MASTER'S THESIS

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IN MOTION: FROM KINETIC ARCHITECTURE THEORY TO COMPUTATIONAL REALISATION.

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CONTENTS

THESIS OBJECTIVES

1. To examine the scale with the theoretical disorganization and disorder inherent in the field of non-static architecture theoretical literature and the gap between the theoretical framework and design practice, conceptualizing potential ways to overcome these challenges.

2. To research the theoretical framework of non-static architecture concepts, aiming to obtain the most comprehensive definition and examine the fundamental criteria influencing architectural motion in the light of the view of the different perpecrives. These defined aspects will be further utilized in the development of a unique model comprehensively analyzing the performance of architectural motion.

3. To examine the theoretical frameworks of the bordered fields keeping the focus on the other research objectives however dealing directly with architecturul motion itself as an important element of those theories making possible to clarify the architectural motion potential to satisfy exact requests, orignigated from the researc fields objectives. The determinated aspects can be mathed together with the criterias identified in the premier concepts of non-static architecture mentioned in the previous point.

4. To defind of the non-static architecture concept on the base of the analised definitions and theoretical framework the most completely matching to the role of the term abling to describe the general theory of architecture utilising motion and incorporating the whole line of the identified criteria of non-static architectural theories

5. To form of the unique theoreritacl model emphasiisng the all identified aspects of non-static architectural concepts abling to explain the role of the functional role and self dependence of each of them on the best of the theoretical review done on the previous stages. The theoretical model has to result with the hierarchy of the possible classifications, insuring the large variability of the kinetic systems and abling to be utilised for analise and design of the all kind of non-static structures, starting from the most simple and competing with the most complex one, emphasising the utilisation of

the smart material, complexly orginised engineering systems and the most advanced achievements of the informational revolution. Adiditonally the resulted model has be possible of the further utilisation and adjustments and be possible to provide the design approach.

6. The application of the resulted theoretical model into the design of the object of non-static architecture with the goal to test the projecting capacities of the method originated from the formed theoretical model. The objective contains several stages:

    6.1. To adapt the resulted theoretical model of the non-static architecture into the design approach, abling to consider the maximum factors influencing the architectural motion and imitate the transformation of movable architectural system and changes occurring within the system itself.

    6.2. Identification of the environmental phenomenon which will influenced the drafting movable architectural system and will ba manageable with it at the same time. Conceptualisation of the fundamental characteristics based on the drafted on the previous stage architectural theoretical model of the projecting system and studying the realised cases of the non static architectural objects inherent with the same identified characteristics.

    6.3. To design the movable architectural system driven by the changes occurring with the considered environmental phenomenin and influenced by it, adidionally respecting the fundamental features identified before. Testing the resulted model with computational software to control it performance and oprimised ot according with the resulted outcome.

7. To conclude the research with the determination of the role of the resulted model in the theoretical field and its contribution it may result. Moreover to summorise the design capacities of the resulted design workflow on the base o its application in the projecting movable architectural system drafted on the previous step.

INTRODUCTION: THE MOVEMENT BEYOND TIME AND MATERIAL: THE GENESIS OF KINETICS IN ARCHITECTURE

"Nothing retains its own form"
Pythagoras

In 1832, Père Prosper Enfantin, one of the leaders of the Saint-Simonian movement, a social and philosophical movement that emerged in France during the early 19th century, admitted:

'Architecture as the theory of construction is an incomplete art: the notion of mobility, of movement is lacking on it' [1]

Since Vitruvius's time, architecture has primarily focused on static and fixed elements such as construction and form, neglecting the dynamic aspects related to how people move within and around architectural spaces. However, the 19th century managed to shift this paradigm by introducing motion, primarily through industrial machines. This shift provided artists with a new source of inspiration. [1]

However, the aspect of motion did not become entirely new in the 19th century, as architects from previous eras had attempted to reconsider the phenomenon of motion in various ways before. Hardy Adam. (2011) admits the two fundamental concepts how movement is expressed in architecture: *'Contained movement (1) - conception/perception of movement in the architecture; and Represented movement (2) - Conception/perception of movement by the architecture' [3].* Within this system of classification, the author indicates nine ways for each category in which movement can be expressed in architecture. The literal representation of motion through real changes within the structure *(association)* or the figurative portrayal of movement *(pictorial representation)* solely constitutes one category. [3] Thus, architects even before the industrial revolution, in their attempts to bring materials into motion, were reflecting on motion and attempting to embody thoughts through means that could be translated into solid material, primarily through rhythm and space.

From the series of premodernistic architectural styles, the most interesting way of interaction between building design and the principle of motion can be found in the Baroque style. In this style, forms were regularly transformed to create a visual effect, often at the expense of interfering with function. The Swiss art historian Heinrich Wölfflin (1888) recognized the fundamental feature of the Baroque style as:

'The baroque never offers us perfection and fulfilment, or the static calm of 'being', only the unrest of change and the tension of transience.' [2,3]

Through the comparison of Renaissance and Baroque, Wölfflin contrasts the dynamic and theatrical qualities of Baroque art with the more restrained and ordered compositions of the Renaissance, creating a associated opposites. A german historian August Schmarsow affirmed the concept of architecture as fundamentally the 'creator of space:

'We cannot express its relation to ourselves in any way other than by imagining that we are in motion, measuring the length, width, and depth, or by attributing to the static lines, surfaces, and volumes the movements that our eyes and our kinaesthetic sensations suggest to us, even though we survey the dimensions while standing still. (Raumsgestalterin) ' [4,3]

Thus, within classical architectural styles, motion functions not only as a design tool within traditional architectural layouts but also as a means of interaction between the observer and the architecture.

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FIGURE 1, 2

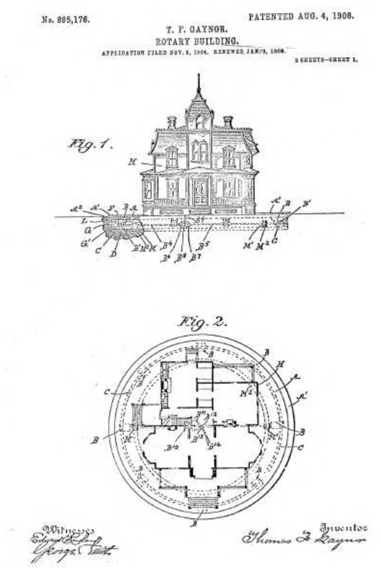
1: Marcel Duchamp. Bicycle Wheel New York, 1951 (third version, after lost original of 1913)

2: Marcel Duchamp. Rotoreliefs (Optical Disks) 1935, published 1953

(https://www.moma.org/collection/works/69630)

However, real motion had not been incorporated into the art object until the beginning of the modernistic movement, at the dawn of the 20th century when Kinetic Art was born, which also gave rise to Kinetic architecture. The roots of Kinetic arts can be traced at the dawn of the modernist architecture movement in the 1910s-1920s years in the ideas of Dada and Constructivist movements [5]. Genuine interest in movement as an art power was embodied in the works of a precursor to Dada Marcel Duchamp, namely in 'Bicycle Wheel' (1913) and Rotoreliefs (1935). [6]. Even not being classified as a kinetic artist Marchel Duchamp challenged the idea of the traditional notion of art as a static, passive object, proposing to a viewer a new perception of the motion of a mechanical element as an artistic performance.

The initial endeavors to integrate motion into architecture trace back to the visionary concepts emerging at the onset of the 20th century. Among the earliest proponents was the American inventor Thomas F. Gaynor (1908), credited with introducing a blueprint for a rotary building. This architectural innovation features a structure with a rotary foundation, enabling the revolving movement of its superstructure around a central axis (see Figure 3) [7]



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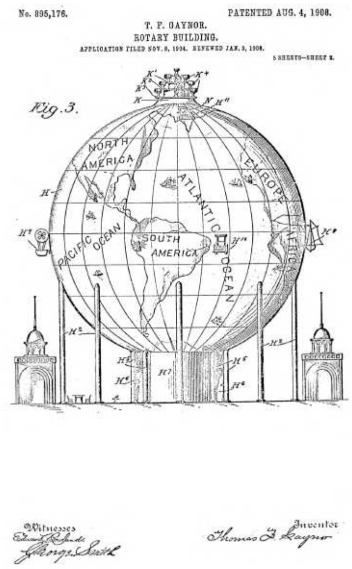

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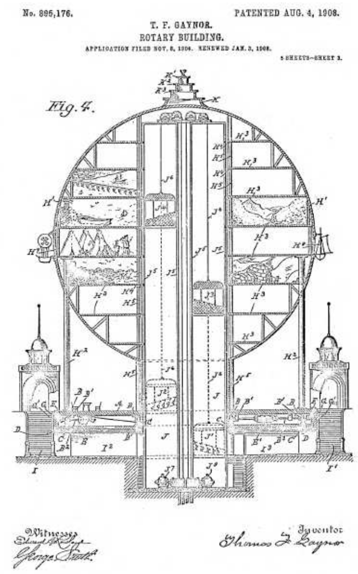

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FIGURE 3, 4, 5

Thomas F Gaynor. Patent for Rotary building US895176A 1908.

3: Elevation of a-dwelling house constructed according to patent with the rotation mechanism indicated as dotted lines. [7]

4: The elevation of the building with the form of a globe, featuring implemented technology for a rotary structure representing Earth's rotation. [7]

5: A vertical section of the building in the form of a globe hosting an elevator inside carrying people on the floors with exhibitions representing different climate zones. [7]

The patent envisions versatile applications, including residential dwellings capable of adjusting their orientation to optimise exposure to sunlight, as well as structures designed for amusement or education, such as panoramic configurations. Additionally, to the idea of the rotary building itself, Gaynor proposed an notable implementation of hist patent in the shape of the globe-shaped building, adorned to represent the Earth's continents: (Figure 4,5):

‘For amusement or educational purposes, a building can be made with its exterior formed in the shape of a globe decorated to represent the cart and the earth's axial rotation simulated to observers outside of it, while its interior can be used for panoramic or cycloramic views or objects, or any other purpose that may be desired. ‘ [7]

The rotary foundation of the building, combined with the capability to rotate the superstructure, indicates a responsiveness to changing conditions and implies an early recognition of user experience and interaction, both of which would later evolve into central themes in kinetic architecture.

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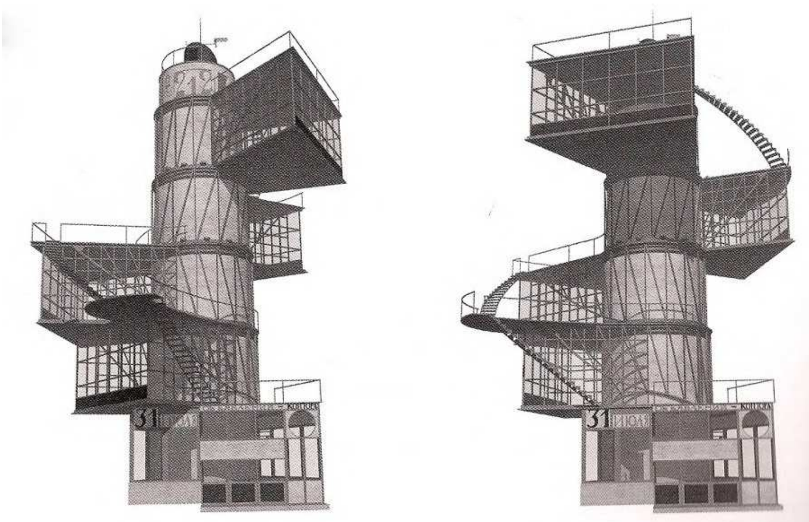


FIGURE 6, 7

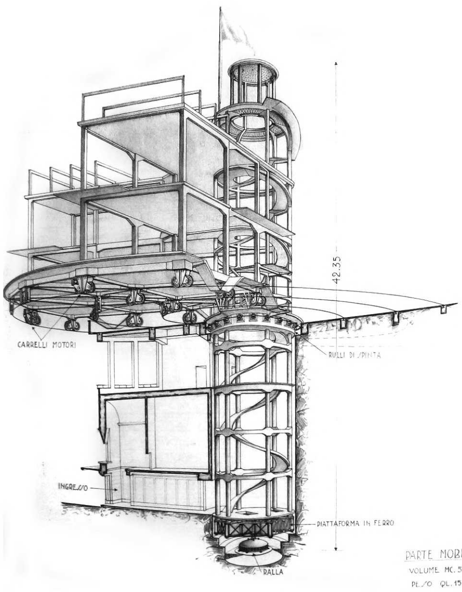
6: Vladimir Tatlin. Model of the Monument 3rd International. 1919-1920. (https://www.phillips.com/article/43416956/vladimir-tatlin-monument-to-the-third-international)

7: Konstantin Melnikov. Model of the Leningrad Pravda(1929) (https://www.architime.ru/specarch/melnikov_3/building_project_len_pravda.htm)

