction among PM voxels and systems?"*[694]

This research will leave the standardization and official industry regulations for others to investigate as it will not incur in any of these implications other than possible, theoretical and/or hypothetical scenarios.

- "**Certifications**—Can PM systems be certified technically through normal channels, or will wholly new certifications be required (e.g., aircraft parts that require rigorous FAA certifications)?"[695]

This was already partially explained in the material design part of this chapter. No more than

[692] Idem.
[693] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 8
[694] Idem.
[695] Idem.

theoretical implications and obvious and corroborated facts will be taken and developed along this dissertation.

- "**Physical and cyber security**—How can we embed programmable capabilities into objects while still ensuring they are secure?"[696]

This aspect, although very important, will be left for others to explore and frame in the social context and legal framework. Its military, domestic and public security concerns are outside of this thesis focus of attention.

- *"**Affordable manufacturing techniques**— Can routine manufacturing of PM systems be made economically viable for small- and large-scale manufacturers?"*[697]

Affordability will only be addressed as a by product of this technique (4DP) and will not be taken in account during the experimentation phase nor in its conclusions, other than as speculative implications.

- "**Characterization**—How will we characterize dynamic systems of voxels? Will new metrology equipment be required?"[698]

This has been explored already in the previous paragraph Digital reality: digitizing physical reality. In which the answer was: a resounding yes.

- "**Recycling**—How can we ensure the voxels can be disassembled and reconfigured for reuse or error-correcting for self-repair?"[699]

This thesis will leave this category also out of its scope of experimentation and will only refer to it as purely speculative hypotheses.

*7.10.1-Possible applications_*

This techonolgy has many promises and possibilities of application in the real world military scenarios. *The US Army and Navy are already developing 3D printing for spare parts in the field or on ships as well as for design and manufacture of cheaper, lighter, and more effective weapons systems.*[700, 701 & 702]

[696] Idem.
[697] Idem.
[698] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 8
[699] Idem.
[700] Drushal, Col. Jon R., "Additive Manufacturing: Implications to the Army Organic Industrial Base in 2030," (2013) (http://public.carlisle.army.mil/sites/Landpower/ Shared%20Documents/Drushal%20CRP.pdf.)
As quoted by: Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 9
[701] M. Llenza, "3-D printing will streamline the Navy's supply chain—and much more," *Armed Forces Journal*, (2013) (http://www.armedforcesjournal.com/print-when-ready-gridley/**.**) (28/03/2015)
[702] Beckhusen, Robert, "Need Ships? Try a 3-D Printed Navy," *Wired*, April 2, (2013) (http://www.wired.com/dangerroom/2013/04/3d-printed-navy/?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+wired%2Findex+%28Wired%3A+Top+Stories%29.) (28/03/2015)

These applications are not just in the grasp of war machines but also survival and more human oriented traits can be achieved and are being actively tried by DARPA and defense agencies across the USA.

"PM could enable uniforms that adjust insulation and cooling to the surrounding environment and the biometrics of the individual; and, perhaps the ultimate vision of some PM researchers, the morphable robot that can shapeshift around and through obstacles as imagined in the movie Terminator 2."[703]

Aside from these science fiction characteristics, the everyday, domestic implications are massive and numerous. This entails a wide range of research branches to be established to achieve all these promises. And although previous promising technologies like Building Information Modeling (BIM) or 3DP have yet to realize most of their promises (in the case of BIM, its most significant one- to cut down "the cost of change" as demonstrated by Daniel Davis in his 2013 thesis *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*) it is conclusive that PM is wider and less *ad hoc* in nature thus its all-encompassing applicable range.

Recent work by MIT on morphable cube-shaped PM could be a precursor to a new form of construction bricks for space applications or quickly deployable structures.[704] Echoing William Zuk and Roger Clark's classification on KA systems, therefore making PM a likely candidate to try and upgrade the deployable structures category. Out of a myriad of examples, Skylar Tibbits enumerates a comprehensive list of possible "digitizing" across design and production domains and disciplines:

- *"Airplane wings that change shape in flight to enhance performance as a result of a signal sent to the wings or an automatic response of the wing to changing air pressure, temperature, or other environmental conditions to minimize air resistance or maximize lift.*
- *Tires that change shape/traction depending on road/weather conditions and driving demands, as an automatic response from sensors.*
- *Shoes/clothes/gear that adapt to the user's performance and the changing environment, thus offering enhanced performance, fit, or style.*
- *Furniture that is packaged flat, but self-assembles in your home after purchase; such assembly could be automatic as one opens the packaging or as the result of a signal sent by the owner.*

703 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 9.
704 Tibbits, Skylar - "4D printing and programmable matter," video TED talk (2013) (http://boingboing.net/2013/04/05/4d-printing-and-programmable-m.html)

Similarly, one could have furniture that could disassemble itself for easier moving or different functionality.

- *Self-healing materials, e.g., micro-cracks self-healing on aircrafts, roads, bridges, and equipment.*
- *Self-disassembling materials for recyclability or information security and protection of confidential materials.*
- *Bridges and roads that adapt to varying load conditions or weather.*
- *Smart valves, connections, and sensors for infrastructure lines that can fundamentally respond to control flow-rates and are adaptable for resilience and protection."*[705]

*7.10-Conclusions_*

We note that more substantial applications will require significant infusion of resources (greater funding, training of researchers, federal centers devoted to PM research, development of new fabrication and measurement equipment, etc.)...

...It does not seem fanciful to imagine a world in which a new form of matter formation could enable form and function modification at the flip of a switch—a world in which one could make intelligent LegoTM-like bricks that can assemble, become multifunctional and morphable into almost any 3D object, and disassemble at will. Such a future—with both its promises and challenges—awaits us."[706]

This thesis is compelled to state the following conclusions:

1. KA, PM, SA and 4DP all share similar concerns and scale limitations. The differences lie for the most part in the methods, ways and means to achieve "animation" in material configurations.
2. At the core of this technique are three main tenets or principles that give rise to the subsequent unleashing of possibilities which are: *"the machine, the material and the geometric*

[705] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 10
[706] Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 10

'programme'[707] thus being its most important aspects material science, computational programming geometric analysis and digital fabrication

3. Material matrices are a central aspect to develop to obtain desired material behaviors and therefore PM, SA, 4DP thus enabling programmable matter based KA.
4. PM, SA and 4DP entail a universe of applicable scenarios and is set to disrupt the whole world and even the human condition.
5. There are significant possibilities of PM, SA and 4DP of becoming terrorist weaponry.
6. It is suggested that PM, 4DP and SA's implications will "spill over" to virtually every domain in the the STEM sciences and there is certain proof that it has already done so into the art world.
7. Scaling up is still a central challenge for PM, 4DP and SA.
8. 4DP, PM and SA are all based in additive manufacturing and, as such, they are within the material "taxo-navigation" conceptual framework elaborated by Liat Margolis. Therefore selecting material and, in the future, designing it from its very fabric, seems not only imminent but a necessity as it enables creative novelty and contingency, something that "conventional" construction coding does not provide.
9. Simulation of these materials is possible and has been started by SAL, DARPA, Virginia Tech and other institutions. It is up to us to develop it further, enabling the following chapters as justified endeavors.

[707] Tibbits, Skylar, *Op. Cit.* (2014) P. 119

*8-Shape Memory Materials (TSM) and the Shape Memory Effect (SME)_*

As mentioned before in this chapter, other forms of PM are available that do not encompass 4DP, one of them are Shape-memory Materials (SMM). Shape-memory polymers (SMP), another kind of SMM will also be looked at, more briefly than SMA, at the end of this chapter and simulated as case studies in chapter IX. Generally speaking, the shape recovery in SMM is *triggered by an external stimulus which is mainly a temperature that passes a critical point.*[708] Yet different materials have differentiated after effects concerning shape-memory and recovery, they share the principles but not necessarily the triggers *it depends on the specific material which type of energy should be added to trigger the shape recovery. There are for example also materials that are triggered by radiation.*[709] Meaning that their underlying "cryptosystem" mechanisms or inner workings vary from each material group to the other. Within the scope of what is called SMM there are, at a basic level, two main groups, these are Shape-Memory alloys (SMA) and Shape-Memory Polymers (SMP) that, in turn, encompass several other subgroups called Linear (LCP) and Multi-block Co-polymers (MBCP) which differentiate from the aforementioned SMA, although there also shape-memory gels and ceramics[710] which lie outside the scope of this research and will not be looked into any further than as a reference.

*8.1-Shape-memory alloys_*

SMA are a very well studied and relatively well understood variety of programmable materials, holding various compound groups within their own small micro-cosmos. They are a very specific and promising breed of shape-shifting which are able to memorize or "remember", in most cases, *a shape constituted in advance. This shape is the permanent shape.*,[711] While also having the ability to transform into a temporary one.

"SMAs sense an external stimulus and respond to it by changing their physical properties which results in a deformation or deflection of the structure. The permanent shape returns again. In this way, they

708 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 1
709 Idem.
710 Lendlein, Andreas, Kelch, Steffen, *Op. Cit.* (2002) P. 2038.
711 Wakjira, J. F. (2001). *The VT1 Shape Memory Alloy Heat Engine Design.* Retrieved 06 2011, from scholar.lib.vt.edu: http://scholar.lib.vt.edu/theses/available/etd-02102001-172947/unrestricted/ETD.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 2

are able to undo a deformation that seemed irreversible at first."[712]

SMA are are ruled by what is called the Shape-memory Effect (SME):

"*The shape memory effect (to be abbreviated **SME** hereafter) is a unique property of certain alloys exhibiting martensitic transformations, as typically shown in figure F.1.1 . Even though the alloy is deformed in the low temperature phase, it recovers its original shape by the reverse transformation upon heating to a critical temperature called the reverse transformation temperature."*[713]

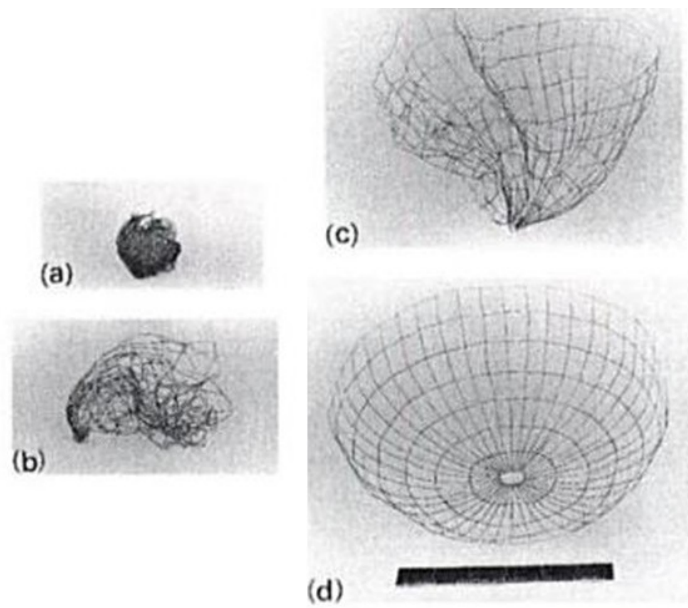

Figure 1 - Demonstration of the SME by a space antenna of Ni-Ti wires, Kazuhiro Otsuka et al. (1999) (Otsuka, Kazuhiro., Wayman, Marvin Clarence, *Shape Memory Materials*, P. 3)

How the SME in SMA works is based on a principle called the "Martensite-Austenite transformation" or "martensitic transformation". Where *Austenitization* means to heat the iron, iron-based metal, or steel to a temperature at which it changes crystal structure from ferrite to austenite. An incomplete initial austenitization can leave undissolved carbides in the matrix[*]. *This transition involves a crystal*

[712] Noor, A. K., Venneri, S. L., Paul, D. B., & Hopkins, M. A. (1999, 01 10). *Structures technology for future aerospace systems.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/
As quoted by:
Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium (2011) P. 2

[713] Otsuka, Kazuhiro - Wayman, Marvin Clarence, *Op. Cit.* (1998)P. 1-2

[*] H.-G. Lambers, S. Tschumak, H. J. Maier, D. Canadinc - *Role of Austenitization and Pre-Deformation on the Kinetics of the Isothermal Bainitic Transformation*, Metallurgical and Materials Transactions A, June 2009, Volume 40, Issue 6, editor: Springer US, USA, P. 1355-1366 (2009). (http://link.springer.com/article/10.1007/s11661-009-9827-z) (16/10/2015)

change from a martensite form, which is stable at a low temperature, to an austenite form, which is stable at a high temperature.[714] The principle itself is very simple and can be summarized as that: *In some alloys, a given plastic strain recovers completely when the concerned alloy is heated above a certain temperature.*[715] To achieve this memory effect, *shape memory alloys (SMA) use a martensite austenite transformation to achieve the shape memory effect (SME) and the super elastic effect*[716]**,**insofar they differentiate themselves from their polymeric counterparts:

"Shape memory polymers (SMP) on the other hand have different types of mechanisms. The characteristics of the polymer chains or the characteristics of the different phases in the material are responsible for this effect."[717]

With their originating processes also differ in technology and material properties and phenomena. *An SMA gets its permanent shape by heat treatment and the permanent shape of a SMP is in general obtained during fabrication.*[718]

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714 Casati, R., Passaretti, F., & Tuissi, A. (2011). *Effect of electrical heating conditions on functional fatigue of thin NiTi wire for shape memory actuators* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/

de Haan, J. (1994, juli). *Geheugenwerking bij NiTi-legeringen.* Retrieved 06 2011, from alexandria.tue.nl: http://alexandria.tue.nl/repository/books/642146.pdf

Wakjira, J. F. (2001). *The VT1 Shape Memory Alloy Heat Engine Design.* Retrieved 06 2011, from scholar.lib.vt.edu: http://scholar.lib.vt.edu/theses/available/etd-02102001-172947/unrestricted/ETD.pdf

As quoted by:
Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 3

715 Tadaki, T., Shimizu, K., Otsuka, Kazuhiro, "Shape Memory Alloys", *Annual Review of Material* Science 1988, Copyright, Annual Reviews Inc. All rights reserved (1988) P. 25

716 de Haan, J. (1994, juli). *Geheugenwerking bij NiTi-legeringen.* Retrieved 06 2011, from alexandria.tue.nl: http://alexandria.tue.nl/repository/books/642146.pdf

As quoted by:
Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 1

717 Casati, R., Passaretti, F., & Tuissi, A. (2011). *Effect of electrical heating conditions on functional fatigue of thin NiTi wire for shape memory actuators* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/

As quoted by:
Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 1

718 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 1

8.1.1-SME Discovery and SMA Origins_

In their seminal article in the *Annual Review of Material Science 1988*, titled *Shape Memory Alloys*, *Tadaki and Shimizu* place its origins *in the first half of 1950s*.[719] Where the SME had been *observed in Au-Cd (1) and In-T1 alloys in the first half of 1950's*[720] (by Chang and Read in 1951[721]).Yet it was not until it was found *in a Ti-Ni alloy (3) in 1963, when the phenomenon was first termed the shape memory effect. A similar phenomenon was found in a Cu-A1-Ni alloy as well.*[722] Which at the time was considered an exclusive phenomenon of Ti-Ni alloy[723]. The shape memory effect was first discovered in 1932 by O. Ölander, who had discovered the pseudo-elastic effect in Au-Cd alloys in the mentioned year[724]. Later that decade, in 1938, Greninger and Mooradian *observed the formation and disappearance of a martensitic phase by decreasing and increasing the temperature of a Cu-Zn alloy*.[725] The shape-memory properties caused by the thermo-elastic effect was also scientifically reported by Kurdjumov and Khandros in 1949 and also by Chang and Read in 1951[726].

8.1.2-Nickel-Titanium (Ni-Ti) alloys_

In a scientific paper that investigated SMM's applications and inner workings, titled *Shape Memory Materials and their applications,* Rottiers Ward, Laurien Van den Broeck, Chris Peeters and Peter Arras affirmed that the ***"best known SMA is a nickel-titanium alloy".***[727] SMA's most widely known compound and the one which started the formal SMA development industry, was first researched and developed at the know disappeared *United States Naval Ordnance Laboratory*, where its comercial name "Nitinol" comes from (an acronym from Nickel Titanium Naval Ordnance Laboratories). There also exist what are called "Ferromagnetic shape-memory alloys" or FSMA, which change shape under strong magnetic fields. These SMA will not be included in this research and will be left to others to investigate their technical aspects leading to establish simulation and design potentials and applications. SMAs have four different *transformation temperatures* that work as "sensitivity" thresholds in the martensite-austenite process, these are: *"the martensite start (Ms), martensite finish*

[719] Tadaki, T., Shimizu, K., Otsuka, Kazuhiro, "Shape Memory Alloys", *Annual Review of Material* Science 1988, *Copyright © 1988 by Annual Reviews Inc. All rights reserved* (1988) P. 25
[720] Idem.
[721] Lendlein, Andreas, Kelch, Steffen, *Op. Cit.* (2002) P. 2037.
[722] Tadaki, T., Shimizu, K., Otsuka, Kazuhiro, *Op. Cit.* (1988) P. 25
[723] Idem.
[724] Otsuka, Kazuhiro - Wayman, Marvin Clarence, *Op. Cit.* (1998)
[725] Idem.
[726] Idem.
[727] Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 1

(Mf), austenite start (As) and austenite finish temperature (Af). These four temperatures are strongly dependent on the applied stress and the material itself."[728]

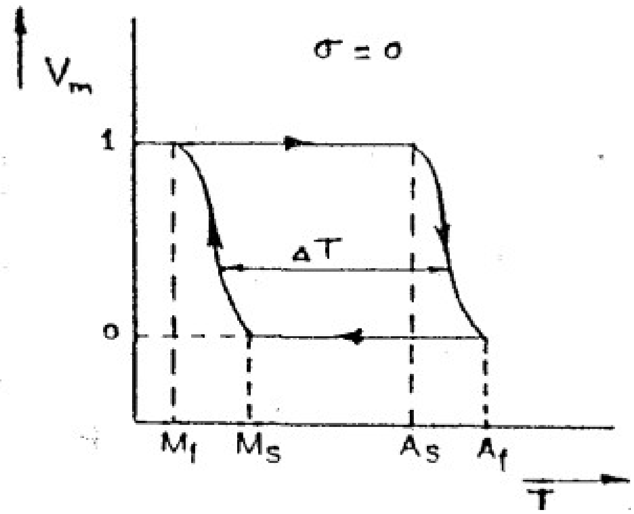
Table 1.1. *Twinning modes in martensite*[21]

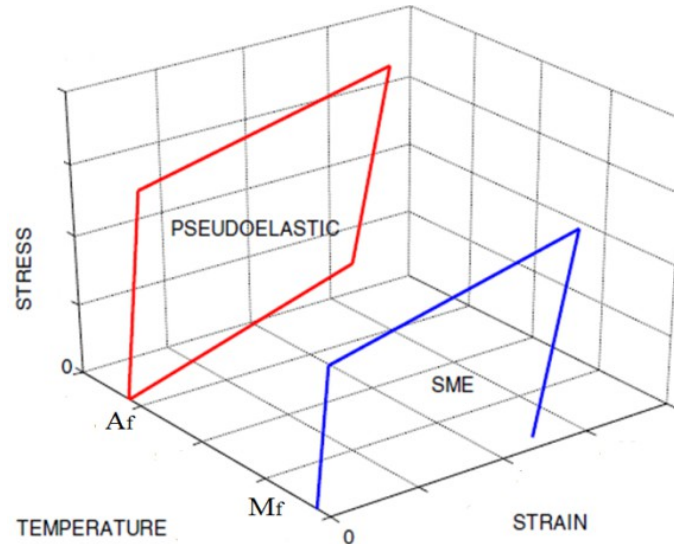
Structure	Twinning Elements					Alloys Observed
	K_1	K_2	η_1	η_2	s	
BCC (FCC → BCC)	$\{112\}$	$\{\bar{1}\bar{1}2\}$	$\langle\bar{1}\bar{1}1\rangle$	$\langle 111\rangle$	$1/\sqrt{2}$	Fe–Ni, Fe–Pt
BCT (FCC → BCT)	$\{112\}$	$\{\bar{1}\bar{1}2\}$	$\langle\bar{1}\bar{1}1\rangle$	$\langle 111\rangle$	$(2-\gamma^2)/\sqrt{2}\gamma^a$	Fe–C, Fe–Ni–C, Fe–Cr–C
	$\{011\}$	$\{01\bar{1}\}$	$\langle 01\bar{1}\rangle$	$\langle 011\rangle$	$\gamma-1/\gamma$	Fe–C
BCT (BCC → BCT)	$\{011\}$	$\{01\bar{1}\}$	$\langle 01\bar{1}\rangle$	$\langle 011\rangle$	$\gamma-1/\gamma$	Au–Mn
FCT (FCC → FCT)	$\{011\}$	$\{01\bar{1}\}$	$\langle 01\bar{1}\rangle$	$\langle 011\rangle$	$\gamma-1/\gamma$	In–Tl, Mn–Cu, In–Cd In–Pb, Fe–Pt, Fe–Pd
Tetragonal (B2 → 3R)	$\{111\}$	$\{11\bar{1}\}$	$\langle 11\bar{2}\rangle$	$\langle 112\rangle$	$\sqrt{2}\gamma-1/\sqrt{2}\gamma$	Ni–Al
HCP (BCC → HCP)	$\{10\bar{1}1\}$	irrational	irrational	$\{4\bar{1}\bar{5}3\}$	$\frac{\sqrt{4\gamma^4-17\gamma^2+27}}{2\sqrt{3}\gamma}$	Ti, Ti–Mo, Ti–V
Orthorhombic 2H (DO$_3$ → 2H)	$\{121\}$	$\{\bar{1},1.5036,\overline{0.5036}\}$	$\langle\bar{1},0.7953,\overline{0.5907}\rangle$	$\langle 111\rangle$	0.261[b]	Cu–Al–Ni, Cu–Al, Cu–Sn
	$\{\bar{1},1.5036,\overline{0.5036}\}$	$\{121\}$	$\langle 111\rangle$	$\langle\bar{1},0.7953,\overline{0.5907}\rangle$	0.261[b]	Cu–Al–Ni
	$\{101\}$	$\{\bar{1}01\}$	$\langle\bar{1}01\rangle$	$\langle 101\rangle$	0.0744[b]	Cu–Al–Ni
2H (B2 → 2H)	$\{111\}$	$\{1,\overline{0.7073},\overline{1.2927}\}$	$\langle 1,\overline{0.3740},\overline{0.6260}\rangle$	$\langle 211\rangle$	0.156[c]	Au–Cd, Ag–Cd, Ti–Ta
Orthorhombic (BCC → Orthorhombic)	$\{\bar{1}11\}$	$\{0.522,0.823,0.221\}$	$\langle 0.788,0.579,0.209\rangle$	$\langle\bar{2}11\rangle$	0.19[d]	Ti–Ta
	$\{0.522,0.823,0.221\}$	$\{\bar{1}11\}$	$\langle\bar{2}11\rangle$	$\langle 0.788,0.579,0.209\rangle$	0.19[d]	
Monoclinic (B2 → Monoclinic)	$\{\bar{1}\bar{1}1\}$	$\{0.2470,0.5061,1\}$	$\langle 0.5404,0.4596,1\rangle$	$\langle\bar{2}\bar{1}1\rangle$	0.310[e]	Ti–Ni
	$\{111\}$	$\{0.6688,0.3375,1\}$	$\langle 1.5117,0.5117,1\rangle$	$\langle 211\rangle$	0.142[f]	Ti–Ni
	$\{0.7205,1,\bar{1}\}$	$\{011\}$	$\langle 011\rangle$	$\langle 1.5727,1,\bar{1}\rangle$	0.280[e]	Ti–Ni
	(001)	(100)	$[100]$	$[001]$	0.238	Ti–Ni

In the above table, irrational numbers depend upon the values of lattice parameters. Thus these values are shown for specific alloys indicated.
[a] $\gamma = c/a$ [b] Cu–Al–Ni [47] [c] Au–Cd [d] Ti–Ta [48] [e] Ti–Ni [49] [f] Ti–Ni [50]

Twinning modes in martensite - Table 1.1, Kazuhiro Otsuka et al. (1999). (Otsuka, Kazuhiro., Wayman, Marvin Clarence, *Shape Memory Materials*, P. 13)

[728] Maenghyo, C., & Sanghaun, K. (2004, 09 21). *Structural morphing using two-way shape memory effect of SMA.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 3





(Left) *The martensite austenite transformation. Vm represents the volume fraction of Martensite. [e]* Thijssen, E. (1992) (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium (2011) P.3 (21/09/2014) (Right) *Stress–temperature–strain diagram to demonstrate SMA behavior in pseudo-elasticity and SME. [c]* , Maenghyo et al. (2011) (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. P. 2) (21/09/2014)

1.1 Invitation to shape memory effect

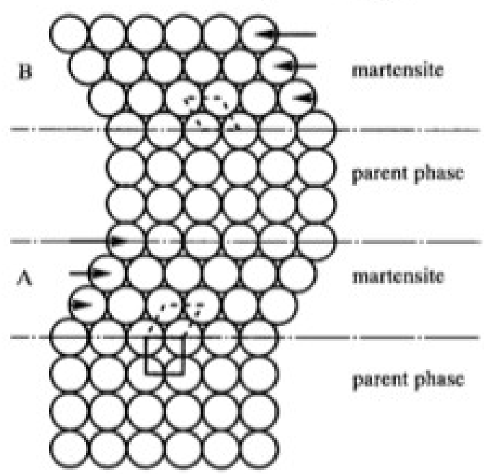


Fig. 1.2. A simplified model of martensitic transformation. See text for details.

Simplified model of martensitic transformation, Otsuka et al. (1999) (Otsuka, Kazuhiro, Wayman, Marvin Clarence, *Shape Memory Materials*, Chapter 1: Introduction, Cambrige University Press (1998) P. 3.)

8.1.3-Twinned and de-twinned martensite_

"When stress-free austenite is cooled below Mf (Figure 4: A-B), its structure will switch to "twinned" martensite whereas the atoms form self-accommodated mirror images or twins of each other. (Figure 5)[729] *This is the energetic most favorable state at a low temperature. This causes no associated macroscopic shape change (Figure 8)"*[730]

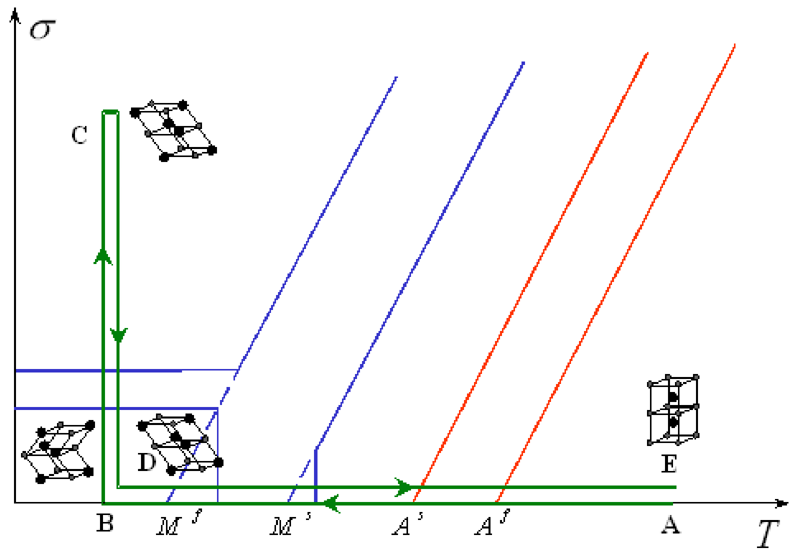


Figure 4 - Schematic representation of the thermo-mechanical loading path demonstrating the SME [a], Texas Agriculture & Mechanics website (2011) [731]*Each thermal cycle (Figure 3) will lead to micro structural changes and eventually to fatigue behavior and flaw [6].* (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. P. 2)(21/09/2014)

"When the material is subsequently deformed, the martensite twins are able to reorient the structure in a simple shearing motion as a result of the applied stress [15]. (Temporarily shape C & D) The structure changed from twinned martensite to detwinned martensite. (Figure 4: B-C)"[732]

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[729] Lagoudas, D. C. (2008). *Shape Memory Alloys - Modeling and Engineering Applications.* Springer.

Wakjira, J. F. (2001). *The VT1 Shape Memory Alloy Heat Engine Design.* Retrieved 06 2011, from scholar.lib.vt.edu: http://scholar.lib.vt.edu/theses/available/etd-02102001-172947/unrestricted/ETD.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 3
[730] Lagoudas, D. C. (2008). *Shape Memory Alloys - Modeling and Engineering Applications.* Springer.
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 3
[731] Idem.
[732] Wakjira, J. F. (2001). *The VT1 Shape Memory Alloy Heat Engine Design.* Retrieved 06 2011, from scholar.lib.vt.edu: http://scholar.lib.vt.edu/theses/available/etd-02102001-172947/unrestricted/ETD.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 4

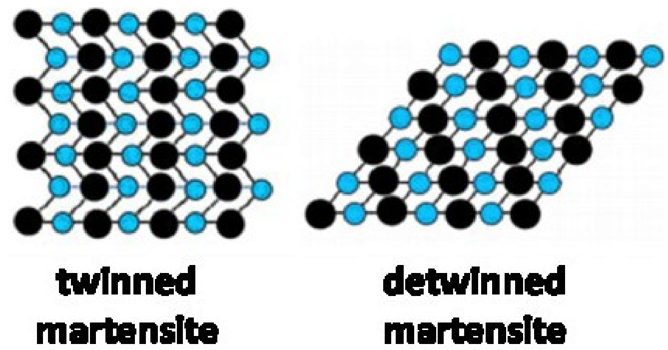

Figure 5 - Detwinning of martensite [f], Zanaboni (2007) (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. P. 2)(21/09/2014)

"Thus the structure is able to compensate this deformation at a stress level far lower than the plastic yield limit of martensite. This is called detwinning and induces a large inelastic strain. This strain induced by detwinning will not be recovered when taking away the mechanical load [3]. (Figure 6) (Figure 4: [steps]*C-D)"*[733]

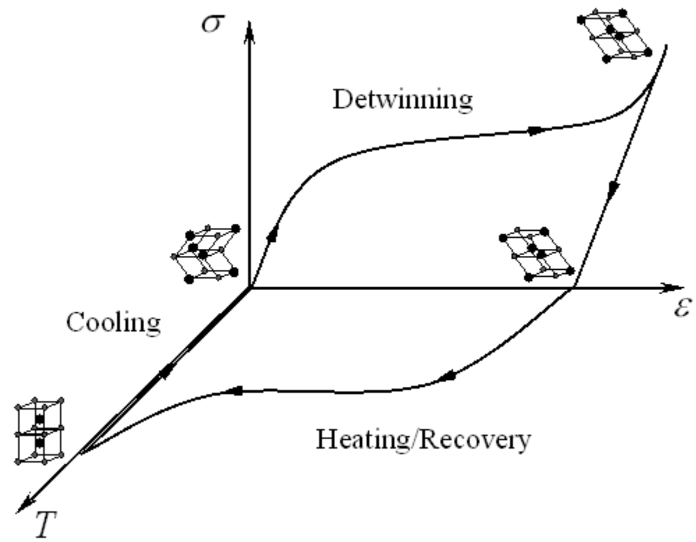

Figure 6 - Stress-strain-temperature diagram exhibiting the SME [a] Texas Agriculture & Mechanics website (2011) (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. P. 2)(21/09/2014)

[733] *Detailed Introduction to Shape Memory Alloys*. (n.d.). Retrieved 06 2011, from smart.tamu.edu: http://smart.tamu.edu/overview/smaintro/detailed/detailed.html
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 4

"Only a large recovery force during the reverse transformation induced by heating (above Af) can obtain an inelastic strain recovery (Figure 4: D-E and Figure 6)[734] *The recovery force is due to contraction of the structure when transforming from martensite to austenite.*[735] *This cyclic phenomenon is the shape memory effect. Nitinol for example has a recovery force between 500 and 900MPa."*[736]

8.1.4-Super Elasticity_

Austenite to martensite transformation (MT) is another property of SMA that sets in motion the martensitic effect and which is very closely related to another property of SMM called Super Elasticity (SE). In their seminal 1999 book titled *Shape-Memory Materials*, Kazuhiro Otsuka and Marvin Clarence Wayman, define the phenomenon known as SE:

"The same alloys have another unique property called "super elasticity" (SE) at a higher temperature, which is associated with a high (several -18%) nonlinear recoverable strain upon loading and unloading... Since these alloys have a unique property in remembering the original shape, having an actuator function and having superelasticity, they are now being used for various applications such as pipe couplings, various actuators in electric appliances, automobile applications, antennae for cellular phones, and medical implants and guidewires etc. Besides, since they the function of an actuator as well as a sensor, they are promising candidates for miniaturization of actuators such as microactuators or micromachines or robots...The martensitic transformation is a diffusionless phase transformation in solids, in which atomes move cooperatively, and often by a shear-like mechanism. Usually tha parent phase (a high temperature phase) is cubic, and the martensite (a low temperature phase) has a lower symmetry. Tha transformation is schematically show in Fig. 1.2. When temperature is lowered below some critical one, MT starts by a sheer-like mechanism. As shown in the figure. The martensites in region A and B have the same structure but the orientations are different. These are called the correspondence variants of the martensites. Since the martensite has a lower symmetry, many variants can be formed from the same parent phase. Now, if the temperature is raised and the martensite becomes unstable, the reverse transformation (RT) occurs, and if it is crystallographically reversible,

734 Maenghyo, C., & Sanghaun, K. (2004, 09 21). *Structural morphing using two-way shape memory effect of SMA.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 4

735 Lagoudas, D. C. (2008). *Shape Memory Alloys - Modeling and Engineering Applications.* Springer.
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 4

736 Maenghyo, C., & Sanghaun, K. (2004, 09 21). *Structural morphing using two-way shape memory effect of SMA.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 4

the martensite reverts to the parent phase in the original orientation. This is the origin of the SME...Thus, even though the relative atomic displacements are small (compared with inner-atomic distance), a macroscopic shape change appears associated with MT, as seen in Fig. 1.2. It is in this respect that MT is closely related to SME and SE."[737]

In their paper, Ward et al. cite de Haan who affirms that SMA's have the ability to utilize stress loads or overloads as external triggers.

"*When the SMA is at a temperature above the (stress free) austenite finish temperature (Af), it can transform into the detwinned martensite phase by using stress as an external stimulus. (Figure 4)"*[738]

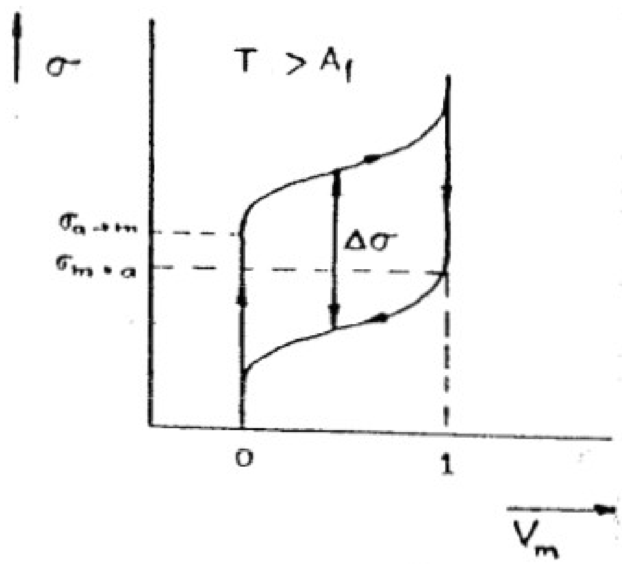

Figure 7 - The martensite austenite transformation by using stress. Vm represents the volume fraction Martensite. [e], Thijssen (1992) (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. P. 2)(21/09/2014)

Citind Maenghyo and Sanghaun, they go on to establish the loading and unloading phases thus describing the phenomenon known as "super-elasticity" (or pseudo-elasticity" according to Ward et al.). *"It is possible to obtain up to 9% strain which can be fully recovered. By unloading, the SMA*

737 Otsuka, Kazuhiro., Wayman, Marvin Clarence, *Op. Cit.* (1998) P. 2-3.
738 de Haan, J. (1994, juli). *Geheugenwerking bij NiTi-legeringen.* Retrieved 06 2011, from alexandria.tue.nl: http://alexandria.tue.nl/repository/books/642146.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011)) P. 4

recovers its original shape by transforming into austenite phase."[739]*...*
...This sequence of loading and unloading above Af is known as pseudo-elasticity or superelasticity.[740]

Citind de Haan again, it is noted that SMAs do not act in elasticity principles, therefore its molecular configuration plays the central role in causing the discussed phenomenon. *This cycle is not totally elastic because of dissipated energy during these transformations. This dissipated energy is due to internal friction.*[741]

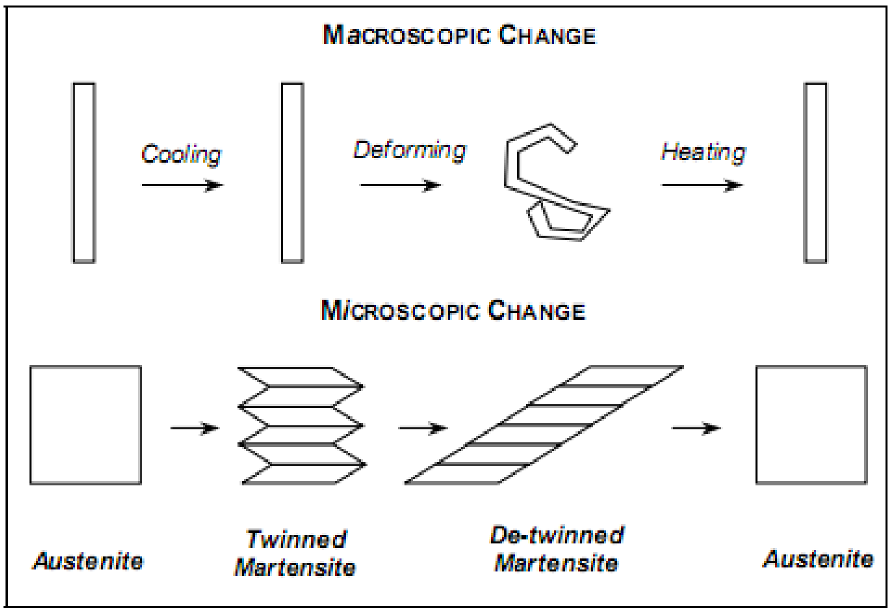

Figure 8 - Overview of the SME [b], Liu (2001) (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. P. 2)(21/09/2014)

*8.1.5-One Way Memory Effect and Two Way Memory Effect_*

Shape-Memory Alloys have two types of SME, these are the One Way Memory Effect (OWME) and Two Way Memory Effect (TWME). Which are decided by the specific molecular composition within the material compound in question. Ward et al., among other phenomena, also defined the two currently known types of SME.

739 Maenghyo, C., & Sanghaun, K. (2004, 09 21). *Structural morphing using two-way shape memory effect of SMA.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 5
740 Idem.
741 de Haan, J. (1994, juli). *Geheugenwerking bij NiTi-legeringen.* Retrieved 06 2011, from alexandria.tue.nl: http://alexandria.tue.nl/repository/books/642146.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 5

"OWME is a cycle between a random temporarily shape and a permanent shape. This OWME is only possible in one direction. When the structure is in the martensite phase after deformation by applying a mechanical load (temporarily shape), it can recover its initial permanent shape only by heating above Af. It is used for a one time actuation application"[742]

The space antenna described at the beginning of this chapter is an example of a one way memory effect application in that the antenna in question has to only deploy once. Whereas the TWME can be used, in principle, repeatedly, because its a two directional phenomenon, meaning that it can go from state A to state B and from B to A.

"*The two way memory effect on the other hand can shift between two permanent shapes. It is possible to impose a permanent shape at a high temperature and another permanent shape at a low temperature. In the future this phenomenon could be used for opening and closing a valve on air- and spacecrafts."*[743]

To make this thermo-mechanical cycle take place, the TWME needs to be induced by a process of what is called"material training", making it *undergo repeated thermo-mechanical cycles along a specific loading path. This is so called "training" and can cause changes in microstructure and subsequent changes in material behavior.*[744] Not only readjusting macroscopic, mechanical emerging properties, but also rearranging lower level ones that act as servomechanisms that can be precisely tuned to achieve bidirectional, repeated functionality and actuation. *Locally, intern*[nally the] *material will be more and more deformed and adjusted so a certain shape can be imposed and larger strains are achieved. During this training, high temperatures are used so diffusion can occur more easily.*[745]

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742 Lagoudas, D. C. (2008). *Shape Memory Alloys - Modeling and Engineering Applications.* Springer.
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 5
743 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 5
744 de Haan, J. (1994, juli). *Geheugenwerking bij NiTi-legeringen.* Retrieved 06 2011, from alexandria.tue.nl: http://alexandria.tue.nl/repository/books/642146.pdf

Lagoudas, D. C. (2008). *Shape Memory Alloys - Modeling and Engineering Applications.* Springer.
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 5
745 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 5

8.1.6-Memory loss_

Memory loss (ML) is an obstacle that "comes with the package" sort of speak. Notwithstanding its almost miraculous properties, SMA bring with them the byproduct of "forgetting" the permanent shape after mechanical overload or too many recoveries that can result *in the loss of the permanent shape or an incomplete shape recovery* [746] This makes it ML *an important concern of the smart technology.*[747]

"First of all, it is the permanent shape and not the SME that is lost. Memory loss occurs when a mechanical overload is applied, a strain is passed, too many thermo-mechanical cycles are run trough or when the temperature is too high."[748]

Actually in reality, the exactitude of SMA's initial shape is not 100% accurate, meaning that an SMA will never return to its exact initial shape, yet for practical purposes, it just appears to do so. *There will always be a certain deviation. If SMAs undergo many transformations, the deviation will increase with every cycle and will eventually lead to memory loss.*[749] Displaying an incremental, unobservable lack of accuracy that will increase until it becomes practically visible. Among other causes of ML we can name:

"Also a deformation above the allowed margin is a cause of memory loss. So recovering its initial shape will be too big of an assignment for the SMA. If larger strains are necessary, it is recommended to "train" the SMA."[750]

New originated defects in crystal lattice during thermal and/or mechanical cycling can also hinder the martensite transformation.[751] Nonetheless, SMA are, because of the nature of their composition,

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746 Kanada, T. (2008, 05 05). *A new drive system using a shape memory alloy (SMA).* (joam.inoe.ro/download.php?idu=1360)
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011)) P. 1

747 Idem.

748 Thijssen, E. (1992, 06). *GEHEUGENMETAAL.* Retrieved 06 2011, from alexandria.tue.nl: alexandria.tue.nl/repository/books/628681.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 5

749 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 5

750 Ibid. P. 6

751 Casati, R., Passaretti, F., & Tuissi, A. (2011). *Effect of electrical heating conditions on functional fatigue of thin NiTi wire for shape memory actuators* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

inherently structural and this is worthwhile when we envision future application, especially in architecture and the AEC industry. *Of all the material groups, the shape memory alloys exhibit (in general) better mechanical properties.*[752]

*8.2-Shape-Memory Polymers_*

As mentioned at the beginning of this chapter, the second group concerning SMM are Shape-Memory Polymer, which are also very important, specially in the bio-medical and bio-mimetic design industries. They are basically plastics that can go from shape A to shape B as in SMA but this thanks to a different molecular process.

"A shape memory polymer (SMP) is able to regain its original shape after a deformation that seemed irreversible. Two sorts of shapes are (in general) distinguishable with the one way shape memory effect. There is a temporarily shape and a permanent shape."[753]

On that matter, Lendlein and Kelch have observed that *the temporarily shape is repeatedly modifiable while the permanent shape is in most cases defined during the fabrication process.*[754] According to Noor et al., the energy type required to activate the memory effect depends on the material compositon:

"The transition between the temporarily shape and the permanent shape is triggered by an external stimulus. The type of added energy that is able to trigger a SMP depends on the specific polymer, but the most common type is thermal energy."[755]

On another hand, Liu et al. have noticed that other types of shape-memory polymers exist or are under development since *another type of energy that can trigger a SMP is radiation with an electromagnetic wave.*[756] Basically, polymers are long chains of small molecules called monomers. *Because of length of*

752 Thijssen, E. (1992, 06). *GEHEUGENMETAAL.* Retrieved 06 2011, from alexandria.tue.nl: alexandria.tue.nl/repository/books/628681.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 1

753 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

754 Lendlein, A., & Kelch, S. (2002). *Shape-Memory Effect - From temporary shape... ...to permanent shape.* Retrieved 06 2011, from www.eng.buffalo.edu: http://www.eng.buffalo.edu/Courses/ce435/Lendlein02.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

755 Noor, A. K., Venneri, S. L., Paul, D. B., & Hopkins, M. A. (1999, 01 10). *Structures technology for future aerospace systems.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

756 Liu, C., Qin, H., & Mather, P. (2007, 03 19). *Review of progress in shape-memory polymers.* Retrieved 06 2011, from http://lcs.syr.edu: http://lcs.syr.edu/faculty/mather/Mather/2007/2007%20j%20mater%20chem%20liu%20review%20of%20progress.pdf

these chains, polymer properties are largely dependent up the arrangement of those chains and interactions between those chains and their sub-parts.[757] Polymer categories are *thermoplastics, thermosets and elastomers.*[758] Shape-Memory Polymers are part of a specific kind of thermoplastics that are also elastomers, therefore emergent properties come arise from their cross-linked monomer structures. In their 2002 article on the german journal *Angewandte Chemie, titled Shape-Memory Effect: From temporary shape. . . T > 46 °C . . .to permanent shape*, , Andreas Lendlein and Steffen Kelch concentrated on shape-memory polymers establishing that, as a consequence of their easy manufacture and programming, they *represent a cheap and efficient alternative to well-established shape-memory alloys.*[759] Since *the consequences of an intended or accidental deformation caused by an external force can be ironed out by heating the material above a defined transition temperature*[760]*,* these plastics promise, notwithstanding their lack of structural performance and application possibilities, more flexibility and re-usability in lightweight and lean applications, properties which are attributed to *the given flexibility of the polymer chains.* [761] Also establishing the fact that the specifics of shape-memory behavior varies from one given compound to another. *Shape-memory behavior can be observed for several polymers that may differ significantly in their chemical composition.*[762]

*8.2.1-Programming_*

In their paper, Lendlein et al. describe the programming process as a a different sorto of "training" one, where fabrication determines or "imposes" the permanent shape, differing to SAM's process where the material is trained to achieve both shapes.

"*First, the polymer is conventionally processed to receive its permanent shape. Afterwards, the polymer is deformed and the intended temporary shape is fixed. This process is called programming. The programming process either consists of heating up the sample, deforming, and cooling the sample, or drawing the sample at a low temperature (so called ™cold drawing∫). The permanent shape is now stored while the sample shows the temporary shape. Heating up the shape-memory polymer above a transition temperature T_{trans} induces the shapememory effect."...*

As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

757 Chai, Shutsu, *Op. Cit.* (2006) P.15.

758 Idem.

759 Lendlein, Andreas, Kelch, Steffen, *Op. Cit.* (2002) P. 2035.

760 Idem.

761 Idem.

762 Idem.

...As a consequence, the recovery of the stored, permanent shape can be observed. Cooling down the polymer below the transition temperature leads to solidification of the material, however, no recovery of the temporary shape can be observed. The effect described is named as a one-way shapememory effect. By further programming, including mechanical deformation, the work piece can be brought into a temporary shape again. This new temporary shape does not necessarily match the first temporary shape."[763]

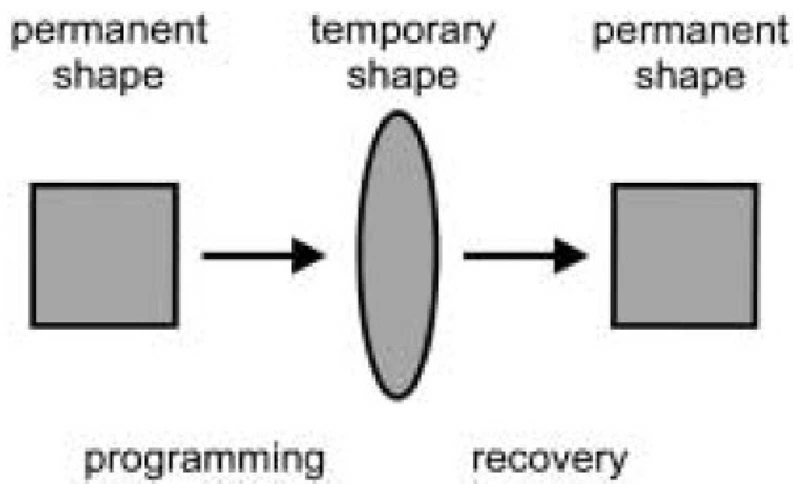


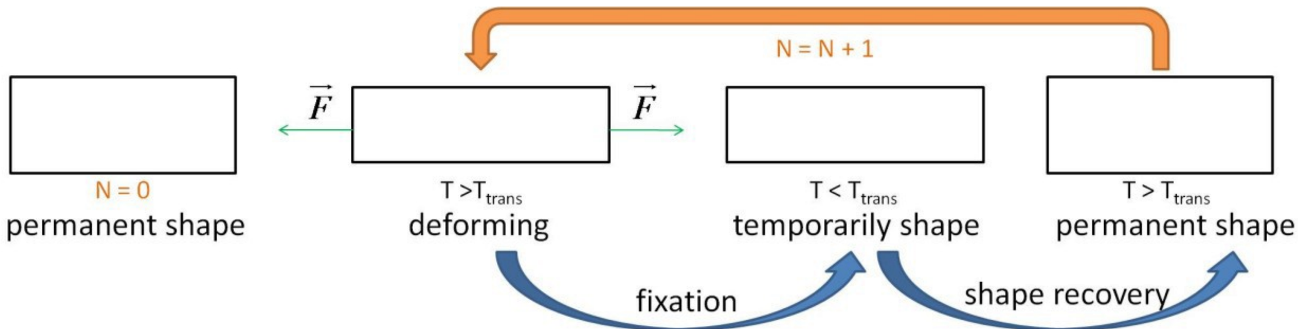
Figure 1. Schematic representation of the thermally induced one-way shape-memory effect. The permanent shape is transferred to the temporary shape by the programming process. Heating the sample to a temperature above the switching transition Ttrans results in the recovery of the permanent shape. Andreas Landlein et al. (2002) (Lendlein, Andreas, Kelch, Steffen, section: Shape-Memory Effect: From temporary shape. . . T > 46 °C . . .to permanent shape, Angewandte Chemie, WILEY-VCH Verlag GmbH, 69451 Weinheim, Germany, (2002) P. 2035.)

8.2.2-Transition temperatures_

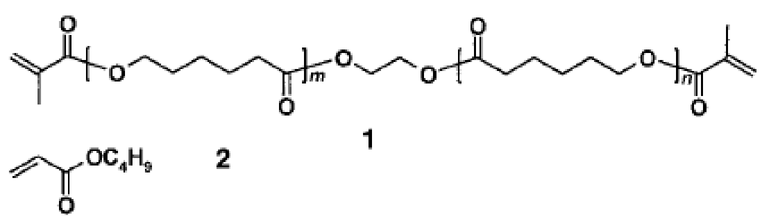
"These elastic materials show at least two separated phases. The phase showing the highest thermal transition T_{perm} *acts as the physical cross-link and is responsible for the permanent shape. Above this temperature the polymer melts and can be processed by conventional processing techniques such as extrusion or injection molding. A second phase serves as a molecular switch and enables the fixation of the temporary shape. The transition temperature for the fixation of the switching segments can either*

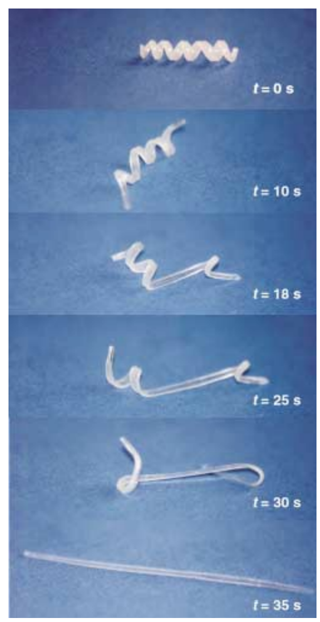
[763] Lendlein, Andreas, Kelch, Steffen, *Op. Cit.* (2002) P. 2035.

be a glass transition (T_g) or a melting temperature (T_m). After forming the material above the switching temperature, but below Tperm, the temporary shape can be fixed by cooling the polymer below the switching temperature. Heating up the material above T_{trans} again cleaves the physical cross-links in the switching phase. As a result of its entropy elasticity (see Section 2.1.3) the material is forced back to its permanent shape."[764]



Principle of the thermally induced one way shape memory effect., Rottiers Ward (2011) (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. P. 7)





Transition from the temporary shape (spiral) to the permanent shape (rod) for a shape-memory network that has been synthesized from poly(-caprolactone) dimethacrylate (1) and butylacrylate (2; co-monomer content: 50 wt%; see Section 2.6.2). The switching temperature of this polymer is 46C. The recovery process takes 35 s after heating to 70C. Andreas Lendlein et al. (2002) (Lendlein, Andreas, Kelch, Steffen, section: *Shape-Memory Effect: From temporary shape. . . T > 46*

[764] Lendlein, Andreas, Kelch, Steffen, *Op. Cit.* (2002) P. 2036.

°*C . . .to permanent shape*, Angewandte Chemie, WILEY-VCH Verlag GmbH, 69451 Weinheim, Germany, (2002) P. 2037.)

Shape-memory polymers can be engineered into what is called *polymer systems* or, more accurately, families of polymers that allow for macroscopic properties to be controlled via variation of molecular parameters[765] that as a consequence opens up a whole sea of material, molecular specific applications.

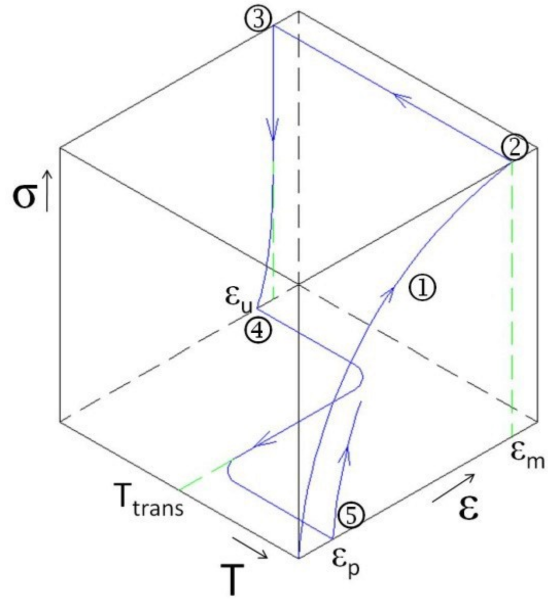
"This makes it possible to tailor the specific combination of the properties of the shape-memory polymers that are required for specific applications just by a slight variation of the chemical composition. The shape-memory material presented in Figure 2(sic) belongs to a family of multiphase polymer networks that are biocompatible and biodegradable. Such materials are highly interesting for applications in the field of minimally invasive surgery."[766]

*8.2.3-Thermo-mechanical cycle_*

Ward et al. propose a mechanical modeling of the properties exhibited by SMPs, which is useful for architectural scale applications, for the moment, this research will focus on macroscopic descriptions in order to provide basic understanding of the phenomena, later in this chapter we will engage with molecular behavior in more detail in order to determine if it is possible to dive into multi-scalar performance modeling leading to animated simulations using the selected software instruments and implementation methods.

"The macroscopic behavior can be quantified in several load cases [7]. The following load case is a tensile load. This thermo-mechanical cycle is useful to compare shape recovery and shape fixation properties of different SMPs.[767]

765 Lendlein, Andreas, Kelch, Steffen, *Op. Cit.* (2002) P. 2037.
766 Idem.
767 Liu, C., Qin, H., & Mather, P. (2007, 03 19). *Review of progress in shape-memory polymers.* Retrieved 06 2011, from http://lcs.syr.edu: http://lcs.syr.edu/faculty/mather/Mather/2007/2007%20j%20mater%20chem%20liu%20review%20of%20progress.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 7



Graphic results of a thermo-mechanical cycle with a shape memory polymer [7] where σ represents stress and ε represents strain. Mohr, R., Kratz, K., Weigel, T., Lucka-Gabor, M., Moneke, M., & Lendlein, A. (2005) (Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Shape Memory Materials and their applications*, Lessius University College, Belgium. P. 7)

The steps in macroscopic behavior can be broken in a series of variables that are analog to the steps in shape-memory transformation, these are:

- *"Origin: permanent shape is visible. (σ* **[stress]** *and ε* **[strain]** *equals zero)*
- *1: Deforming to the desired temporarily shape*
- *2 : The desired temporarily shape is achieved.* $\varepsilon = \varepsilon_m$
- *2-3: Decrease of the temperature below* T_{trans}
- *3-4: Removal of the stress by removing the material out of the testing machine*
- *→2-4: Fixation of the temporary shape*
- *4-5: Increase of the temperature above* T_{trans}
- *→ Shape recovery"*[768]

768 Lendlein, A., & Kelch, S. (2002). *Shape-Memory Effect - From temporary shape... ...to permanent shape.* Retrieved 06 2011, from www.eng.buffalo.edu: http://www.eng.buffalo.edu/Courses/ce435/Lendlein02.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 7

According to Ward et al., this thermo-mechanical cycle depicts two imperfections:

“The actual thermo-mechanical cycle shows two imperfections. The difference between εm and εu indicates that the actual temporarily shape differs from the desired temporary shape. The other imperfection is that after 1 cycle an irreversible plastic deformation εp appears. These imperfections can be quantified in two key figures. These key figures summarize the thermo-mechanical cycle.”[769]

1) The strain recovery rate is defined as[770]*:*

$$R_r(N) = \frac{\varepsilon_m - \varepsilon_p(N)}{\varepsilon_m - \varepsilon_p(N-1)}$$

“The strain recovery rate is a coefficient that expresses how well the permanent shape is approached after the shape recovery process. Rr values above 99% are possible [7]! When this thermo-mechanical cycle is run through N times, εp(N) - εp(N-1) reduces when N enlarge. This is because the polymer chains re-organize in function of the applied deformation during the first cycles.”[771]

2) The strain fixity rate is defined as[772]*:*

$$R_f(N) = \frac{\varepsilon_u(N)}{\varepsilon_m}$$

“The strain fixity rate is a coefficient that expresses how less the actual temporarily shape differs from the desired temporarily shape. This coefficient expresses the efficiency of the fixation process.
The work needed to stretch the SMP is stored in the material as latent strain energy during the fixation of the temporarily shape. Therefore the shape recovery process is energetically possible.”[773]

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769 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 7-8.

770 Lendlein, A., & Kelch, S. (2002). Shape-Memory Effect - From temporary shape... ...to permanent shape. P. 2041. Retrieved 06 2011, from www.eng.buffalo.edu: http://www.eng.buffalo.edu/Courses/ce435/Lendlein02.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 8.

771 Idem.

772 Idem.

773 Liu, C., Qin, H., & Mather, P. (2007, 03 19). *Review of progress in shape-memory polymers.* Retrieved 06 2011, from http://lcs.syr.edu: http://lcs.syr.edu/faculty/mather/Mather/2007/2007%20j%20mater%20chem%20liu%20review%20of%20progress.pdf

According to Lendlein et al., the most important aspects or properties that describe SMP's material macroscopic manifestation and behavior are Maximum entropy (ME) and polymer cross-links (CL).

*"The behavior of the polymer chains is dictated by their urge to seek the most energetically favorable state. Therefore a state with a **maximum of entropy** is the most probable state because the inner energy is identical for every conformation. The polymer chains are strongly coiled in this state. This most favorable state is achieved when the macroscopic form is the permanent shape which is achieved during fabrication. Note that the temporary shape is less favorable compared to the permanent shape."*[774]

Liu et al. seem to agree, adding that polymer chains do not seem to disentangle or slip during the deformation process *because of the* ***covalent cross-links between the polymer chains***.[775]

"Therefore the permanent shape is still "remembered" by the material. The permanent shape is fixated by the cross-links who are almost unbreakable. These cross-links are constituted during fabrication (casting, molding ...) and therefore the permanent shape is almost not adaptable afterwards. A mechanical overload that breaks the cross-links can be considered as memory loss."[776]

Lendlein et al. cite these two as the most defining aspects of SMPs and their memory effect.

"These two properties (cross-links and maximum entropy) explain why the material returns to its permanent shape after a shape recovery. The reason why the polymer chains return to the favorable conditions in terms of entropy is called entropy elasticity."[777]

As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 8.

774 Lendlein, A., & Kelch, S. (2002). Shape-Memory Effect - From temporary shape... ...to permanent shape. P. 2039. Retrieved 06 2011, from www.eng.buffalo.edu: http://www.eng.buffalo.edu/Courses/ce435/Lendlein02.pdf
As quoted by:
Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 8.

775 Liu, C., Qin, H., & Mather, P. (2007, 03 19). *Review of progress in shape-memory polymers.* Retrieved 06 2011, from http://lcs.syr.edu: http://lcs.syr.edu/faculty/mather/Mather/2007/2007%20j%20mater%20chem%20liu%20review%20of%20progress.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 8.

776 Idem.

777 Lendlein, A., & Kelch, S. (2002). Shape-Memory Effect - From temporary shape... ...to permanent shape. P. 2039. Retrieved 06 2011, from www.eng.buffalo.edu: http://www.eng.buffalo.edu/Courses/ce435/Lendlein02.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 8.

According to Lendlein et al., the two explain the "rigidity" of the permanent shape (in the case of ME and CL together acting as a single mechanism) and the material's ability to return or "remember" the permanent shape. As opposed SMA where the mechanisms are based in "twinned" and "de-twinned" martensitic transformations.

*8.3-SMP compared to SMA_*

For Ward et al., differing with Lendlein et al., SMAs represent a more "popular" choice in SMM application cause of their stronger structural capacities, inherent in their material nature even though SMPs show more attractive biodegradation, compared low price and better "memory" among other positive characteristics. But hey do state that, in the end, the choice between them depends on the end application. *Both groups of smart materials have different properties. The choice between SMP and SMA (and of course the specific material) depends on the application itself.*[778] In this respect, there are opposite feelings and expectations regarding some authors.

While Lendlein et al. seem to advocate the development of SMP with the biomedical industry as a main target, they state:

"The SMPs have much better shape memory properties compared to SMAs.1 Another advantage of SMPs is their relatively low price. Some SMPs are also biodegradable which can be useful in medical applications. Therefore are SMPs in some cases a good alternative for the more used SMAs [7]. Polymers have (in general) a lower density, lower Young's modulus and a lower melting temperature compared to alloys."[779]

Liu et al. seem to favor SMAs with structural performance as their motif for speculation and forseen applications, they assert:

"The advantage of the SMAs is their better mechanical properties. Alloys are in general stiffer than polymers. But the SMAs generate also more stress during recovery than SMPs. Guidance values for the

778 Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 10.
779 Lendlein, A., & Kelch, S. (2002). Shape-Memory Effect - From temporary shape... ...to permanent shape. P. 2035-57. Retrieved 06 2011, from www.eng.buffalo.edu: http://www.eng.buffalo.edu/Courses/ce435/Lendlein02.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 8.

generated stress during shape recovery are 1-3 MPa for SMPs and 150-300 MPa for SMAs [8]. This explains why many applications are still made out of SMAs."[780]

So the application itself will determine which material type should be used in SMM based kinetic, self-assembly or self-organizing structures design-simulation-fabrication, decision making process and therefore model in the experiments phase in chapter IX.

*8.4-Hydrophilic Polymers_*

In a 2014 article in *Nature* magazine's *Science Reports*, a multi-institutional and multi-disciplinary team composed by researchers Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar and Skylar Tibbits, published a method that scientifically describes and quantifies a series of new-made "self-evolving" structures projects, along with some of the earlier experiments show in SAL's previous work, and others not published before the fact, utilizing the same principles and design and production tools stated in their curriculum. This work was done thanks to the collaboration of various industry companies and research institutions:

"Camera Culture Group, Media Lab, Massachusetts Institute of Technology, 75 Amherst St, Cambridge, MA, 2Bio/Nano/ Programmable Matter Group, Autodesk Research, 3Self-Assembly Laboratory, 4Stratasys, Singapore University of Technology and Design, Bio/Nano/Programmable Matter Group, Autodesk Research."[781]

And although they do not state their work as shape-memory polymer applications, it is obvious that the technology they use and implement is part of the SMP world, as state by Lendlein et al. and Ward et al. and previously shown in this chapter. Therefore this research considers it a part of SMM and SMP, and will analyze it as foundation for the case studies later on in chapter IX. The difference between this specific publication and the previous ones about 4DP and PM is that it actually discloses the

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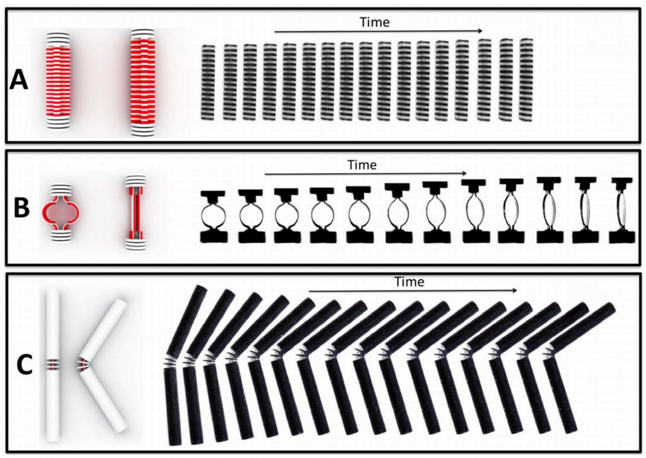
[780] Liu, C., Qin, H., & Mather, P. (2007, 03 19). *Review of progress in shape-memory polymers.* Retrieved 06 2011, from http://lcs.syr.edu: http://lcs.syr.edu/faculty/mather/Mather/2007/2007%20j%20mater%20chem%20liu%20review%20of%20progress.pdf
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 8.

[781] Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 1

engineering and part of the material science behind their almost “magical” material configurations thus serving as a reliable source of information and technical data to use when translating shape-memory phenomena into computational simulation models, therefore the will be used as technical data source in the experiments. Basically, they designed two multipurpose, multi-adaptable joint and folding systems that coupled with rigid plastic parts to conform bending/stiff material matrices that they called “stretching primitives”. In short they are *an assembly of rigid disks with expanding materials in the middle. By adjusting the ratio of expanding materials to rigid disks, it is possible to control the length of stretching.*[782] There are two joint controller designs or , the “linear stretching primitive” or “disk” design and the “ring stretching primitive” or “ring” design. In the disk design model, the disks in the center act as “stoppers” and by adjusting the distances between the middle disks (stoppers) it is possible to control the folding angle[783]. Whereas in the ring design model, which is based on the ring's expansion into a bar, by controlling the the ring's radius it is possible to adjust its stretch length.[784]



(A) Left: rendered illustration of the linear stretching primitive. It is an assembly of rigid disks with expanding materials in the middle. By adjusting the ratio of expanding materials to rigid disks, it is possible to control the length of stretching. Right: video frames of the fabricated primitive stretching in water over time. (B) Left: rendered illustration of the ring stretching primitive. This is based on expansion of the ring shape into a bar. We adjust the stretching length by controlling the radius of the ring. Right: video frames of the fabricated primitive stretching in water over time. (C) Left: rendered illustration of the folding primitive. This design is also composed of bars and disks. The disks in the center act as stoppers. By adjusting the distances between the stoppers it is possible to set the final folding angle. Right: video frames of the fabricated primitive folding in water over time, Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits

[782] Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 2
[783] Idem.
[784] Idem.

(2014) (Raviv, Dan et al. , *Active Printed Materials for Complex Self-Evolving Deformations*, Scientific Reports, Nature, P. 2)

They built simulations using a "spring-mass" model with non-linear constraints, to avoid to fully encompass the folding and stretching behavior they observed int their physical models. And although they emphasize that they did not simulate movement in the molecular scale, but *but learned the kinematics movement of the entire model.*[785] *Our* [the team's] *simulator is based on the Nucleus system18 from Autodesk embedded in a design platform called Project Cyborg, with additional functionality to better simulate the temporal behavior of our materials.*[786] For simulation purposes, through an angle-distance evaluation, they were also able to quantify and parametrize a set of ecuations, formulations based in Strenght, shear and twist[787] that attempted to describe the material's kinetic behavior and compare it to actual physical model data.

These are the equations:

"*Given N disks the radius of the folding angle a can be approximated as* [:]

$$\alpha \approx \frac{Nd}{r}.$$

Where *D* = disk diameter and *d* = disk thickness.

Total length on rings:

$$l \approx \alpha\left(r + \frac{1}{2}d\right) \approx \alpha\left(\frac{Nd}{\alpha} + \frac{1}{2}d\right) = Nd + \frac{1}{2}d\alpha$$

[788]

Where *r* = folding radius and *l* = total length.

785 Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 4
786 Idem.
787 Idem.
788 Idem.

"*We* [they] *divided the joint by uniformly inserting the disks, hence, for these **N + 1** links each of the segment will have a length of **l/(N+1)**. Finally, the length of all other links (marked as red lines in Figure 2C), are evaluated using triangular similarity. Folding with additional stretching: Once stretching is added to the system we provide additional elasticity to the tips of the bars while preserving the length of the centered section (marked as purple in the Figure 2E). As before we evaluate the angle between connected bars, however, we now consider two angles on both sides of the bar, denoted as* $\boldsymbol{\alpha}$ *and* $\boldsymbol{\beta}$*. We further denote the length of a bar i in between joints* $\boldsymbol{P_i}$ *and* $\boldsymbol{P_{i+1}}$ *as* $\boldsymbol{L_i}$*, and the length of the joints which is the sum of their center links as* $\boldsymbol{l_{Pi}}$ *and* $\boldsymbol{l_{Pi+1}}$ *, respectively. The latter were calculated as was described above. Now, the center section of a bar is approximated as* [:]

$$L_i = \|P_i - P_{i+1}\|_2 - \frac{l_{P_i}}{2} - \frac{l_{P_{i+1}}}{2}$$

[789]

"*From the dual radius folding angles a, b and centered bar length Li we approximate the remaining rest length of the bar's springs. As can be seen in Figure 2E, we first consider one folding radius as the mean of a double sided folding by* [:]

$$r = \frac{L_i}{4}\left[\tan\left(\frac{\alpha}{2}\right) + \tan\left(\frac{\beta}{2}\right)\right]$$

[790]

...and it immediately follows that for an arbitrary spring a of radius d its rest length becomes [:]

$$L_\alpha = \frac{d}{r} L_i.$$

"[791]

[789] Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 4

[790] Idem.

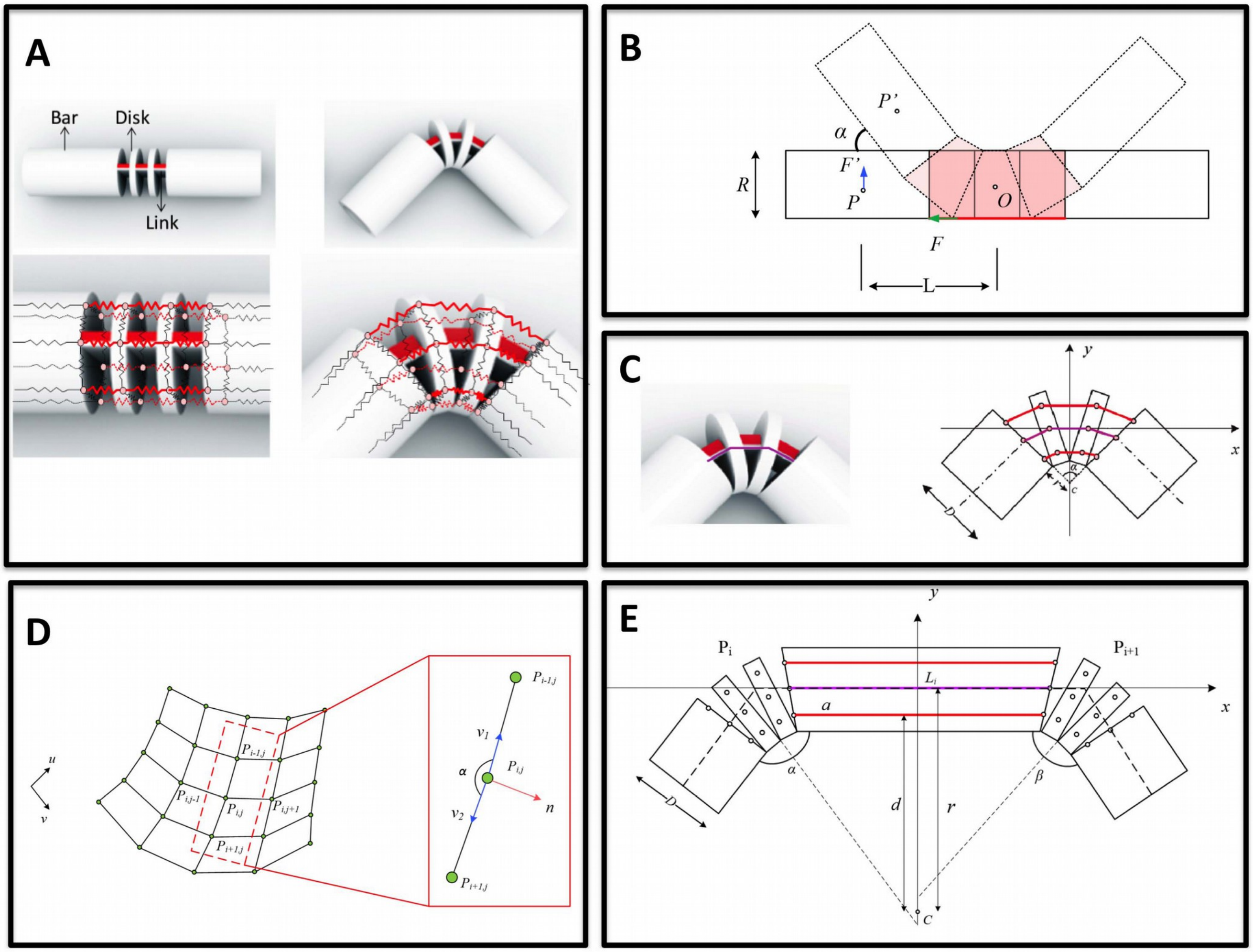
[791] Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 4

Using this method, they were able to prove that a variety of complex, self-evolving geometries and derived structures can be fabricated and simulated. As stated in their conclusions, they were able to build 1D, namely the SAL and MIT letter/strands models. 2D folding models transforming a 2D grid into both a sinusoidal wave and a hyperbolic surface.