One of the earliest applications of kineticism in architecture can be also traced back to the projects of architects who were part of the Soviet Constructivism movement in the 1920s, notably Vladimir Tatlin and Konstantin Melnikov. This approach was deeply rooted in the revolutionary ideals of the movement, integrating movement and technology as symbols of the new 'proletarian' art, with the aim of creating a dynamic and utopian vision for the future. The Monument to the Third International (1919), a grand structure with a towering height of almost 400 metres, was intended to be constructed using metal and glass. (Figure 6) Within its double spiral design, it housed three geometric shapes: a cube, a cone, and a cylinder, each set to rotate at different speeds corresponding to a year, a month, and a day, respectively. Another example of kinetic architecture from that era was designed by Melnikov for the new Moscow bureau of the newspaper Leningrad Pravda (1929) on a small land plot measuring 6 by 6 metres. (Figure 7) Consequently, the top four levels from the initial plans were designed to rotate along the central static core, which housed all vertical communications. However, most of these buildings are projected by constructivists and equipped with mechanised structures that remained unmaterialized due to the high costs associated with unique technological solutions and monumental shapes. [8]

In the 1920s, the influential Swiss architect Le Corbusier asserted, emphasizing the fundamental principles of modernistic architecture, dominating in the architectural philosophy the all beginning of the XXIth century:

'We claim in the name of the steamship, the airplane, and the automobile, the right to health, logic, daring, harmony, and perfection' [9]



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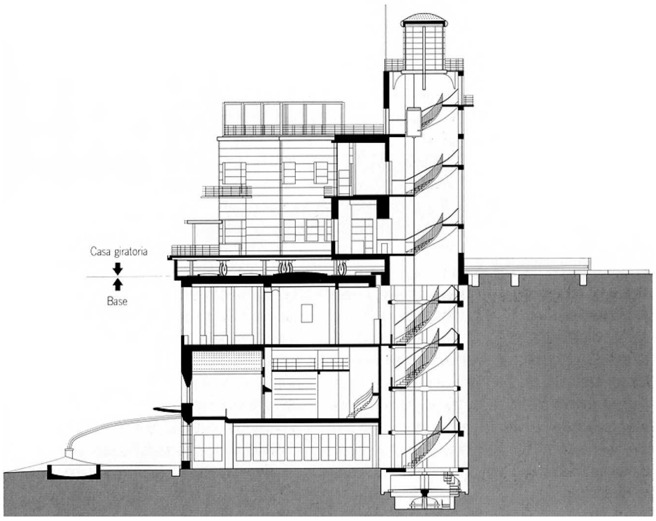

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FIGURE 8, 9

Villa Girasole was constructed according to the project of an italian architects Angelo Invernizzi and Ettore Fagiuoli. in 1935 and abling to rotate around the central axis, following the sun path.

8: The mechanics of the building's movement were designed by Romolo Carapacchi on the principles used in railway locomotives (rails and carriages) and the field of electrical engineering (motors). Drawing courtesy of Fondo Angelo Invernizzi, Archivio del Moderno, Mendrisio, Switzerland [10]

9: The section of the building together with the core, contraining the vertical communication of the vila []

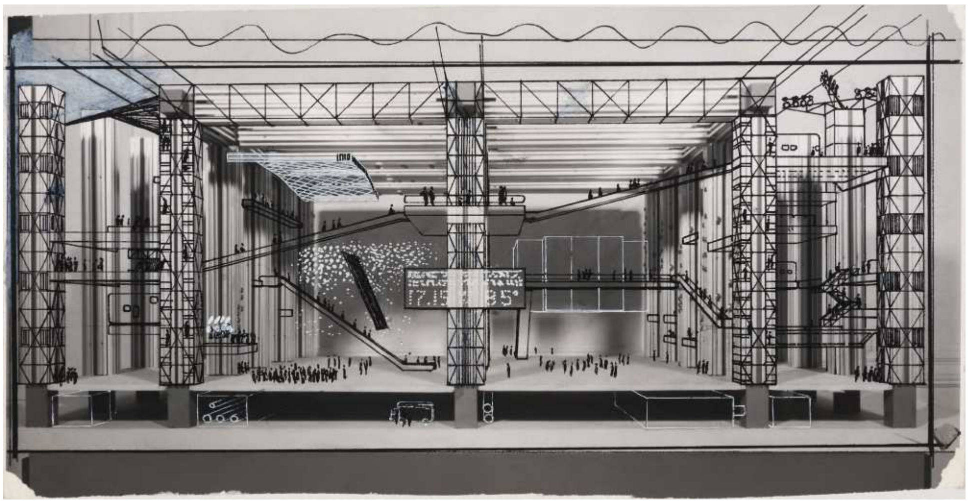
For designers, that claim signified a call to reconsider the latest achievements of the industrial and technological revolution, seeking a way to integrate the mechanized era into artistic objects. In this paradigm, motion emerged as a notable feature of modernistic projects, setting them apart from traditional architecture and challenging the static nature of materials. Ironically, as a wheel as one of the earliest human inventions, rotational motion became a primary focus for early visionaries attempting to bring building into motion. All previously examined projects in the realm of kinetic art and architecture from the early 20th century employed a specific type of motion, namely rotation, as a means to transform materials: Marcel Dushamps's Bike wheel and Rotoreleiefs, Tatlin's tower of the IIIrd Internationale, Melnickov's project of the newspaper headquarter, Gayoner's patent (Figure 1-7). The Villa Girasole, built in 1935 near the Italian city of Verona, adheres to this logical order but diverges from other rotating buildings. Unlike its counterparts, the Villa does not embrace a symmetrically revolved volume. Instead, the pivotal point is precisely located at the corner of the L-shaped building, prompting its wings to pivot (Figure 8, 9) [9].

As the first realised rotating building, Villa Girasole functions as one integral engine, manually controlled to allow the alteration of the orientation of façades and provide more environmental comfort for users, proving its name, which has a literal translation from Italian meaning sunflower. [10,11] Resting on a circular base with a diameter of around 44 m, the two-story house features a central turret standing at 42 m tall, serving as the pivot point for its rotational movement.

'A diesel engine powers the rotation, allowing the house to glide along three circular tracks. With the assistance of fifteen trolleys, the 1500-ton building moves smoothly at a speed of 4 mm/s. The entire rotation process takes approximately 9 hours and 20 minutes to complete. [12]'

However, the structural complexity of the vila caused serious problems in the building lifecycle. Following time cracks appeared in the concrete exterior, leading to its substitution with aluminum panels. Over time, it became apparent that the tolerances of the entire system surpassed the absorbing capacity of its structure. Despite being constructed from lightweight fiber-reinforced concrete, the structure started to deteriorate gradually. [11] A similar result occurred later with numerous kinetic objects, such as the case of the Institut du Monde Arabe. The complexity of the utilized technologies led to difficulties in building utilization and high costs of refurbishment. When the system broke down, it often remained unused.

Thus, The primary role of Villa Girasole in kinetic architecture is to showcase the dynamic relationship between architecture and the environment. Thus principle adaptability later was extorpolated on the other kinetic buildings, resulting into a energy efficiency.



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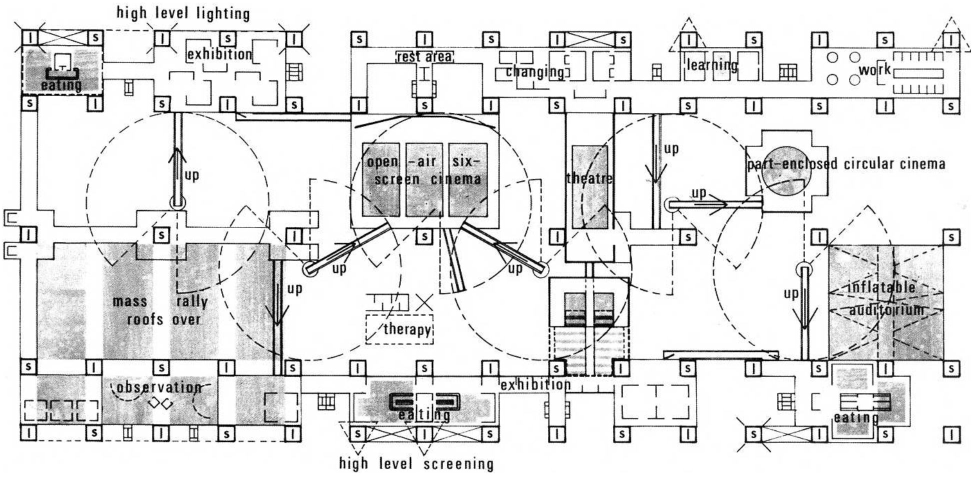

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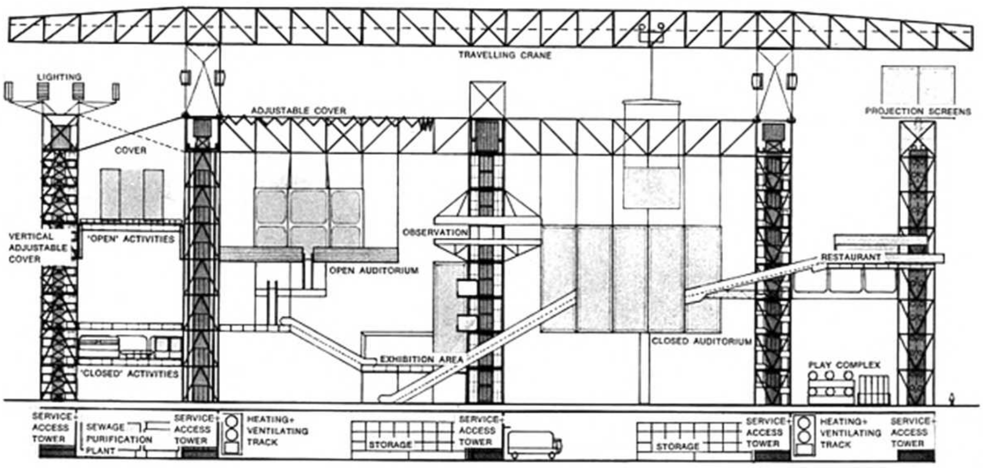

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FIGURE 10, 11, 12

The project of the Fun Palace developed by Cedric Price to be build in London in 1964

10: The paln of the building designed by Cedric Price. University Of Brighton, 2014, Exemplary Project

11: Interior perspective, 1964. Black and white ink over gelatin silver print, 12.6 x 24.8 cm. DR1995:0188:518, Cedric Price fonds, Canadian Centre for Architecture, Montréal.

12: The section of the building with vertical and horizontal communication designed by Cedric Price. University Of Brighton, 2014, Exemplary Project

Rayner Banham (1965) points out that there are fundamentally two approaches to environmental control: seeking refuge beneath a tree, tent, or roof (essentially constructing a shelter), or engaging with the local environment through the mediation of a campfire, admitting that:

'A campfire has many unique qualities which architecture cannot hope to equal, above all, its freedom and variability' [13,14]

In this context, Chris Perry (2013) views Cedric Price's Fun Palace (Figure 10 - 12) as a pivotal development in architecture, marking a shift from a focus on representation to instrumentality. Perry suggests adapting buildings to a changing environment. While the previous machine age found embodiment in the efficient designs of Antonio Sant'Elia, a member of the Italian Futurist movement, particularly in his work La Città Nuova, integrating architecture into mechanized urban networks, the Fun Palace emerges as a groundbreaking example of architecture that allows movement and alteration of architectural elements. [13] While the shift towards architecture interacting with the environment had already begun, as seen in examples like Villa Girasole, the flexibility introduced by Fun Palace takes this evolution to a new level.

'A large shipyard in which enclosures such as theatres, cinemas, restaurants, workshops, and rally areas, can be assembled, moved, re-arranged, and scrapped continuously. Its mechanically operated environmental controls are such that it can be sited in a hard dirty industrial area unsuited to more conventional types of amenity buildings.' [15]

The Fun Palace was not conceived as a typical building with static rooms or a flexible open-plan space. Instead, it was envisioned by Price and Littlewood as a *'cultural launching pad'* – a constantly changing structure wired with the latest information technology. [16] Thereby The Fun Palace promoted the idea of user participation and engagement. It was conceived as a space where users could actively shape their environment, blurring the boundaries between performers and audience.

While the Fun Palace was never realized in its intended form, its influence can be observed in subsequent kinetic architectural projects that embrace similar principles. Concepts such as deployable structures, adaptive facades, and interactive spaces owe a debt to Cedric Price's forward-thinking ideas. In this manner, the Fun Palace aligns with modernistic architectural visions originating in the 1960s, aiming to redefine the context of architecture. Examples include the Walking City by Ron Herron (1964), Yona Friedman's Ville Spatiale (1958-1960), and Buckminster Fuller's Gyroscopically Stabilized Skyscrapers (1960s).

Generally, the two decades of the 1960s and 1970s emerged as a pivotal period for kinetic architecture. This epoch witnessed the birth of numerous non-static architectural concepts, propelling kinetic architecture into the realm of academic scrutiny. Even the dawn of modernistic architecture in the 1920s and 1930s was characterized by the influential conceptualization of potentially integrating the principle of motion into architecture, with these theories primarily highlighting changability as a tool. However, as the mid-20th century unfolded, the focus shifted towards a thorough exploration of motion itself, resulting in the rise of the number of realized buildings, development of theoretical frameworks, and the complexification of visionary concepts.

Furthermore, kinetic architecture experienced the transformative impact of the burgeoning informational revolution and the sustainable movement, steering it along the trajectory it continues to pursue. Projects from this period are distinguishable by an elevated degree of interaction between the building and its surroundings, acting as a mediator connecting users with the dynamically changing environment. In this paradigm, architects started to cultivate an interest in building skins, acknowledging their potential to regulate the microclimate within a structure.