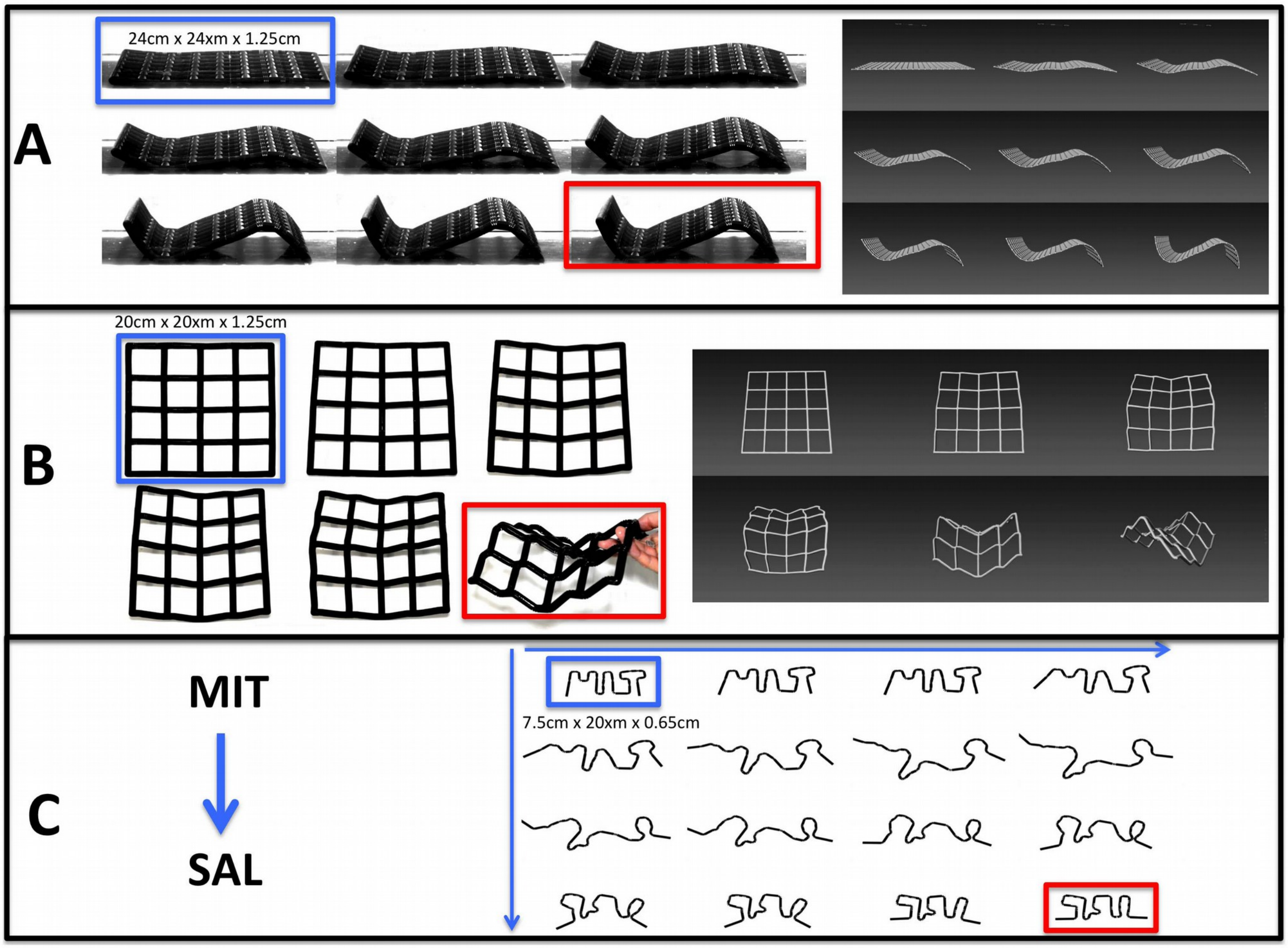
"*In these examples, only rigid folding joints are used, while stretching primitives are not embedded. The sinusoidal wave is isometric to the grid and the Gaussian curvature remains zero, thus, folding alone provides strong results. For a hyperbolic surface, since stretching occurs, we only obtain the approximated final deformation, yet the result is reasonably accurate.*"[792]

And ultimately 2D folding/stretching models that deformed a 2D grid into a double curvature surface (concave and convex).

[792] Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 5



(A) Renderings of an initial joint and its folding (upper row), with their corresponding spring-mass systems shown in the lower row. The lateral black springs represent the rigid bars and disks. The red springs represented the links that cause the joint to fold. (B) Variables in this schematic are used for calculation of stiffness coefficients. (C) Illustration of computing the joint length. Each joint is modeled using two disks, and the length of each inner limb is calculated according to its distance from the center of rotation. The center link (marked as purple) remains constant in time. (D) Illustrations of the folding angle and axis. (E) Illustration of computing the bar length for a folding and stretching element. We evaluate the angles between connected bars a, b and the bending radius r. The length of the centered section (marked as purple) remains constant in time, while the length of the remaining elements (e.g. a) are approximated accordingly, Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits (2014) (Raviv, Dan et al. , *Active Printed Materials for Complex Self-Evolving Deformations*, Scientific Reports, Nature, P. 5*)*



(A) Deformation of a grid into a sinusoidal wave. From left to right and top to bottom, we observe the grid as it folds into the desired shape. Only angular primitives were used. (B) Deformation of a grid into a hyperbolic surface. On the top we visualize the fabricated model and on the bottom the simulated version. The final deformation provides a reasonable approximation despite using only folding bars in the simulation. (C) Fabricating a time-varying curve. From left to right and top to bottom, the curve deforms over time to a different shape, Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits (2014) (Raviv, Dan et al. , *Active Printed Materials for Complex Self-Evolving Deformations*, Scientific Reports, Nature, P. 6*)*

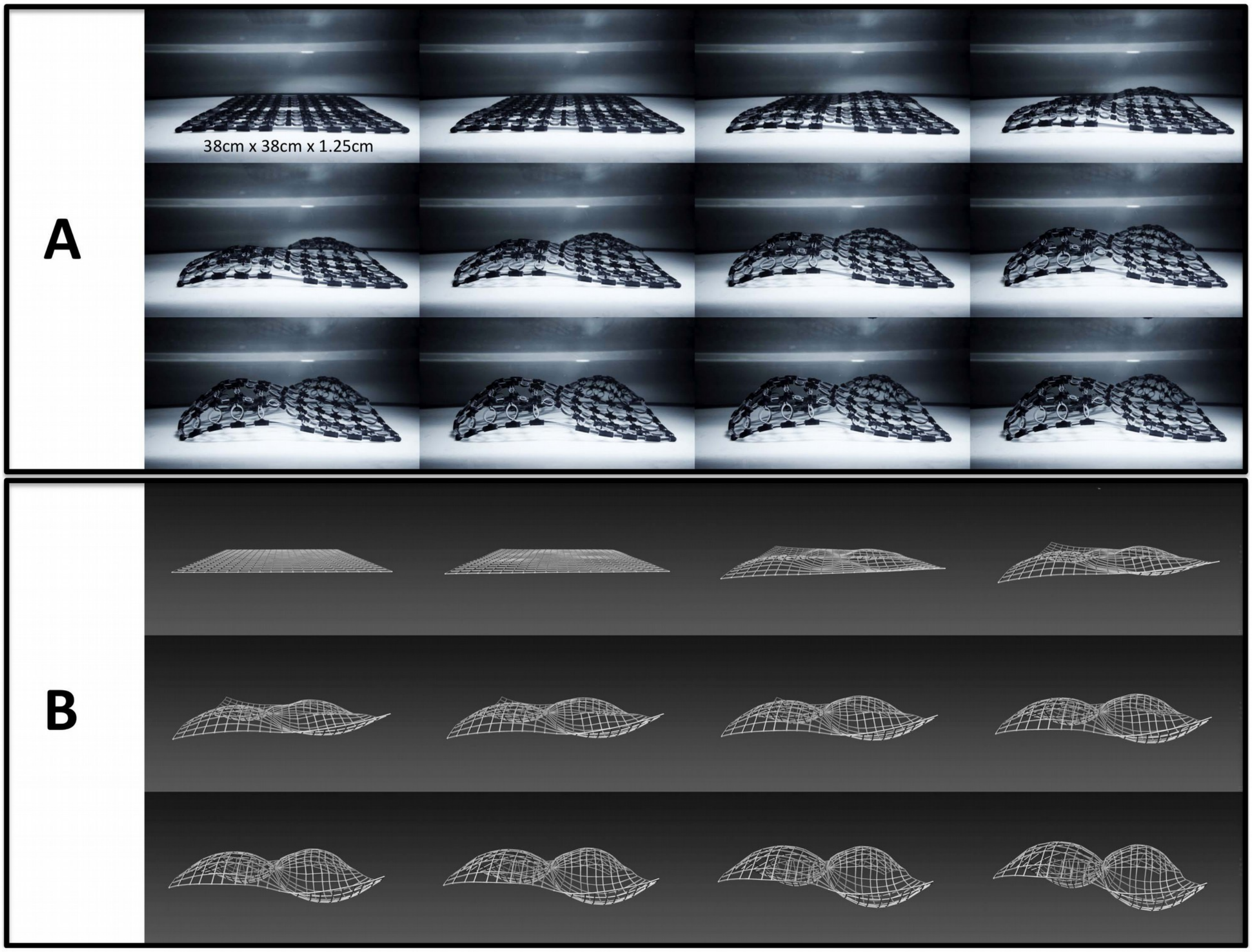


Figure 5 | Deformation of a grid into a double curvature surface (convex and concave). The time line follows the orders of left to right and top to bottom. The printed schematics (initial grid) can be seen in Figure 2C, Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits (2014) (Raviv, Dan et al. , *Active Printed Materials for Complex Self-Evolving Deformations*, Scientific Reports, Nature, P. 7*)*

*8.5-Limitations of 4DP_*

Even though these experiments showed tremendous potential and displayed an enormous set versatility when it comes to application and design method integration, it does come at a price, according to the team's experience, there are still limitations that raise concerns, including "memory loss", stretching length limitations, life span related phenomena.

"*Several limitations must be taken into consideration:*

1. The linear expansion is fragile and limited to 30% of the linear stretching primitive, which can be improved by exploring new materials. Although the ring stretching primitive does not suffer from this limitation, the spatial sampling of the grid restricts it.

2. Reversibility of the transformation may be currently limited if the desired application requires many cycles of folding/unfolding or wetting/drying. Further testing is required to fully understand the complete lifespan of the materials and the degradation. However, our initial tests suggest that there is mechanical degradation due to many cycles of repeated folding/ unfolding and degradation of the expanding material due to repeated wetting/drying cycles. However, with a small number of cycles the parts are able to fully recover their original shape upon drying and once dipped in water again, they transform once more.

3. We have only explored behavior of the structure due to water immersion, while other activating mechanisms such as heat and light can be used and are currently in development.

4. ***The simulation based on a spring-mass system provides strong results, however, the physical system is not constructed of springs and masses, which means that a solid simulation might provide more realistic results. In the future, we plan to evaluate the physical properties of the expanding materials and simulate their behavior on the molecular level..”***[793]

Highlighted here is a key consideration that, in the scope of this research will not be possible, but which will be attempted to achieve what was briefly outlined in the previous chapter as “material design” which basically means to achieve multi-scalar modeling to parametrically simulate lower level servo mechanisms that trigger higher level actuation and physical macroscopic material behavior.

*8.6-Conclusions_*

Possibilities and applications in virtually every domain that we can think of, promise of biodegradability (therefore enforcement of sustainable agendas in design) and spacecraft adaptability to unknown habitats (engaging with space exploration scenarios)in real time and directly responding to

[793] Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 6

changing to environmental changes and to different environments among other considerations and criteria, make applicability in architecture all the more imminent and makes the case of this research the more necessary for the present and next generation of architects that will, most likely, design on other planets.

8.6.1-Possible future applications_

"*The future will see aerospace vehicles made from programmable multifunctional materials and structures that will have the possibility to adjust their shape and mechanical, electromagnetic, optical and acoustic properties on demand."*[794]

However, not only the vast world of space exploration will benefit from these shape-shifting new structures and devices, but everyday life itself will be reshaped, from the most common to the most significant implications, the way we do everything and use everything, the time taken, the efficiency, effectiveness. *A commercial use of this technique can be a damaged car bumper that regains its original shape after heating.*[795] From flight technology to crane and load bearing techniques and methods in commercial delivery and international commerce and trade. Noor et al. express similar expectations:

"*Smart rotorcraft blades and aircraft wings will be one of the first applications of smart material in aerospace."*[796] **"***They could increase the maneuverability and controllability by changing the shape of their control surface. In this way it is possible to manipulate lift and twist. Or it can be used to reduce drag."*[797]

[794] Noor, A. K., Venneri, S. L., Paul, D. B., & Hopkins, M. A. (1999, 01 10). *Structures technology for future aerospace systems.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/

Lagoudas, D. C. (2008). *Shape Memory Alloys - Modeling and Engineering Applications.* Springer.

As quoted by:
Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

[795] Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

[796] Noor, A. K., Venneri, S. L., Paul, D. B., & Hopkins, M. A. (1999, 01 10). *Structures technology for future aerospace systems.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/

As quoted by:
Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

[797] Noor, A. K., Venneri, S. L., Paul, D. B., & Hopkins, M. A. (1999, 01 10). *Structures technology for future aerospace systems.* Retrieved 06 2011, from ScienceDirect: http://www.sciencedirect.com/

Although, among other concerns like up-scaling and fabrication standardization. *Memory loss is a main concern of the smart technology and therefore concerns an important matter*[798], which remains unsolved and a clear setback in SMM incorporation in multiple way shape-memory applications, especially for architectural efficiency and effectiveness, which at the same time that it should comply with AEC industry readability, has to withstand environmental, construction and operation conditions and parameters that can be, at times, as uncertain, wild and unpredictable as a weather forecast. This remains a core concern in this research's experiments questions to be answered: Do simulations processes help clearing out uncertainty? Environmental insertion and analysis? And if such is the case. How?

Concerns to further develop to be able to achieve KA through PM, specifically using SMA and SMP:

1. Scaling up systems to address architectural applications and scale.

2. Fabrication standardization and industrial implementation, meaning that we need to make their fabrication and programming processes cheaper in order to fully profit from all their promises and in all fields of application.

3. Memory loss is the main obstacle as it hinders effectiveness and re-usability thus diminishing its sustainability potentialities.

4. Architecture, as a discipline, has to embrace these technological advances and probably include them, some way or another, in school curricula and graduate programs as standart practice.

5. Design studios need to start profiting from these material configurations and matrices for in this field lies the future of architecture, not just kinetic, but the field at large.

Djavareshkian, M., Esmaeli, A., & Parsani, A. (2011). *Aerodynamics of smart flap under ground effect* Retrieved 07 2011, from ScienceDirect: http://www.sciencedirect.com
As quoted by: Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6
[798] Ward, Rottiers, Van den Broeck, Laurien - Peeters, Chris – Arras, Peter, *Op. Cit.* (2011) P. 6

*9-Performance Software implementation in the PM based Kinetic Architecture design process_*

In chapter VII, Dennis Dollens provided a digital strategical *modus operandi* which comprised the combination of several software tools (including animation and parametric software) after which it was established that, although it does open up oceans of possibilities in morphogenetic and form-finding processes, animation software lacks functionality to successfully simulate, not only SMM, but kinetic architectural design at large and that parametric modeling in a design environment proves to be a more adequate method in [799]*that design is not something an architect does with a 'completed parametric model', but rather something that happens iteratively throughout the parametric modelling process,* therefore animation software cannot provide the necessary modeling traits (other than the kinematic aspects of a given kinetic design). Based on this fact, this research has established that the most popular software tools do not provide faster, more accurate and resource economical method and hence a more intuitive, tactile and organic KA, PM design and research process (Currently one in which the designer has to go through to "understand" and merely separate the *motions with the most potential*[800] -in Fenwick's and El-Zanfaly's cases), reproduce already built structures (in Fotiadou's case) is a long, time consuming and tortuous process of, almost blindly, choosing movement that are to be subsequently tested with physically built models and outside references, not entirely a counter productive method but, as this research has established, it is now possible to optimize this process, even if we still use physical models, to a level where the designer can scan different ideas and possible outcomes *a priori.* Thus promising a more organic relationship with the KA design decision making process. A context that suggests a *practice whereby the tool user and toolmaker are indistinguishable*[801]*,* or as Michael Weinstock has suggested and as we established in chapter II, *to be a craftsman in the digital age, you have to be a tool maker, you have to make digital and fabrication tools.*[802] This is a shared belief within some of the most important software engineers and computational design architects in contemporary literature and professional world. Namely Mark Burry (director of Antoni Gaudi's project construction of La Sagrada Famìlia's completion) and Edsger Dijkstra (a belief that, in Dijkstra's case, dates back to

[799] Davis, Daniel, *Op. Cit.* (2013) P. 211
[800] Fenwick, Tess, *Op. Cit.* (2011) P. 57
[801] Davis, Daniel, *Op. Cit.* (2013) P. 211
[802] Weinstock, Michael, "Fabrication Intelligence: Michael Weinstock", *The Embedded Intelligence Lecture Series, Architectural Association video lectures*, London, (2015) (https://www.youtube.com/watch?v=LiNvucaCd5E) (18/03/2015)

1970).

"Computers are extremely flexible and powerful tools and many feel that their application is changing the face of the earth. I would venture the opinion that as long as we regard them primarily as tools, we might grossly underestimate their significance. Their influence as tools might turn out to be but a ripple on the surface of our culture, whereas I expect them to have a much more profound influence in their capacity of intellectual challenge."[803]

Dijkstra 1970, 7

And Burry agrees, citing Dijkstra and paraphrasing his initial user/toolmaker comparison axiom with a contemporary designer/software engineer one:
He continues:

"the tool user (designer) becomes the new toolmaker (software engineer)" (M. Burry 2011, 9 [brackets are Burry's]). This unification of the user and the maker calls into question the distinction between user and maker that has been inherited from other CAD software."[804]

Artists and architects are often reluctant to get into psycho-rigid and time consuming tasks as to program and carry out mathematical analysis when they are coming up with their ideas. But that has been changing for some time. For Casey Reas, creator of *Processing*, what is important is to somehow be present in both realms *"What I do envision is a new breed of artist… a man who is extremely competent in both technology and the arts."*[805] And in this idea Reas seems to agree with Burry, Davis et al. can be a paradigm shift within the practice of art at large.

"Existing programming languages and environments have been written by software engineers to meet their specific needs, which have always been different from the needs of artists. The open-source software movement has provided a way for artists to collaborate on the production of their own tools.

[803] *Dijkstra, Edsger. 1968. Notes on Structured Programming*. Second Edition. Eindhoven: Technological University of Eindhoven.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 209
[804] Davis, Daniel, *Op. Cit.* (2013) P. 209.
[805] Reas, Casey, *Op. Cit.* (2006) P. 33

It is my hope these open-source art software initiatives (see http:/ www.artsoftware.org) will serve as a catalyst for a dramatic shift in the use of software within the arts."[806]

Based on these statements, this thesis original project was to build a complete software package or a plug in that could simulate SMM material behavior in order to produce parametric models that would in turn generate design environment simulation in the decision making process in kinetic intelligent systems, but another researcher was a lot faster and efficient at achieving this. As of March 2011, Daniel Piker, a design systems analyst at *Foster + Partners* and developer at *Mcneel*[*] developed and released a *"live Physics (sic) engine for interactive simulation, optimization and form-finding directly within Grasshopper"*[807]*,* itself embedded within the *Rhinoceros* (at the time version 4.0) work-space, this physics engine is known as Kangaroo. Grasshopper, itself being a plugin within Rhinoceros[*] developed, works "remembering" the model step by step, meaning *rhino history is recorded while you model and can then be played back, Grasshopper history is defined from scratch while the model is created as an afterthought.*[808] Also returning to what has been established in chapter II, that *anybody involved in any job that ultimately creates instructions that are executed by a computer, machine or* ***even a biological entity****, can be said to be programming.*[809] Be it visual or script programming we argue that the experiments in this chapter, although not developing the actual add-on to Grasshopper (GH), have contributed to Kangaroo's (Kgr) development by building custom code configuration using it to reproduce actual or approximate physical situations and building reusable definitions that other designers can take advantage of and develop further. Therefore it is established that the tool user in fact becomes the toolmaker in that while using the tool (GH) he can also develop the tool's specific applications (code writing and scripting). From the literature in chapter IX we have derived a theoretical data-flow diagram to reveal algorithmic variable relationships that could, in turn, provide with insight in the construction in flexible parametric models to simulate SMM behavior in macroscopic manifestation. Even though graphics do not look alike, this research's data-flow diagram

806 Reas, Casey, *Op. Cit.* (2006) P. 33

* Mcneel is software the company that developed Rhinoceros and Grasshopper (the work of David Rutten, originally named Explicit History which itself was developed *as a way to automate tasks without the need to write textual code*).

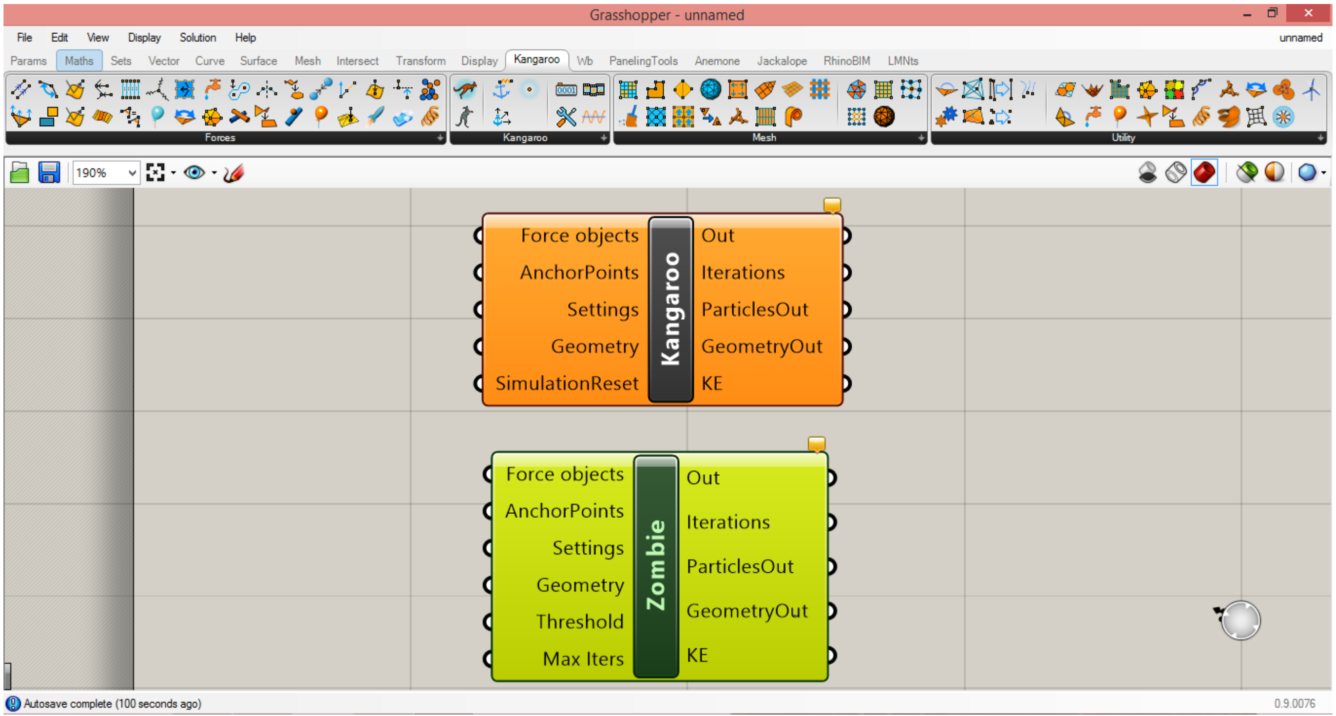
807 Piker, Daniel, *Kangaroo Physics*, Food 4 Rhino.com, (blog) (http://www.food4rhino.com/project/kangaroo?page=2&etx=) (2011) (02/12/2014)

* Original development lead by David Rutten as a way to automate tasks without the need to write textual code.

808 Rutten, David, "GH's Origin", *Grasshopper3d.com*, (blog post comment thread (http://www.grasshopper3d.com/forum/topics/gh-s-origin) (2007) (11/02/2015)

809 Rutten, David, "Programming: Conflicting Perspectives"*, I Eat Bugs For Breakfast* (blog) (2012) (https://ieatbugsforbreakfast.wordpress.com/?s=anybody+involved+in+any+job+that+ultimately+creates+instructions+) (11/02/2015)

to model SMM can be evaluated and developed using the same principles of CC, being that they can be applied to virtually any case of code structure as Davis has demonstrated in his research. So we proceeded to evaluate the aforementioned diagram with McCabe's simplified formula for CC shown in the next figure.



Kangaroo physics engine and "zombie" engine (version 0.099), Daniel Piker (2011) The normal engine runs physical simulations using newton's classical mechanics laws and the "zombie" component basically does the same but with a limit introduced by the user, it either sets a threshold factor or a maximum number of iterations that turn-off the actuating forces.

In 2013 Daniel Davis wrote a thesis about flexibility in parametric modeling called *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture.* In which he successfully measured some aspects (both qualitative and quantitative) of parametric modeling's "cost of change" problematic in relation to project development, meaning that he was able to, probably for the first time in history, define a set of criteria by which directly address the development of parametric models that are opened to change in the late phases of architecture projects, which is when changes in design cost the most. While also questioning the nature of contemporary design practice in relation to computation and, specifically parametric modeling's intertwined with software development structure oriented conceptual framework. "*My* [Davis's] *research tentatively indicates that designers require some understanding of software engineering to get past the point of making tools that solve isolated* *tasks."*[810]

"Admittedly there is something counter intuitive to the notion that programmers can teach architects about contemporary design representation but, while it can be hard to discern, in some respects the contemporary practice of architecture has more in common with the software engineers of Silicon Valley than the sketchpads used by previous generations of architects."[811]*A*

Davis remarks in his thesis that *Schultz, Amor, and Guesgen demonstrate that testing methods "inspired by research in software engineering" may be applied to "qualitative spatial" problems* [and] *this presents an opportunity to expand the practice of parametric modelling by borrowing new programming paradigms from software engineers.*[812] Davis's thesis argued that parametric models can be built from bottom-up logic setting up the lower level rules before the overall form and late aspects of the project would be defined and still be cost and resource effective. In order to do so he also researched software engineering's classification about programming languages, more adequately referred to as "programming paradigms". *A programming paradigm in this context is the set of underlying principles that shape the style of a programming language.* [813] Although making an important clarification in that *an important caveat is that creating software is similar, but not identical, to creating architecture.*[814]. But that the two have connections settled on:

"...shared challenges, shared research methods, and shared design practices. These connections position software engineering as an important precedent for architects; a relationship that has implications for how parametric modelling is taught, for how parametric modelling is integrated in practice, and for how we conceive of parametric modelling."[815]

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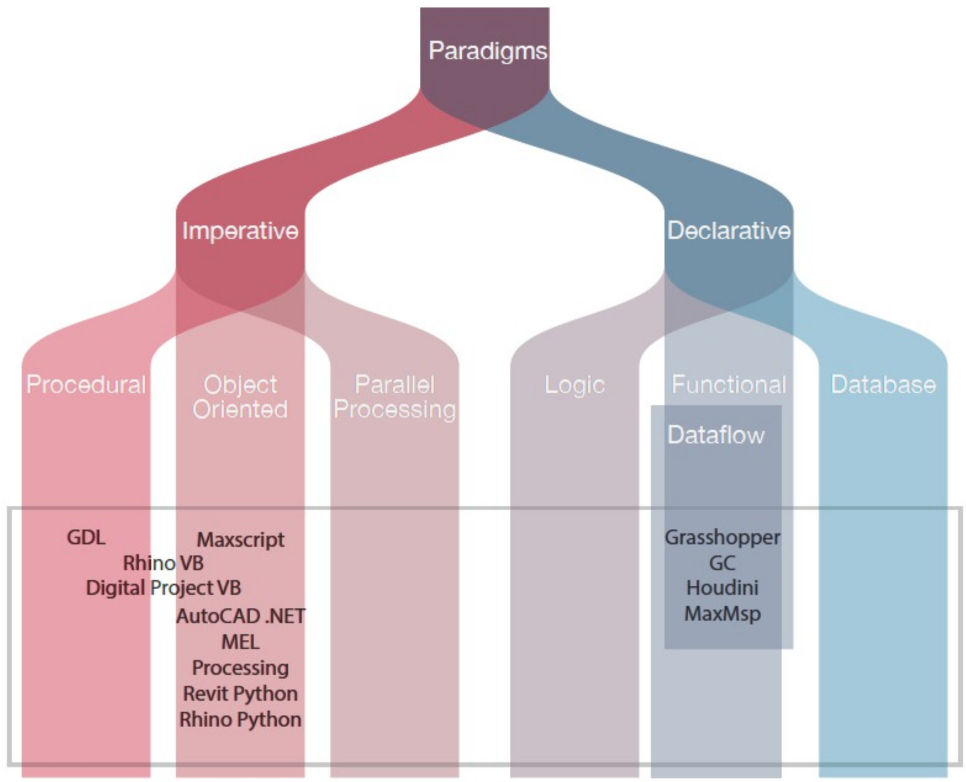
810 Davis, Daniel, *Op. Cit.* (2013) P. 204.
811 Ibid. P. 212.
812 Schultz, Carl- Amor , Robert- Guesgen, Hans, "Unit Testing for Qualitative Spatial and Temporal Reasoning." In *Proceedings of the Twenty-Second International Florida Artificial Intelligence Research Society Conference*, Lane Chad and Hans Guesgen, Florida: AAAI Press, (2009), P. 402–407.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 65.
813 Op. Cit. Davis, Daniel, *Op. Cit.* (2013) P. 99.
814 Ibid. P. 196.
815 Ibid. P. 194.

*9.1-Imperative & Declarative paradigms in parametric modeling_*

"Programming paradigms are roughly divided by Van Roy and Haridi (2004) as well as others like Appleby and VandeKopple (1997) into imperative paradigms or declarative paradigms (fig. 32). Imperative languages describe a sequence of actions for the computer to perform – much like imperative verbs in the English language. In contrast, declarative languages "define the what (the results we want to achieve) without explaining the how (the algorithms needed to achieve the results)" (Van Roy and Haridi, 2004, 114). Imperative and declarative languages can be further classified into more specific paradigmatic subcategories, as shown in figure 32. Most programming languages are based on at least one of these subcategories, and many spread out to embody multiple paradigms within the one language."[816]

Figure 16: The programming languages architects use categorised by Appleby and VandeKopple's (1997, xiv) taxonomy of programming paradigms.



Programming languages architects use categorized by Appleby and VandeKopple's (1997, xvi) taxonomy of programming languages, Daniel Davis (2013) (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 62)

According to Davis, architects only take advantage of a small stream in programming paradigms,

[816] Op. Cit. Davis, Daniel, *Op. Cit.* (2013) P. 99-100.

because:

"*...the major textual CAD programming languages4[*] are all predominantly imperative with a bias towards procedural programming; whereas, the major visual CAD programming languages5[*] all reside in a very narrow subsection of declarative programming known as data-flow programming. While the two bands of paradigms occupied by CAD programming languages are well researched, they are ultimately limited. For architects this means they have a confined range of styles available to express ideas programmatically."*[817]

Daniel Davis has pointed out that programming paradigms are a substantial element in the practice of parametric modeling in that they *influence – at the very least – the parametric model's construction time, modification time, latency, and extendability.* [818] Based on Davis's findings, this research is compelled to test generally one programming paradigm: ***declarative paradigm***. Future research work will involve how to test their combination in the form of Python scripting implemented into Grasshopper to produce a new add-on for that interface, as a hybrid ***imperative/declarative in-between paradigm***. Python belonging to ***imperative programming*** while Grasshopper to a subsection of ***declarative programming*** called ***data-flow programming***. Having revised various sources as basis for his software engineering evaluation, Davis settled the one single document that, in his optics, best described the practice of software engineering in a away that could be translated into parametric modeling's practice, the document is the *Software Engineering Body of Knowledge 1.0* (or SWEBOK.1999 1.01 as proposed by Hilburn, Hirmanpour, Khajenoori and Turner in 1999, which is a general compendium of competences and skills needed to achieve the status of software engineer. The process of development of the software is defined, in a general manner, by two models, the Waterfall model, developed in the 1980s (which privileges linear Gant-like stages and information front loading) and the Agile model, which privileges prototyping and constant testing (which has reduced the costs considerably while soared success rates for most software development projects). The former was coined by Winston Royce in 1970 as *a common way to suppress change*[819]*,* the latter was coined in

[*] This includes: 3dsMax: Maxscript; Archicad: GDL; Autocad: AutoLISP; Digital Project: Visual Basic; Maya: Maya Embedded Language; Processing: Java; Revit: Visual Basic & Python; Rhino: Visual Basic & Python; Sketchup: Ruby.

[*] This includes: Grasshopper; GenerativeComponents; Houdini; and MaxMsp.

[817] Davis, Daniel, *Op. Cit.* (2013) P. 63.

[818] Ibid. P. 117.

[819] Royce, Winston, "Managing the Development of Large Software Systems." In *Proceedings of IEEE WESCON*, (1970) P. 328–338.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 65

2001 in a *Manifesto for Agile Software Development*[820] by Kent Beck; in itself derived from research that measured the cost of change in software development projects, as a reacting practice shift due to immensely low success rates in the software development business starting in the 1960 (a historical process that is known as the *Software Crisis)* a problem that would last nearly 40 years to be really overcome, and that can be both summarized in two graphs (Kent and Boehm's curves) show below these lines.

Figure 12: Boehm's curve plotted on a linear scale (Beck 1999, 26).

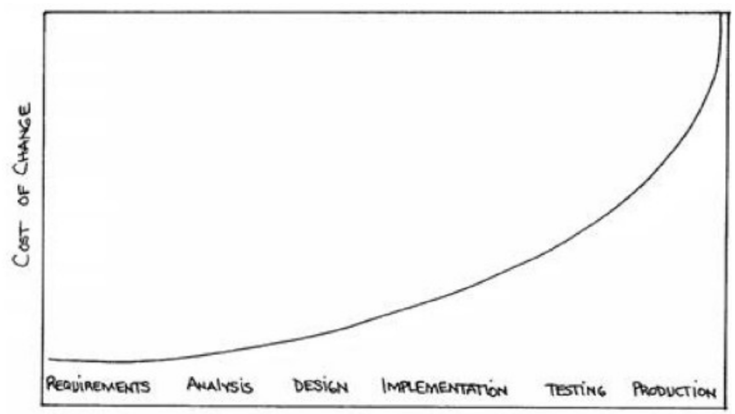
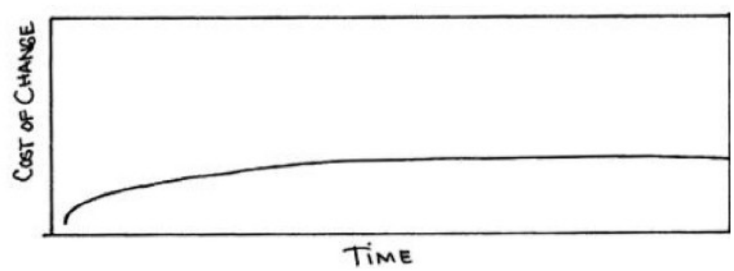
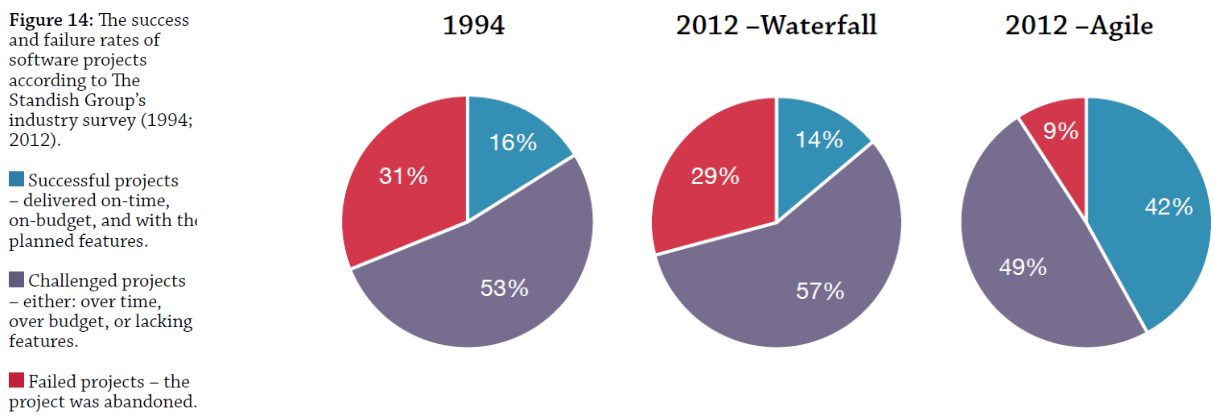


Figure 13: Beck's curve (1999, 28). There are no project stage demarcations on the horizontal axis because the relatively constant cost of change allows the project to cycle rapidly through iterations, which enables traditionally early stage activities, like developing the project requirements, to continue late into the project – and vice versa (Beck 1999, 28).



Boehm's curve, Barry Boehm (1976) plotted on a linear scale and *Beck's curve,* Kent Beck (1999) (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, RMIT University, P. 54)

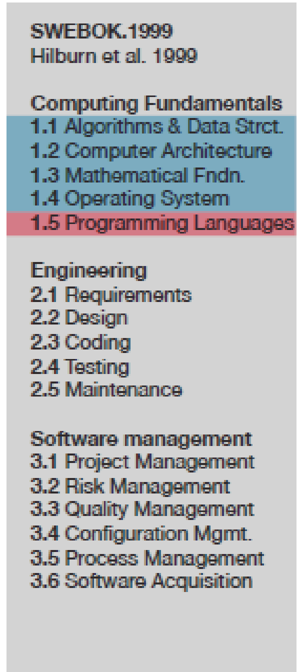
820 Beck, Kent – Beedle, Mike - van Bennekum, Arie - Cockburn , Alistair - Cunningham, Ward – Fowler, Martin - Grenning, James, *Manifesto for Agile Software Development* (2001) (http://agilemanifesto.org/.) (18/03/2015) As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 65



The success and failure rates of software projects according to The Standish Group's industry survey (1994; 2012), Daniel Davis (2012) based on: The Standish Group (1994) (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 62)

"...computing fundamentals category and the software management category. While software management reappears in all the other SWEBOK, the computing fundamentals category is unique to the SWEBOK.1999 and covers areas of knowledge – like computer hardware and programming languages – that are potentially applicable to parametric modelling."[821]

[821] Davis, Daniel, *Op. Cit.* (2013) P. 61



SWEEBOK.1999 1.0, list of contents, Hilburn - Hirmanpour - Khajenoori - Turner (1999) (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 61)

"Software Testing [2.4] involves verifying code correctness. Programmers like to automate this process, either by using metrics for measuring performance [2.4.4], or by automated unit testing of the code itself [2.4.1, 2.4.2], or even with quantitative experiments like A/B testing user behaviour. Anecdotally, architects seem to test their models by manually verifying the outputs, which can lead to problems like change blindness."[822]

*9.2-A brief history of CAD_*

"Slightly after Moretti held his Parametric Architecture exhibition in 1960 (Bucci and Mulazzani 2000, 114), Ivan Sutherland (1963) created the first parametric software, Sketchpad. However, it was not until Parametric Technology Corporation released Pro/ENGINEER in 1988 that parametric modelling software became commercially viable (Weisberg 2008, 16.10), and it took at least another decade for parametric modelling software to be specifically designed for architects.[*] *"*[823]

[822] Davis, Daniel, *Op. Cit.* (2013) P. 65
[*] Sutherland, Ivan. 1963. *"Sketchpad: A Man-Machine Graphical Communication System."* PhD dissertation, Massachusetts Institute of Technology.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 22
[823] Davis, Daniel, *Op. Cit.* (2013) P. 62

Sketchpad, Ivan Sutherland (1963). The first parametric software ever created at Massachusetts Institute of Technology. Parametric modeling still remained at large from architecture until the beginning of the 1990's with Frank Owen Gehry's projects for the sculpture in the Barcelona seafront and later the Guggenheim Bilbao.

While the beginnings of computational design can be tracked back to the early 1960's when, according to Ingeborg Rocker, *"...cellular automata were tested across the sciences. In 1968, the theoretical biologist and botanist Aristid Lindenmayer devised – based on chomsky's grammars- L-systems for modeling the growth of plants. L-systems consist of four elements: a starting point, a set of rules or syntax, constants and variables. Diversity can be achieved by specifying varying starting points and different growth times. L-systems grow by writing and rewriting the code, and expression of the code depends on the graphical command selected. They are still used to model plant systems, and to explore the capabilities of computation."*[824] Lindenmayer and other scientists were trying to brake down natural patterns and event evolution, along with developmental biological processes and came up with these methods that highly influenced several domains, mainly in the natural sciences and physics. Yet architectural application of these would not be evident and spread until theoretical thinkers and practitioners as Luigi Moretti started trying to design with algorithmic definitions (even though Gaudí and Frei Otto had already started their gorund breaking work, they remained pretty much the only ones

[824] Rocker, Ingeborg, *Op. Cit.* (2006) P. 21

in the world that were carrying out parametric arrangements in their projects. And while computational design does not mean and is not the same s parametric modeling, they appear to have met in the wake of automatizing computation and parametric modeling, around 1989, Malcom Mcullough, project manager for *Autodesk* in the beginnings of *Autocad*'s commercial insertion states:

"Harvard introduced what may have been the first programming course required for all professional degree candidates in a leading school of architecture. The software basis for this initiative was a program called TopDown, written mainly at UCLA, by Robin Liggett and William Mitchell. This may have been inspired by shape grammars, and in part by the existing pedagogy of teaching design theory through programming, and in part by recent improvements in ready made interface widgets." Top Down provided a visual and dynamic way to combine substitution and dimensional variations on a compositional motif. To make a beginning artefact in it involved in the order of 20 lines of pascal code. Even this was alien..." [825]

Then evidence suggests that pascal code was the first language, at least in an educational environment, that was used to introduce architects to programming and might have just been the beginnings of computational design (in architecture) as a popular method and practice. For simulations (which have been around since more than a hundred years in mathematical problem form) it would take a decade to filter down into the AEC industry with software like *ANSYS, SAP, Pro Engineer* (now known as *PTC Creo Elements/Pro*). Now there are multiple software tools in teh realm of what is known as CAD/CAM (computer-aided design, and computer-aided manufacturing, respectively) and the choice of which to use is just as important as the project to develop and these shown be as consonant as possible nontheless software from outside the discipline can also be introduced to tackle tasks that are not possible or very difficult to achieve with standard tools, as demonstrated by Dollens et al.

[825] Mcullough, Malcolm, "20 Years of Scripted Space", Programming Cultures: Art and Architecture in the Age of Software, *Architectural Design*, Wiley Academy Press, United Kingdom (2006) P. 14

9.3-From a design-fabrication-simulation work-flow to a design-simulation-fabrication one?_

Steps to achieve the design of self assembly and PM, according to Raviv et al., are:

Design:

Propose a computational approach for designing self-evolving structures that vary over time due to environmental interaction.

Fabrication:

Provide an implementable framework by specifying readily printable self-evolving elements that pair with computational models.

Simulation:

Realistically imitate the deformation of the materials for enhancing design capabilities.[826]

Our approach:

Design:

Propose a computational approach for designing self-evolving structures that vary over time due to environmental interaction.

Simulation:

Realistically *modeling* the deformation of the materials for enhancing design capabilities.

Fabrication (which will not be tested in this Thesis's context):

Provide an implementable framework by specifying readily printable self-evolving elements that pair with computational models.[827]

Our goal here is to swap places between the simulation and fabrication stages thus changing the work-flow's order. We speculate that by doing this the designer can have a more fluid, intuitive and fruitful design-to-production process and that the communication between designers and contractors therefore can be more understandable.

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826 Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin -Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 1-2

827 Montás, Nelson (2015) based on:
Raviv, Dan - Zhao, Wei - McKnelly, Carrie - Papadopoulou, Athina - Kadambi, Achuta - Shi, Boxin - Hirsch, Shai - Dikovsky, Daniel - Zyracki, Michael - Olguin, Carlos - Raskar, Ramesh - Skylar Tibbits, *Op. Cit.* (2014) P. 1-2

*9.4-Physics-based simulation: case studies_*

"The idea of animation as simulation provides architects with an additional opportunity to explore new methods of design ideation by approaching design as a set of parameters responding to dynamic, material and variable contextual forces over time."[828]

The case studies were all chosen and developed according to an answer to a specific research question: *Does a digital, all-encompassing, material behavior simulation tool exist?*(which has been already answered and it does not exist, although it remains an ideal for simulation development) *Or, if it does not, can it be created? And then how?*

*9.4.1-Hypothesis_*

The current framework of Design-fabrication-simulation work-flow stated and developed by Raviv et al. can be substituted by a Design-simulation-fabrication-design one using declarative programming to achieve data-flow interactivity, approximated accuracy and rigor when addressing simulation modeling of SMM. As it is evident that Fenwick, Fotiadou, El-Zanfaly and virtually everybody that has attempted to design and build kinetic structures done so through decision making processes with logical, conditional and procedural similarities and, as made evident by Fotiadou's research, especially in the application of digital computational tools. This thesis hypothesizes that, with parametric tools such as Grasshopper and Generative components with embedded physics engines like Kangaroo and adding a share of scripting (either VB, Python, or similar and which has not been developed in this chapter's simulations but that are being currently written by the author as a compilation library for future simulation tool development, this process will take several months and it is tentatively proposed as a post-doctoral research project) it is possible to expand the design capabilities while at the same time to lower the time, resource spending and difficulty rates shown by Fotiadou while raising its success probabilities by achieving and applying what Davis calls "parametric flexibility" to material behavior based KA design within the PM paradigm addressing the question of *how well can we approximate real conditions in the context of simulation?*

[828] Kolarevic, B (ed): 2003, Architecture in the digital age - design and manufacturing, Spon Press, New York, pp.13-28. As quoted by: Attar, Ramtin; Aish, Robert; Stam, Jos; Brinsmead, Duncan; Tessier, Alex; Glueck, Michael; Khan, Azam, *Op. Cit.* (2009) P.2.

9.4.2-Research method_

The case studies in this research have been defined and implemented according to different settings, scales and parametric construction that *might offer a way to understand flexibility without needing to isolate research from practice.*[829] This as the yet to know and master skills of KA design and material programming are still in their infancy, therefore have no real metrics due to lack of population sample, therefore making it irrelevant to provide with statistical analysis (within the PM paradigm) concerning their success and accuracy rates. These were all developed following Ruth Thomas's three step simulation building: model coding, experimentation and implementation (see chapter VI for details).

"*One method is to conduct the investigation from within practice, a method Schön (1983) describes as reflection in action and reflection on action. This method has a constructivist worldview where, according to Creswell and Clark (2007, 24), multiple observations taken from multiple perspectives build inductively towards "patterns, theories, and generalizations." While this may be closer to social science than the hard science origins of software engineering, Andrew Ko (2010, 60) argues such an approach is "useful in any setting where you don't know the entire universe of possible answers to a question. And in software engineering, when is that not the case?"*[830]

This is a particular method that Davis and Schön call *"reflective practice"*[831] and that we could summarize into the phrase "observation and research by doing", a method that borders on inductive and abductive reasoning and which resembles *"Kemmis and McTaggart's (1982) cycle of "planning, acting, observing and reflecting" on actions in practice."*[832] Meaning that, during the research process the path followed is that of "theorizing", "drawing data form other pertinent, similar work", "running experiments" and lastly "observing again" and "reflecting" on the given results. Based on Daniel Davis's findings and following his guidelines and methodology to build parametric models that are oriented to a more flexible and efficient practice. His method was based in Cyclomatic complexity, a concept developed by software engineers to evaluate code structure under a series of tenets that were used to evaluate parametric modeling's "efficiency when facing the cost of change" among other

829 Davis, Daniel, *Op. Cit.* (2013) P. 71
830 Ibid. P. 10
831 Schön, Donald. 1983. *The Reflective Practitioner: How Professionals Think in Action*. London: Maurice Temple Smith. As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 71
832 Kemmis, Stephen, and Robin McTaggart. 1982. *The Action Research Planner*. Geelong: Deakin University. As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 11

instruments, using modules as principle guidelines when constructing logical and algorithmic statements in whatever program's text based API or visual API. Module utilization, generally, has a set of "benefits" that make model sharing, collaboration and flexibility in the practice of parametric design, which we will look at more closely later in this chapter: decomposition, composition, understandability, continuity, protection. The experiments were done using already research and laboratory proven data from peer-reviewed publications on material science and tried to reproduce them using the parametric modeling instruments stated below. Although before going into the actual material's "realistic" definitions, there were some experiments that, using a "generalized" material configuration implementation, tested the programs capabilities to speculate on possibilities concerning fenwick's "unobtaniums" or materials that do not exist, but are desired by designer and thus could be developed in the future.

*9.4.3-Implementation_*

Observation and research by doing, something very close to Schön's "reflective practice", by which to continuously test solutions on a "data-flow" model within a "declarative programming" paradigm, graphic programming environment (in this case Grasshopper version 0.9.0076 + Kangaroo version 0.099 for Rhinoceros 5) to later implement them on a subroutine scripted component (Python script for GH)and then build a full scale software platform (future work). This way is easier to visualize the algorithms working on demand and apply them to specific circumstances without having to go through the "imperative" programming Edit, Compile, Run loop cycle, therefore bypassing time consuming processes that hinder intuitive design decisions that mostly happen on the fly. Utilize these advances to later implement them in a single software package, first as a scripted component inside the Grasshopper environment and later as an "add on" tab in its API (Application Program Interface) and UI (User Interface), embedding it to the Grasshopper environment and expanding its UX (User Experience).[*]

*9.4.4-Cyclomatic Complexity_*

Although there are not enough cases to make a significant statistical table that show any pattern in how users utilize, quantitatively, parametric modeling aimed at designing and producing PM based KA, there is a useful, individual model metric, referred to as "cyclomatic complexity" or (CC) that can help reveal a parametric model's structure thus is able to provide insight into its cognitive understandability

[*] Rhinoceros (Mcneel & Asocs. 1998), Grasshopper (David Rutten, 2006) and Kangaroo (Daniel Piker, 2011).

and therefore revealing hidden knowledge on how it might be shared with other modelers that work on the model but were not its original creator. *The cyclomatic complexity indicates how much work is involved in understanding a piece of code.*[833] And even though CC was intended to to measure code structure within software engineering, Daniel Davis has convincingly demonstrated its usefulness in the context of parametric modeling, which also happens this research's method of choice for implementation.

“In technical terms, the cyclomatic complexity is the number of independent paths through a directed acyclic graph (DAG).

Thomas McCabe formalized cyclomatic complexity's most typical formula[834]:

$$\mathrm{CC}(G) = e - n + 2p$$

Where:
G: the graph.

e: number of edges. I count parallel edges between identical nodes (duplicate edges) as a single edge.

n: number of nodes. I do not count non-functional nodes such as comments in text boxes.

p: number of independent graphs (parts)...

...McCabe's formula assumes the DAG has only one input node and one output node, which is infrequently the case with parametric models. In an appraisal of common modifications to McCabe's original formula, Henderson-Seller and Tegarden (1994, 263) show that “additional (fictitious) edges” can be introduced to deal with multiple inputs and outputs. Thus the cyclomatic complexity formula becomes:

$$\mathrm{CC}(G) = (e + (i-1) + (u-1)) - n + 2$$

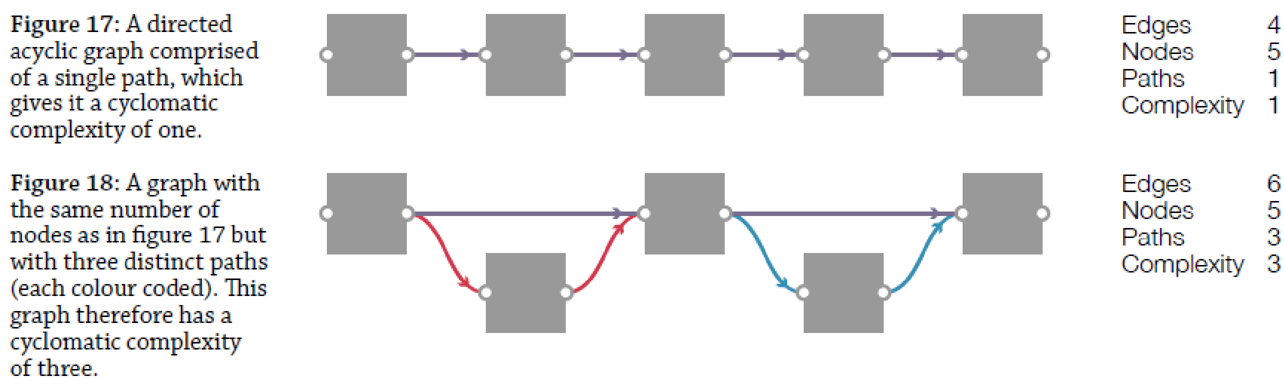
Which (assuming p to be 1) simplifies to:

$$\mathrm{CC}(G) = e + i + u - n$$

833 Davis, Daniel, *Op. Cit.* (2013) P. 78
834 Ibid. P. 77-78

Where:
i: number of inputs (dimensionality).

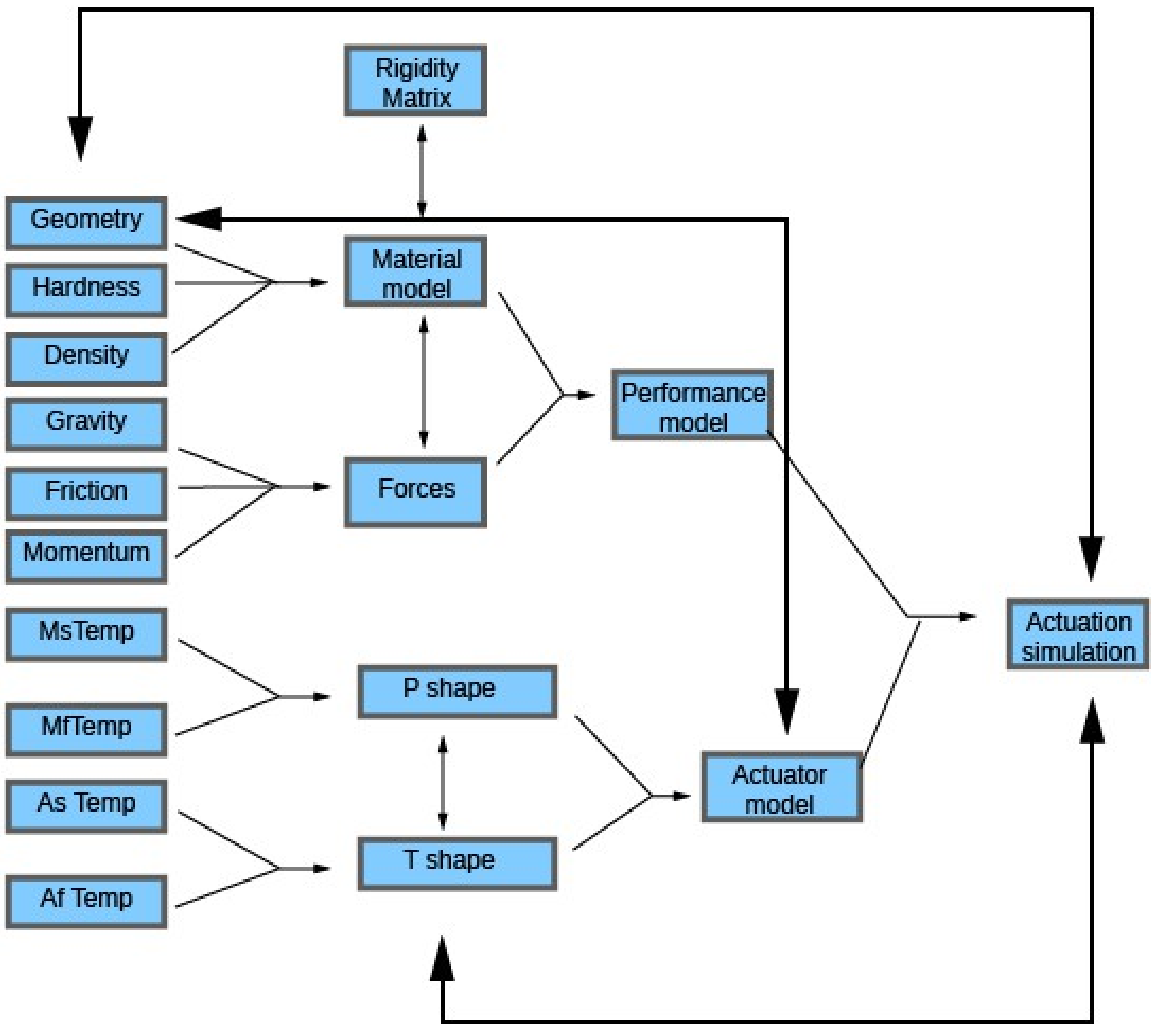
u: number of outputs."[835]



(Top) *A directed acyclic graph comprised of a single path, which gives it a cyclomatic complexity of one.*
(Bottom) *A graph with the same number of nodes as in figure 17 but with three distinct paths (each colour coded). This graph therefore has a cyclomatic complexity of three.* (Daniel Davis (2013) (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 65)

From the literature in chapter IX we have derived a theoretical data-flow diagram to reveal algorithmic variable relationships that could, in turn, provide with insight in the construction in flexible parametric models to simulate SMM behavior in macroscopic manifestation. Even though graphics do not look alike, this research's data-flow diagram to model SMM can be evaluated and developed using the same principles of CC, being that they can be applied to virtually any case of code structure as Davis has demonstrated in his research. So we proceeded to evaluate the aforementioned diagram with McCabe's simplified formula for CC shown in the next figure.

[835] Davis, Daniel, *Op. Cit.* (2013) P. 77-78



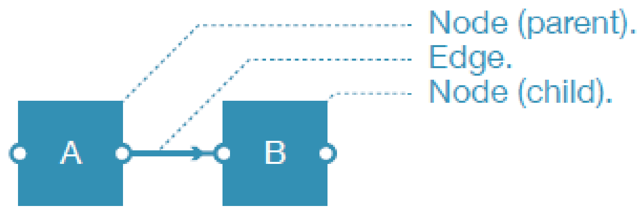
Theoretical data-flow diagram, case study simulation 1, Nelson Montás (2014). Edges: 14, Nodes: 17 , Paths: 14, Inputs: 7; Outputs: 16. Thus applying McCabe's formula we get CC(G) = e+i+u-n = 14 + 7 + 16 + 7 – 17 = 27.

Since Daniel Davis has established that, up until his thesis, the median in the *Grasshopper3d.com* uploaded models database was that of (10), we acknowledge that this diagram which has resulted in a Cyclomatic Complexity of ten (10), even though abstract, is almost three times higher than what was dubbed "medium sized" CC by Davis. Therefore this simple operation suggests that we almost certainly will need to simplify it or rebuild the logical relationships from scratch. One possibility is to embed the first column into the second one as parameters instead of nodes themselves because it is the one column that adds the more edges, nodes, paths, inputs and outputs, therefore increasing its final CC result.

9.4.5-Data-flow programming_

John Sharp's definition of data-flow programming (DFP) in his 1992 book Data Flow Computing is that a DFP is a program *"in which the ordering of operations is not specified by the programmer, but that is implied by the data interdependencies."* [836] What this means is that a data-flow language ways of interconnecting computational operations instead of listing them in precise order (as in imperative programming). The computer derives(or more accurately infers) the order of operations from the set of given operations. *Many visual programming languages operate on a similar principle since the connections between operations can be represented using a type of flow-chart know as a Directed Acyclic Graph (DAG).*[837] The data direction is defined by the parent-child associative relationship, in which *the source of data is termed the parent and the receiver of data is termed the child (fig. 33)...* [Therefore]*dataflow programming removes the need to specify an order of operations.* [838]

Figure 33: The parts of a DAG.



The parts of a DAG, Daniel Davis (2013) (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 101)

Daniel Davis has done an extensive study about analyzing advantages concerning DAG in data-flow driven models and textual models. In the context of his thesis, this was done to compare it to logic programming and imperative programming (a bit like this research does in terms of selecting the right paradigm to make the experimental models) setting the criteria basis for paradigm selection when it comes to implement and code parametric models. Overall underlining the importance of paradigm and specific programming language selection from the start of the project, taking in consideration the given project's aims and reach and highlighting the fact that we as architects do not have a lot of space to

[836] Sharp, John. 1992. "A Brief Introduction to Data Flow." In *Dataflow Computing: Theory and Practice*, edited by John Sharp. Norwood: Ablex.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 101

[837] Davis, Daniel, *Op. Cit.* (2013) P. 101

[838] Ibid. P. 102

choose from when it comes to programming paradigms.

“*Since programming paradigms cannot normally be switched without rebuilding a model, selecting an appropriate programming paradigm for the context of a project is a critical initial decision. This is a decision that has an evident affect on many aspects of a parametric model's flexibility yet, unfortunately, it is a decision largely unavailable to architects; they often cannot choose more, less, or different – just: data-flow or procedural.*”[839]

And he also established that, in fact, the tenets to follow when choosing a paradigm were not very clear to begin with, so it was imperative to devise a set of criteria to follow when doing so. Therefore he studied building the same models implemented using three subsets within the two main programming paradigms, these were mainly Logic Programming opposite both Data-flow (Grasshopper version 0.8.0052), programming and Object Oriented Programming (Rhino Python -in Rhino 5, version 2011-11-08). *Nevertheless, the variance in construction time demonstrates that programming paradigms can significantly affect projects, although these affects are dependent upon the circumstances of the project.*[840]

[839] Davis, Daniel, *Op. Cit.* (2013) P. 117
[840] Ibid. P. 114

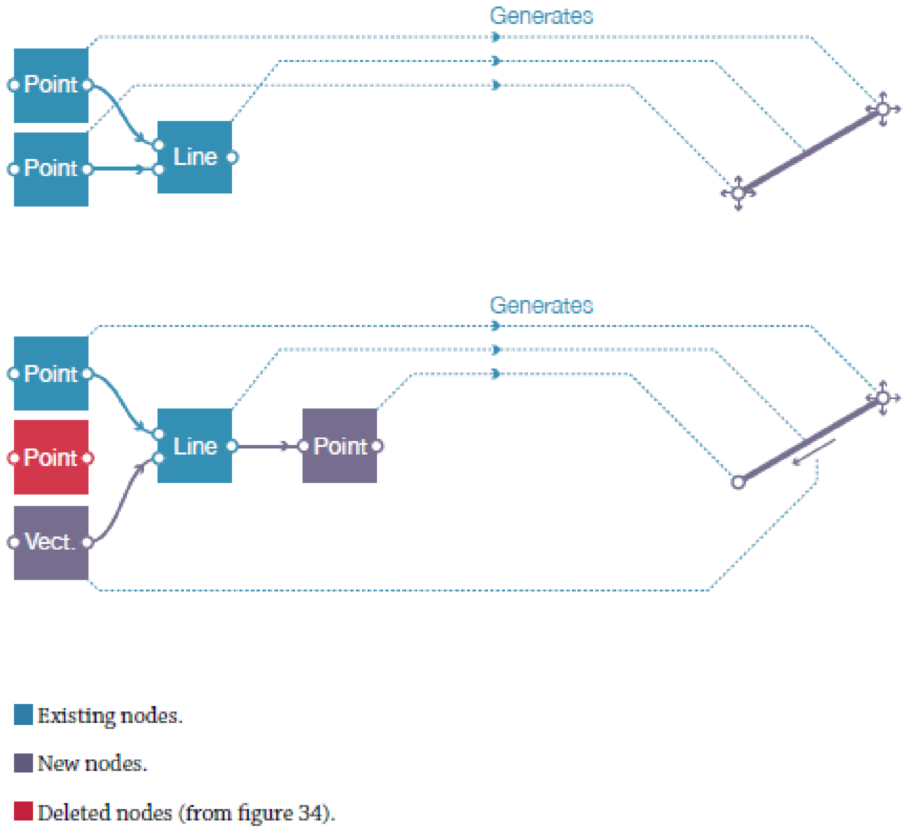


Figure 34: The relationship between a DAG and the geometry it generates. In the DAG the line is a child of the two points, accordingly, the line's geometry depends entirely on the location of the points. Moving the geometry of either point would also move the line.

Figure 35: Modifications to the DAG from figure 34. The geometry is the same but the connections have been changed: one of the points is now a child of the line. In the geometric model, the child point can no longer be moved directly since its location now depends on the line's position (the parent of the point). While the geometry is the same as figure 34, the change in hierarchy requires adding and removing a number of nodes.

The relationship between a DAG and the geometry it generates. In the DAG the line is a child of the two points, accordingly, the line's geometry depends entirely on the location of the points. Moving the geometry of either point would also move the line. Modifications to the DAG from figure 34. The geometry is the same but the connections have been changed: one of the points is now a child of the line. In the geometric model, the child point can no longer be moved directly since its location now depends on the line's position (the parent of the point). While the geometry is the same as figure 34, the change in hierarchy requires adding and removing a number of nodes. Daniel Davis (2013) (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 102)

"We do know that architects tend not to structure their models, with two possible factors being both the education of architects and the way modules are implemented in parametric software."[841]

Regarding their application to a specific case in parametric modeling, this case study involving the Straightening of the Sagrada Família's frontons with a logic programming paradigm and a dataflow paradigm in which logic programming was four to five times faster at building the initial model, but

[841] Davis, Daniel, *Op. Cit.* (2013) P. 135

data-flow was a slightly faster at modification time[842].

"This success does not confirm the agility of dataflow programming as much as it confirms the importance of the designer's intuition in setting up a model's hierarchy, and the importance of what Meyer (1997, 12-13) calls the modelling environment's functionality (having the right vocabulary to express an idea or change)."[843]

Davis theoretically posited that probably it was feasible to reduce modification time in an already built *the challenges of modifying the hierarchy of relationships in a data-flow language and ...the time associated with these modifications could theoretically be reduced if the computer – rather than the designer – organised the parametric model's hierarchy.*[844] Which after realizing the comparison experience he cleared out by stating after the fact that *yet in reality the opposite happened: when used to generate the parametric model of the Sagrada Família's frontons, logic programming actually lengthened the modification time.*[845] Concluding that basically logic programming was better suited for extracting relationships from preexisting parametric models (which is the exact opposite of the typical parametric process[846]. Yet *however, both methods produced large and intricate models that were hard to verify as being correct.*[847] Due to this fact, this research has selected data-flow as its main code environment and when trying to address SMM modeling.

*9.4.6-Structuring code_*

Davis also remarks that, in the light of parametric modeling, authors and eminent software engineers like Edsger Dijkstra, Corrado Böhm and Giusseppe Jacobini[848] had, very early on the software development era, noticed the hazards concerning unstructured code writing in the process of software development and its link with the software crisis failed projects.

"In March 1968, Edsger Dijkstra (1968) wrote a letter to the Association for Computing Machinery

[842] Davis, Daniel, *Op. Cit.* (2013) P. 115
[843] Ibid. P. 117
[844] Ibid. P. 115
[845] Ibid. P. 117
[846] Ibid. P. 119
[847] Idem.
[848] Böhm, Corrado, and Giuseppe Jacopini. 1966. "Flow Diagrams, Turing Machines And Languages With Only Two Formation Rules." *Communications of the Association for Computing Machinery* 9 (5): 366-371.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 126.

entitled Go To Statement Considered Harmful. At the time, the GOTO statement was the primary mechanism of controlling a computer program's sequence of execution (the GOTO statement allows a program to skip ahead or jump backwards in a chain of programming commands). Dijkstra (1968, 148) argued that the intertwined jumps programmers were producing with GOTO statements were "too much an invitation to make a mess of one's program." Building on the work of Böhm and Jacopini (1966), Dijkstra proposed reducing the mess with simple structural commands such as if-then-else, and while-repeat-until. Although these structures now underlie all modern programming languages, they were not an obvious development in 1968."[849]

The introduction of If-else statements, While-repeat-until functions and statements and so on, was a turning point for the software development era and helped greatly surpass the crisis in the years to come, to the point that most contemporary programming languages have adopted this function evaluation notion of program structure. *The benefits of modularisation are so pervasive that some modern programming languages, like C# and Java, make it impossible to write code not contained within some sort of module.*[850] In visual programming environments, their equivalent would be what Sharps denominates a module. *In the lexicon of the various software, modules have come to be known as features*[851] in Bentley's Generative Components, *digital assets* in Sidefx's Houdini, and *clusters* in McNeel's Grasshopper.

9.4.7-Modules_

In their 1992 section article titled *A Specification and Design Methodology Based on Data Flow Principles* in the book *Dataflow computing: Theory and Practice Y*uk Kui Wong and John Sharp define a module as *"a sequence of program instructions bounded by an entry and exit point" that perform "one problem-related task."*[852] According to Davis, modules have great advantages when it comes to code structuring that can be well utilized in the context of parametric modeling which are enumerated next: Decomposition, Composition, Understandability, Continuity and Protection.

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849 Davis, Daniel, *Op. Cit.* (2013) P. 126
850 Ibid. P. 129
851 Ibid. P. 130
852 Wong, Yuk Kui, and John Sharp. 1992. "A Specification and Design Methodology Based on Data Flow Principles." In Dataflow computing: Theory and Practice, edited by John Sharp, 37-79.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 127.

"*If employed successfully, modules have five principle benefits according to Bertrand Meyer (1997, 40-46):*

1.***Decomposition:*** *A complicated problem can be decomposed into a series of simpler sub-problems each contained within a module. Decomposing problems like this may make them easier to approach and may make it easier for teams to work together since each team member can work on a separate sub-problem independently.*

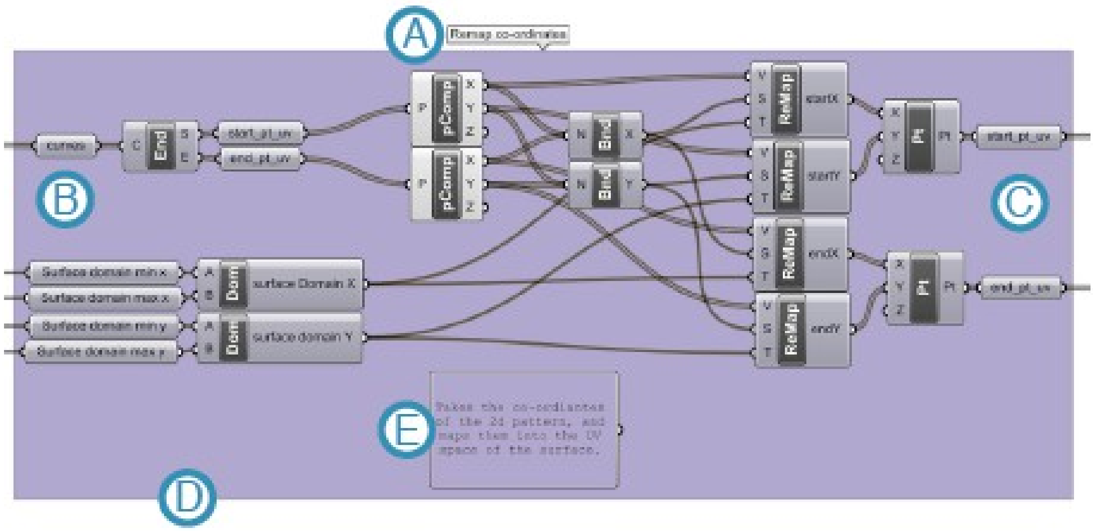
1.***Composition:*** *If modules are adequately autonomous they can be recombined to form new programs (a composition). This enables the knowledge within each module (of how to address a sub-problem) to be shared and reused beyond its original context.*

2.***Understandability:*** *If a module is fully self-contained, a programmer should be able to understand it without needing to decipher the overall program. Conversely, a programmer should be able to understand the overall program without seeing the implementation details of each individual module. Dijkstra (1968, 148) worried this would lead to less transparency but most have since argued that abstraction helps understandability. For instance, Thomas McCabe (1976, 317) has posited that modularisation improves understandability since it reduces the cyclomatic complexity, making it "one way in which program complexity can be controlled." Meyer (1997, 54) points out that modularisation aids a programmer's comprehension of the code through the names given to inputs, outputs, and the module itself.*

1.***Continuity:*** *A program has continuity when changes can be made without triggering cascades of other changes. In a program without continuity, changing one module will affect all the dependent modules,*

setting off a chain-reaction as all the dependent modules are changed to accommodate the original change and so on. Continuity has much to do with how a program's structure is decomposed. David Parnas (1972, 1058) suggests that projects should be broken around "difficult design decisions or design decisions which are likely to change" so that each anticipated change is contained within a module in such a way that it does not impact the other modules.