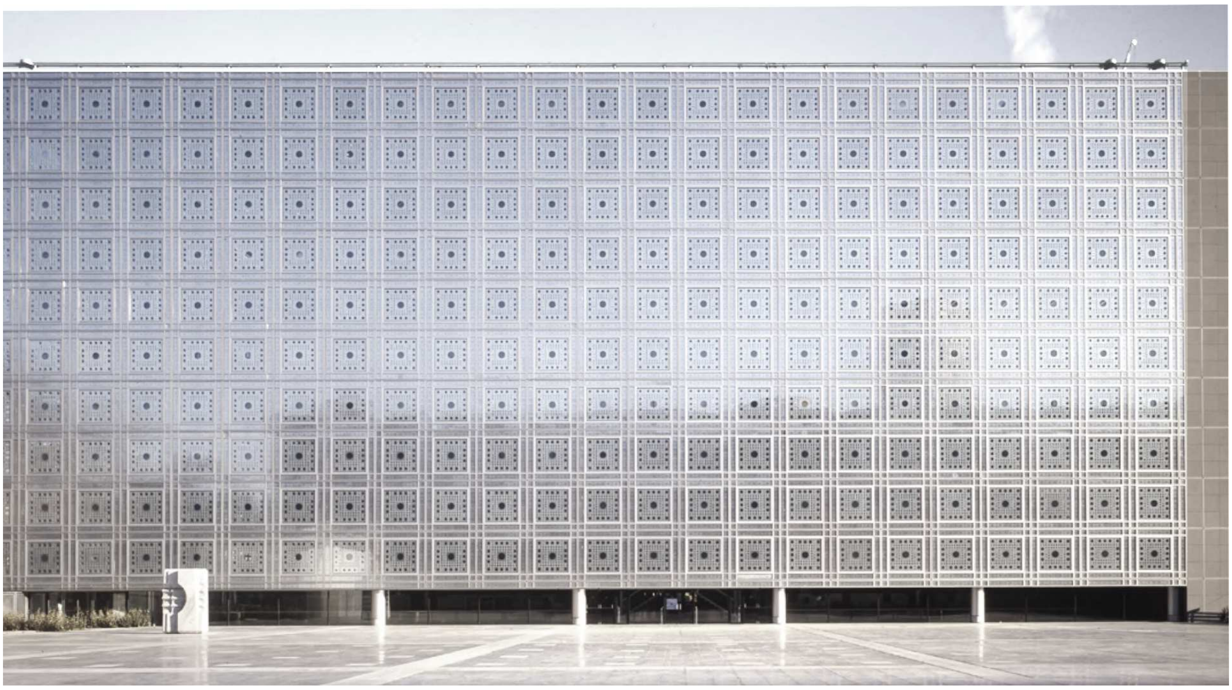
In the context of adaptable building skins, the project of the Institut du Monde Arabe (Figure 13-15) marked a significant advancement in the evolution of kinetic architecture. It introduced a novel form of mechanized facade that seamlessly blends aesthetic innovation with functional adaptability, drawing inspiration from cultural references and symbolically representing the integration of tradition and modernity:

'Nouvel's proposal for this system was well received for its originality and its reinforcement of an archetypal element of Arabic architecture – the mashrabiyya. He drew inspiration from the traditional lattice work that has been used for centuries in the Middle East to protect the occupants from the sun and provide privacy. ' [17]

Adaptrive The mashrabiya units operate like camera shutter diaphragms, serving as metallic irises. These structures filter sunlight through the glazed surface, retaining 10% to 30% of the light:

'During the various phases of the lens, a shifting geometric pattern is formed and showcased as both light and void. Squares, circles, and octagonal shapes are produced in a fluid motion as light is modulated in parallel. Interior spaces are dramatically modified, along with the exterior appearance. ' [17]

The flat southern facade consists of 240 panels, each with 16,320 kinetic modules forming lozenges, squares, hexagons, circles, and combinations. (Figure 14, 15) Reflecting mosaic patterns from the Institut's floors, each panel includes a central large diaphragm, surrounded by sixteen medium-sized and fifty-five small diaphragms. [18, 19]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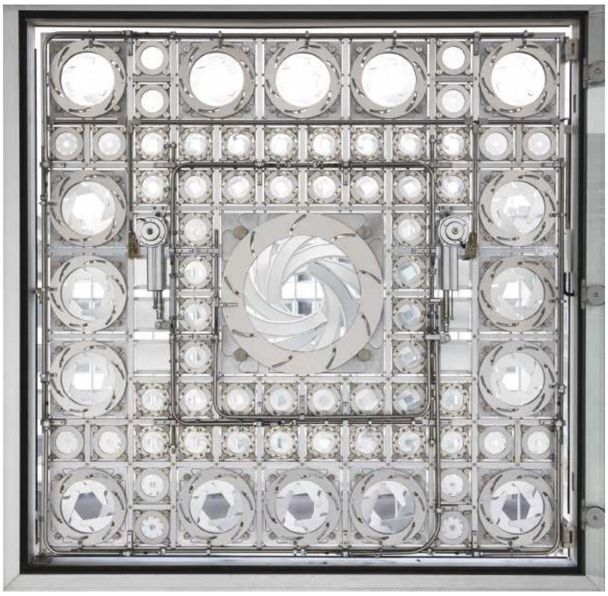
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FIGURE 13, 14, 15

The Institut du Monde Arabe constructed in 1987 according to the project of Architecture-Studio, Ateliers Jean Nouvel in Paris and hosting the first sample of the kinetic facade.

13: The south-facing elevation represents a pattern of the traditional Arab architecture. Photo taken by archello.com

14: The mashrabiya of the south facade, containing diverse types of mobile apertures allowing for natural light control based on the amount of sunshine. Photo taken by www.imarabe.org

15: The detail of the mechanised mashrabiya. Photo taken by www.imarabe.org

Aditionally, the institute's kinetic southern facade functions as a computer output device, with interconnected mashrabiya diaphragms controlled by photovoltaic cells adjusting based on sunlight intensity. Users cannot alter the diaphragms to change environmental settings. [19] However, as acknowledged in the case of Villa Girasole, technological complexity increases the risk of accidental breakdowns.

'Later on, more and more electric motors broke down and it was not until 2017 that they were renewed, namely in a large-scale façade renovation measure to mark the 30th anniversary of the institute.' [18]

The facade of the Institut du Monde Arabe played a pivotal role in the development of kinetic architecture, serving as a strong reference for later adaptable skins where form and function collaborate seamlessly. Its primary function focuses on environmental optimization by decreasing solar gain and creating a healthy microclimate for users. Additionally, the facade symbolically acts as a cultural showcase, contributing to the field's evolution through its potential for cultural expression. Thus, the envelope of the Institut du Monde Arabe emerges as a model of a successful multifunctional facade, effectively achieving its primary functional goals while also serving aesthetic purposes.

The last decades have been marked by the continued development of kinetic architecture, driven by emerging demands for sustainability and heightened standards of comfort, coupled with the integration of new technologies. Consequently, kinetic systems have been enhanced with computational technologies, resulting in an augmentation of the adaptive capabilities of kinetic buildings. Modern kinetic envelopes regularly incorporate sensors and actuators that respond to environmental factors such as sunlight, temperature, and user interactions, collecting data to preserve and utilize further during the calculation of new adaptation strategies. In this way, it is clear that contemporary modern kinetic systems will continue to develop towards further automation and self-learning abilities to increase their operational efficiency and define the best responsive scenarios.

The integration of sensors into the kinetic system aligns with the central focus of kinetic architecture on sustainable aspects. Design solutions explore ways to use kinetic elements for energy generation or conservation. Over the years, adaptable architecture considers the environmental impact of buildings more comprehensively and deeply. It appears that today the primary function of kinetic systems is the mitigation of climate impact. It is evident that in the near future, given the ongoing climate change, kinetic architecture will continue to evolve in its interaction with the environment, further accelerated and deepened by continuous advancements in information technologies.

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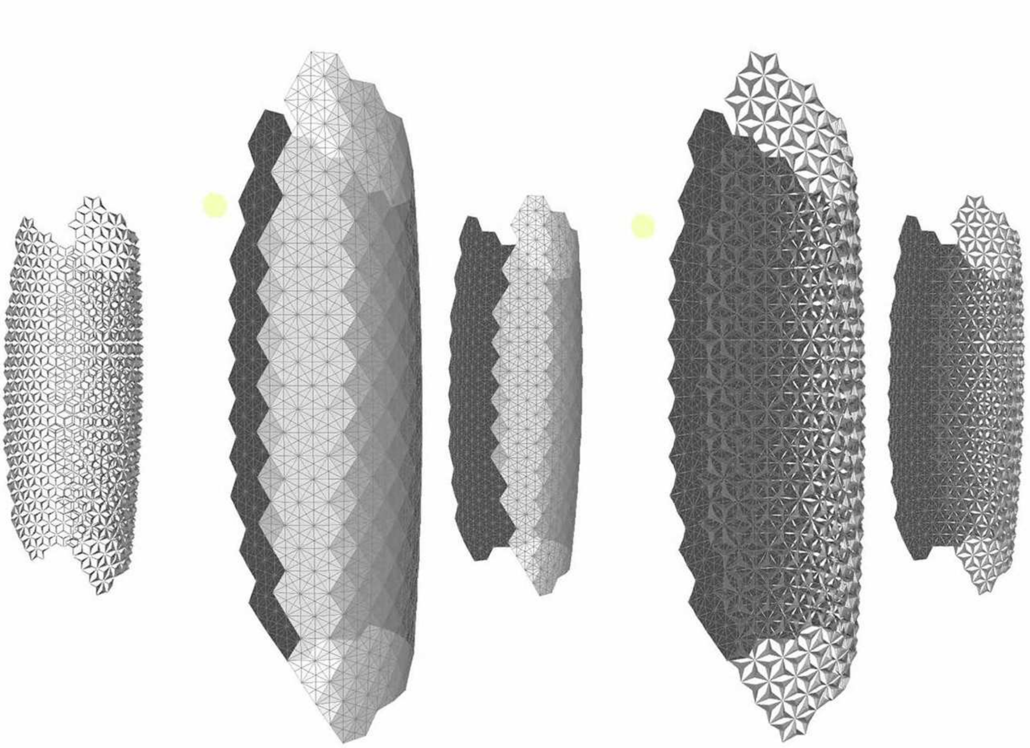

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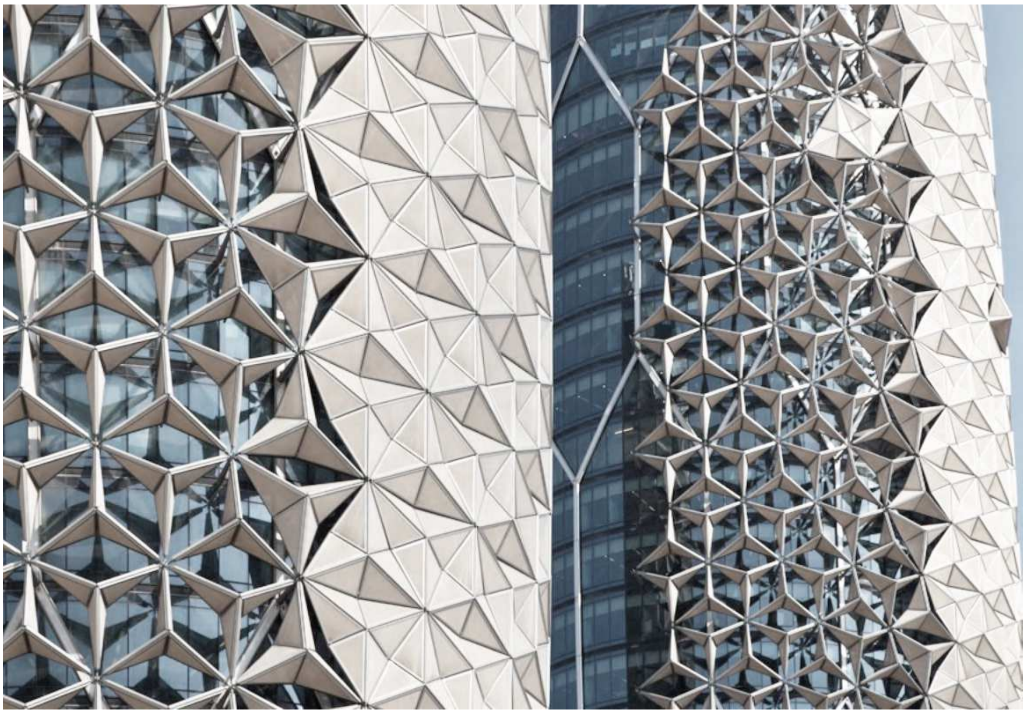


FIGURE 16, 17

Al Bahar Towers constructed in 2013 by AHR (former Aedas) in Abu Dhabi and containing largest smart envelope.

16: The curtain wall constituired of triangle coated with fiberglass and programmed to respond to the movement of the sun

17: The fiberglasss triangle, opening and closing according with the path of the sun

The most recent notable project, marking a significant advancement in the chronological order of buildings and pushing the concept of movable architecture to a qualitatively new level, is the facade of the Al Bahar Towers in Abu Dhabi. (Figure 16, 17) These tower stands out as the most extensive implementation of responsive architecture thus far. In comparison to Jean Nouvel's Arab World Institute, which relies on an energy-consuming and intricate system, the responsive facade of the Abu Dhabi tower is uncomplicated and energy-efficient. This is accomplished through the utilization of shape memory alloy wires to activate the origami patterns. [20]

The primary purpose of the responsive facade is to block direct sunlight from entering occupied spaces between 09:00 and 17:00, effectively minimizing solar gain and controlling solar glare [21]. This is accomplished through an innovative dynamic solar screen consisting of triangular units that unfold, akin to origami umbrellas, adjusting to different angles in response to the sun's movement for optimal solar exposure. (Figure 17) This folding geometry goes beyond the limitations of traditional louvers on complex buildings, transforming the screen from a seamless veil into a lattice-like pattern, providing shade or light as required.

"At night they will all fold, so they will all close, so you'll see more of the facade. As the sun rises in the morning in the east, the mashrabiya along the east of the building will all begin to close and as the sun moves round the building, then that whole vertical strip of mashrabiya will move with the sun." [22]

Projected to control solar radiation, the implementation of the kinetic envelope, according to Karanouh's calculations, has led to a series of benefits:

"• 50% energy savings for office spaces alone, and up to 20% for the building overall
• 20% reduction in carbon emission with up to 50% for office spaces use alone
• 15% reduction in overall plant size and capital cost
• 20% reduction in materials and overall weight due to the highly fluid, rational and optimised design' [21]

In this manner, the Al Bahar Towers exemplify a successful collaboration between computational design focused on enhancing energy performance, the use of modern materials enabling the construction of deploying elements, computer technologies allowing the system to operate as one integrated mechanism, and sustainable architectural design that employs passive and active strategies to minimize the building's impact on the environment.

Consequently, the brief review of the implementation of the motion principle into architecture aims to highlight the key stages in the evolution of kinetic architecture, emphasizing the fundamental characteristics inherent to kinetic architecture that developed as a result of its evolution. Thus, it can be concluded that while motion has been explored in various ways in architectural theory and design since the origins of architecture, material limitations prevented architects from bringing structures into motion. However, with the industrial revolution and the emergence of the aesthetic of the new mechanized world, artists initially attempted to reconsider motion in terms of artistic expression. Thus, it can be acknowledged that kinetic architecture traces its origin from kinetic art and is an exclusive output of modern architecture, emerging in the 1910s - 1920s.

During the 20th century, kinetic architecture underwent several stages. It began with the *conceptualization phase (1)*, led by visionary architects experimenting with rotary buildings and seeking a purpose for architectural motion. The second period, which unfolded in the post-war decades and can be labeled as *experimental (2)*, marked a shift in focus to architectural motion as a tool. This phase resulted in a series of projects pushing the boundaries of architecture. The culmination of this stage was the establishment of kinetic architecture as an independent architectural concept and philosophy, opposing traditional static architecture. In this light, Zuk's and Clark's fundamental work 'Kinetic Architecture' arises as the most visible evidence, as these authors considered movable structures as the next step of architectural evolution. In the subsequent phase, characterized by a notable increase in cases involving the implementation of motion principles into architecture, emphasis was placed on *adaptability (3)* to the external environment as the primary objective of kinetic architecture. From this point onward, a kinetic system is viewed as the intermediary between the building and its context, existing within the framework of a tripled paradigm: environment - kinetic system - microclimate. In this context, external adaptive envelopes play a crucial role. Moreover, in this stage, the adaptability of the kinetic system closely aligned with building sustainability and efficiency. Efforts were made to enhance the adaptability of kinetic systems by integrating the latest achievements of the technological and informational revolution. The last stage, which began in the early XXI century, is characterized by the shift of the Kinetic System to *interaction (4)* with a line of categories: with a user, with a context, and with the hosting building. In this way, the adaptability of kinetic architecture expands, transforming into a permanent dialogue and integral tandem among these mentioned objects, where architectural motion serves the role of a connector and mediator.

CHAPTER 1. LOST IN TRANSLATION: MOTION TERMINOLOGY WITHIN THE NON-STATIC ARCHITECTURAL THEORIE

The examination of non-static architecture encounters a wide spectrum of terminology, each representing diverse approaches to conceptualising and implementing this concept in architectural design. Terms such as 'kinetic architecture,' 'adaptable architecture,' 'transformable architecture,' ‘responsive architecture’, deployable structures,' and 'intelligent architecture' emerge as distinct interpretations of the principle of motion within architecture. These concepts interpret the motion principle in architecture in various ways, shifting the light from different aspects related to the employment of non-static architecture: the transition process, its goal, the ways it happens, etc. Another challenge associated with the study of non-static architecture lies in the lack of a shortage of theoretical frameworks. in the context of rising interest in the subject and its commercialization. This gap in theoretical understanding has become increasingly evident while these dynamic architectural approaches are gaining influence in the construction sphere. Joshua David Lee in his master's thesis, regarding the study the terminology of adaptable, kinetic, responsive, and transformable architecture admits the key problem of the non-static architecture studying:

'Further complicating this is the fact that it is quite common for both groups (architects and architectural journalists) to redefine or coin their own terms. ... It is not that the general public is marginalised by the use of specialised terms, but that the meaning is sufficiently diffuse as to be practically meaningless.' [23]

Considering the serious linguistic challenges and the limited number of studies that compare the variety of determinations of non-static architecture, a concise overview of the existing concepts will be provided in this chapter, endeavouring to provide a comprehensive view of how non-static architecture is represented in the literature. The final output of the chapter will be established in a coherent and interconnected terminology system, that will mirror the interrelationships among various definitions and aid in identifying the most fitting term for describing an adaptive and responsive architectural envelope.

Establishing the chapter's foundational premise, the term 'non-static' architecture serves as an encompassing word for architectural forms involving application elements or structures capable of change. This terminology unites various architectural concepts that celebrate the principle of adaptability as a fundamental one, contrasting to stable, fixed architectural forms. Thus, the term 'non-static' architecture is not established as a specified term but rather as a general description encircling all concepts related to adaptable structures. It is derived from the fundamental contrast between the 'movable' and the 'static'. However, this approach may encounter challenges in defining 'motion' within the building context, primarily because of the diverse interpretations of this phenomenon. Therefore, this thesis will restrict the meaning of the motion to repetitive actions that result in distinct changes in the building characteristics all while ensuring that its functionality remains intact. Consequently, actions such as the winding or compression of the building due to temperature fluctuations, changes in the chemical composition of enclosing materials, or the operation of ventilation systems will not be considered as examples of 'non-static' architecture. The demarcation line between static and non-static architecture lies in assembling and mobile structures. While every process of assembling and disassembling does indeed involve the change of fundamental building features, such as its structural integrity, it should still be regarded as an element of non-static architecture. It holds true as long as this process is reproducible.

1.1 KINETIC ARCHITECTURE

The first concept of non-static architecture under observation is the synonymous term that traces its origin to the Ancient Greek word 'κῑνητικός,' meaning "moving." As such, the Cambridge Dictionary defines kinetic as *'involving or producing movement' [2]*, while the Oxford Dictionary offers a similar definition as *'of or produced by movement' [3]*. According to Google Books Ngram Observer, the introduction of this term occurred during the heyday of modernist architecture marked by various experiments with innovations in design, materials, and architectural philosophy. However, a new wave of interest in kinetic architecture over the past few decades, along with a growing number of practical applications of movable systems in real projects, contradicts the lack of a sufficient theoretical framework in this field. Dr. Angeliki Fotiadou admits:

'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 research that are performed and are constantly being presented make the overall view. However, this means that kinetic architecture is positioned in the middle of the interest and that is a promising area in the field of construction.' [26, 80]

Introduced in the mid-19th century, the word "kinetic" was initially employed in scientific contexts, such as physiology (1850s), dynamics (1860s), chemistry (1880s), and cell biology (1890s), and only in the 1950s that the term was first applied to the visual arts [5]. In 1968, French art and technology historian Frank Popper published his book 'Origins and Development of Kinetic Art,' in which he identifies kinetic art as a branch of plastic art characterised by the fundamental principle of motion. According to Popper, this characteristic, in turn, is an inherent element of the environment, with representations of it found in various spheres.

If we turn to the remote sources of kinetic art - inspiration from nature, from art itself, and indeed from psychological states of mind - the variety is immense. Artists have derived inspiration from - or at least determined their choice of method in response to - intellectual and imaginative tendencies such as the dynamic philosophy of vitalism, the mathematical calculus of movement, and other theories of the relationship between time and movement, also from the notion of progression as a factor of movement. [28]

From Popper's charts, it's evident that he characterises kinetic art not just as objects capable of physical motion (spatial) but also as transformation in physical attributes like light, colour, texture, and more (non-spatial).

The term kinetic architecture itself was first introduced in 1970 by Zuk, William, and Roger H. Clark in their work with the same name 'Kinetic Architecture, wherein they characterised it as *'architecture with the capability of adapting to change through kinetics [29]* Thus, Zur's and Clark's conception of kinetic architecture traces their roots from the opposition of motion to static, of a dynamic system to a fixed one that embodied all architecture of the human past. By providing such a flexible definition, they left freedom of interpretation of kinetic architecture, viewing it as a process where the concept of motion could be expressed by architects in various ways, thereby advancing the notion of architecture beyond its traditional static forms. In Zuck's and Clark's vision of kinetic architecture, its mission is as global as its definition:

'Since the time of early man, ... By analogy to biological evolution, architecture has been at a low evolutionary level, with little or no adaption potential as is found in higher biological or technological developments. However, certain exceptions occur historically in this pattern of staticism which indicates a definite evolution to kinetics.' [29]

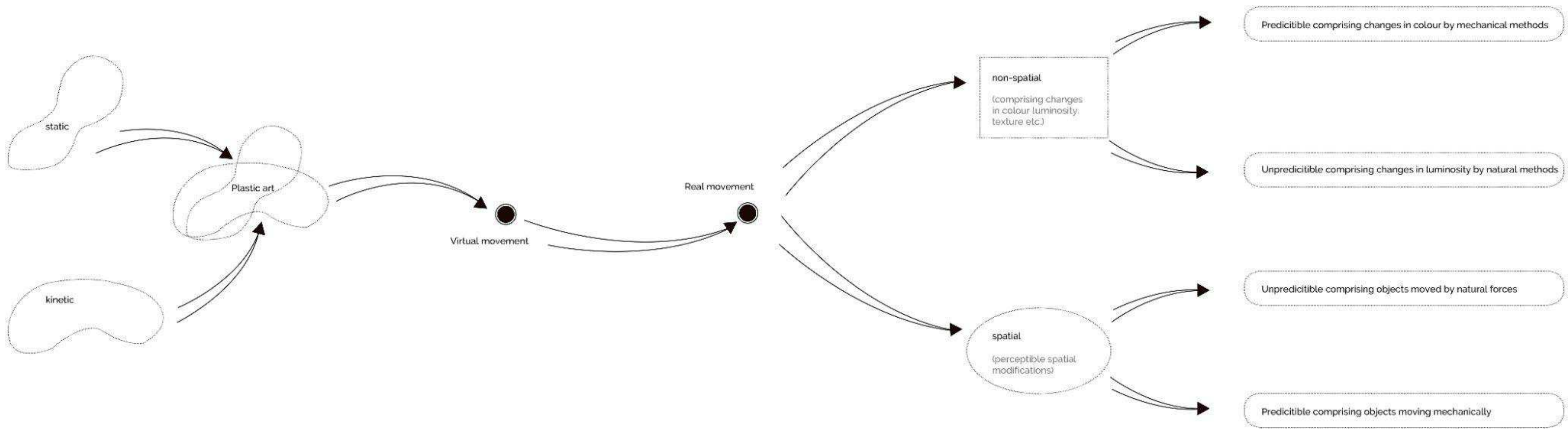


FIGURE 18
Frank Popper’s Classification of Kinetic Art [28]

Even this somewhat generalised perspective on the development of architecture might face criticism, especially for its positivism and for defining a form as a main aspect, while potentially overlooking the historical and cultural contexts that were regularly neglected by modernist architects. Nevertheless, Zuk's and Clark's concept of kinetics is presented as an evolutionary approach where kinetic architecture logically and inevitably follows static architecture, the first and more simple stage. The reasonability of this process is based on a concern that adaptable forms better respond to *a need to satisfy a dynamically changing society [28]* and secondly, this assertion is substantiated by the increasing number of applications involving structures that respond to changing environments.

Even while proposing an open-ended definition of kinetic architecture, Zuk and Clark identified eight specific ways to describe how the principles of movement could be applied in architecture, with the possibility of merging these methods to create more complex systems. *(Figure 19).*

1. *Kinetically controlled static structures:* Being affected by different loads such as wind, and vibrancy overheating, all static buildings are susceptible to moving and, sometimes, the influence of these forces can approach a critical point for structural integrity. A controlling adaptation system can serve as a counteracting force, absorbing external forces and enhancing the building's stability. Thus, in this category kineticism is represented as a measure to prevent building movement.

2. *Dynamically self erecting structures:* Instead of the traditional construction approach, in which elements and materials are assembled until the structure is completed, this method intends a self-deployable structure that requires no external intervention. In this way, motion acts as a way to transfer a structure from one static condition to another: from the disassembled to the deployed condition.