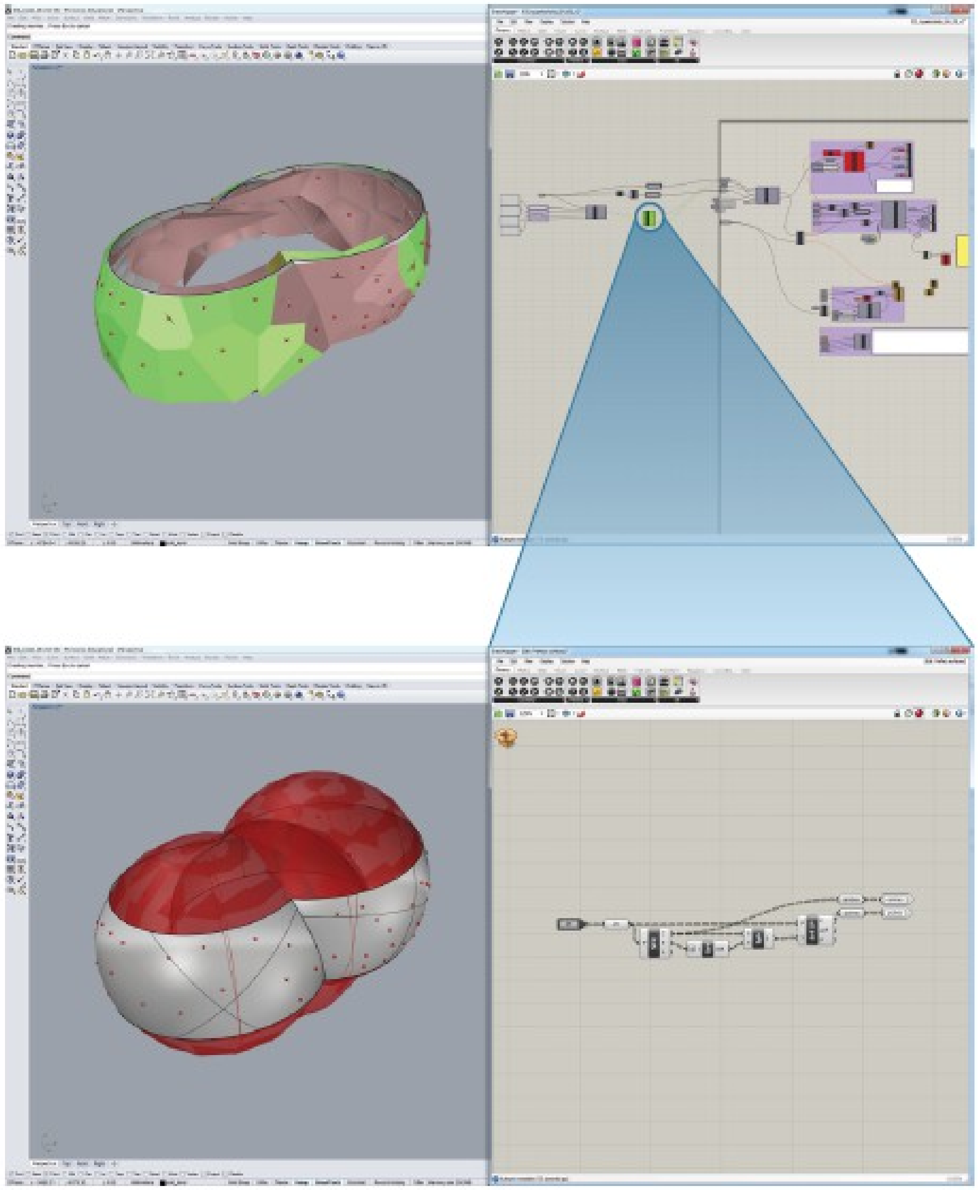
5. ***Protection:*** *Each module can be individually tested and debugged to ensure it works correctly. But if something does go wrong within a module, the module can contain the error and thwart its propagation throughout the program (protecting the rest of the modules from the error).”*[853]



successfully, modules have five principle benefits according to Bertrand Meyer (1997, 40-46):

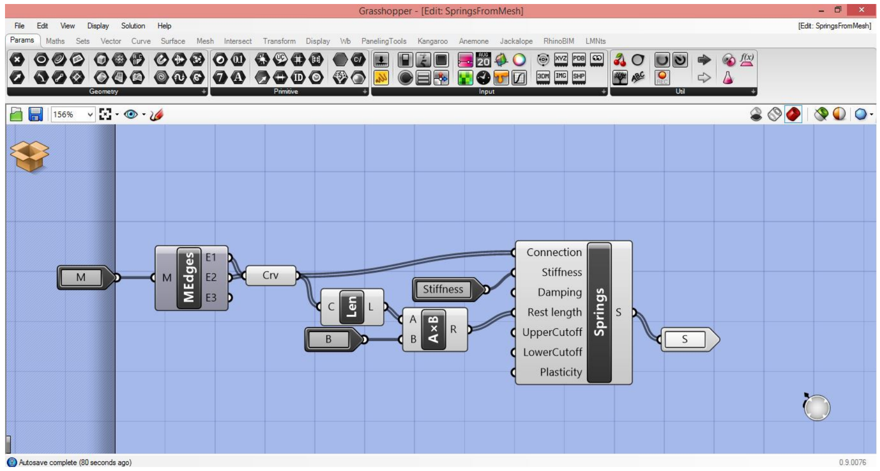
A typical module in Grasshopper. The grey boxes are operations (themselves small modules) that have been linked together to form a larger module. More recent versions of Grasshopper have native support for modules (which are called clusters in Grasshopper) however at the time of my research this version of Grasshopper had not been released.
A: The name of the module. B: The inputs – the only place data enters the module. C: The outputs – the only place data leaves the module. D: The operations of the module are encapsulated so that they can only be invoked by passing data through the module’s inputs. E: A description of what the module does – a module does one problem-related task. Daniel Davis (2013) (Davis, Daniel,

[853] Davis, Daniel, *Op. Cit.* (2013) P. 128-129.

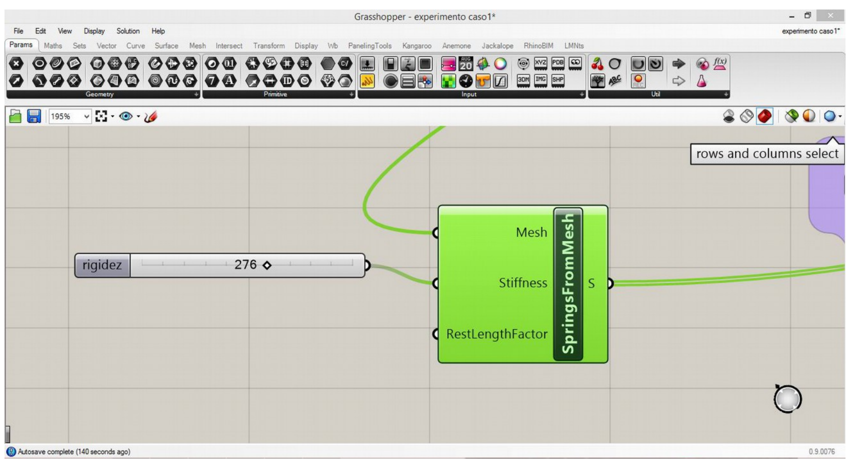


Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture, P. 128)

A cluster in Grasshopper (a model used in chapter 7 by Davis -2013- for the FabPod). Top: The full parametric model with the cluster in its most abstract form. Bottom: Opening the cluster to reveal the operations it encapsulates, however, opening the cluster also hides the rest of the model, which impedes the model's visibility and juxtaposability. (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 131)



Case study 1's Kangaroo module or "cluster" (child) named "Springs from mesh", Nelson Montás (2014), which, in this specific model, is used to generate a "spring-mass model" to build a parametric simulation of generalizations within SMM behavior. This is done by assembling a set of operations that produce a determined output based on different inputs and extracting parameters to display in the parent component. In this case, those parameters are: Mesh (M), Stiffness (Stiffness), Rest length factor (B) and Spring (S) which are the higher level inputs and outputs.

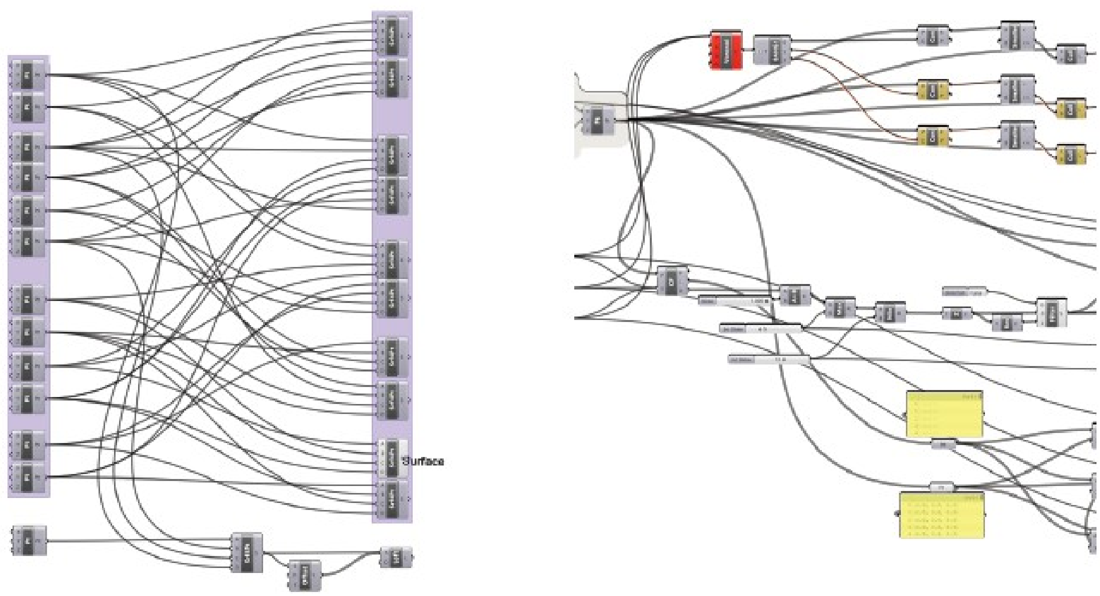


Case study 1's Kangaroo module or "cluster" (parent) named "Springs from mesh", Nelson Montás (2014), which, in this specific model, is used to generate a "spring-mass model" to build a parametric simulation of generalizations within SMM behavior. Parent component displaying extracted parameters (higher level inputs and outputs): Mesh (M), Stiffness (Stiffness), Rest length factor (B) and Spring (S).

Davis conducted a metric quantitative analysis with data extracted from the Grasshopper3d.com online data base, out of 2002 GH models that he individually evaluated concerning CC and so on, his survey concluded:

"...yet despite the pervasive benefits of modularisation, architects creating parametric models in visual

programming languages still tend to create unstructured models...[854]*In chapter 4.3's sample of 2002 Grasshopper models, 97.5% of the models did not employ modules...*[855]*In addition to being unstructured, the models generally have a high cyclomatic complexity (see chap. 4.3) and possess what Meyer (1997, 678) calls the "unmistakable 'spaghetti bowl' look" of interwoven relationships and long chain dependencies (fig. 48)"*[856]



Examples of spaghetti forming in two unstructured Grasshopper models. Neither model gives any hint (through naming or otherwise) as to what the crisscrossed connections do and it is impossible deduce simply from inspection.[857] Daniel Davis (2013) (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 130)

A phenomenon that he attributes to two possible explanations: the first, citing Thomas Green and Marian Petre [858], being that Grasshopper clusters do not exhibit edacuate visibility and juxtaposability that showed more useful at the end of the design process rather than at the middle of it, he states:

[854] Davis, Daniel, *Op. Cit.* (2013) P. 130
[855] Idem.
[856] Ibid. P. 128-129
[857] Ibid. P. 130.
[858] Green, Thomas, and Marian Petre. 1996. "Usability Analysis of Visual Programming Environments: A 'Cognitive Dimensions' Framework." *Journal of Visual Languages & Computing* 7 (2): 131-174.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 132.

"While the abstraction brought about by less transparency may be beneficial in a textual language, in a visual language structural abstractions can hinder access to code according to Green and Petre (1996, 164). Their widely cited research on the usability of visual programming languages indicates that the understandability of a program is dependent upon visibility (how readily parts of the code can be seen) and juxtaposability (the ability to see two portions of code side-by-side) (Green and Petre 1996, 162-164). Clusters in Grasshopper constrain visibility by limiting the view to one particular level of abstraction at a time (fig. 49). Juxtaposability is currently impossible in Grasshopper since two levels of abstraction cannot be seen at the same time, or side-by-side. Furthermore, cluster reusability is impeded since cluster changes do not propagate through related instances of reused clusters. Owing to these limitations, the clusters in Grasshopper are more suited to packaging finalised code rather than supporting the decomposition and composition of an evolving program (the way structure is typically used in textual programs). This may be one reason for low cluster use in Grasshopper."[859] These characteristics inherent to the Grasshopper visual environment, enchained other higher level of abstraction to its sphere of code structuring consequences. Regarding hierarchy, Davis and a group of researchers tested these principles in the context of a research experiment that was to be built, which threw interesting results in relation to the way modularity is supposed, theoretically, to be inserted in the modeling to improve flexibility in the later stages of the design process. He continues:

¨Breaking the project into a hierarchy of stages seemed to make it possible for designers to collaborate using disparate software, while the modules within the models seemed to promote model reuse and improve model understandability. At both scales, structure was difficult to impose at the start of the project and instead tended to emerge from an unstructured beginning to be later refactored with a few relatively minor changes. Perhaps most significantly, the flexibility of this working method facilitated the reorganisation of the design process, which enabled the designers to delay critical decisions until they had the best understanding of their consequences, rather than forcing the decisions early in order to avoid the cost of later changes."[860]

The conclusive evidence at the end of the analysis, shows that it is not very clear if using clusters as modules is a general purpose valid and effective strategy (it depens on the case and it is acknowledged that Grasshopper is not yet a finished development, therefore cluster may be changed or improved in

[859] Davis, Daniel, *Op. Cit.* (2013) P. 132.
[860] Ibid. P. 149.

later version, something that 2 years after the fact has not yet happened, clusters still work pretty much the same way they did when Davis conducted his study). So, very much *à la* Ockham's razor, in that the simplest answer to a symmetrical problem is always the right one Davis confirmed that *the most effective strategies seem to be clearly naming parameters, and grouping nodes together by function with defined inputs and outputs.* [861]

9.4.8-Imperative programming: the edit-compile-run loop_

"Here's how coding works: you type a bunch of code into a text editor, kind of imagining in your head what each line of code is going to do. And then you compile and run, and something comes out… But if there's anything wrong, or if I have further ideas, I have to go back to the code. I go edit the code, compile and run, see what it looks like. Anything wrong, go back to the code. Most of my time is spent working in the code, working in a text editor blindly, without an immediate connection to what I'm actually trying to make."[862]

Bret Victor 2012, 2:30, *Inventing on Principle* (2012)

While using the data-flow programming paradigm (a declarative programming subset) what this research is trying to establish is that, it is possible to get around the edit-compile-run loop. *For architects, the delayed feedback from the Edit-Compile-Run loop proves problematic.*[863] Which is a time consuming but, more importantly, cognitively confusing instrument when designing and coding at the same time, as established by Davis. *Ivan Sutherland (1963, 8) disparagingly called this "writing letters to rather than conferring with our computers."*[864] At the middle of this problem lies a contradiction between programmer and designer idiosyncrasies; *shortcutting this process using mental simulation, as good programmers often do, clashes with Nigel Cross's (2011, 11) observation that "designing, it seems, is difficult to conduct by purely internal mental processes."*[865] While the first one continuously

[861] Davis, Daniel, *Op. Cit.* (2013) P. 153.
[862] Victor, Bret. 2012. "Inventing on Principle." Presentation at *Turing Complete: Canadian University Software Engineering Conference*, Montreal, 20 January. Digital video of presentation, accessed 19 November 2012. http://vimeo.com/36579366. (2:30 min.)
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 159.
[863] Davis, Daniel, *Op. Cit.* (2013) P. 160.
[864] Sutherland, Ivan. 1963. "Sketchpad: A Man-Machine Graphical Communication System." PhD dissertation, Massachusetts Institute of Technology.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 160.
[865] Cross, Nigel. 2006. *Designerly Ways of Knowing*. London: Springer-Verlag. ———. 2011. *Design Thinking: Understanding How Designers Think and Work*. Oxford: Berg.

runs “mental simulations” in his mind while he codes, the designer is tied to a physical world making practice thus needing to visually encounter temporary results to evaluate and test outside the abstract realm of algorithmic construction and, in fact, it is a back and forth communication process between the computer and the designer but in a more straight forward manner. The edit-compile-run loop process is broken down by Bret Victor in his presentation at the *Turing Complete: Canadian University Software Engineering Conference* in 2012 [866] as:

“...edit the code, compile and run, see what it looks like.” This sequence of events is commonly known as the Edit-Compile-Run loop. In the loop, the programmer edits the text of the code, presses a button to activate the code, and then waits. They wait first for the computer to validate the code, then they wait for the computer to compile the code into machine-readable instructions, and finally they wait for the computer to run this set of instructions. Only then can the programmer see what their code produces.”[867]

Davis's observations and *Cross's contention that designers need to have continual feedback, separate from their internal monologue*[868] are consonant with other authors conclusions like Ivan Sutherland, Bret Victor, Nigel Cross, Donald Schön among others, and it is also related by Davis to the phenomenon of “change blindness”. Davis remarks:

“This view is reinforced by design cognition research that shows any latency between a designer's action and the computer's reaction is problematic for architects since delays exacerbate change blindness, which makes it hard for designers to evaluate model changes.”[869]

As quoted by:
Davis, Daniel, *Op. Cit.* (2013) P. 160.

866 Victor, Bret. 2012. “Inventing on Principle.” Presentation at *Turing Complete: Canadian University Software Engineering Conference*, Montreal, 20 January. Digital video of presentation, accessed 19 November 2012. http://vimeo.com/36579366. (2:30 min.)
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 159.

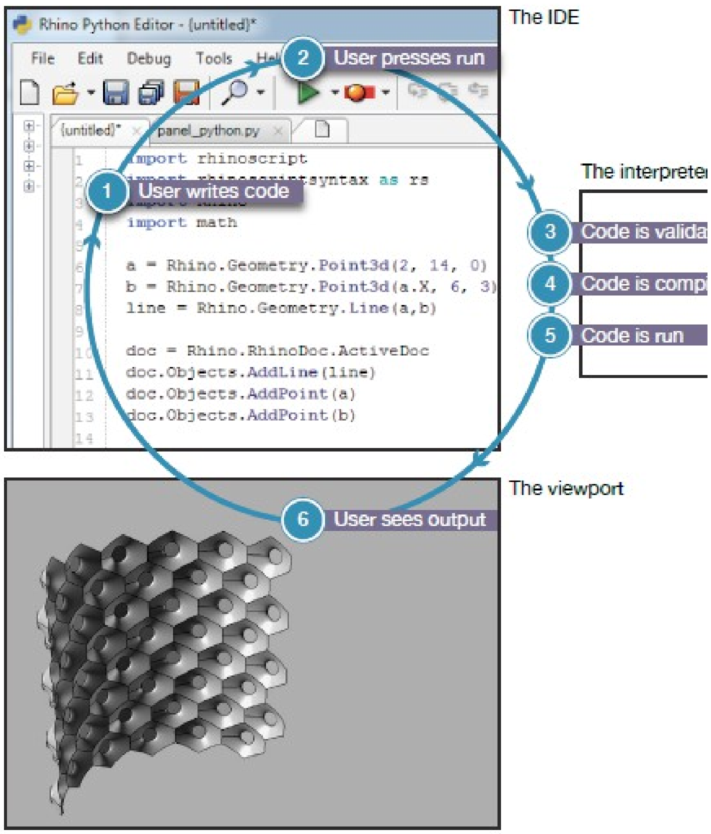
867 Op. Cit. Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, School of Architecture and Design College of Design and Social context, RMIT University (2013) P. 159.

868 Cross, Nigel. 2006. *Designerly Ways of Knowing*. London: Springer-Verlag. ———. 2011. *Design Thinking: Understanding How Designers Think and Work*. Oxford: Berg.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 160.

869 Erhan, Halil, Robert Woodbury, and Nahal Salmasi. 2009. “Visual Sensitivity Analysis of Parametric Design Models: Improving Agility in Design.” In *Joining Languages, Cultures and Visions: Proceedings of the 13th International Conference on Computer Aided Architectural Design Futures*, edited by Temy Tidafi and Tomás Dorta, 815–829. Montreal: Les Presses de l'Université de Montréal.

Later on he continues, citing Rick Smith, about change blindness and its counterproductive effects on the design process:

"With designers potentially blind to the changes they make, Rick Smith (2007, 2) warns that a change to a parametric model "may not be detected until much later in the design phase, or even worse, in the more expensive construction phase."[870]



The Edit-Compile-Run loop for a Rhino Python script. A designer must go through this loop every time they want to see what their code produces. In the best case it takes a couple of seconds to move between writing code [1] and seeing the output [6] but this period can be much longer if the script is computationally intensive to run.[871] (Davis, Daniel, *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*, P. 131)

Nasirova, Diliara, Halil Erhan, Andy Huang, Robert Woodbury, and Bernhard Riecke. 2011. "Change Detection in 3D Parametric Systems: Human-Centered Interfaces for Change Visualization." In *Designing Together: Proceedings of the 14th International Conference on Computer Aided Architectural Design Futures*, edited by Pierre Leclercq, Ann Heylighen, and Geneviève Martin, 751–764. Liège: Les Éditions de l'Université de Liège.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 160.

[870] Smith, Rick. 2007. "Technical Notes From Experiences and Studies in Using Parametric and BIM Architectural Software." Published 4 March. http://www.vbtllc.com/images/ VBTTechnicalNotes.pdf.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 160.

[871] Davis, Daniel, *Op. Cit.* (2013) P. 131.

9.4.9-Origins and lack of interactivity_

Most programming languages and their editing environments do not show fluidity in the way they exchange code information and executed operations between machine and coder (being the response threshold of 0.10 of a second to be considered interactive). Victor attributes this to the fact that:

"...most programming languages "were designed for punchcards" where "you'd type your program on a stack of cards, and hand them to the computer operator, and you would come back later" – an "assumption that is baked into our notions of what programming is." While punch-cards may explain the origins of the Edit-Compile-Run loop in programming."[872]

Contemporary editing environments are known as Integrated Development Environments (IDEs) which show interactive traits like autocompletion, interactive debugging:

"Modern IDEs often augment the Edit-Compile-Run loop so programmers do not have to wait for feedback. For example, some IDEs identify simple logical errors before the code is run, and some IDEs suggest and explain programming commands while programmers are writing them (a feature known as autocompletion). Other IDEs allow the basic editing of running code, which enables programmers to make minor changes without cycling back through the edit-compile-run loop (this is known as interactive debugging)...

…The interactive feedback mechanisms of many modern IDEs have not filtered down to the environments architects write code in. Like professional programmers, architects use languages based on the Edit- Compile-Run loop, with Leitão, Santos, and Lopes (2012, 146) pointing out that even popular languages like "RhinoScript are a descendant of a long line of BASIC dialects that started much earlier, in 1964."[873]

The lack of programming interactivity causes large latency gaps *between the designer writing code and the computer generating the geometric results, which makes evaluating code changes potentially*

[872] Victor, Bret. 2012. "Inventing on Principle." Presentation at *Turing Complete: Canadian University Software Engineering Conference*, Montreal, 20 January. Digital video of presentation, accessed 19 November 2012. http://vimeo.com/36579366. (28:00 min.)
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 159.

[873] Leitão, António, Luís Santos, and José Lopes. 2012. "Programming Languages for Generative Design: A Comparative Study." *International Journal of Architectural Computing* 10 (1): 139–162.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 161.

difficult for architects.[874] This provoking recurrent “change blindness” in parametric design processes and hindering practicality in the model building process. And in accordance with Davis et al., and as established earlier in this chapter, the parametric modeling implementation of SMM simulations cannot be tested accurately if it is not possible to evaluate code and physics's correctness.

*9.4.11-Interactive programming_*

In programming languages like Python, there exist what is known as “event driven programming” which is based in the use of “handler” functions which basically make the program wait until something happens to set the code in motion again, in turn using input parameters as questions, mouse drag, key pressing and timers, these in turn known as “event queues”. There are also what are known as “while” statements, mentioned earlier in this chapter, that basically do some automated, repeated task while a condition remains the true. *A **while** loop statement in Python programming language repeatedly executes a target statement as long as a given condition is true.* [875] *The origins of interactive programming date back to the programming languages LISP (first version: 1958) and SmallTalk (first version: 1971), both of which allow programmers to modify code while it runs.*[876]

Some of the interactive characteristics found in programming languages can be used in the context of design as guidelines bu which structure interactively driven “event” modeling. Parametric modeling environments already show inherent interactive functionality such as Grasshopper and Kangaroo, thanks to its data-flow implementation. According to Davis, they achieve this in three ways: automation, Sequencing and hot-swapping.

“Automation: Automation Rather than waiting for the user to manually tell the Edit- Compile-Run loop to execute, the loop can be set to run automatically and display the results whenever the code is changed...

...Sequencing: However, for architects doing computationally demanding geometric calculations, generating geometry rhythmically is not as important as generating geometry quickly. For this reason, sequencing is unsuitable in an architectural context...

[874] Davis, Daniel, *Op. Cit.* (2013) P. 161.
[875] Python while Loop Statements, *tutorialspoint.com* website, (http://www.tutorialspoint.com/python/python_while_loop.htm) (29/10/2015)
[876] Davis, Daniel, *Op. Cit.* (2013) P. 161

...Hot-Swapping:

Instead of compiling every line of code, hot-swapping allows small chunks of code to be independently compiled and then integrated with the unchanged parts of the program – while the overall program continues to run. This reduces the latency of compilation but does not reduce the latency of running the code. Since geometric calculations take orders of magnitude longer than the compilation of code, the savings from hot-swapping in an architectural context are likely comparable to those of automation."[877]

Davis's analysis's conclusions were blunt and straight forward, architects cannot avoid the edit-compile-run loop.

"Although there are a range methods for reducing the latency between writing and running code, none of the existing methods are suited to the unique challenges of performing geometric calculations in real time. These are challenges not present in other design disciplines currently using interactive programming (such as web-design, musical performance, and two-dimensional animation). Despite the range of textual interactive programming environments available to other designers, architects currently have no option but to contend with the separation induced by the Edit-Compile-Run loop."

Yet in the act of model building itself we can further utilize these conceptual frameworks to achieve data interactivity. This research speculates that the combination of OOP and data-flow (Python script and node based visual programming, available in Grasshopper version 0.9.0076 + Kangaroo version 0.099 for Rhinoceros 5) can bypass the edit-compile-run loop process and make the simulation modeling of SMM interactive and intuitive, and in this fashion integrating it to the design process.

*9.4.12-Visual programming_*

This research's proposition of integrating both textual and visual programming environments to produce fluid, interactive simulation models and moderately accurate realistic results compared to those possible using animation software as a modeling tool derive from Davis's findings that demonstrated visual programming's affinity in solving and structuring complex, large problems and visual programming's propensity towards interactivity and hence user-friendliness, which architects

[877] Davis, Daniel, *Op. Cit.* (2013) P. 161

tend to love and exploit the most.

"While visual programming enables architects to work interactively, there are still limitations when compared to textual programming. In the previous chapter (chap. 6) I [Davis] *demonstrated that visual programming environments do not support structure as elegantly as many textual programming environments do. Partly citing my research from the previous chapter, Leitão, Santos, and Lopes (2012, 160) conclude, "learning a textual programming language takes more time and effort than learning a visual programming language, but this effort is quickly recovered when the complexity of the problems becomes sufficiently large."*[878]

In these case studies, the research orientation has been set to qualitative metrics such as in Davis's thesis, these are:

"Functionality: Are all the modelling tasks able to be performed by every programming method?
Correctness: Do programs do what is expected?
Ease of use: Are the modelling interfaces easy to use?"[879]

Whereas also taking into consideration, yet not producing, quantitative metrics such as:

"Construction time: How long did the respective models take to build?
Lines of Code: How verbose were the various programming methods?
Latency: How quickly did code changes become geometry?"[880]

This research proposition is one which Davis seems to affirm as a valid. *In reducing parametric model latency there is a balance to find between extendability, correctness, reusability; a balance activated by the architect's ability to explore multiple ways of generating parametric models.*[881] Based on one of his research experiments, Davis concludes that it demonstrates that, depending on the confection of the parametric model itself and its orientation to the specific problem at hand, *designers can further reduce*

[878] Leitão, António, Luís Santos, and José Lopes. 2012. "Programming Languages for Generative Design: A Comparative Study." *International Journal of Architectural Computing* 10 (1): 139–162.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 167
[879] Davis, Daniel, *Op. Cit.* (2013) P. 174
[880] Ibid. P. 175
[881] Davis, Daniel, *Op. Cit.* (2013) P. 186

latency by trading off extendability, correctness, and reusability.[882] *These qualities can themselves be designed through the composition of the parametric model or through the selection of the programming environment.*[883] Therefore, the conclusion data from Davis agrees with this research's proposition of design simulation experiments in that the combination of imperative and declarative methods seems as a logical way to start such an exploration. This method will be outlined subsequently in the next sections.

*9.5-Rhinoceros + Grasshopper + Kangaroo modeling method_*

"Although some classes of form can be codified to a single size variable, such a is designated for a hat or a pair of shoes, most cannot. Although many more arbitrary classes of form can be constructed if the number of independent variables is sufficiently large, the parametric process is more valuable if that set of variables is kept manageably low. The value is in [how] *the use of dependent variables generate relatively detailed instances from relatively few inputs. This is especially true if those inputs can couple the generation of form to the ranges and constraints of the machine processes by which they are to be fabritaced."*[884]

Malcolm McCollough

Malcolm McCollough, a professor and software developer at Autodesk around the time that Autocad came out commercially, gives us a very straight forward way of thinking about how to model parametrically. Basically if you model stays simple and tied to the fabrication process it will undergo in the production phase, your project will get done and will have "more value", this we intuit means that the simpler you keep independent variables (inputs to the *dependent* variables) and its inputs are tied to fabrication processes, the better your model will work for you. The experiments were divided in two main groups: Kinematic and Kinetic models. As mentioned earlier in this thesis, In the introduction, we very briefly stated that often kinetics and kinematics are confused with each other. In this experimental setup, both will be used to illustrate both their definitions and their potential uses when parametrically modeling simulations. It is imperative not to confuse the two (something that is more often then not the case) and clearly define and understand the tow fields for their subsequent integration in the aid to

[882] Davis, Daniel, *Op. Cit.* (2013) P. 192
[883] Idem.
[884] Mcullough, Malcolm, *Op. Cit.* (2006) P. 13-14

produce kinetic architecture. In their seminal book *Vector Mechanics for Engineers: Dynamics,* Ferdinand P. Beer & E. Russell Johnston Jr define kinetics as a branch of dynamics (itself a branch in physics that studies moving bodies) that studies:

"Kinetics is the branch of dynamics that studies the relationship that exists between the acting forces on a given body, the mass of the body and its movement. Kinetics is used to predict the movement caused by given forces or to determine required forces to produce a certain movement"[885]

In addition, *kinematics* is the part of mechanics that studies the movement of particles and systems without taking in account the forces that produce it or, more simply put, the *geometry of movement* and which *is used to relate displacement, velocity, acceleration and time, without making reference or the cause of the movement.*[886] This sort of movement control is the one used in applications such as 3Dmax or Maya's *Inverse Kinematics solvers* (or *IK solver*). Then based on the notion that *Kinetics* is the part of dynamics that studies the vector systems that produce movement. These experiments will provide practical cases studies that point out, through their mathematical and physics parametric construction, that they can however be used to produce simulation models that address different ends and produce different, yet in fact complementary, design output. This research will use what are known as "particle systems" to get material behavior approximations that can be esteemed "tolerable". According to Daniel Piker, Kangaroo understands particle systems as this:

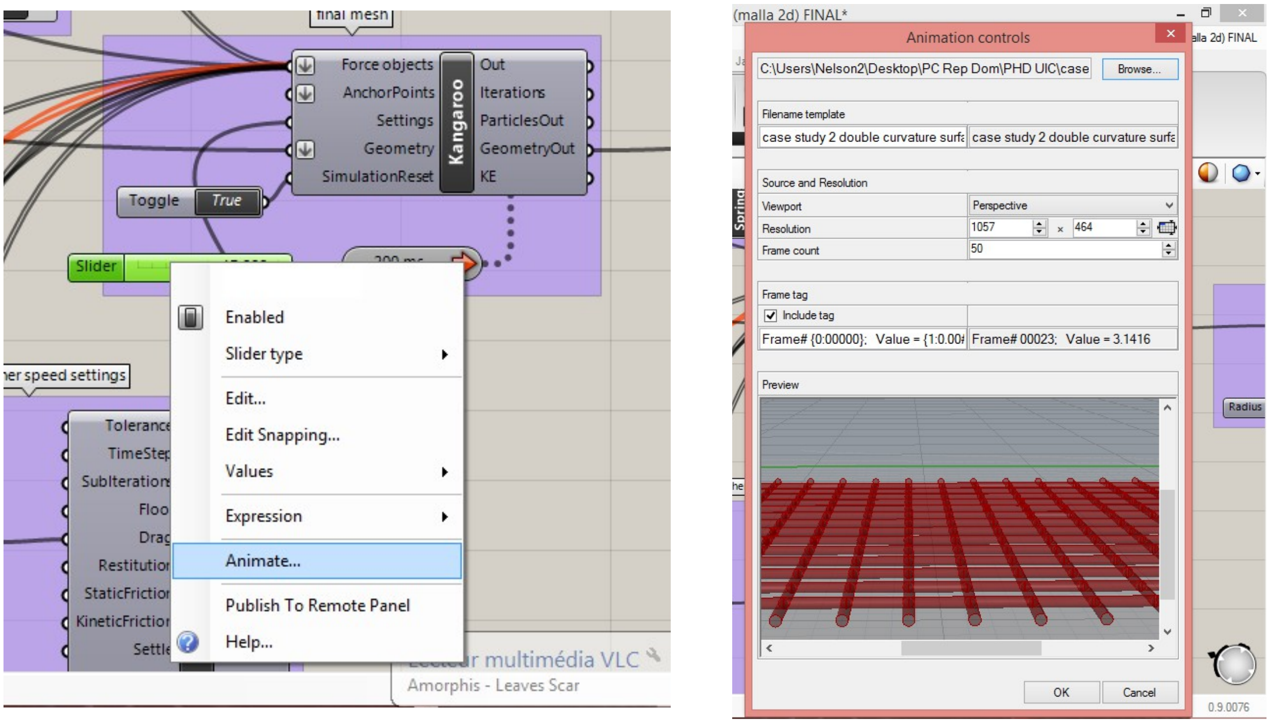
> *"Particles are objects that have mass, position, and velocity, and respond to forces, but that have no spatial extent.. ..Despite their simplicity, particles can be made to exhibit a wide range of interesting behavior. For example, a wide variety of nonrigid structures can be built by connecting particles with simple damped springs."*[887]

And even thougth "*the particles we deal with in Kangaroo are an abstraction"*[888] they are an abstrction with what he argues a "strong connection with how things work in relaity at a fundamental level, therefore *"macroscopic properties of materials such as their behaviour in bending, shear and torsion can actually be seen as emergent on a molecular level from simple interaction between pairs of*

885 Beer, Ferdinand P. - Johnston, E. Russell, *Op. Cit.* (1999) P. 582
886 Idem.
887 Baraff & Witkin's Siggraph *'97 course notes* (http://www.cs.cmu.edu /~ baraff/sigcourse/) (http://www.pixar.com/companyinfo/research/pbm2001/)
As quoted by: Piker, Daniel. - Cervellione, Robert – Piacentino, Giulio, *Using Kangaroo (Grasshopper version)*self published online DRAFT, , P. 2-3 (https//:grasshopper3d.com/)
888 Piker, Daniel. - Cervellione, Robert – Piacentino, Giulio, *Using Kangaroo (Grasshopper version)*self published DRAFT (2011) P. 2-3 (https//:grasshopper3d.com/)

particles."[889] The difference between the real world and simulations run on kangaroo are evident, real objects carry a lot more particles than those in the simulation, but Piker argues, *"if some care is taken about how we distribute the points and their masses we can get quite good approximations of real physical behaviour using this method."*[890] Concerning user-friendly-ness He continues about its (Kangaroo's) reliability:

"While they do have their limitations, one great advantage of particle systems is that they are easily understood and controlled (compared with more sophisticated continuum models).