3. *Kinetic components:* A small, mobile autonomous component within a larger, static or movable building system. In this manner, motion becomes an integral part of the building's functional program.

4. *Reversible architecture:* This category is approached similarly to dynamically self-erecting structures but takes it a step further by considering a structure that can be disassembled in the same way it was assembled, with the potential for this cycle to repeat multiple times. This concept transforms motion into a continuous cycle, transitioning the structure from a collapsed state to a deployable one and back again.

5. *Incremental architecture:* While the class shares similarities with reversible architecture, it distinguishes itself by offering a broader range of structural configuration possibilities, thanks to its capacity to implement various pre-made modules. Zuk and Clark identify three possible operations in the frame of the incremental architecture: addition, subtraction, and substitution. In this context, the linear transformation cycle characteristic of reversible architecture transforms into a multitude of potential building transformation scenarios.

6. *Deformable architecture:* The transformation that occurs in this type of structure involves the existing components of the original structure, without the necessity of applying or removing external modules. In deformable architecture, motion manifests through a variety of potential scenarios, much like incremental architecture. However, instead of the latter, where the range is limited by the capacities of external elements, deformable architecture's motion is constrained by the internal capabilities of the kinetic structure.

7. *Mobile architecture:* the buildings that could be moved as an entire structure, where elements within the building remain stationary with respect to each other, while the entire volume of the structure is involved in the motion relative to the context.

8. *Disposable architecture:* The parts of the buildings or themselves that could be replaced when they do not meet the functional, aesthetical, and/or physical requirements.This way, the future scenarios of the building's motion remain undetermined, necessitating that the structure attain maximum flexibility to adapt in the future. [29]

Thus, the categories of implementation of kinetic architecture proposed by Zuk and Clark in their book depend on which ways, scales, and contexts the principle of motion is applied to architecture. A motion can serve as a counteracting force, ensuring the stability of the building, or it can be applied to the entire structure, relocating it to a new position. A motion may be limited to a single, unique event, or repeated several times in a cyclic way, or be disintegrated in various scenarios, or even remaining potential and open-ended, with no predetermined realisation It can target a single building component or scale across the entire structure, interacting with external modules or relying only on the structure's internal capabilities. The authors' list of kineticism implementations in architecture is not full and can be expanded with new categories that truce from combining such means of motion representation as scenarios, scales, and contexts. Nonetheless, its breadth allows us to view it not merely as another concept within non-static architecture but as an umbrella term, incorporating other concepts that interpret motion in different ways.

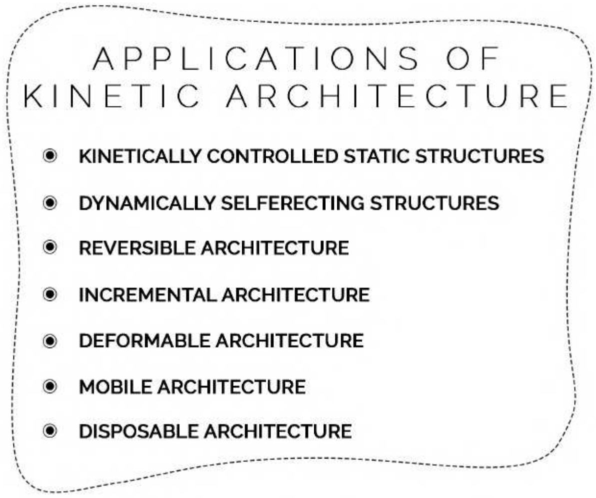


FIGURE 19

The 8 architectural applications proposed by William Zuk and Roger H. Clark [29]

Another notable theorist of kinetic design, Michael Fox, co-founder of the Kinetic Design Group at MIT, proposes a more concrete perspective on kinetic architecture by aligning it with engineering and characterising kinetic architecture through the various ways and means by which it is realised. Instead of Zuk and Clark who examined kinetic architecture as a future step of architectural development, proposing different possible cases of the implementation of this approach, the concept of Michael Fox is *oriented in the present, grounded in science fact and not science fiction [29]*. and analyses only available technologies, materials, and structures .

At the same time, widely defined kinetic architecture as *buildings and/or building components with variable mobility, location, and/or geometry [30],* Michael Fox introduced another term ' Advanced kinetic architectural systems' which is a multidisciplinary result of the intersection of such fields as *structural engineering, embedded computation and adaptable architecture [25].* In Michael Fox's concept, the term kinetic architecture is performed as a result and a final goal of the advanced kinetic systems, becoming inalienably linked with the performance of computational technologies.

'What we are describing then with advanced kinetic systems in architecture is a structure as a mechanistic machine that is controlled by a separate non mechanistic machine: the computer.' [30]

In turn, the advanced kinetic system is realised in 4 **ways**, each classified by a type of movement: *folding, sliding, expanding, and transforming in both size and shape [30]*. These movements are achieved through the application of one or some of the 5 **means** that describe the type of forces to the kinetic system for its maft: *pneumatic, chemical, magnetic, natural, or mechanical [30]* (Figure 20). While Michael Fox's general definition of kinetic architecture shares similarities with the ideas put forth by Zuck and Clark, emphasising movement as a pivotal characteristic, the fundamental distinction lies in Fox's approach to kinetic design as an integral result of the interaction of such fields as structural engineering and computational technologies.

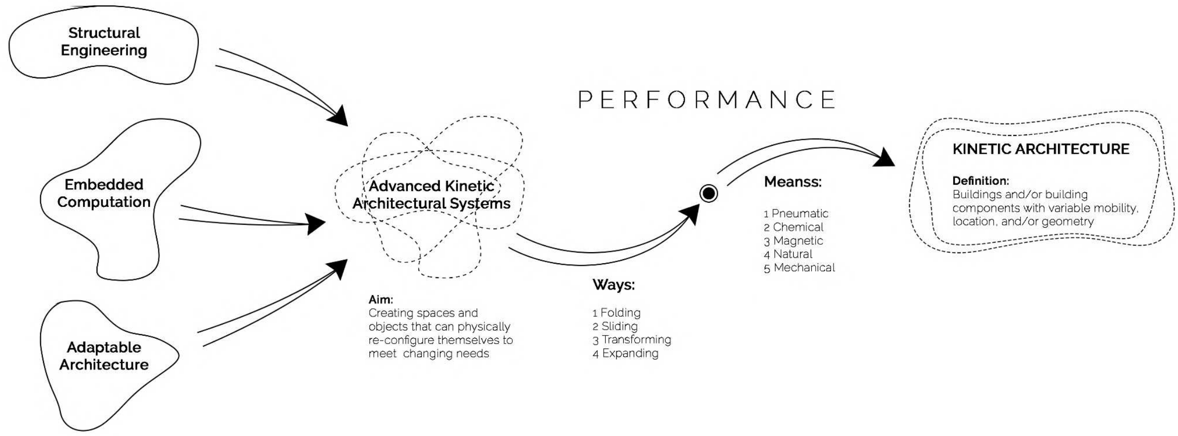


FIGURE 20

The diagram describing an interconnection between Kinetic Architecture and Advanced Kinetic Architectural Systems, design on the base of Michael Fox's concept of Advanced Kinetic Architectural Systems presented in the article "Ephemeralization' // Oz: Vol. 23 (2001)

Even the contemporary evolution of kinetic architecture, coupled with a lack of a comprehensive theoretical framework, makes it challenging to provide an exhaustive definition of this phenomenon, it can be asserted that the foremost research of kinetic design converges on the determination of motion as a fundamental principle of kinetic architecture. As Michael Fox demonstrated, further categorization and interpretation are contingent upon the ways and means motion is performed in architecture. In this term, this process is inherently linked to father innovations in structural engineering and computational capacities. As kinetic architecture continues to develop, it remains open-ended, allowing flexibility in attempts to categorise it for further research, however, all theories intersect at the determination of the principle of motion as a key source of kinetic architecture. It should be noted that 'kinetic architecture' is not the only term used to describe the incorporation of motion in architecture. The purpose of this chapter is to explore alternative definitions used to describe 'non-static architecture', to determine whether 'kinetic architecture' is an one more term within the line of non-static architecture concepts or if it serves as an umbrella term encompassing other theories, such as adaptable, transformable, responsive, deployable, and intelligent architecture.

1.2 ADAPTABLE ARCHITECTURE

According to Cambrdidge dictionary, adaptable means *'able or willing to change in order to suit different conditions' [24].* However, in architectural theoretical literature, the term 'adaptability' is frequently linked to similar concepts, including *'flexibility', 'variability', and 'polyvalence' [31]*. Li Guopeng in his book Design for Adaptability in Mass Housing admits

Confusion can arise since definitions of different terms can have similar and overlapping meanings, whereas definitions of the same word be distinctly different. Moreover, some of them have meaning and multiple levels which cover all forms of others. [31]

In his work, Le Guopeng offers 51 definitions of 'adaptation' and terms with similar meanings that have been employed in architectural literature since 1973. To avoid delving further into the unnecessary details, the matrix below will provide only definitions that share the same root as the word 'adaptable'

The adaptable house	The house which could easily be altered as circumstances changed	Great Britain, Ministry of Housing and Local Government, 1961 and Ranebeck, Sheppard and Town, 1973
Adaptable	It is based on carefully considered variety in room sizes, relationship between rooms, slightly generous usable floor area, generous openings between spaces, and little overt expression of room function. In contrast to the flexible, it emphasises planning and layout.	Ranebeck, Sheppard and Town, 1974
Adaptability	Adaptability is the general term that encompasses both flexibility and variability and can be thought of as the potential of a designed entity to passively accommodate or actively respond to different functions or external conditions. Within the broader context of adaptability, specific aspects related to building actualization useful as a basis for design considerations are: contextual adaptability, external adaptability, internal adaptability, and responsive adaptability.	Medlin, 1975
Adaptability	Adaptability is a way to fulfil a large variety of needs and change of needs of housing users (dwellers and owners) within the same building by using the potential means which the building techniques and management system offers.	Jia, 1995
Adaptable building	The adaptable building is both transfunctional and multifunctional and must allow the possibility of changing use. The buildings that have proven to be the most adaptable, were those not originally planned for flexibility.	Maccreanor, 1998
Adaptability	Adaptability is a different way of viewing flexibility. Adaptability is not primarily concerned with flexibility.	
Adaptability	Adaptability refers to the capacity of buildings to accommodate substantial change. The concept of adaptability can be broken down into a number of simple strategies: flexibility, convertibility, and expandability.	Ruseell and Moffat, 2001

Adaptation	"Adaptation" is derived from the Latin ad (to) and aptare (fit). In the context of this book, it is taken to include any work to a building over and above maintenance to change its capacity, function or performance (i.e. any intervention to adjust, reuse or upgrade a building to suit new conditions or requirements).	Douglas, 2002
Adaptability	Adaptability is obviously a key attribute of adaptation. It can be defined as the capacity of a building to absorb minor or major change. The five criteria of adaptability are: convertibility, dismantle ability, disaggregate ability, expandability, and flexibility.	
Adaptability	Providing occupants with forms and means that facilitate a fit between their space needs and the constraints of their homes either before or after occupancy.	Friedman, 2002
Adaptability	Adaptability is the potential of a system to harmonise with the environment. The adaptability of a space is the potential to change or adjust the elements constructing the space to respond to the changing environment.	Li, 2003
Adaptability	Adaptability means designing a building to allow the hierarchical layers to change, each in their own timescale.	Gorgolewski, 2005
Adaptable housing	Adaptable housing is the term generally used to denote housing that can adapt to users' changing physical needs, in particular as they grow older or lose full mobility.	Till & Schneider, 2005
Adaptability	Adaptability is achieved through designing rooms or units so that they can be used in a variety of ways. Adaptability covers polyvalency.	Schneider & Till, 2007
Adaptability	Adaptability increases the capacity for change over time while reducing the efforts and expenditures to do so through the way the building is designed, increasing the longevity (i.e. sustainability) of our built stock.	Schmidt III, Austin and Brown, 2009
Adaptability	Adaptability as a design characteristic embodies spatial, structural, and service strategies which allow the physical artefact a level of malleability in response to changing operational parameters over time. Adaptability is the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through life.	Schmidt III, Eguchi, Austin and Gibb, 2010
Adaptability	Adaptability is a building's ability to accommodate change throughout time, fundamentally extending its life.	Kelly, Schmidt III, Dainty and Story, 2011
Adaptability	Adaptability is the potential for the fabric of a workhome to be modified with relative ease to accommodate change.	The Workhome Project, accessed June, 2011

Table 1

Definitions of adaptive architecture and single-rooted terms that have appeared in architectural theoretical literature since 1973, as collected by Guopeng Li in his book [31]

From the provided list of definitions, it is possible to identify two main approaches to adaptive architecture: the first approach views adaptability as the capacity of the building entity to transform without interference in the original structure, while the second approach encompasses a broader perspective, including the potential of the building to be modified structurally. Within these concepts by Renebeck, Meldin, Maccreanor, Russell, Moffat, Douglas, Schneider, and Till, it's important to note that the term 'adaptability' is mentioned alongside other terms, including 'flexibility,' which has two distinct meanings.