This conceptual simplicity makes it possible for designers to apply and manipulate the physics simulation in a very direct way, without needing specialist technical knowledge."[891] *Kangaroo pop-up command named "Animate",* Daniel Piker (2011). Right-clicking on any "slider" in grasshopper, a pop-up menu shows up with this particular command with which the user can extract real-time live still-frames and that, using Kangaroo, can be used to illustrate with still and to make up photo-grams sequences or edit movies in software such as *Moviemaker* or *iMovie*.

*9.5.1-Kinetic models_*

Case study 1:

For the the first case study, we chose to go to the simplest form of abstraction concerning kinetic application into the Kangaroo interface. This comprised building what is known as a " points and lines" model; adding force vector to produce the desired *kinesis*. The experiment was conducted like this:

1) We made a similar movement pattern as the one in the Kuwait Pavillion by Calatrava, not

[889] Piker, Daniel. - Cervellione, Robert – Piacentino, Giulio, *Op. Cit.*(2011) P. 2-3
[890] Idem.
[891] Idem.

reproducing it, but building a structure capable of making the same type of movement. Angeliki Fotiadou calls this type of movement a "one degree of freedom" one.

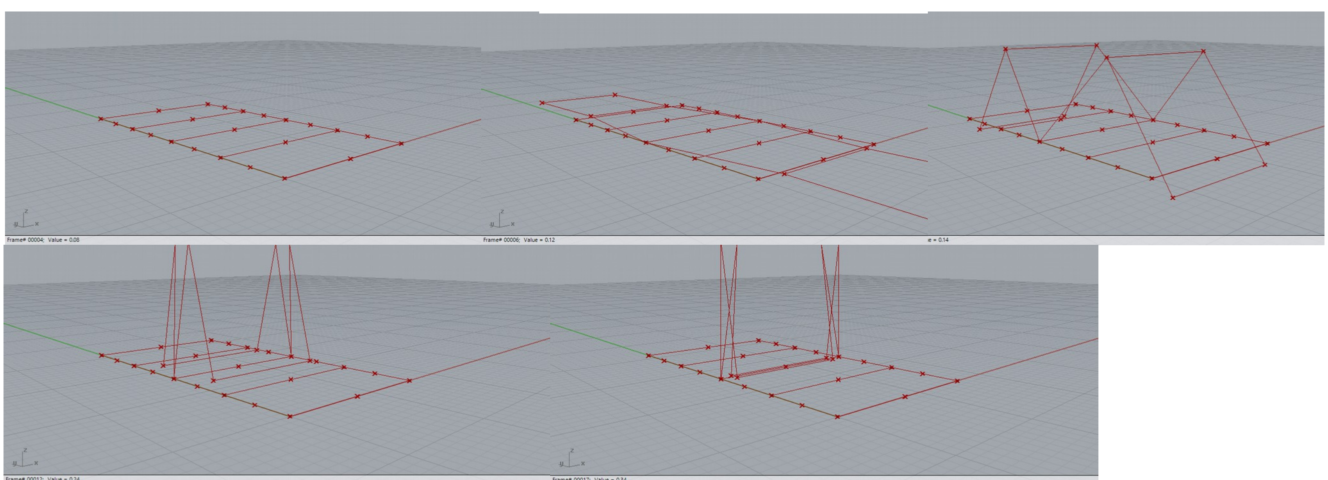
2) Using "spring from lines" components, we defined the elasticity capabilities of the material we wanted to represent, which was a rigid, steel like stiff material.

3) Positioned force components adding direction vectors to guide the motion, setting up all points to a value of 9.81 representing gravity.

4) We then proceeded to set up the Kangaroo physics engine and the point reference (to reference pivot vertices) and curve components (to reference lines in the original design).

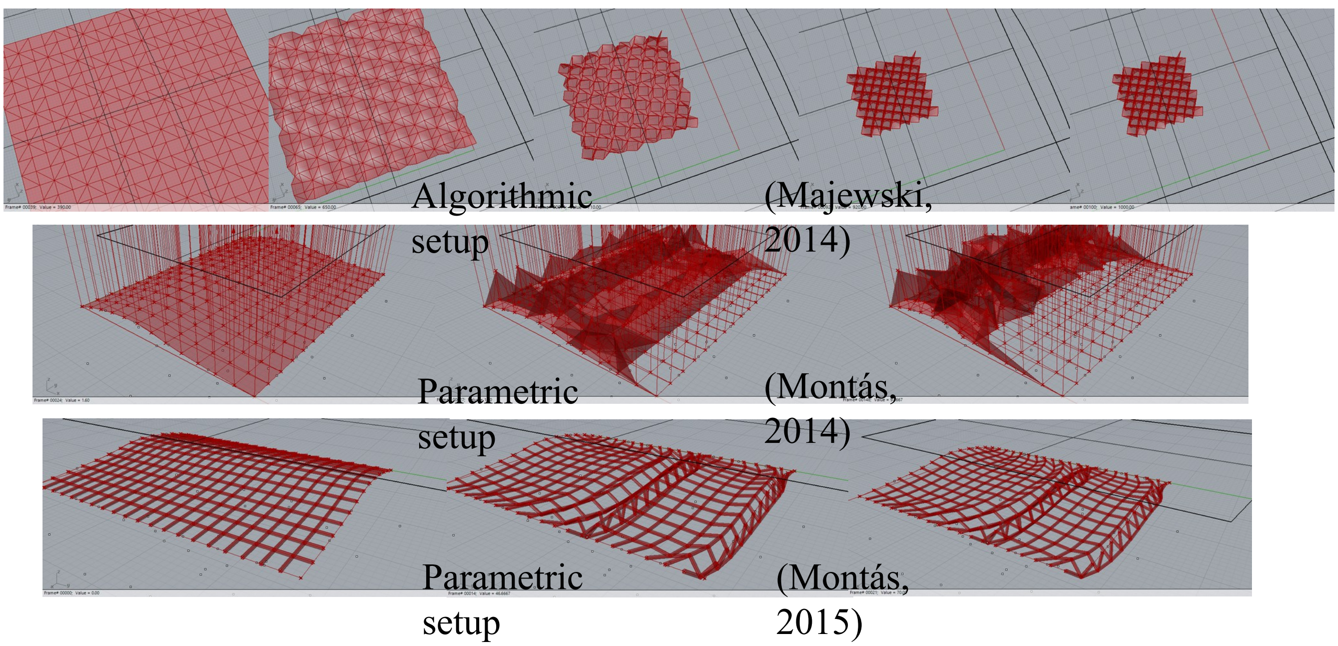
5) We ran the simulations and verified the correctness of the movement.

This model was built keeping cyclomatic complexity low and implementing the fewest variables possible.

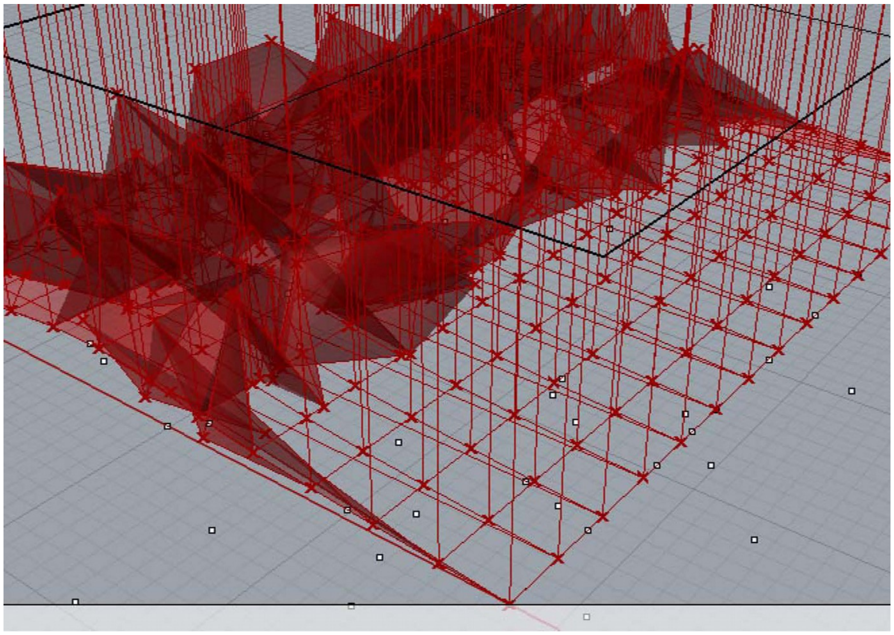


Case study 1 simulation, Nelson Montás (2014)

In 2014 Riccardo Majeswki uploaded a grasshopper definition on Youtube.com that showed how to construct a matrix to make a kinetic model titled "Origami waterbomb"; reproducing a folding paper piece making a 3d fold from a 2d flat subdivided plane. Majewski used a matrix and the "pull to surface" component to drive the folding vertices to be guided to whatever type of surface you program it to be pulled to. The disadvantage with the kind of parametric modeling he used is that, even though the surface type (therefore the shape-shifting of the general matrix made plane) can be controlled, it is not possible to do the same with the subdivisions or the size of the plane itself unless you reconstruct or modify its matrix components, one by one, afterwards it is possible to control the drag factor (to speed up or slow down the effect) and the multiple "springs from line" parameters like stiffness, rest length and so on. This, although a masterful use of mathematical matrices to produce a kinetic simulation, is what we can denominate an "algorithmic setup", one in which the ensemble cannot be changed unless reconstructed from a given point in the model, or that is requires heavy model modification or restructuring to change its fundamental composition and result. Opposite what we define as a "parametric setup" which, to be modified does not require restructuring or heavy reconstruction, often just limiting the act of reconstruction to adding new parameters or components. It is an "expanding" modeling framework which is thought and built to fit that criteria from the start of the modeling process. That does not mean using the "front loading model" but actually building an "open configuration" or one that is open ended in its modeling reach. Meaning that it allows for modification, not necessarily reconstruction.



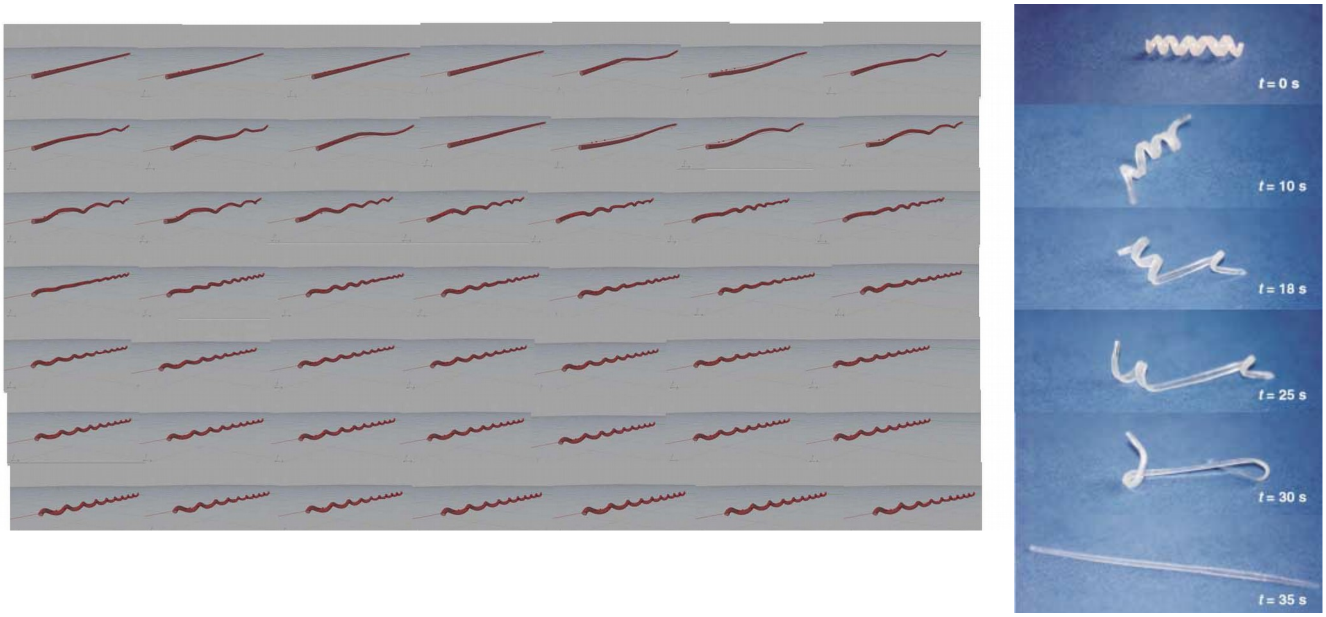
(Top) *Origami waterbomb*, Riccardo Majewski (2013). Grasshopper + Kangaroo simulation controlled with a matrix based mesh subdivision + allign + spring from lines + pull to surface components. (algorithmic approach = one possible configuration). **(Middle)** *Case study 2*, Nelson Montás (2014). Grasshopper + Kangaroo controlled with spring from lines + anchor points + vector force object components for testing purposes (rest length +/- 200, stiffness +/- 15 (parametric approach = various possibles geometric configurations). **(Down)** *Case study 2*, Nelson Montás (2015). Grasshopper + Kangaroo controlled with spring from lines + anchor points + vector force object components for testing purposes (rest length +/- 20 , stiffness +/- 1000 (parametric approach = various possibles geometric configurations).



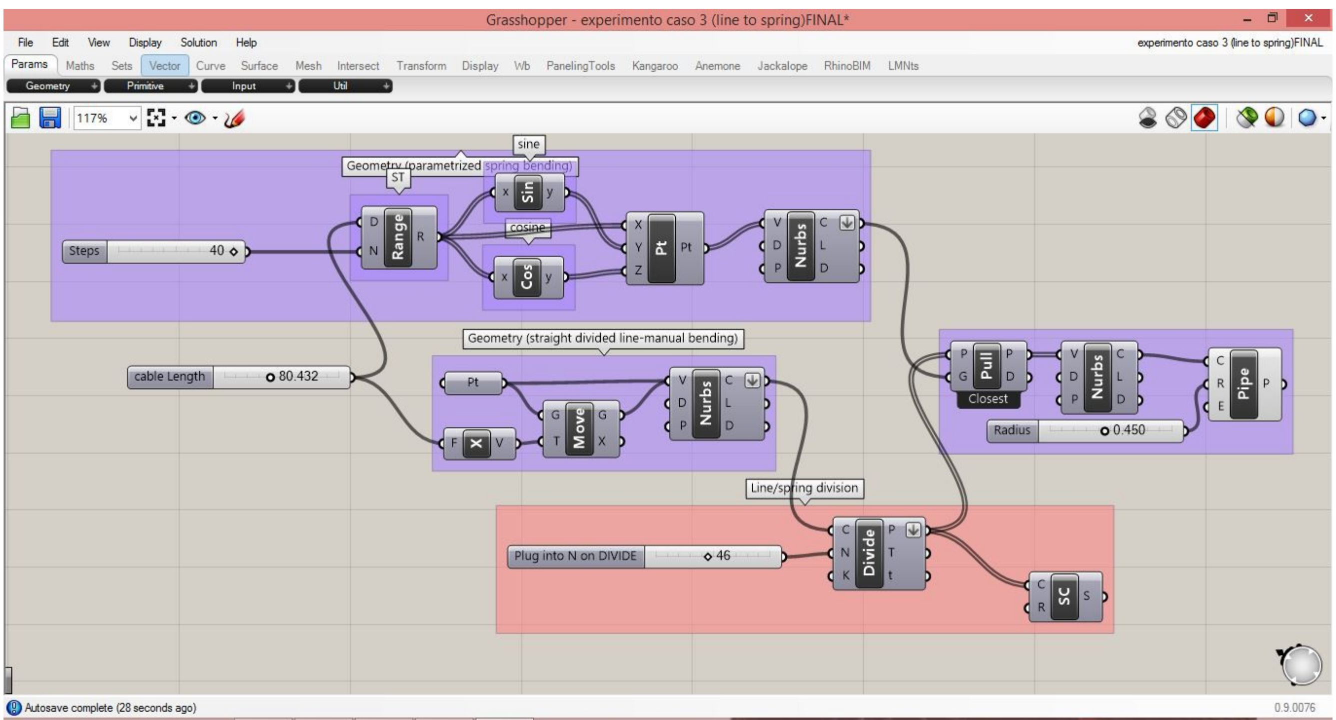
Case study 2 simulation, Nelson Montás (2014). “Spring from line” testing, in this screen-shot, the component is in its raw general setting, it is up to the user to setup the constratins that define each specific material's elasticity, rest length and stiffness. In this picture the material behaves like an elastic fabric being teared apart by the vector forces seen also in the screen-shot.

*9.5.2-Kinematic models_*

In the first of the kinematic models (although it was actually case study 3 in chronological order) reproduced a classic application in Flexinol and other commercially available Ni-Ti based alloys. It was modeled without the Kangaroo physics engine because the model was to be created following the Shape A – Shape B definitions of macroscopic behavior, therefore only studying how to program a material to go geometrically from shape to shape without force vectors and instead using the *Active Shapes* (geometry driven, therefore kinematic modeling approach) criteria by Dina el-Zanfaly that used shape grammars to inflict transformation upon a given shape (see chapters IV and V). A force, non vector component named “Pull point” in the Kangaroo tab was used to approach or “pull”, point by point, a line that itself was built with a Sine and Cosine function, a point and a range of values to be generated (a standard grasshopper beginner's exercise); approximating the original, force-less, straight line to the ideal curvature of a double sine and cosine-wave function curve. In this arrangement the active shape A was a straight strand and Shape A->(t)A was a spring shaped strand.



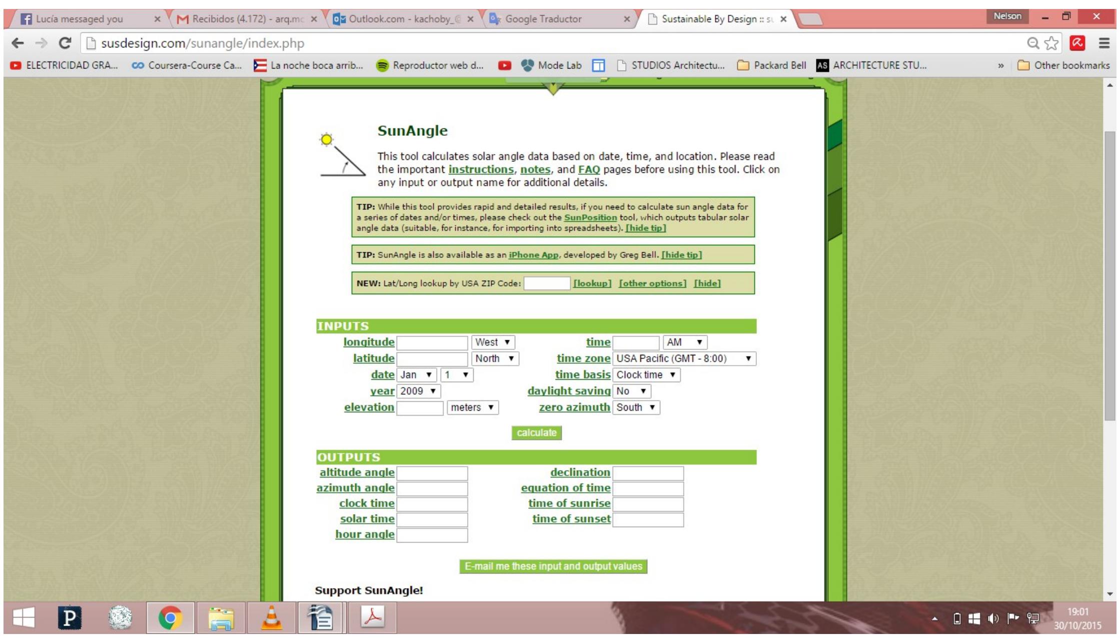
(Left) *Case study 3 simulation*, Nelson Montás (2014). This particular case study investigated the use of visual programming to implement "kinematic" models to simulate SMM systems. I this case, a geometry based definition as used opposed a vector based one used in "kinetic" based models. This specific case modeled the behavior of a SMA strand that goes from a 'straight line" form towards a "spring" one. No forces were used in the construction of this model. (Right) actual straight strand to spring.



Grasshopper +Kangaroo visual code implemented to build the simulation of *Case study 3 simulation,* Nelson Montás (2014).

*9.5.3-Nick Senske's sunlight parametrics_*

Back in 2013, this thesis's author while training in grasshopper and kangaroo, ran into a youtube.com recorded class from the University of North Carolina, dictated by professor Nick Senske, a computational design specialist and architect. In his class Senske promoted the use of parametric modeling to address environmental constraints and stimuli in architectural design. He came up with several grasshopper definitions in various matters, one of them was a definition that calculated the position of the sun anywhere on the planet, using any given place's sunrise, noon and sunset sun azimuth, which he got using a sun angle calculator online application located in a page called *Sustainable by design*[*] that in turn required that the you enter, among other criteria, the specific place's latitude and longitude.



Sustainable by Design website sun angle calculator, Christopher Gronbeck (1998-2009) (http://susdesign.com/index.php)

During the summer of 2015, the author had the opportunity to have a research stay at the *Modélisations pour l'Assistance à l'Activité Cognitive de la Conception* laboratory (MAP-MAACC), itself adjunct to the *Ecole Nationale Supérieure d'Architecture de Paris La Villette* (ENSAPLV). Using the mentioned definition made by Senske, we were able to address a research project by Natasha Heil that looked for possible applications of computational design to the practice of bio-mimetic design methodology. There were several research case studies, but one of them proved to be ideal to apply Senske's definition to,

[*] Sustainable by design's online URL is: (http://susdesign.com/index.php)

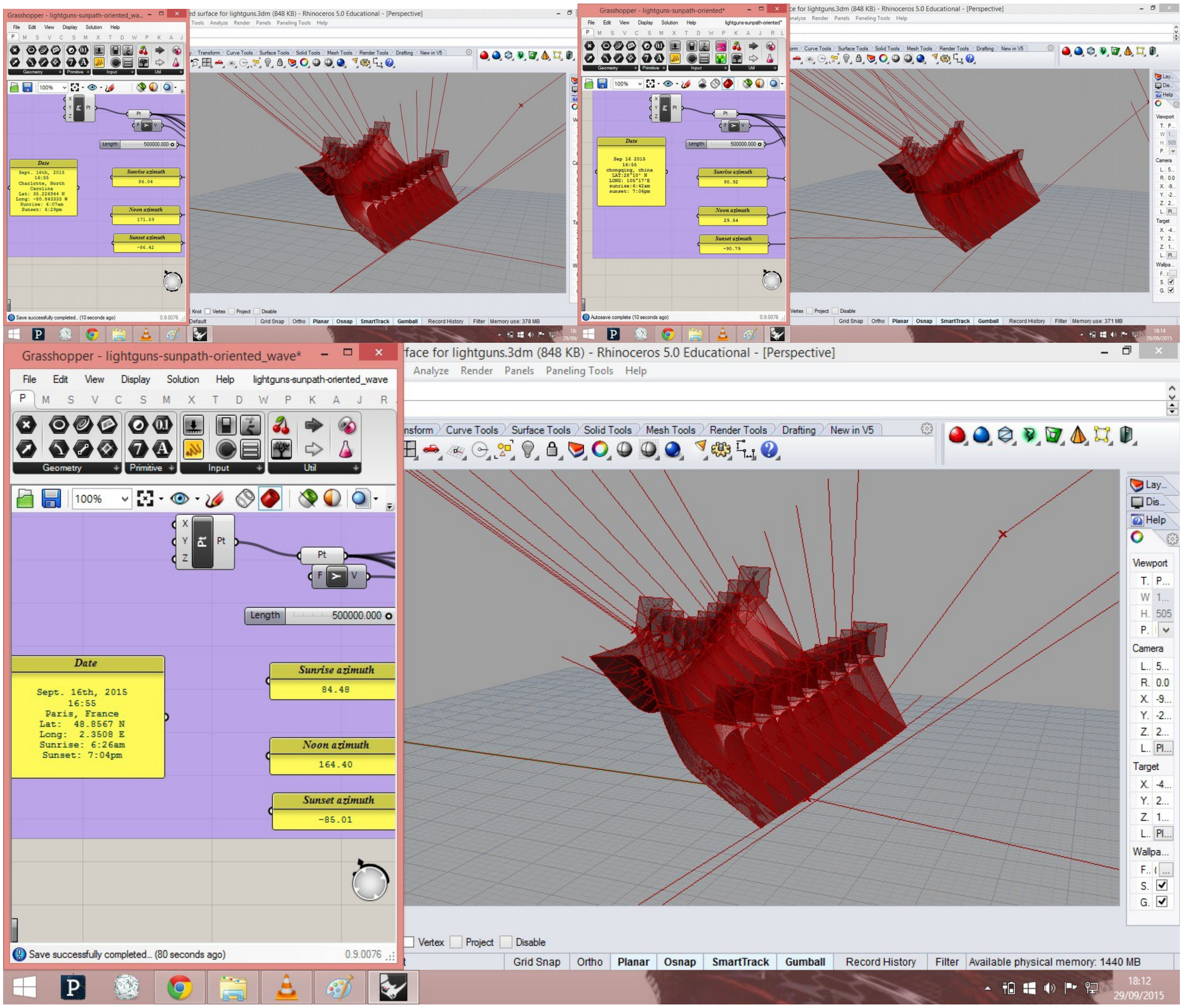
specifically in the case of designing a structure that mimicked the sunflower's capability to track the sun as a mean to attract more direct sunlight towards itself, a characteristic known as helio-tropism, which is the exact logic that Senske used to build his “sunlight parametrics” definitions. As a case experiment, we modeled several cities around the world (specifically Paris, France; Charlotte, N. C. and Chongging, China) to see how this definition adapted its sunlight evaluation to different points in the globe. The specifics of how the definition works, oversimplified, are broken down in the following:

1) There is an algorithm that calculates the mentioned sun path and position according to sunrise, noon and sunset azimuths.

2) Afterwards, there is an “evaluate length” component that remaps the the sun path and which allows the designer to choose the desired specific time of day in hours and minutes with the possibility to also change the sunrise and and sunset times to control light capacity and which the designer also derives from the sun-angle calculator at susdesign.com.

3) Then the sunlight rays are projected into whatever objects (in this case light-guns designed to capture optimal amount of light at any time of day) the designer introduces into the definition. In our specific case, we used the light-guns definition because it is very close to the dynamic of a sunflower, light-guns, photo-voltaic panels, solar-thermal panels are all designed using similar principles, except that panels cannot track the sun, a feature that we would like to introduce in the future as a passive system. This is calculated and referenced to almost any surface in any position on world coordinates (UCS) in the work space.

4) And last, the definition takes all that data produced by the sun-path calculator and the length evaluation and produces a normalized, perpendicular vector to the sun-ray to position what were in this case rectangles to then loft a surface around and between the base surface and the created rectangles.



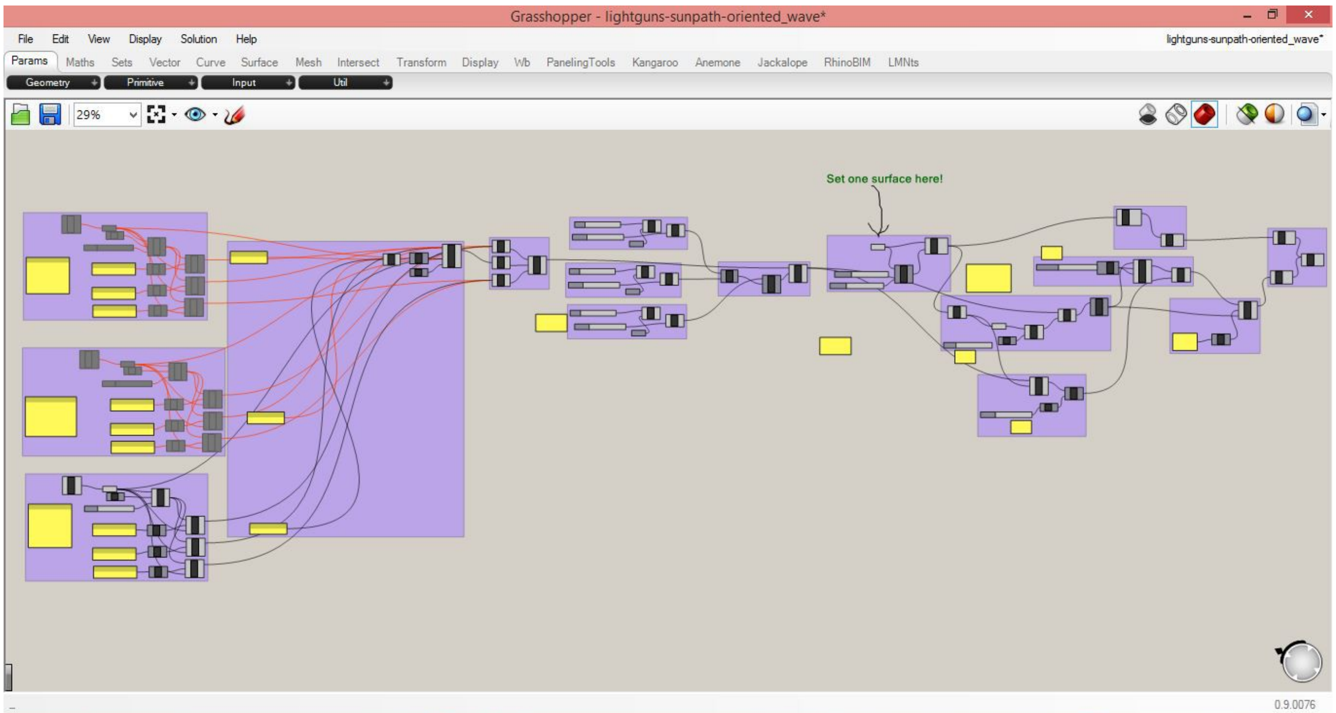
Case study 4

(top left) *"Charlotte, N. C." application of Senske's definition*, Nelson Montás and Natasha Heil (2015) based on Nick Senske. Grasshopper.

(top right) *"Chnongging, China" application of Senske's definition*, Nelson Montás and Natasha Heil (2015) based on Nick Senske.. Grasshopper.

(Lower) *"Paris, France"application of Senske's definition*, Nelson Montás and Natasha Heil (2015) based on Nick Senske. Grasshopper.

And although these models are parametric but cannot be called physical simulations, they are indeed simulations of another sort, in that they allow the designer to simulated, even though "static", states on a larger times-scale, and predict environmental conditions in which to insert objects and buildings. This can be used as an initial conditions of environmental stimuli to later transform into physical actuating simulation models. We hope to keep working based on these kinds of models in the future and determine a way to somehow joint the two kinds in a single work-flow. This remains undone an is a future project in the same line of this thesis's aims, a unified theory, method and work-flow for SMM and PM.



Grasshopper +Kangaroo visual code implemented to build the simulation of *Case study 4 simulation,* Nelson Montás (2014) based on Nick Senske (2011)

*9.6-Implementing visual programming for kinetically modeling SMM behavior_*

*9.6.1-Implementing Ni-Ti simulations_*

The SMA implementation model was built taking material behavior validated technical data from the Robotshop.com website. An online site that sells Flexinol commercially, which is a business name for Nickel Titanium alloys. This brand provides, publicly, useful technical data tables to derive factual information from. What is to be achieved here was a parallel model to a Raviv et al. experimental article published in *Nature* magazine (specifically the “ flat to double curvature grid” case, in which a flat 2D lattice becomes a 3D double curvature surface, see chapter VIII) and which was be used as formal objective basis for the modeling. The experiments were done using a “spring-mass” model similar to the one used by Raviv et al yet simulating the same form-finding experiment using Ni-Ti mechanical behavior information provided by the Robotshop.com webtsite.

Next is the table from which we used the data:

Flexinol® Technical Data

If Flexinol® actuator wire is used within the guidelines then obtaining repeatable motion from the wire for tens of millions of cycles is reasonable. If higher stresses or strains are imposed, then the memory strain is likely to slowly decrease and good motion may be obtained for only hundreds or a few thousand of cycles. The permanent deformation, which occurs in the wire during cycling, is heavily a function of the stress imposed and the temperature under which the actuator wire is operating. Flexinol® wire has been specially processed to minimize this straining, but if the stress is too great or the temperature too high some permanent strain will occur. Since temperature is directly related to current density passing through the wire, care should be taken to heat, but not overheat, the actuator wire. The following chart gives rough guidelines as to how much current and force to expect with various wire sizes.

Diameter Size (Inches)	Resistance (Ohms/ Inch)	Maximum Pull Force (grams)	Approximate* Current at Room Temperature (mA)	Contraction* Time (seconds)	Off Time LT=70° C Wire** (seconds)	Off Time HT=90° C Wire** (seconds)
0.0010	45.0	7	20	1	0.10	0.06
0.0015	21.0	17	30	1	0.25	0.09
0.002	12.0	35	50	1	0.3	0.1
0.003	5.0	80	100	1	0.5	0.2
0.004	3.0	150	180	1	0.8	0.4
0.005	1.8	230	250	1	1.6	0.9
0.006	1.3	330	400	1	2.0	1.2
0.008	0.8	590	610	1	3.5	2.2
0.010	0.5	930	1000	1	5.5	3.5
0.012	0.33	1250	1750	1	8.0	6.0
0.015	0.2	2000	2750	1	13.0	10.0
0.020	0.16	3562	4000	1	17.0	14.0

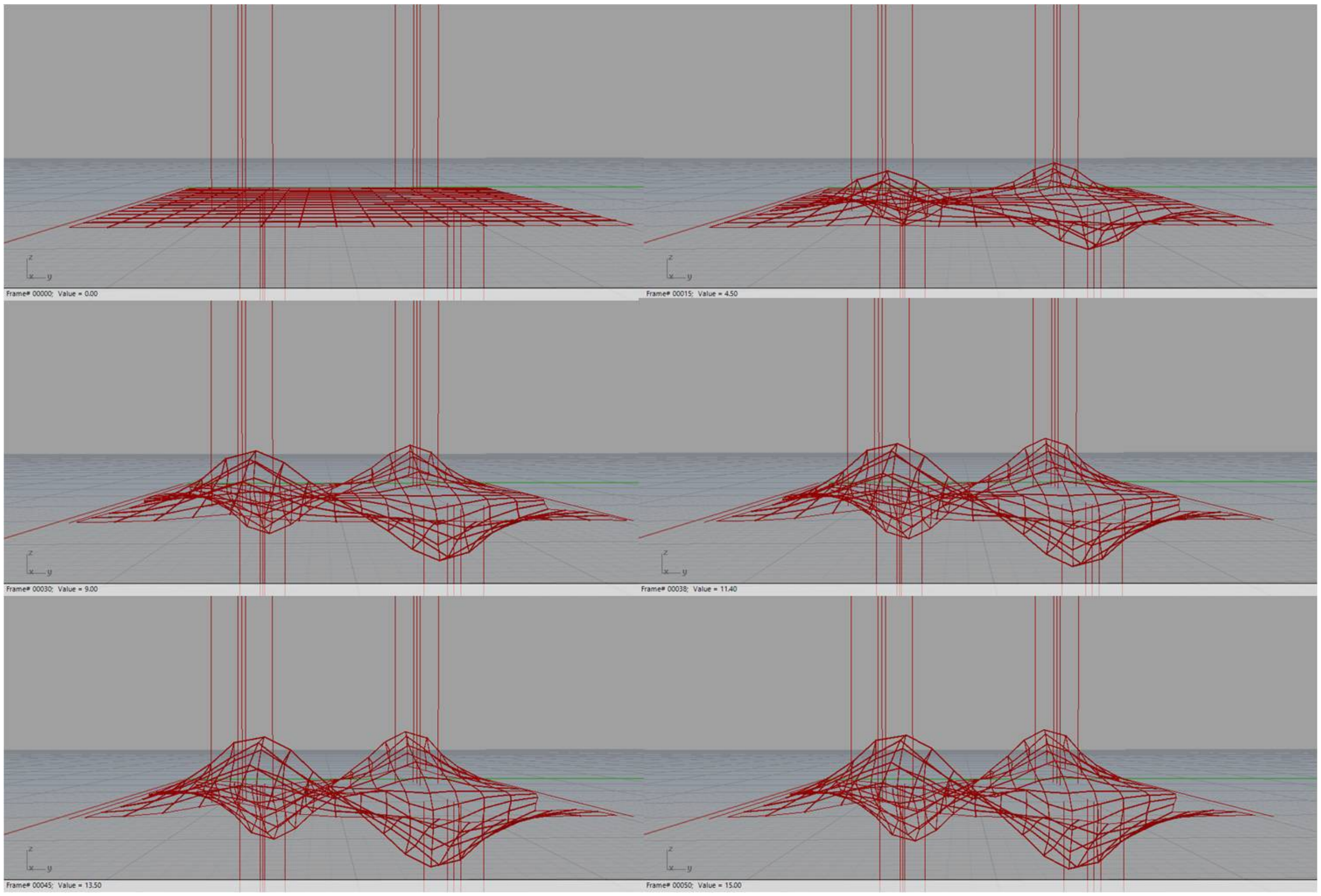
* The contraction time is directly related to current input. The figures used here are only approximate since room temperatures, air currents, and heat sinking of specific devices vary. On small diameter wires (</= 0.006" diameter) currents which heat the wire in 1 second can typically be left on without over-heating it. Both heating and cooling can be dramatically changed (see section 3 of the technical characteristics in the standard literature for more information.)

** Approximate cooling time.

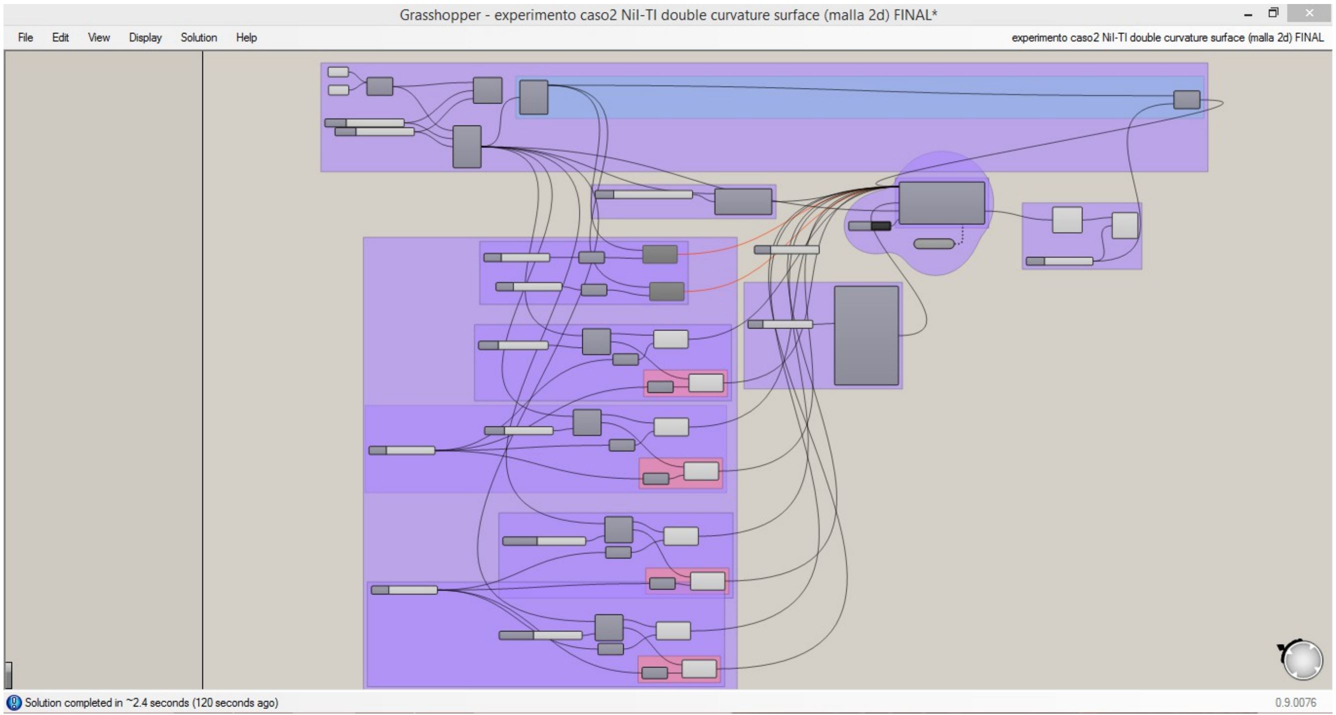
Flexinol technical data table, Robotshop website (http://www.robotshop.com/media/files/pdf/flexinol-technical-data.pdf) (18/12/2014)

*9.6.2-2D Ni-Ti grid to double curvature surface_*

A 40cm x 40cm model was produced using, as mechanical input, the last diameter measure on this table, 0.020 inches, which is the equivalent of 0.0508cm (that, according to Robotshop's technical data table, produces a maximum of 3562g of force, scaled to millimeters (the scale that was used to produce the geometrical model) is converted to 35.62cg. The resulting simulation model showed that it is possible to make the same physical experiment using Ni-Ti wires from the Robotshop catalog. This experiment



Case study 5, simulation of the deformation of a 2D grid into a double curvature surface using Ni-Ti mechanical properties, still-frames sequence (elevation view) Nelson Montás (2015) based on Raviv et al. (2014) while using Roboshop.com's technical data as basis for mechanical performance.



Grasshopper +Kangaroo visual code implemented to build the *simulation of the deformation of a 2D grid into a double curvature surface using Ni-Ti mechanical properties*, Nelson Montás (2015) based on Raviv et al. (2014) while also using Roboshop.com's technical data as basis for mechanical performance.

This simulation exercise demonstrates that Ni-Ti Flexinol wires can be modeled and tested prior to the fabrication and execution of a given design. It also demonstrates that not only it is possible, but that it is not difficult nor time consuming and that it reproduces a realistic situation in great approximation.

9.6.3-Implementing polymer simulations_

For the SMP simulation models, the research focused in Dan Raviv et al's work on hydrophilic, having proven to be a completely disclosed process that, in great detail, showed with what and how their experiments were done and developed extensive data tables to derive technical information from. The material's chemical composition and some of the mechanical macroscopic data are available int their publication in *Nature* magazine and which was be used as basis for the modeling. The experiments were done using a “spring-mass” model similar to the one used by Raviv et al. in their simulation work in which strands are modeled as stiff, rigid parts and the joints are modeled as rest-length based flexible, super-elastic pieces. Up next there are several chemical composition, joint calibration and activation timing tables exhibited in the experiments they carried out in their research into hydrophilic polymers.

Table 3 | Material components of the expanding printable material. It is composed of hydrophilic acrylated monomers that create linear chains upon polymerization with a small amount of difunctional acrylate molecules

Component	Amount (%w)
Vinyl Caprolactam	50
Polyethylene	30
Epoxy diacrylate oligomer	18
Iragcure 819	1.9
Wetting agent	0.1

Chemical composition, Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits (2014) (Raviv, Dan et al. , *Active Printed Materials for Complex Self-Evolving Deformations*, Scientific Reports, Nature, P. 4*)*

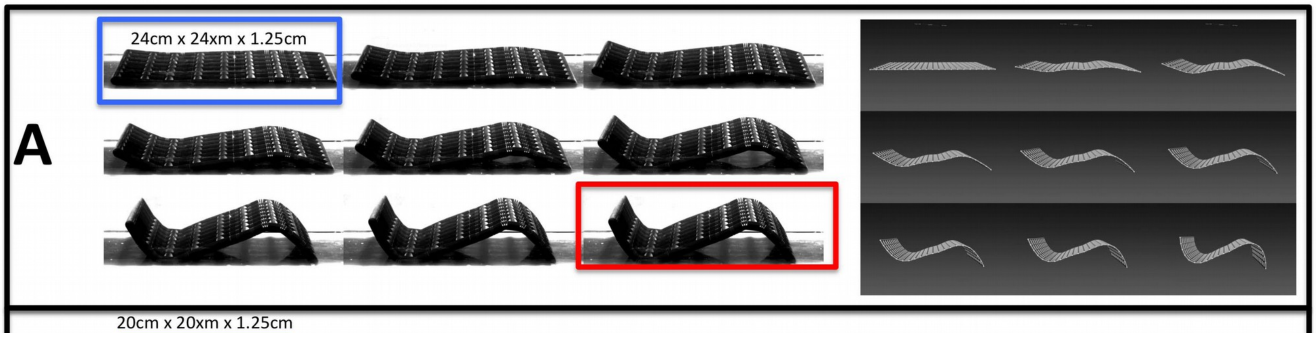
Table 1 | Experimental calibration of the folding joints. Each row represents (from left to right): the distance between disks, expected angles between bars and the measured angles between bars after water immersion. The experiments were done on the hexagon in 2D for mapping distances between disks to angles between bars

Distance (*inch*)	Expected angle (*deg*)	Real angle (*deg*)
0.082	101	095
0.073	109	103
0.069	113	105
0.065	117	109
0.062	120	115
0.054	127	119
0.053	128	120

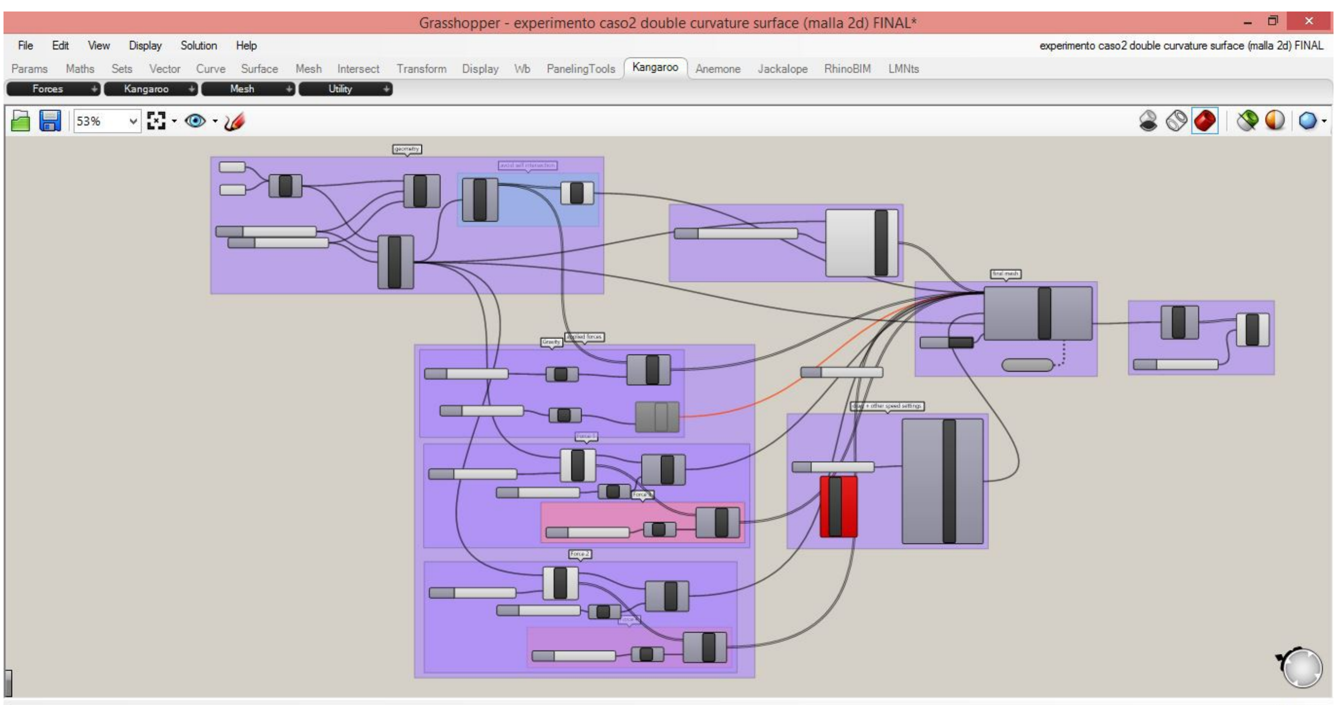
Joint calibration, Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits (2014) (Raviv, Dan et al. , *Active Printed Materials for Complex Self-Evolving Deformations*, Scientific Reports, Nature, P. 4*)*

In this experiment we tried to simulated two of the published projects by Raviv et al. int their article in *Nature* magazine. From these, we have chosen two specific cases that resemble significantly to the definition for *case study 2*, developed to simulate the general behavior of a 2d grid itself made kinetic and controlled via vectors only opposite, for example, to *case study 3* where the final form was ready made before the simulation runs. The selected projects were the *flat to sinusoidal wave grid* and *flat to* *double curvature grid*, because the previous research suggests that it is possible to use a vector model and spring-mass system to induce kinetic, programmable matter traits and actuation to a Kangaroo physical simulation model. A future modeling strategy is to write a Python script that calculates the angle, velocity and acceleration of the folding to be applied to the spring-mass model.

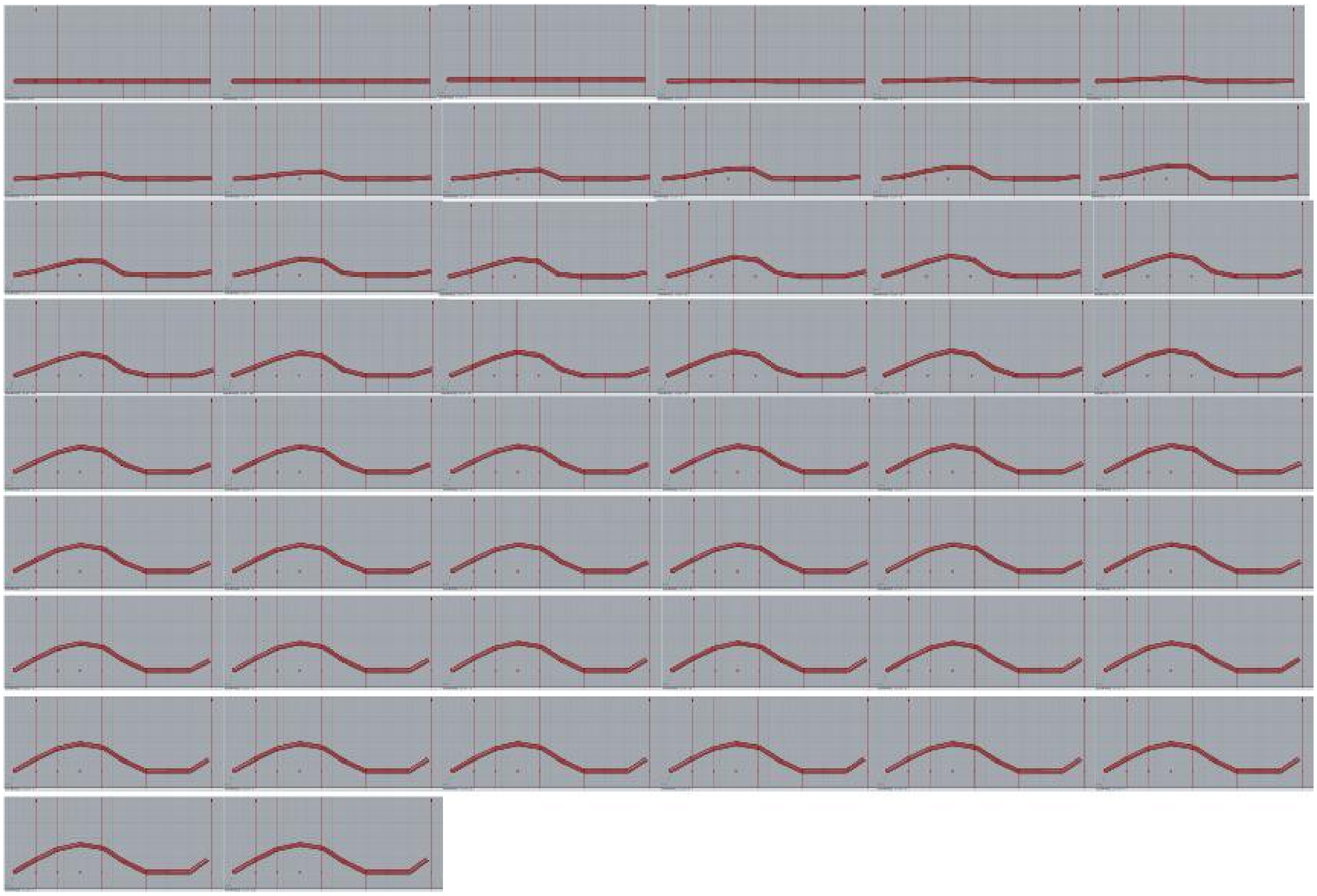
*9.6.4-2D grid to sinusoidal wave_*



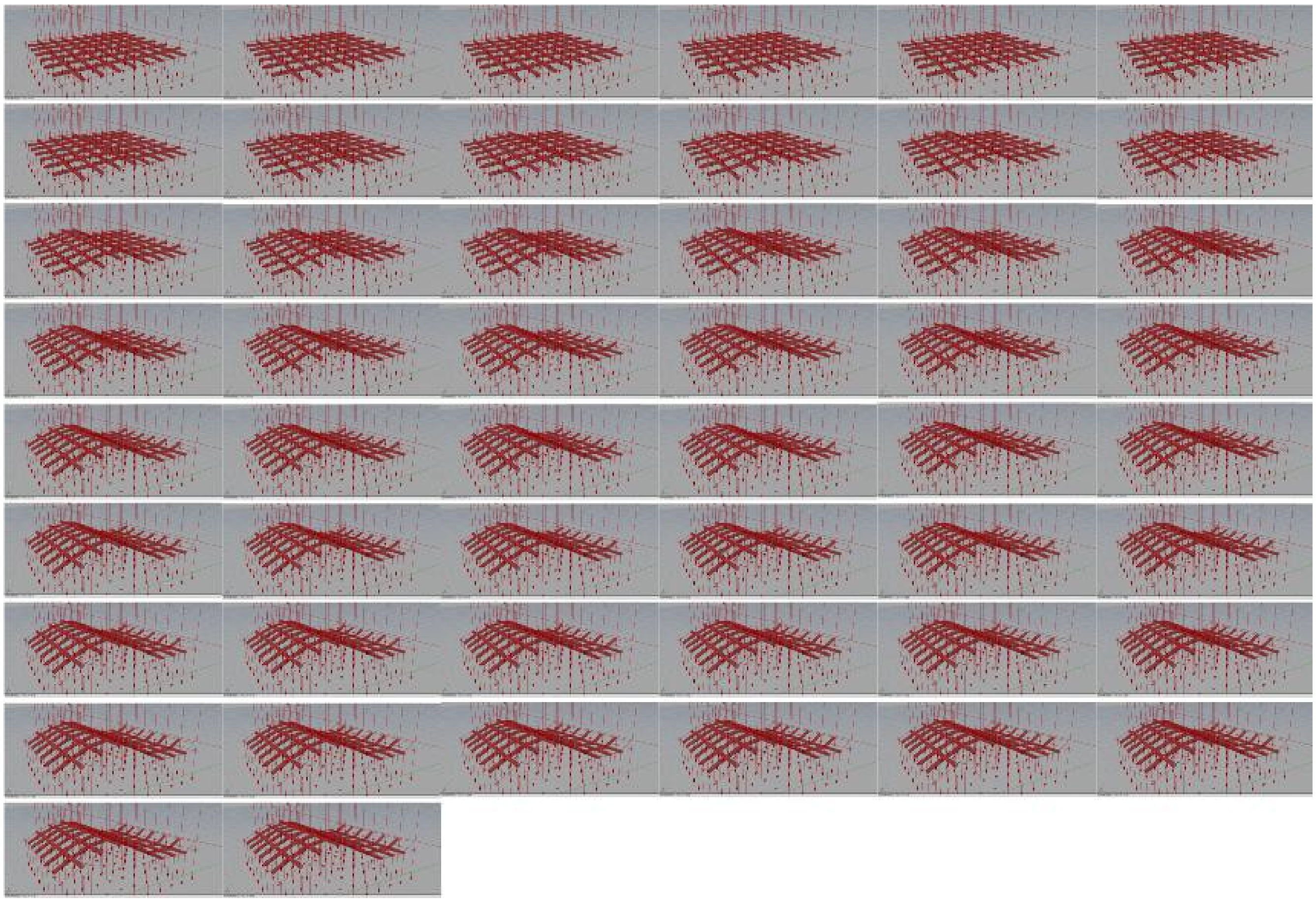
Case study 6, deformation of a grid into a sinusoidal wave, Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits (2014) (Raviv, Dan et al. , *Active Printed Materials for Complex Self-Evolving Deformations*, Scientific Reports, Nature, P. 6*)*



Grasshopper +Kangaroo visual code implemented to build the *Case study 6 simulation* of the deformation of a 2D grid into a *sinusoidal wave* (convex and concave), Nelson Montás (2015) based on Raviv et al. (2014).

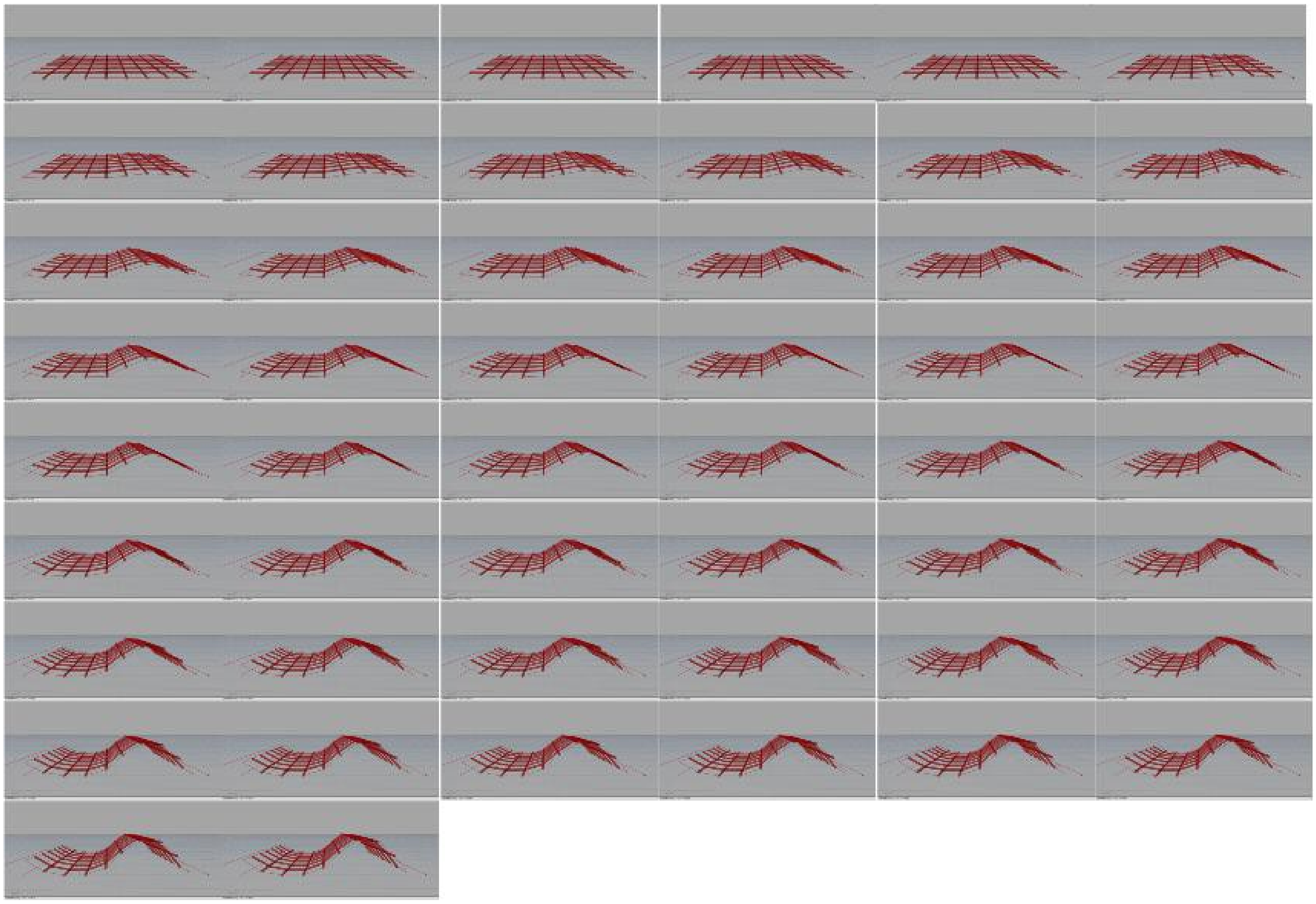


Case study 6, Simulation of the deformation of a 2D grid into a sinusoidal wave, still-frames sequence (left side elevation) Nelson Montás (2015) based on Raviv et al. (2014).

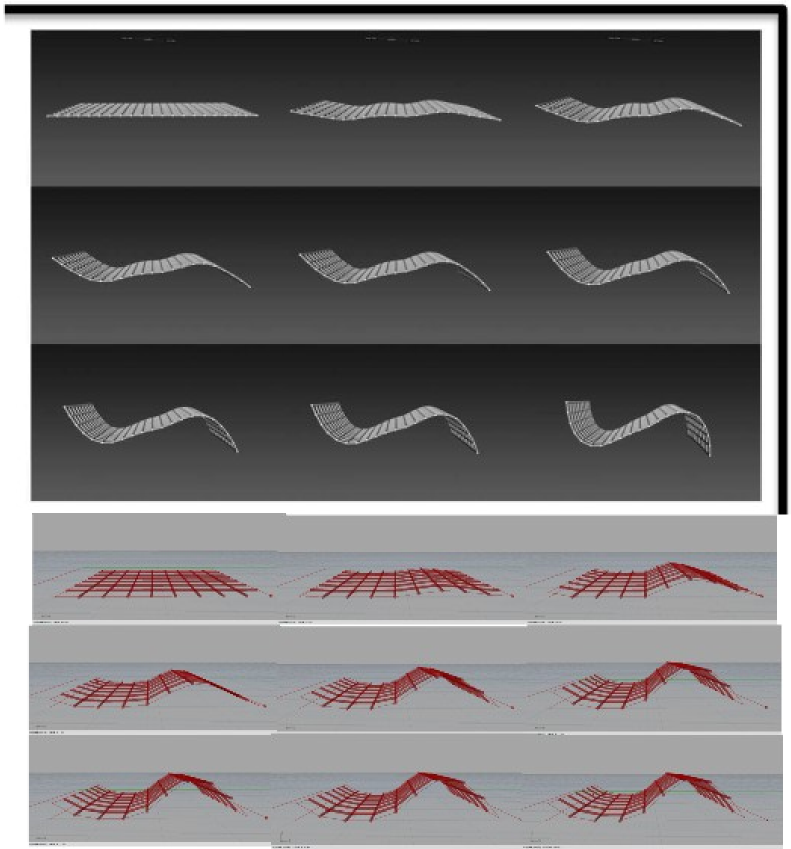


Case study 6, simulation of the deformation of a 2D grid into a sinusoidal wave, still-frames sequence (perspective view) Nelson Montás (2015) based on Raviv et al. (2014).

The sinusoidal wave modeling was done with relative ease, orthogonal resultant vector were used in the construction of the force system as in Raviv et al simulation. The results were very close as approximation. This leads us to conclude that it is not only possible but reliable to construct this kind of simulation (2D grid bent in one axis, therefore one dimensional in nature). Resultant vectors are useful and straight forward to implement and which will not be the case of the next experiment.



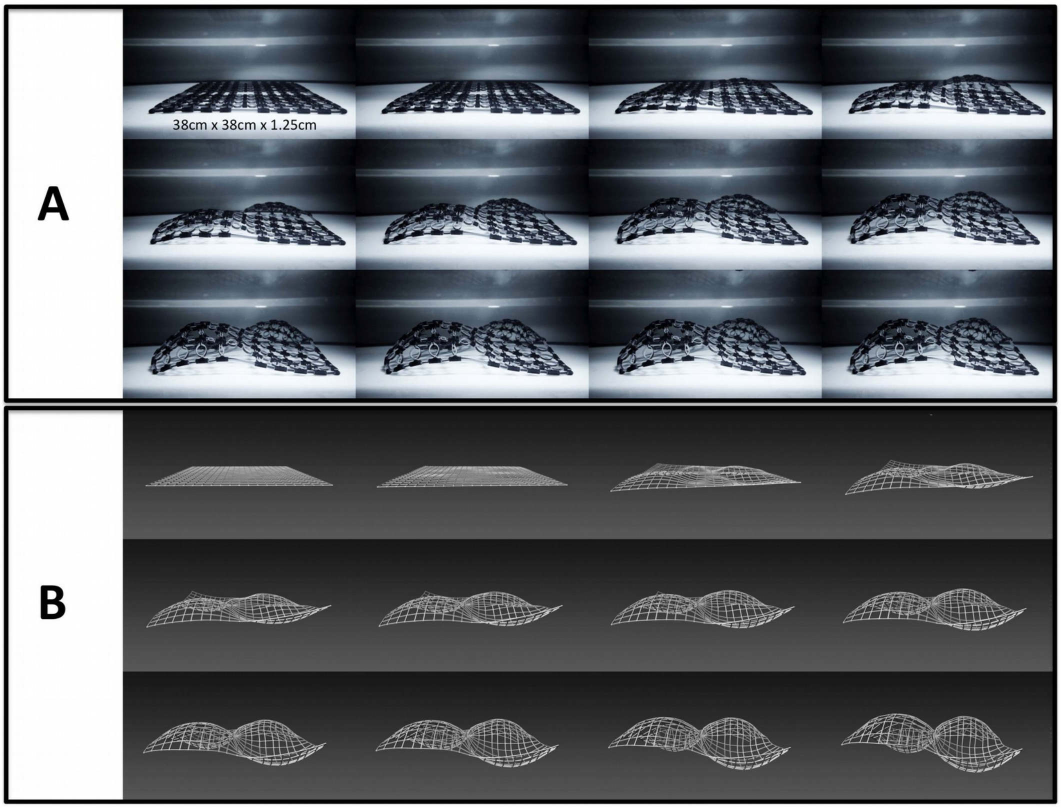
Case study 6, simulation of the deformation of a 2D grid into a sinusoidal wave, still-frames sequence (perspective view) Nelson Montás (2015) based on Raviv et al. (2014).



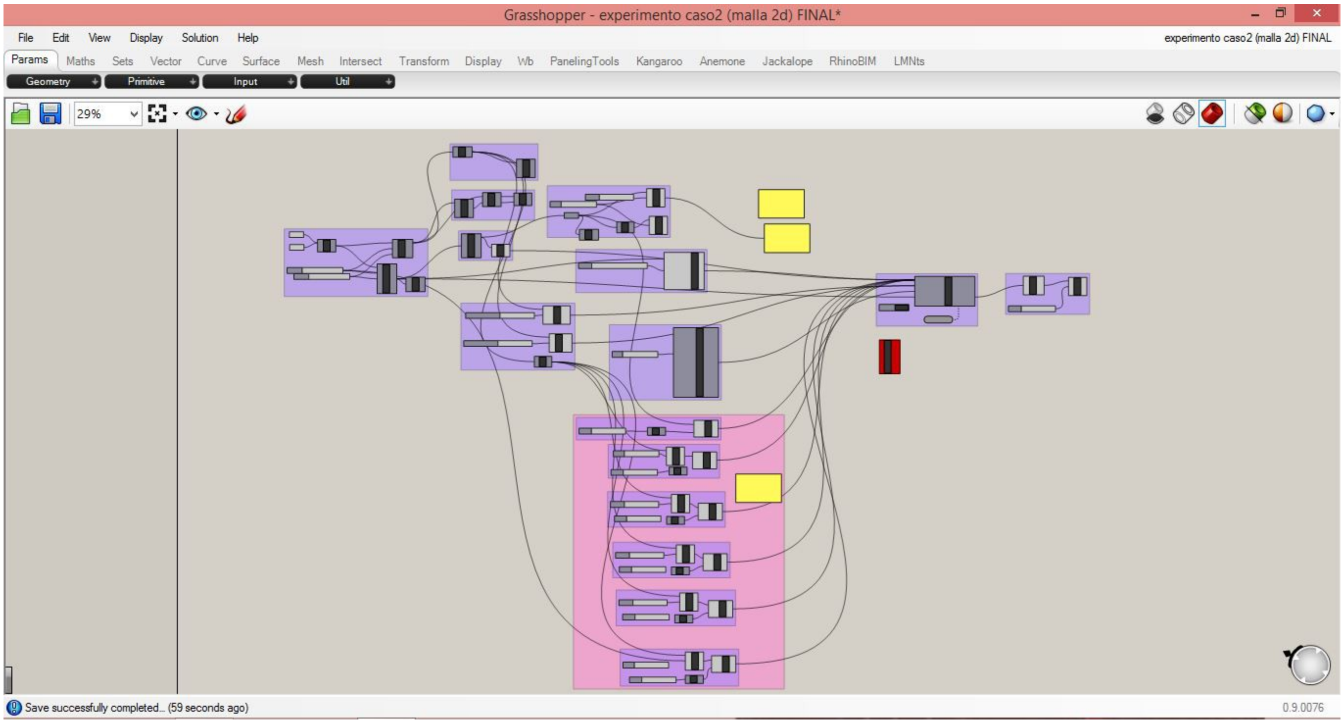
Case study 6, comparison of both (original and replicated) simulations of the deformation of a 2D grid into a sinusoidal wave, still-frames sequence (perspective view) Nelson Montás (2015) based on Raviv et al. (2014). Here the double curvature deformation compared to that of the Raviv et al. simulations and physical models is an astonishingly close approximation to the real models in the original experiments.

*9.6.5-2D grid to double curvature_*

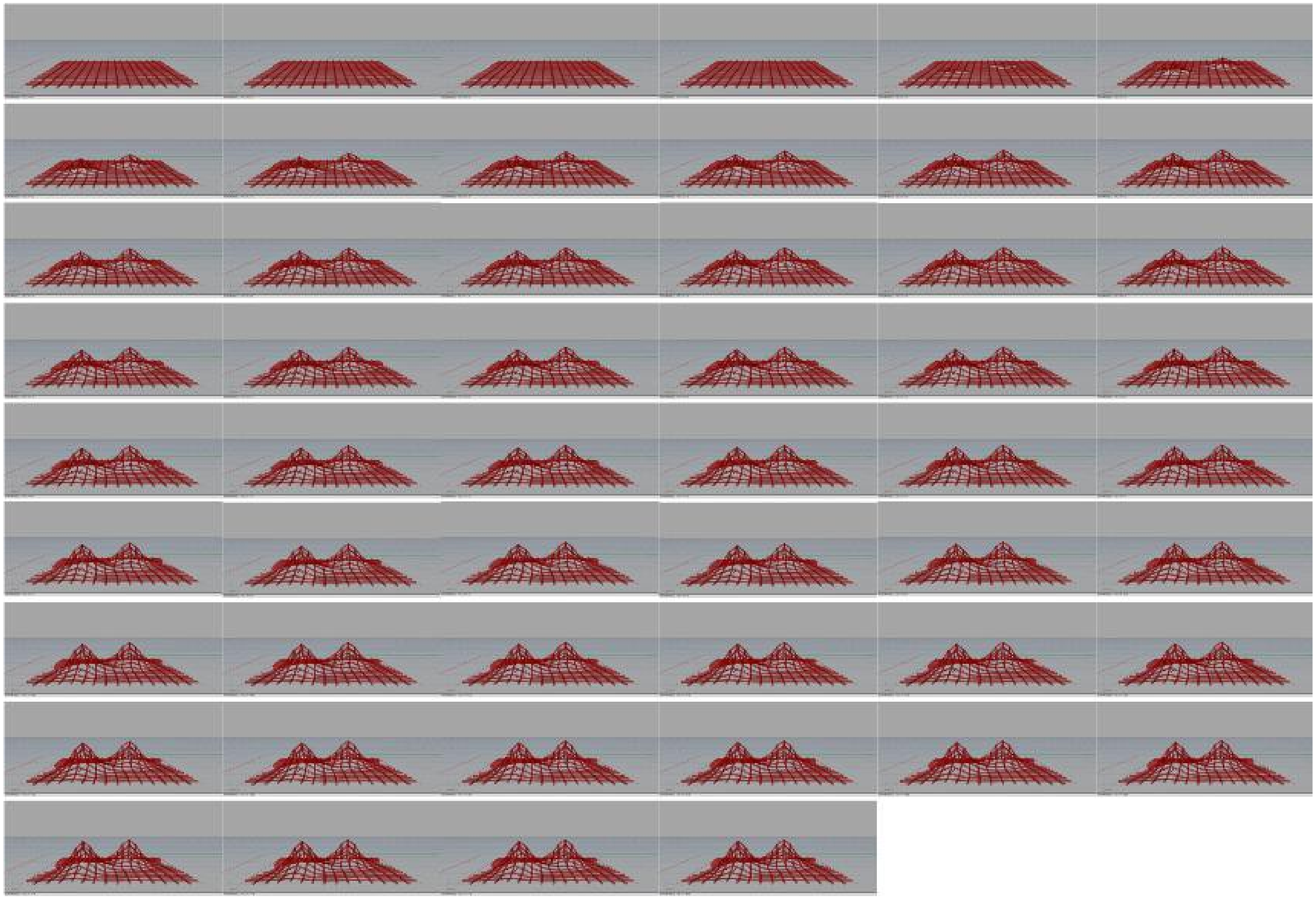
In the case of simulating Raviv et al's. transformation of a two dimensional grid into double curvature (see chapter VIII) was not as easy and, in fact, using the spring-mass system built with resultant orthogonal vectors did not work to output an very close approximation like the sinusoidal wave case did. The reason is that the real polymer model built by Raviv et al. was transformed using shear twist stress programmed loads onto the ring connections between joints and bars. Raviv et al. also used simple spring-mass folding bars in their simulation as this experiment was carried out, yet the approximation is tolerable but it is obliged to be explained that the tolerance deviation is significant and that shear twist mechanical behavior has to be implemented to better approximate the original physical model. As vector forces have to be controlled one by one in this kind of aggregate logic model, to “find” the double curvature surface's exact shape, or even an admissible approximation implies programming every point in the surface opposite defining a double curvature equation to guide the shape adjustment like in our earlier shown kinematic model in case study 3.