'Flexibility, alterability, and extendability, as the possibility of an entity to change physically, are used to describe the opposite meaning of adaptability. The other faction asserts that flexibility denotes the potential of spatial planning to accommodate changes' [31]

Summarising the provided definitions, Le Geopeng determined three aspects concerned with the definitions of adaptable architecture: *(the changes that need to be accommodated; the ability to accommodate such changes; and the forms and means of the ability)[31]* and provides own definition of this term:

'Adaptability can be defined as the ability of housing without major physical fabric change to accommodate or respond to a variety of different conditions or individual requirements by utilising designed forms or means.' [31]

In the article 'What Is The Meaning of Adaptability In The Building Industry?' by Robert Schmidt III, Toru Eguchi, Simon Austin, Alistair Gibb from Loughborough University determined 4 meanings in which adaptability was used in literature:: *accessibility, open plan, building responsiveness, performance-based building. [32]* They proposed a definition of the adaptability by synthesising these four aspects: *the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through life. [32].* In essence, the fundamental goal of building transformation is the optimization of its performance, ultimately benefiting its users. Contrasting with the concept of kinetic design, adaptive architecture goes beyond mere motion as a fundamental aspect. It incorporates an additional focus on the aim of the transformation process, represented in the efficiency and usability of the building.

In the paper 'Adaptive architecture' from 2007, Lelieveld C. M. J. L., Voorbij A. I. M., Poelman W. A. introduced a more complex approach to definition of the adaptability, composed of 6 adaptation levels, organised on a gradient based on the system's capacity for self-regulation: *flexible, active, dynamic, interactive, intelligent, smart. [33]* (Figure 21) While the lowest step on this continuum, referred to as *'flexible,'* is defined as a system capable of adjusting only under user control, the more advanced level, known as *'smart,'* possesses the capacity for self-learning and maintains maximum alignment with users and the environment. [33]

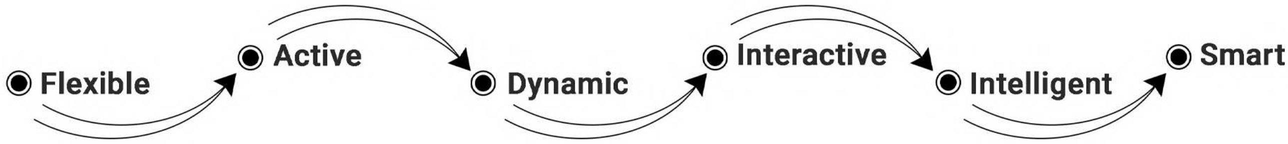


FIGURE 21

Levels of adaptation in order of sophistication introduced by Lelieveld, C. M. J. L., Voorbij, A. I. M., Poelman, W. A. (2007).

Upon examining cases of adaptive architecture implementation, the authors conclude that the higher the level of adaptability a technology possesses, the later it was invented. In other words, the adaptability of the building is directly dependent on technological progress, and according to their chart (Figure 22) the level of 'smart' still remained unreachable in 2007. At the same time, C.M.J.L. Lelieveld, A.I.M. Voorbij, and W. A. Poelman determines the term adaptive architecture as

'An architecture from which specific components can be changed in response to external stimuli, for example the users or environment. This change could be executed by the building system itself, transformed manually or could be any other ability to transform by an external force'. [33]

Contrary to the definitions put forth by Schmidt III, Eguchi, Austin, and Gibb, adaptability was interpreted as a building's response to the environment to achieve more effective performance. In the definition proposed by Lelieveld, Voorbij, and Poelman, the aspect of the adaptation goal was omitted and the focus was shifted to the degree of adaptability, explaining it as a building reaction of the exact level of self-regulation to the environment or user factor.

Summarising the provided definitions below, it can be argued that the term 'adaptable architecture' involves the line of 'fundamental aspects' that allocate it from kinetic architecture. First and foremost, adaptable architecture is defined as a structure responding to external forces, serving as a subject that reacts to outer pressures, compelling it to change. In contrast, definitions of kinetic architecture often do not address the role of motion within a specific context, potentially making kinetic systems more context-independent. Secondly, some definitions of adaptability attribute a function, identifying not just the reason but also a goal or beneficiary of a transformation. In contrast, kinetic architecture focuses solely on the act of motion itself. However, the third important aspect of adaptability such as the means by which it is performed is also characteristic of kinetic architecture.

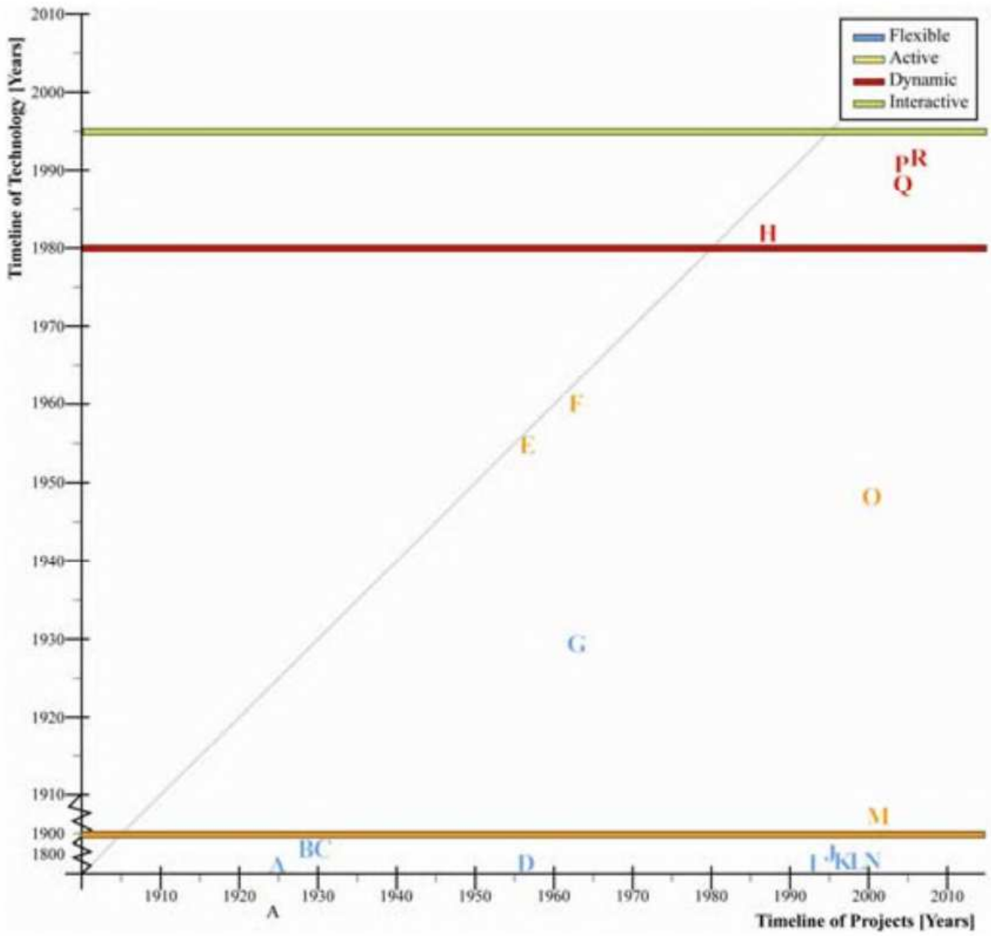


FIGURE 22

Year of realisation of studied housing projects compared to the year of availability of technology used and the level of adaptability by Lelieveld, C. M. J. L., Voorbij, A. I. M., Poelman, W. A. (2007)

The adaptive architecture faces the issue of defining the boundaries of the allowed interventions in the original structure with the objective of successfully completing the transformation process. As highlighted by Le Geopeng, some theorists reject any possibility of structural interventions, suggesting that the scope of adaptability should be limited to the internal capacities of the structure, while others are open to various interventions, including Le Geopeng himself, who supports the idea of adaptation without significant physical alterations [32].The flexibility of this demarcation can be interpreted as the theory of adaptable architecture assuming the presence of a certain 'essence of the building,' more a philosophical notion than a physical one, where any damage can lead to the creation of an entirely new structure. At the same time, according to some definitions, this demarcation distinguishes adaptability from flexibility. Some forms of kinetic architecture, as described by Zuck and Clark, involve structural interventions, including complete building reassembly. However, the crucial point lies in the requirement that such interventions must be planned before the building's completion. Being applied to adaptive architecture, this approach can solve the problem of definition of adaptive architecture and flexible architecture.

1.3 TRANSFORMABLE ARCHITECTURE

Cambrdige Dictionary defines the word 'transform' as *'to change completely the appearance or character of something or someone, especially so that thing or person is improved' [24].* According to Oxford's English Dictionary (OED) the verb transform means *'to change in the form, nature, or appearance of something' [27].* When comparing the definition of the term 'transform' as provided in vocabularies to the previous term, 'adapt,' it becomes evident that, despite having similar definitions, the former emphasises the importance of the purpose of the change, while the latter shifts the focus to the visual and physically observable results of the transformation. The congeniality of these two categories of architecture, working in tandem with the flexible terminological interpretation inherent to theoretical architectural literature, has led to a variety of concepts in which these words are represented with significantly different hierarchical meanings and synonyms.

Robert Kronenburg in his books 'Flexible: architecture that responds to change' (2007), provided his own definition of transformable architecture where it was represented one of four essential characteristics *(adaptation, transformation, movability and interaction*) of *flexible architecture*:

"buildings that change shape, space, form or appearance by the physical alteration of their structure, skin or internal surface, enabling a significant alteration in the way it is used or perceived "[34].

Thus, adaptability, which is defined by Kronenburg as *'looks at "loose fit" architecture that adjusts to a variety of users, functions, and our changing climate' [34]* fully aligns with the defining characteristics of the two terms found in Oxford and Cambridge vocabularies.

The famous American artist, architect, and engineer Chuck Hoberman, in his 2015 lecture at the Architecture Association in London, provided two definitions of transformable design from the two different aspects: *'a technology to make objects and structures that smoothly change their size and shape'* (technological aspect) and *'a strategy to create products and environments that are instantly responsive to changing conditions'.* (broader view) *[35].* In addition to the aspect mentioned in Kronenburg's definition, which focuses on the physical results of transformation, Hoberman linked the process of change with the impact of external forces on a structure, highlighting characteristics of responsiveness that identify transformable architecture. An interesting point in Hoberman's definition is the three principles of transformability, opposed to mobility: *complete form change (1), continuous process (2) and movements is internally motivated (3),* instead of movability principles: *overall form is unchanged (1), sequence of discrete steps (2), separate device initiates movement (3) [35]* In this manner, as per Hoberman's concept, transformable architecture can be reinterpreted as a structure with interdependent systems engaged in a continuous dialogue with the environment, responding to external changes. Such a building cannot be defined by one or several fixed forms, as it is always situated within the transformation process.

Maziar Asefi in the work 'Transformable and Kinetic Architectural Structures' identified transformable structure as

'a distinct class of structures consisting of rigid, or transformable elements, connected by moveable joints that can change their geometry reversibly and repeatedly and have the innate characteristic of controlled reconfiguration" [36]

Simultaneously, in his book, Asefi refrains from defining transformable architecture in a fixed manner; however, he portrays a transformable structure as a means to achieve the realisation of transformable architecture, which can be *'applied to the development of architectural spaces' [36]* to address *'functional requirements, weather conditions, or even for aesthetic expression'.[36].*
However, in the article 'An Architectural Evaluation of Transformable Roof Structures', Asefi provides a brief definition of a transformable architecture: *a distinct class of structures that can change their geometry and shape when required [37].* Therefore, Asefi, like Hoberman and Kronenburg, emphasised in the definition the aspect of the physical results of motion and the structure's dependence on the context and its utility for users. At the same time, he provided a classification of transformable structures in terms of structural principles and transformation mechanisms, thereby emphasising the structure as a key factor in the typology of transformable structures. (Figure 23)

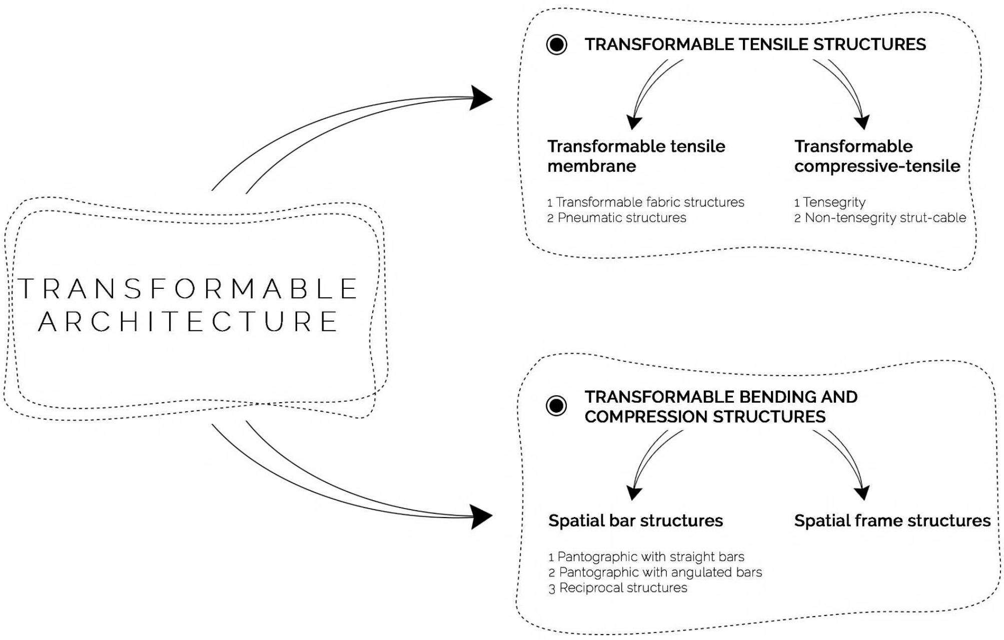


FIGURE 23
Structural types of transformable architecture by Maziar Asefi

However, in architectural literature, the term "transformable architecture" could carry a broader connotation. For instance, in the introduction to the book "The Transformable House" (2000), written by Jonathan Bell and Sally Godwin, the authors presented a more extensive definition of the concept of transformability:

'the integration of technology into the home, the use of modular systems to facilitate construction and planning, and the development of complex devices for modifying and customising architectural space on a day-to-day basis'. [38]

In contrast to previous authors, Bell and Godwin redirected attention from the physical performance of movement itself to key elements enabling the adaptation process: implemented technologies, prefabricated standardised systems, and specialised mechanics facilitating the alteration and customization of architectural space. In essence, this definition of transformable architecture underscores the transformability as an approach to create a controlled multifunctional living environment that could be customised by users. Hence, Bell's and Godwin's definition might be construed as a continuation of adaptable architecture.