Case study 7, deformation of a grid into a double curvature surface (convex and concave) Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar & Skylar Tibbits (2014) (Raviv, Dan et al. , *Active Printed Materials for Complex Self-Evolving Deformations*, Scientific Reports, Nature, P. 7*)*

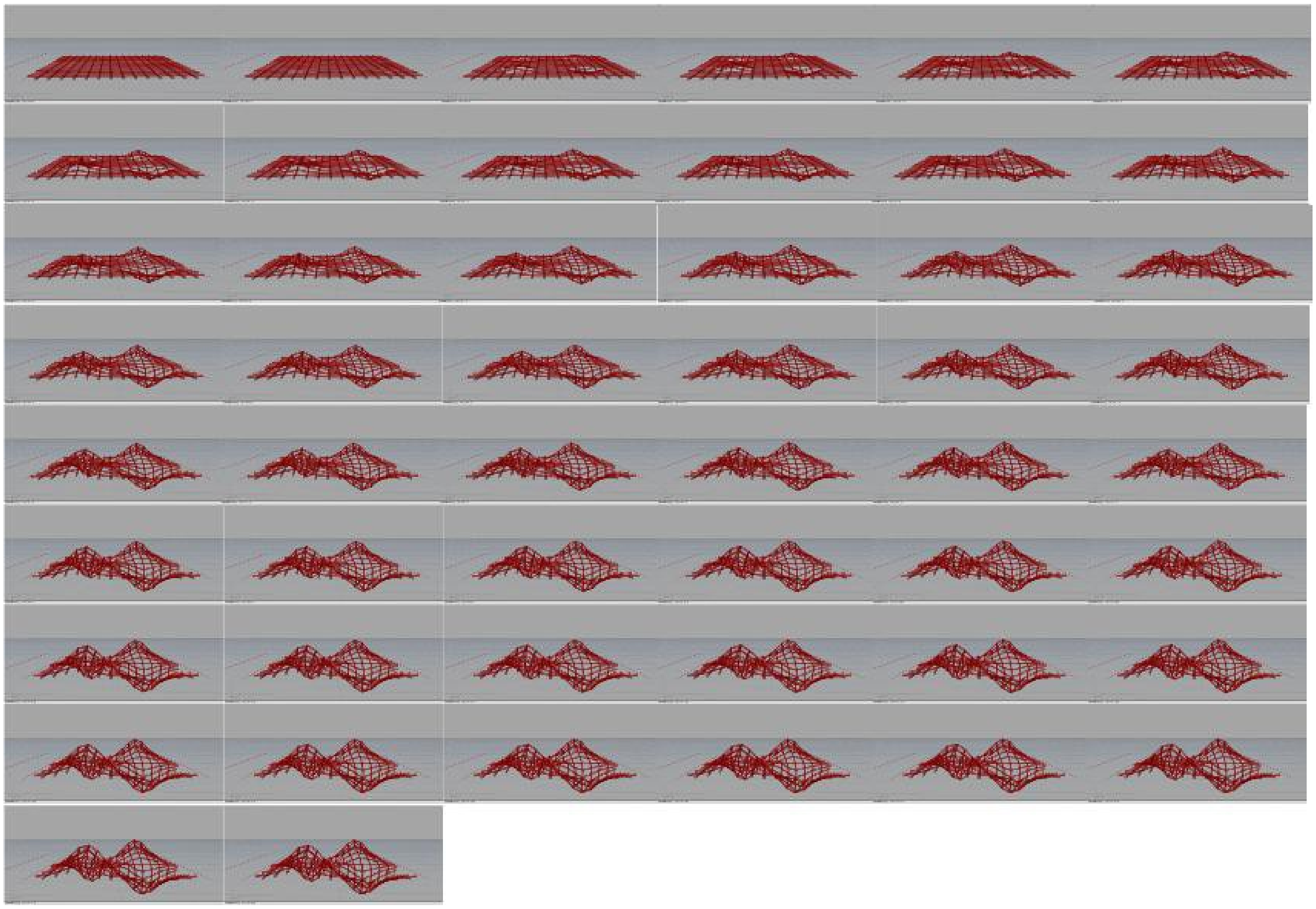


Grasshopper +Kangaroo visual code implemented to build the *Case study 6* simulation of the deformation of a 2D grid into a *double curvature surface*, Nelson Montás (2015) based on Raviv et al. (2014).

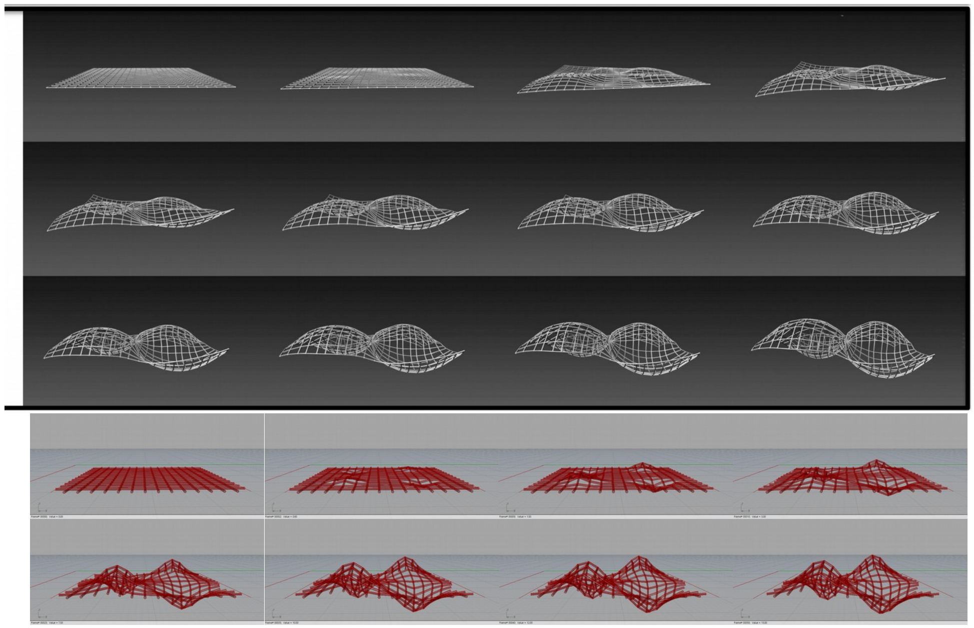


Case study 7, simulation of the deformation of a 2D grid into a double curvature surface (convex and concave) still-frames sequence (left side one-point perspective) Nelson Montás (2015) based on Raviv et al. (2014).

Still using vector induced folding, a second simulation run showed that adjusting (or “fine tuning”) vector intensity thoughtfully and carefully, a very acceptable approximation was able to be achieved. This approach (vector control), while intuitive and didactic, requires the user to “learn” or, better yet, be taught the physics behind the phenomenon by the Kangaroo engine itself. Therefore it has implications for both teaching and research into kinetic design.



Case study 7, simulation of the deformation of a 2D grid into a double curvature surface. Here, the double curvature deformation compared to that of the Raviv et al. simulations and physical models results in an astonishingly close approximation to the real models in the original experiments. It is fair to state though that this particular model required some model empirical “tuning”, or “tweaking”, this evidence suggests that vector force “tuning” is a relatively easy and intuitive method to arrive a otherwise relatively complex mathematical calculations and that this phenomenon, as a principle, can be scaled up to more complex forms.



Case study 7, comparison of both (original and replicated) simulations of the deformation of a 2D grid into a double curvature surface (convex and concave) still-frames sequence (left side one-point perspective) Nelson Montás (2015) based on Raviv et al. (2014). The graphic animations show a strong resemblance of the replication simulation with the original one, suggesting that it is probable that force vector analysis is a viable method to simulating programmable matter kinetic systems.

*9.7-Conclusions_*

1. Parametric modeling and CAD technology although coming from different disciplines appear to have converged, at least academically, first at Harvard University.

2. It is of most importance to choose the appropriate programming paradigm to build a given simulation in the best way possible, but at the end, it is up to the designer to make that choice.

3. Architects seem to only have between procedural, OOP and data-flow to build parametric models.

4. Visual programming does effectively bypass the edit-compile-run loop but at a price, the computer's RAM memory availability is diminished making models slower and obliged to be smaller in size.

5. Using modules proved to be of much aid, as suggested by Davis in that they made the phenomenon that were to be understood be broken down to fundamental "parts".

6. Cyclomatic complexity proved to be also an effective correction tool to bring down code size.

7. Answering Davis's questions regarding experimenting with parametric models:

   Functionality: Are all the modelling tasks able to be performed by every programming method? Correctness: Do programs do what is expected? Yes

   Ease of use: Are the modelling interfaces easy to use? Not established as a sure fact, lacking group experiments to confirm, but it appears to be the case.

   Construction time: How long did the respective models take to build? Not measured.

   Lines of Code: How verbose were the various programming methods? Most of the cases were able to be built using relatively small parametric definitions.

   Latency: How quickly did code changes become geometry? The interactivity exhibited is considered sufficient for these models specifically, more complex models should decrease their interactivity proportionally.

8. Code correctness exhibited in the experiments remains tolerably functional.

9. Design-simulation-fabrication processes are possible and an invaluable tool when designing programmable matter powered kinetic architecture structures using physical simulation models embedded in CAD/CAM software (both SMA and SMP), yet it is noticed that the learning curve is high and that it takes substantial amounts of time understanding the phenomena to model non the less they can be easily modified and reusable if structured correctly and orderly.

10. Vector control, in certain situations, can indeed replace geometrically defined IK solver

methodology to “find” shape B in programmable matter kinetic applications, non the less, this method seems to have a handicap: it can become increasingly more difficult as complexity increments, therefore it is established empirically that form complexity and difficulty are directly proportional.

11. This approach (vector control), while intuitive and didactic, requires the user to “learn” or, better yet, be taught the physics behind the phenomenon by the Kangaroo engine itself (it was possible to achieve a double curvature surface without the mathematical equation).

12. It is proven that, in the case of kinetic architecture and programmable matter, visual programming data-flow paradigms are the most intuitive tool yet developed, effectively exhibiting more flexibility, easiness and real behavior modeling than the tools studied by Angeliki Fotiadou (3Dmax).

13. More research and development is in order to further optimize this current method to simulate SMM and PM based KA. Special attention has to be put on molecular, numerical and multi-scalar modeling in order to achieve more accurate and precise simulation outputs. In this experiments phase, a subdivided surface model as tried in order to abstract molecular formation, treating “strand to spring” experiment thread as a multi-agent solid mass model but the computer crashed and the model, just at the beginning of parametrically defining it, does not allow for interactive tinkering, thus making it unsuitable for design purposes, therefore this alternative was not pursued further. The crashing is attributed to a data overloading on RAM memory by the thousands of individual “dots” that made up the “strand”. Maybe a differently built parametric model could work yet this question is not answered accurately in this experiment, future work will include modeling molecular solid-mass models.

*10-General conclusions_*

This thesis project's most important theoretical objective was the finding of ways in which to utilize these materials within the conception and development of passive kinetic architecture systems (K. A. which is, as of today, mostly computer controlled --therefore, electricity consuming). Specifically, this was done using simulation models, these new coded simulations can give architects and engineers the ability to design and test-run kinetic components, within tolerable approximations, in a digital work space before having to do so in a lab. To paraphrase Skylar Tibbits: "in the future we will program materials like we program computers today".

*10.1.-Short recap_*

In the introductory phase, borrowing concepts from engineering, computer science, material science, art and biology, this thesis sought to reveal how all of the above come together in the practice of producing design methods that in turn make possible a kind of truly autonomous, programmable matter based kinetic architecture within the bigger framework of genetic architecture. In the theoretical phase, this thesis concentrated on kinetic architecture's origins and historical development and how it knots with computational design to address both geometric and dynamic complexity. The issue of Trans-disciplinary research was addressed and established as a central tool to develop this thesis and address both KA and PM. While the link between civilization and tool-making has also been established as a main framework in the state or the arts and further development of the theory of software engineering and architecture and their subsequent implementation to achieve autonomous architecture. Genetic architecture's aspiration to engender animate and alive objects and transmuting organisms has been established.

In the historical background phase, architecture and design have been genealogically mapped and a thread has been uncovered that proves that kinetic art and architecture both descend from animation, which in turn comes from chrono-photography, a consequence of morphology, that itself derives from painting. To demonstrate this, the fact that Botticelli's drawings for the *Paradiso* and *Inferno* in Dante Alighieri's *Divine Comedy* (1481) have been established as the oldest known drawings represents the origins concerning the dimension of time in kinetic artwork. In that line of thinking, *Contre-Reliefs Liberes Dans L'espace* (1915) by Vladimir Tatlin is established as the first kinetic art piece ever exhibited, *XXV years of peace transportable pavillion* (1969) by Emilio Pérez Piñero is established as the first kinetic building scale construction. Chuck Hoberman (1990-XXXX) continues Pérez Piñero's path constructing building scale kinetic arches while a later Mark Goulhorpe revolutionizes kinetic architecture with his *Aegis hyposurface* (2001) in that is fully controllable and re-programmable. Dollens and Pérez Arnal propose using animation software as design and exploration tools. This last view about how animation software can forge the design process and change our perception of what nature is in the case of "The Cathedral" by Tomek Baginski (2002) is set as the basis of this research's orientation towards digital tool utilization in the context of kinetic architecture, the conclusions regarding this approach is that, in turn, the animation driven design process does give a certain "outside" look on movement evidenced by the medium's interactivity embedded UI and UX, as in the case of Angeliki Fotiadou's "Analysis of Design Support for Kinetic Structures" (2007) investigation. Interactive architecture, a concept outlined by Kas Oosterhuis, supports these approaches while adding game theory to its already ground shaking propositions. This general framework sets the stage for the development of kinetic and interactive buildings and environments and make it, not just a possibility, but both a necessity and an obligation.

In the theoretical phase, kinetic systems have been demonstrated to theoretically address, through "dynamic flexibility", the problem of "change" and uncertainty". Daniel Rosenberg has theoretically demonstrated that kinetic design is the response to the age old question concerning change and uncertainty, in his master's thesis "Designing for Uncertainty" he explains how Zuk and Clark's concept of kinetic architecture stands as an effort to frame this "way of conceiving design into a specific science field, one that can accurately define and face "change" as a "Rosetta-stone" in the process of design. Kinetic sytems have been also shown to give rise to emergent phenomena and that its definition stands as none other that of a dynamic system. As in Helen Castle's definition: "*emergence already surfaces as a model capable of sophisticated reflexive attributes exceeding any mechanistic or static notion of architectural form-one that could perhaps define new levels of interaction within natural* [and artificial] *ecosystems."*[892]

Also, a classification has been established that arranges kinetic systems according to their energy sources and divides them in three major groups: mechanically sourced, electrically sourced, passive systems. Among which our main focus is classified within the programmable matter systems

[892] Emergence and Design Group, *Op. Cit.* (2004) P.9

subdivision. It has been established, as a theoretical basis, that active shapes are a useful tool to model kinetic actuation from lower to higher level transfer yet it still might need automation and computational implementation to test material behavior driven actuation. It has been theoretically argued that kinetic control systems can be generated in ways different than sensor driven, computer regulated, ubiquitous gadgetry assembled systems positing the possibility of programmable matter as a main source of kinetic actuation traits. Ubiquitous computing, also known as ambient intelligence, is proposed by some as an alternative to flexibility than kinetic systems, yet no development is neither cited nor carried out thus remaining a theoretical proposal, nevertheless calling on researchers for its immediate investigation. Although full of potential, these assertions remain to be tested.

Tess Fenwick's "Progamme: Morphosis" master's thesis (2011) outlined a conclusion about KA that states that *"...There are too many parameters, and too many areas in designing a whole kinetic structure has [have] to be explored and researched."* while Dina El-Zanfaly concludes in her thesis "Active Shapes: Introducing guidelines for designing kinetic architectural structures" that "*The materiality should also be studied as a major transformation parameter in the active rules"* which is evidenced in the 4D printing and PM theoretical foundations as a main driving argument in establishing its time oriented, dynamic propositions.

"*In addition to exploring the rest of the possible transformations in the active rules, the presented guidelines should be put in a framework for designing the kinetic structures, which should also contain: The design mediums, which include the simulation softwares (sic) and physical prototyping"*[893]

"Some of these elements should be also connected in a loop like the virtual design and the physical prototyping to maintain the connection of geometry and physics to materiality, mechanics and scalability."[894] This also being another conclusion that relates with the aims of this research in producing a software tool that models SMM behavior to continuously simulate them in the decision making process within design.. These conclusions further proved the top-down approach rather inefficient and tortuous and also points out that the bottom-up approach holds better chances (although not a complete victory is announced, for bottom-up still has a lot of uncertainty to deal with in real world applications) of successfully addressing kinetic architectural implementation under local

893 El-Zanfaly, Dina, *Op. Cit.* (2011) P. 68
894 Idem.

interactions in lower levels. Although it is difficult for the designer to predict the exact behavior of motion of a kinetic structure in the design process*,* after a certain complexity is reached as concluded in the prior case studies, it is this thesis's hypothesis that neither "top-down" nor "bottom-up" are completely advantageous on their own when engaging with fundamental to practical application in the context of kinetic systems (with a significant tendency favoring bottom-up approaches). Therefore a synthesis between the two paradigms ("top-down" or "symbolic", and "bottom-up", this merger dubbed the "sub-symbolic" paradigm by Karl Chu) is needed to fully grasp the complexity that can be achieved and dealt with at different scales when designing and implementing intelligent kinetic systems design into the architectural environment. Programmable matter was proposed as a material definition, material design as a methodology and craft, and performance driven simulation as a design instrument. These will be thoroughly scrutinized and tested in digital experiments at the end of this thesis.

10.2-Discussion_

Answering this thesis's most relevant question that is:

"To develop a piece of code that can deal with current design and material behavior through simulation in a phenomenological and efficient manner; drawing information from intrinsic and extrinsic variables according to specific contexts stimuli such as environmental, thermal differential conditions and specific materials properties, hence material performance." (Is it possible to build material behavior simulations that efficiently replicate or approximate PM performance actuation within contextual and intrinsic phenomenological stimuli? If so, how?)

This investigation concludes that pursuing the simulation of kinetic structures in animation software is not only not viable, it is not an adequate design exploration tool, therefore not suited for form-finding nor emergent behavior envisioning, making it a very "closed end" tool. Fotiadou's "by hand", non-parametric CAD modeling procedures proved being time consuming and leading to too many dead ends, this research implemented another method that addresses complexity issues while modeling: ***parametric modeling.*** Further do we conclude that *Rhinoceros + grasshopper +Kangaroo* is a definitive choice to develop further as it permits, in an declarative visual programming environment, to set up parametric models in which to carry out reliable approximations in material behavior within physical simulations, specifically those of SM systmes and SMM.proven to be very effective and useful when facing visualization, performance and geometric. Furthermore, KA, PM, SA and 4DP all share similar concerns and scale limitations. The differences lie for the most part in the methods, ways and means to achieve “animation” in material configurations. At the core of this technique are three main tenets or principles that give rise to the subsequent unleashing of possibilities which are: *“the machine, the material and the geometric ‘programme’*[895] thus being its most important aspects material science, computational programming geometric analysis and digital fabrication Material matrices are a central aspect to develop to obtain desired material behaviors and therefore PM, SA, 4DP thus enabling programmable matter based KA. PM, SA and 4DP entail a universe of applicable scenarios and is set to disrupt the whole world and even the human condition. There are significant possibilities of PM, SA and 4DP of becoming terrorist weaponry. It is suggested by Raviv (2014), Tibbits (2012) and Campbell et al. (2014) that PM, 4DP and SA's implications will “spill over” to virtually every domain in the the STEM sciences and there is certain proof that it has already done so into the art world. Scaling up is still a central challenge for PM, 4DP and SA. 4DP, PM and SA are all based in additive manufacturing and, as such, they are within the material “taxo-navigation” conceptual framework elaborated by Liat Margolis (2011). Therefore selecting material and, in the future, designing it from its very fabric, seems not only imminent but a necessity as it enables creative novelty and contingency, something that “conventional” construction coding does not provide. Simulation of these materials is possible and has been started by SAL, DARPA, Virginia Tech and other institutions. It is up to us to develop it further, enabling the following chapters as justified endeavors. Fabrication standardization and industrial implementation remains an also still to develop phase in the implementation of such systems like KA, PM and SMM suggesting that we need to make their fabrication and programming processes cheaper in order to fully profit from all their promises and in all fields of application. Memory loss is also one of the main obstacles of PM and KA, as it hinders effectiveness and re-usability thus diminishing its sustainability potentialities, it is suggested as future work that material science pertaining these promising materials be further developed and assessed. Architecture, as a discipline, is to embrace these technological advances and probably include them, some way or another, in school curricula and graduate programs as standard practice in order to fuse them into the discipline as a core conceptual and technical knowledge basis, much like engineering has become to the mathematical side of

[895] Tibbits, Skylar, *Op. Cit.* (2014) P. 119

architecture. It is therefore suggested that design studios start profiting from these material configurations and matrices for in this field lies the future of architecture, not just kinetic, but the field at large. In terms of parametric modeling, Visual Programming does effectively bypass the edit-compile-run loop but at a price, the computer's RAM memory availability is diminished making models slower and obliged to be smaller in size while the using of modules proved to be of much aid, as suggested by Davis in that they made the phenomenon that were to be understood be broken down to fundamental “parts”. Cyclomatic complexity proved to be also an effective correction tool to bring down code size, this suggests that solutions of some the most important aspects of simulation construction in order to address PM and KA within the SMM context may lie within the software engineering paradigm as suggested by Daniel Davis (2013). Answering Davis's questions regarding experimenting with parametric models:

> *Functionality: Are all the modelling tasks able to be performed by every programming method? Correctness: Do programs do what is expected?* Yes
>
> *Ease of use: Are the modelling interfaces easy to use?* Not established as a sure fact, lacking group experiments to confirm, but it appears to be the case.
>
> *Construction time: How long did the respective models take to build? Not measured.*
>
> *Lines of Code: How verbose were the various programming methods? Most of the cases were able to be built using relatively small parametric definitions.*
>
> *Latency: How quickly did code changes become geometry?* The interactivity exhibited is considered sufficient for these models specifically, more complex models should decrease their interactivity proportionally.

Although RAM memory was by the most part affected by the computational expensiveness of some of the simulation models, code correctness exhibited in the experiments remains tolerably functional. While design-simulation-fabrication processes are possible and and invaluable tool when designing programmable matter powered kinetic architecture structures using physical simulation models embedded in CAD/CAM software, yet it is noticed that the learning curve is high and that it takes substantial amounts of time understanding the phenomena to model non the less they can be easily modified and reusable if structured correctly and orderly. Vector control, in certain situations, can indeed replace geometrically defined IK solver methodology to “find” shape B in programmable matter kinetic applications, non the less, this method seems to have a handicap: it can become increasingly more difficult as complexity increments, therefore it is established empirically that form complexity and difficulty are directly proportional. This approach (vector control), while intuitive and didactic, requires the user to “learn” or, better yet, be taught the physics behind the phenomenon by the Kangaroo engine itself (it was possible to achieve a double curvature surface without the mathematical equation). It is proven that, in the case of kinetic architecture and programmable matter, visual programming data-flow paradigms are the most intuitive tool yet developed, effectively exhibiting more flexibility, easiness and real behavior modeling than the tools studied by Angeliki Fotiadou (3Dmax). More research and development is in order to further optimize this current method to simulate SMM and PM based KA. Special attention has to be put on molecular, numerical and multi-scalar modeling in order to achieve more accurate and precise simulation outputs. In this experiments phase, a subdivided surface model as tried in order to abstract molecular formation, treating “strand to spring” experiment thread as a multi-agent solid mass model but the computer crashed and the model, just at the beginning of its construction definition, did not allow for interactive tinkering nor freely exploring its outputs due to model stagnation, thus making it unsuitable for design purposes, therefore this alternative was not pursued further. The crashing is attributed to a data overloading on RAM memory by the thousands of individual “dots” that made up the “strand”. Maybe a differently built parametric model could work yet this question is not answered accurately in this experiment, future work will include modeling molecular solid-mass models. This discovery suggests that it is possible to determine highly complex forms in a form-finding process that does not involve excessively complicated calculations, this has been demonstrated in case study 5 and 7 in which this research developed a flat to double curvature transforming surface, reproducing a similar model by Raviv et al. (2014) by means of parametric modeling, finally demonstrating that a double curvature can be defined by vector control in an arithmetically simple way rather than the usual calculus based equation definition avoiding calculus and achieving the same results.

*10.3-Final assessment_*

The experimental phase of this research carried out investigation concerning previous academic thesis, scientific papers and laboratory work about kinetic architecture, material science and computational design (more specifically parametric modeling) driven by laboratory, experimentally proven facts from all these disciplines and their authors, provided properly cited. Further in its development, digital experiments were based on data from previous laboratory investigations of different authors, specifically within the fields of architecture, digital simulation, software engineering & development while also all the previously named sciences. All this, trying to provide an answer to Angeliki Fotiadou's question about "*the possibility of using a scripting language in the software*" that asks if "*only by this way* [scripting] *it will be possible to modify the chosen software and create new functions that there might be needed*[?][896]*"* specifically within the kinetic architecture and programmable matter simulation joint field (see Scope and contributions heading at the beginning of the thesis). Our initial hypothesis was that it is the only way that current software allows for such customization yet this hypothesis beckons another equally important question that remained constant throughout the research process: *how well can we approximate real conditions in the context of simulation?* As proposed in the beginning of this thesis, all this was achieved using a range of case studies, our own research instruments and tools:

According to Daniel Davis, *"by employing multiple case studies, the anomalies of one can be balanced by the rest"*[897]. Robert Stake calls this a *"collective case study"*[898] *where multiple projects "are chosen because it is believed that understanding them will lead to better understanding, and perhaps better theorising, about a still larger collection of cases."* [899] In total, six case studies were conducted whereby to experiment oriented on this thesis's objectives and from which to draw conclusions using what Davis and Donald Schön call "reflective practice"; a method that borders on inductive and abductive reasoning and which resembles *"Kemmis and McTaggart's (1982) cycle of "planning, acting, observing and reflecting" on actions in practice."*[900] Meaning that, during the research process

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896 Fotiadou, Angeliki, *Op. Cit.* (2007) P. 17

897 Davis, Daniel, *Op. Cit.* (2013) P. 11

898 Stake, Robert. 2005. "Qualitative Case Studies." In *The SAGE Handbook of Qualitative Research*, edited Norman Denzin and Yvonnas Lincoln, 443-466. Third edition. Thousand Oaks: Sage.

As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 11

899 Idem.

900 Kemmis, Stephen, and Robin McTaggart. 1982. *The Action Research Planner.* Geelong: Deakin University.

As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 11

the path followed was that of “theorizing”, “drawing data form other pertinent, similar work”, “running experiments” and lastly “observing again” and “reflecting” on the given results. As mentioned at the beginning of this thesis, Daniel Davis, Paul Gruba and David Evans agree in a research instrument ***“****is any technique a scientist might use to carry out their ‘own work'.”*[901] *Typical examples include interviews, observations, and surveys.*[902] Unfortunately, since there are no explicit research instruments to measure kinetic architectural design correctness or accuracy, let alone to evaluate it in realistic terms. This research used, as a barometer, an existing thesis that measured “difficulty” using *Autodesk's 3Dmax* (an exercise that proved to be too complicated and with too much issues to solve concerning basic and advanced software functionality) which was used as a base of knowledge to choose our design research's platform and direction, the thesis in question was an investigation carried out by Angeliki Fotiadou in 2007 (see “Methodology”), where she compared several software packages regarding file basic functionality, modeling and animation tool availability and so on (a study that was detalied in chapter VII. In her investigation , she developed “difficulty” rating metrics that included: *“importing 2D drawings”, “create primitive elements shape”, “deform mesh”, “copy elements/mesh”, “create bones/skeleton/IE chain”, “define constraints of rotation”, “layout objects” and finally “animate”* . Her evaluation showed that using this software package had too many problems and could not address complex form developed from kinetic criteria, therefore this research, even thought considering it a crucial contribution to the field of kinetic design, has decided not to pursue this direction and particular platform, considering that there are better ways to address programmed matter kinetic structures. Therefore, by analyzing previous techniques, using, discarding or combining them new ways to address the matter of kinetic architectural design and simulation were developed in chapter IX. This research tentatively analyzed ways to understand how to mathematically model the selected material's properties in order to compute and simulate their behavior in relation to the stimulus/form/movement phenomenology and subsequently code it in the program's application programming interface and work space (-API- and/or user interface-UI-) through the development certain examples of kinetic architecture simulation as case studies answering the research questions at the “general objectives” heading at the beginning of the thesis, out of all of these, the ones pertaining to the development of experiments to prove initial assumptions stand out as crucial to understanding the connection between architecture, more specifically KA, with PM and 4D printing applications better:

[901] Evans, David, and Paul Gruba. 2002. *How to Write a Better Thesis*. Second edition. Melbourne: Melbourne University Press, P. 85.
As quoted by: Davis, Daniel, *Op. Cit.* (2013) P. 11
[902] Davis, Daniel, *Op. Cit.* (2013) P. 11

“To develop kinematic and kinetic software simulations that explore material behavior and optimize CAD visualization in the context of kinetic applications. “ (is it possible to optimize CAD visualization in the context of kinetic applications? If so, how?) Answer: yes.

“To conduct experiments that support or discard the assumptions and speculations proposed by the initial theoretical hypothesis.” (Do architects today take advantageous positions regarding the potential to create kinetic architectural components, structures or even envision “living like”cities?) Answer: very little.

Also in the “specific objectives” heading we find experimental concerns to build tools by which to gain further understanding of the PM phenomenon in relation to art, architecture and design, which were:
“To develop design methods utilizing available software tools and potentially develop further their functionality , based on observation of nature as a framework and initial basis.” (How does nature fit into the tool development agenda and how does it influence PM based KA?) Answer: biological systems aid in the construction of artificial life-like systems.

Answers to both latter questions: The most overwhelming implication of PM in terms of kinetic architecture and design at large is the possibility of generating building components and whole buildings that can “feel” in reaction to external stimuli. In chapter VII it was highlighted that the replacement of sensors with “sensing matter” has indeed set a stage where PM's applications could be virtually omnipresent; you name it: bio-medical, bio-mechanical, transportation, engineering and so on, the world is staring at an abyss through this technology. The great shift in regard to KA is that, while Fox, Zuk and the original theoreticians that started the scientific field were conceptualizing within the framework of mechanical, pneumatic and ubiquitous sensor technology and computer controlled systems, this paradigm shift, coming from the depths of matter itself, has started a whole new chapter within KA providing construction and objects with far intelligence that, since embedded within matter itself, have abilities that belong to a whole different category when it comes to work logic, complexity managing and application limits. *More complex assemblies, different nanomaterials and raw materials, and different activation energies (water, heat, light, etc.) could theoretically be utilized to create a* *potpourri of novel applications for PM.*[903] Campbell et al. describe the relationships between how natural elements come together to produce intricate and complex compounds which servo higher level material properties.

"If fewer than two dozen element types give rise to all biological life, a few basic voxel types can also open a large range of possibilities... ... let's combine rigid voxels and soft voxels. Using just those two types of voxels, it's possible to make hard and soft materials. Add conductive voxels, to make wiring... ...Add resistor, capacitor, inductor and transistor voxels, to make electric circuits. Add actuator and sensor voxels and you have robots."[904]

*10.4-Genetic architectural implications and digitizing reality_*

As Neil Gershenfeld from MIT's Center for Bits and Atoms has proposed in terms of digital materials has shed light into the way we need to re-orientate the discipline's relationship to materials and the science behind it. Digital material's (interchangeably PM and SMM) comparison does not come out of nowhere but the intention to provide the same genetic, biological logic to the building of digital matter.

"In a forest there's no trash; you die and your parts get disassembled and you're made into new stuff. When you make a 3D print or laser cut, when you're done there's recycling attempts but there's no real notion of reusing the parts..."[905]

One of this research's most firm conclusions is that we are not just talking about recycling here, the far reaching implications go all the way up to inherent properties like metrology, error correction, material combination and inerweaving (material matrices). This does not mean, for example, that a property like metrology as such will disappear, but that it will change its origin and systemic behavior in terms of the object that it generates (or organ, system or organism, for that matter). And while stating all these profoundly game changing emergent processes, there is also a line drawn between digital communication, computation and fabrication that shows the invisbile thread that is what is called digital, hence its real meaning: a construction of material reality, but not the one we know as such, but

903 Campbell, Thomas – Tibbits, Skylar - Garrett, Banning, *Op. Cit.* (2014) P. 7

904 Lipson, Hod - Kurman, Melba,*Fabricated: The New World of 3D Printing* Indianapolis: Indiana: John Wiley & Sons, (2013) P. 277

905 Gershenfeld, Neil, "Digital Reality: A Conversation with Neil Gershenfeld", on *Edge.org* website (http://edge.org/conversation/neil_gershenfeld-digital-reality)

another kind that is closer to organic living matter than inert, inorganic one.

...The metrology coming from the parts, detecting and correcting errors, joining dissimilar materials, disconnecting, reusing the components—those are all the things Shannon and von Neumann taught us. They're digital fabrication. But the crucial distinction is that the code isn't in the computer, it's in the materials themselves. It's digitizing physical reality. There's an exact historical alignment between going from analog to digital in communication and analog to digital in computation, and now analog to digital in fabrication. That's the research revolution: digitizing fabrication, coding construction."[906]

Gershenfeld has clearly stated that the road to digitization is that of *discreet metrology* and that, in turn, error correction and, because of the nature and repeated usefulness of the building-blocks, also re-usability derives from that metric property. This suggests that digital materiality has an inherent nature to it that produces diversification and emergent self-assembly properties embedded within the concept and that it is observable in every application of the digital that we have developed, specifically meaning digital communication, computing and fabrication. Also in agreement with Campbell et al., this potential building scenario suggests a total shaking of the AEC industry. We have drawn upon this concept and built a connection between material and digital system logic following Gershenfeld's idea of digital material. Following this line of thinking, this investigation has concluded that, the specific method of implementing a given material's properties (mechanical in these cases) through digital computational simulation models in order to program it from within which has been, both speculatively and experimentally through several case studies, successfully proven as true, scalability remains an unsolved problem within PM and SMM and one that is being still studied by the author and other researchers. All this demonstrates at least one way in which one of the first assumptions of this research can be implemented and attempted as a contribution to architectural theory and practice in general: that through computational design, digital simulation and PM's convergence or, to steal Marcos Novak's term, Trans-vergence (transcendental/ transversal, and convergence) design-simulation-fabrication processes can give rise to ***performance driven, digital simulations that make kinetic architecture's decision making process more fluid, feasible and intuitive, in turn placing responsive nano-tectonics and autonomous buildings within our reach.*** This is considered to be this research's main contribution to the young, yet ever growing, field of design support for kinetic architecture.

[906] Gershenfeld, Neil, "Digital Reality: A Conversation with Neil Gershenfeld", on *Edge.org* website (http://edge.org/conversation/neil_gershenfeld-digital-reality)

"Buildings or structures that takes on life-like qualities. Instead of casting brick or pouring concrete, we instead pour a building-size volume of PM into a foundation, and then program the PM elements to 'grow' into a full building with all the accoutrements of embedded electricity, plumbing, and information technology."[907]

While it is not completely clear what will happen in the context of kinetic architecture and intelligence embedded kinetic systems, one thing is sure: that it needs to be further driven to its full potential realization. To fully grasp and achieve genetic architecture's tenets and push architectural design to its (and our) next phase of evolution, PM based PM and SMM self-assembly and emergent systems need to be given a more central research, application, production and philosophical position in the current architectural discourse. Our schools currently are beginning to address these promising material assemblies and matrices in the benefit of morpho-genetic and morpho-dynamical approaches in the practice, but it largely remains *ad-hoc* and too high sloped for the low to medium experienced designer, furthermore, consulting from outside specialists is still needed in the design-simulation-fabrication processes concerning the material design paradigm, yet this research has demonstrated that these systems can be simulated to meet tolerable approximation without conventional, over complicated calculations in a more fluid, intuitive and accurate methodology. And although many things remain to be seen in the kinetic architectural arena, one thing is still very much sure: that kinetic architecture, nonetheless beginning scientifically in 1970, is still in its infancy, to paraphrase Michael Fox, "*it appears that kinetic architecture is not at the beginning, nor is it by any means at the end; but it is, in a sense, at the end of the beginning"* and it came to change the face of the world forevermore.

[907] Michio Kaku, *Physics of the Future: How Science Will Shape Human Destiny and Our Daily Lives by the Year 2100*, New York: Doubleday (2011) and Arkenburg, Chris, "Cities of the Future: Built by Drones, Bacteria, and 3D Printers," (http://www.fastcoexist. com/1681891/cities-of-the-future-built-by-drones-bacteria-and-3-d-printers.)
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