From the definitions presented in architectural theoretical literature, it can be deduced that transformable architecture places a significant emphasis on the physical outcomes of change and the technological aspects that enable this change. This sets it apart from the concepts of kinetic architecture, which primarily focus on the types of motion. Additionally, the classification of transformable architecture is rooted in the mechanical typologisation of systems that enable building transformation, differentiating it from adaptable architecture, which concentrates on how structures respond to external forces. To the similar concussion Annebregje Snijders and Marcel Bilow arrived in their work, providing a generalised definition of transformable architecture on the base of the literature review:

'So transformable architecture are designs that can be changed according to different functions. The focus lies less on the aesthetic appearance but more on the functional performance'. [39]

However, the most comprehensive term encompassing all the features of adaptable architecture was introduced by Joshua David Lee in his master's thesis, based on a thorough analysis of related theoretical literature:

'buildings and structures that are able to rapidly take on new shapes, forms, functions, or character in a controlled manner through changes in structure, skin and/or internal surfaces connected by articulated joints' [23]

As such, the term "transformable architecture" emerges as one of the terms describing non-static architecture, which keeps focus on the structural aspects of motion incorporation into architecture. However, this term cannot serve as an umbrella term to describe all non-static architecture, as it is more specific than the term 'kinetic architecture'.

1.4 RESPONSIVE ARCHITECTURE

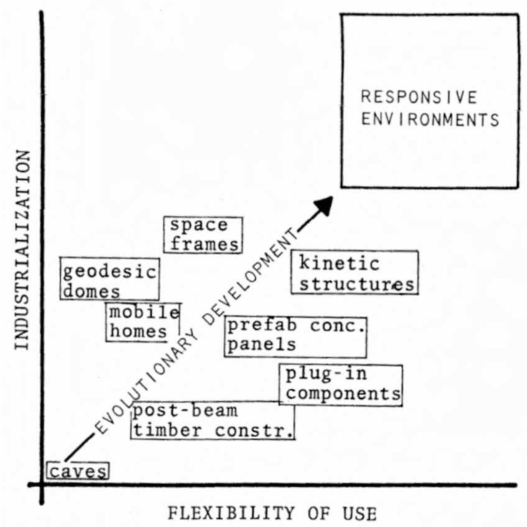
The word *'responsive'* derives from the Latin *'responsus,'* which is a form of the verb *'respondēre',* meaning *'to answer'* and serving as the source of the English term *'respond'.* According to the OED, the adjective *'responsive*' is defined as *'reacting quickly or keenly to something' [27].* This aligns with the description provided by the Cambridge Dictionary: *'saying or doing something as a reaction to something or someone, particularly in a prompt or positive manner' [24]*. In architectural theoretical literature, the term 'responsive' gained prevalence during the same time period when other descriptors for non-static architecture were introduced, notably in the 1970s. The selected papers from 'The Shirt-Sleeve Session in Responsive Housebuilding Technologies,' titled 'The Responsive House,' organised by MIT on May 3-5, 1972, represent the initial comprehensive and multifaceted approach in modern architectural history to examine the phenomenon of responsiveness in architecture from various perspectives. Although no exact definitions of responsiveness were provided during these sessions, the various writings offer a sufficient theoretical framework to comprehend the methods for implementing responsiveness in architecture [23].

For instance, Wolf Hilbertz celebrated the emergence of cybernetic and in addition, the global shifts occurring in the various aspects of human-inhabited environments and aimed to elucidate their role in the architectural historical process. He acknowledged that with the advancements in industrialization, the adaptability of buildings increased, driven by the application of modern technologies. This evolution could potentially lead to the creation of a '*responsive environment'*, which, according to Hilbetx, is the highest level of usage flexibility (Figure 24).

'Beginning with existing and modified cave volumes such a progression eventually leads to the evolution of a cybernetic technology which leads to responsive environment systems. This implies that the user becomes the stimulus to which the environment responds' [40].

Hilbertz's approach to the concept of motion intersects with the idea of adaptability, emphasising both the external forces inducing motion and the user's requirements. However, Hilbert's responsiveness shifts the emphasis shifts toward the outcomes of these transformations which the final goal is the integration of the built environment with human interaction. Consequently, a responsive environment emerges as an ongoing dialogue between humans and an adaptive reality guided by machines that take into account a wide range of influencing factors. This concept echoes Chuck Hoberman's idea of transformability, depicted as an ongoing process of environmental change. However, Hilbertz takes this notion a step further by introducing the concept of an *'evolutionary environment'*. It is a theoretical next step where a responsive environment becomes the system that might not only react to human needs but also exert an influence on humanity itself, essentially becoming an extension of human continuity (Figure 25).

'The development of these environment appears o be morley a requisite stepping stone on the way to achieving what I refer to as evolutionary environemnts' [40].



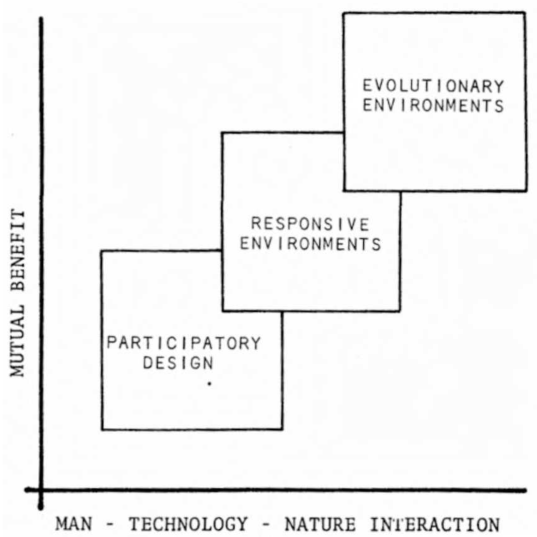


FIGURE 24, 25

24: The relation of a building functional flexibility and the degree of industrialization by Wolf Hilbertz [40]

25: Evolutionary environment as the next step of a responsive environment of man-technology-nature interaction by Wolf Hilbertz [40]

It should be noted that Hilbertz's vision blurs the boundaries not only between the building and the built environment but also between the built environment and the social and cultural milieu. This interpretation might be considered as the complex transformation of architecture, or perhaps even a 'death of architecture'.

‘Whereas the responsive system produces a ‘mindless fit’, the evolutionary system accelerates both socio-cultural and biological evolution through purposeful stimulation. The evolutionary system is comprised of man, his extensions, and nature; being simultaneously beginning and end, originator and result, producer and user’ [40[(Figure 26).

Therefore, by moving the focus of responsiveness implementation from the building to the environment in general, Wolf Hilbertz was among the pioneers who examined the reciprocal nature of user interaction with reactive architecture. At the point, when a human starts to be affected by building, the evolutionary environment begins to emerge, emphasizing the dialogue between humans and the environment as the highest level of responsiveness.

During the same sessions in 1972 at MIT, another notable theorist of responsive architecture, Nicholas Negroponte, took part in public discussions, proposing three distinct types of responsiveness.

‘There is a responsive design technology that people are talking about participation, advocacy planning. There is a responsive building technology. Ant the third is responsive architecture itself. I think the three are reasonably different, and that quite offers they are confused’ [40].

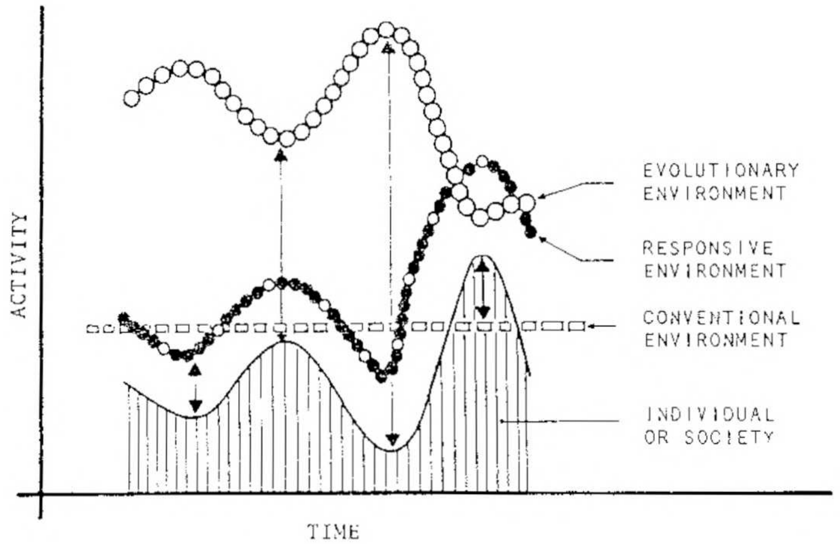


FIGURE 26

The dependence of a responsive environment on a social activity and the interdependence of an evolutionary environment and a social activity by Wolf Hilbertz [40]

In his speech, he raised several important issues regarding the mutual understanding between the responsive environment and the user: how the physical environment can acquire knowledge about human needs and wishes, and the ways in which the environment can respond to the user. It should be noticed that from the public discussion, it becomes clear that an issue of whose needs the responsive architecture should satisfy also does not appear consensus. Nevertheless, all evidence suggests that, for the concept of responsive architecture, the factor causing the movement and the outcome of this transformation seem to be the most significant. This attribute allows it to adopt a more philosophical orientation compared to other approaches already mentioned in non-static architecture. However, this approach blurring the borders between architecture and the environment presents a series of challenges in defining which problems could be addressed through building and space design and what should be resolved through other innovations that simplify daily life. For example, in his concluding speech, Negroponte proposed a device *"which knew me well enough to synopsize the news each night, and tells me if there happens to be something interesting on television today or tomorrow, without having to read TV Guide."[40]* Today, half a century later, in an era marked by electronic devices and services, this concept has become a regular part of our daily behaviour. However, the impact of the informational revolution on the built environment remains limited in most cases by art proposals and regulating the microclimate and energy performance of buildings. Thus, practical experience has shown that architecture in general, and responsive architecture in particular, should not strive to address all aspects of human existence, as envisioned by modernist thinkers because some fields of science and human activity have more tools for solving.

Nicholas Negroponte could be regarded as one of the most influential architectural theorists in the realm of responsive architecture. His books, "The Architecture Machine" (1970) and "The Soft Architecture Machine" (1975), along with his numerous papers, laid the theoretical foundation for this concept. Within his work, Negroponte proposes that responsive architecture

' the natural product of the integration of computing power into built spaces and structures' [41].

He also extends this belief to include the concepts of '*recognition, intention, contextual variation, and meaning into computed responses and their successful and ubiquitous integration into architecture' [41]*. Hence, in his concept, Negroponte directed attention to the primary challenges he discussed during the MIT Sessions in 1972, which might arise in the implementation of responsiveness within a built environment: the user's interaction with a machine and the functionality of responsive architecture.

Tristan d'Estrée Sterk from The School Of The Art Institute Of Chicago, in his paper extended Negroponte's theory with contemporary methods and techniques for producing responsive architecture, offering a new hybridised control model (Figure 27). He categorised architecture into three components: the functional needs of the building user, the external envelope with the structural skeleton, and the inner space, supporting this classification with the historically derived design methods of 'outside-in' and 'inside-out. Applying to the resulting model the aspect of interaction, Sterk introduced the model of responsive architecture where it is represented as an outcome of dialogue between two adapting components: space and structure [19]. In the case of responsive architecture, the division of architecture into external and internal elements could be considered as a new approach to building design which ultimately discards two traditional methods of building design (from outside to inside and vice versa), instead advocating for a singular user-oriented design philosophy where form follows human needs.

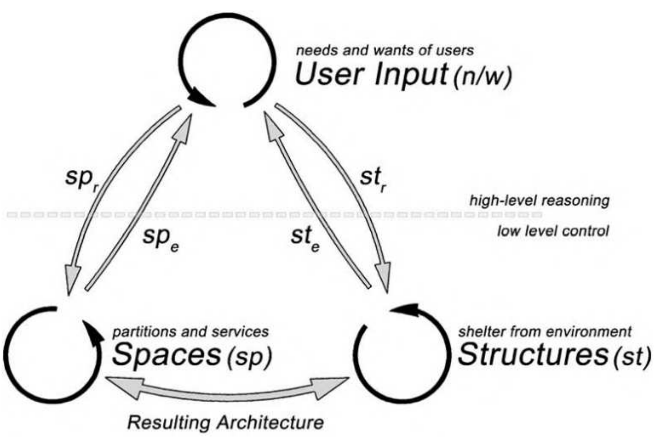
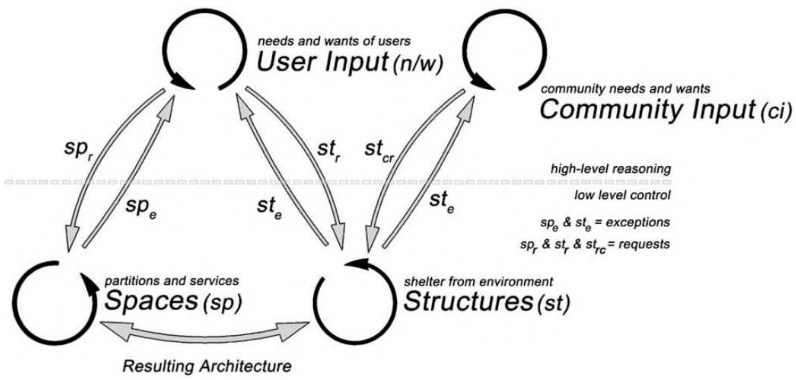


FIGURE 27

The proposed hybridised control model for use within a functional responsive architecture by Tristan d'Estrée Sterk [41]

Similarly, Sterk proposed how the model could be applied to manage a cluster of responsive buildings, using the *'"hybridized" model of control'* developed by Coste-Manières and Simmons in 2000: *'Hybridized models are commonly used within the field of robotics to allow separate reasoning processes of a reactive (or low-level) and deliberative (or high-level) nature to be present within the same model' [41].* According to Sterk, such a model can help reach such benefits as *controlling complexity, balance and stability, and user-friendly design [41]*. As a result, buildings integrated into a unified network would have the ability to coordinate their adaptations and better withstand external forces with reduced effort and increased efficiency. The diagrams drafted by Sterk (Figure 28 and 29) could be viewed as one of the optional models of Wolf Hilbertz's evolutionary environment, wherein each cluster's elements interact not only with users individually but also with one another, transforming a static built environment into a decentralised and continuously adapting system, abling influence significantly on human beings.



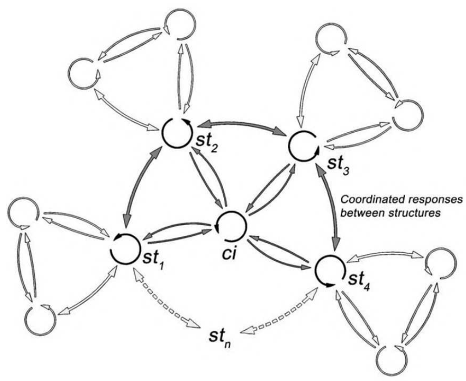


FIGURE 28, 29

28: Extending the proposed model—to enable responsive networks between buildings by Tristan d'Estrée Sterk [41]

29: The framework of a responsive network that stretches across a cluster of buildings by Tristan d'Estrée Sterk [41]

Another noteworthy architectural theorist in the field of responsive architecture is Philip Beesley, who, along with coauthors Sachiko Hirosue and Jim Ruxton, in the introduction of their book "Responsive Architectures: Subtle Technologies," aims to delineate the concept of responsive architecture by scrutinising its various aspects and tracing its origins.Initially, they emphasise *'sensitivity'* as a core element of responsive architecture while acknowledging that:

'Responsiveness implies sensitivity. But stability and isolation - as we see it the opposite of sensitivity - are often seen as necessary for analysis of complex systems... In the papers of this book, we observe art, technology, and design dissolving many of these artificial distinctions.' [42]

By showcasing historical instances where nature inspired architects and engineers to devise innovative shapes and structures, Beesley, Hirosue, and Ruxton celebrated the impact of industrialization and the informational revolution as tools capable of fundamentally altering the construction process. In this envisioned landscape, characterised by a diverse array of software, novel structural materials, and architectural experimental projects in the society which *becoming more cerebral that we crave increased movement around us [42]* responsive architecture appears to be the inevitable next phase in architectural evolution: '*A wave of new industrial processes is transforming building design and construction. The next generation of architecture will be able to sense, change and transform itself' [42].* Philip Beesley's approach to responsive architecture emphasises a range of stimuli for architectural reactions, encompassing not only human needs but also climate changes and natural forces. In these terms, it could be characterised as a techno-optimistic, and perhaps neo-modernistic, method proposing a philosophical foundation for the integration of technology and biology."

In his article 'Designing for Change: The Poetic Potential of Responsive Architecture,' Mark Meagher briefly described the concepts of Negroponte and Sterk, proposing a broad definition of responsive architecture: '*any building or building component designed for adaptation to change in its surroundings' [43],* clarifying *responsiveness involves a primary focus on either changing patterns in usage (the activities of the building's inhabitants) or changes in the (exterior or interior) environment.* Contrary to prior assertions, Meagher presents responsiveness as the interaction between architecture and the changing environment, relegating the aspect of the user as an actor in the background. This definition diverges from the continuous process of defusing borders between structure and environment or nature, potentially resulting in the creation of a qualitatively new reality. However, it keeps the primary focus on the goal of the motion which is more markable for the concept of adaptable architecture. However, one can reconcile Sterk's components of Resulting Architecture from the Hybridized Control Model (Figure 27) with Meagher's division of responsive architecture into two categories: '*one which concerns the changing environment and another the activities and needs of the building's inhabitants' [43].*

In this way, it can be concluded that responsive architecture is one of the concepts of non-static architecture that emerged in theoretical literature in the late 1960s and early 1970s, inspired by the rising computer era. It distinguishes itself from other non-static architectural concepts through its focus on the interactive process between users and the adaptable structures, as well as the reciprocal impact of the building on its users. The early works of responsive architecture pioneers like Hilbertz and Negroponte could be defined by their comprehensive multidisciplinary approach, aiming to articulate the formation of a new environment through an ongoing process of dialogue between human and building. While kinetic architecture analyses different forms of motion and their potential implementations in architectural design, transformable architecture encompasses technical aspects enabling the building or its components to adapt; adaptive architecture, one of the concepts closely related to responsive architecture, mainly emphasises the transformation of structures in response to external forces. In his thesis, Lee proposes a comprehensive understanding of responsive architecture that highlights the majority of its fundamental aspects, shaping the concepts within responsive architecture:

'Responsive Architecture: any element or social process of the built environment that quickly answers to a stimulus (either social or environmental) during the design, construction, and/or maintenance phases of a project.' [23]

In addition to this definition, it is important to note that in responsive architecture, the concept of motion aims to realise the maximum number of factors to achieve the highest possible level of co-integration between humans and the building into a single system.

CHAPTER 2. MOTION ON CROSSROADS: ADDITIONAL CONCEPTS ENCOMPASSING ELEMENTS OF NON-STATIC ARCHITECTURE

In the preceding sections of the chapter, the four concepts exceptionally analyzed the principle of motion in architecture were reviewed, while within the architectural literature, there is a group of theories describing other aspects of architecture where the component of moving architecture is also present. As evidenced later, in some publications the most of these terms are used interchangeably with kinetic, adaptive, flexible, transformable, and responsive architecture, leading to confusion in terminology. However, their synonymity in certain cases allows us to explore the aspect of motion in architecture within a different context, delving into the connectivity between non-static architecture, civil engineering, information technologies, and society. In this way, the final part of the chapter aims to examine the theoretical literature, describing concepts primarily focused on other sectors of architecture while incorporating the aspect of motion as a key element within their frameworks.

2.1 DEPLOYABLE STRUCTURES

Being applied in various fields such as aerospace, civil and mechanical engineering, telecommunications, and art installations, deployable structures have also gained popularity in architecture, particularly in cases necessitating swift spatial transformations. Contrary to the previous concepts, the deployable structures have witnessed a substantial increase in theoretical analyses and classifications, developed during the last two decades. (Figure 30).

The engineering term "deployable structure" lacks a single well-defined meaning. However, from the definition provided below, one can discern its fundamental characteristics, such as a repetitive and reversible process of shape transformation, achieved using smaller elements, a system that consists of them has an initial and final state.

Gunnar Tibert (2002): *Deployable structures are structures capable of large configuration changes in an autonomous way. Most common is that the configuration changes from a packaged, compact state to a deployed, large state. [45]*

C.R. Caladine (1998): *Such structures may pass from a 'folded' to an 'erect' state; and in many cases the component parts are connected throughout topologically, but alter their geometry through the process of deployment. In the process of deployment the initial mobility is transformed into a final rigidity. [46]*

Pellegrino S (2001): *Structures as being convertible, having the capacity of undergoing large configuration changes in an autonomous manner and refers to the reverse process as retraction. [47]*

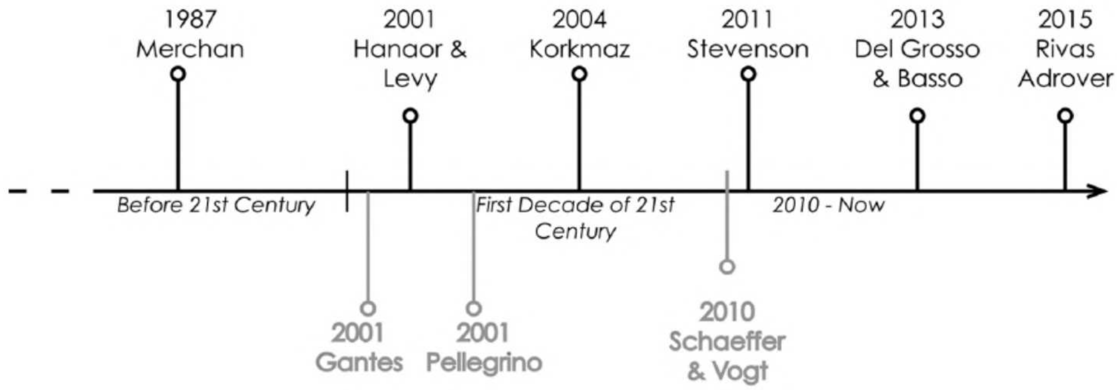


FIGURE 30

Timeline of deployable structures reviews and classifications. Fenci GE, Currie NG (2017) [44]

Theoretical literature dedicated to deployability in architecture primarily focuses on means through which the transformability is embodied in architecture, along with its history and classification. Similarly, the classification of structures remains a fundamental challenge for the theoretical framework in this field, as several attempts at classification of deployable structures have been drafted over the last few decades. Typically, classifications are primarily based on the types of loads working inside deploying structures (tension, compression, or bending), and/or their geometrical morphology (pantographs, 2D panels, cables, membrane, pneumatic structures, and etc.), and/or, the way in which a structural assembly moves at a macro-scale (deform, fold, deploy, retract, slide and etc.) [44]. In this context, the theoretical framework of deployable structures primarily focuses on the engineering mechanisms facilitating actions, which occasionally prompts authors to refer to this category of movable structures as 'kinetic' architecture.

Starting with the work of Professor Korkmaz Koray, titled *'An analytical study of the design potentials in kinetic architecture',* where this shift in terminology occurred, we will commence with a brief review of deployable structures classification.Kokhmas begins his work with analyses of the aspects of making movable architecture actual in our days, indicating *'physical pressures'*: heat, sound, light, climate, and area; and *'non-physical pressures'*: human mental, physiological, sociological, and cultural bases, ideologies, moral and ethical codes, economic conditions, political situations [26]. He defined kinetic architecture as a third new approach to architecture, distinct from the two already established paradigms (Figure 31):

Number 1: In the typical static solution changing pressures are either uncomfortably accommodated or physically sound building is remodeled or replaced. Number 2: The universal space attempts to solve all functions but very often actually satisfies none. [48]

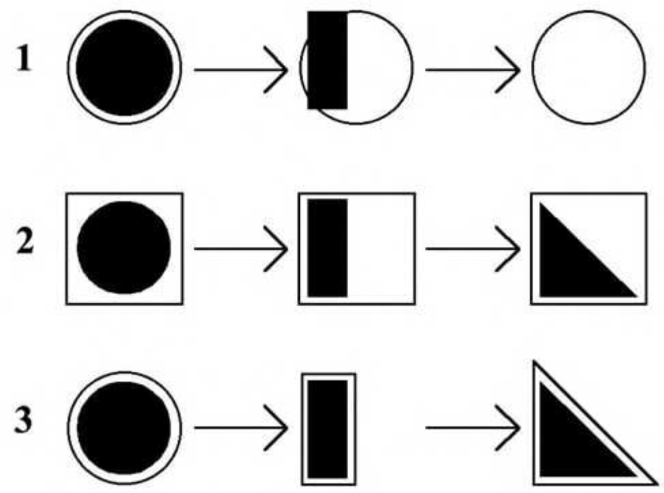


FIGURE 31

Three different conceptual approaches to the problem of change by Korkmaz Koray [48]

The third theoretical approach proposed by Korkmaz aims to adapt building design by distributing spatial and structural resources in a more rational manner to effectively respond to various types of 'pressures' [48] (Figure 31.3). Additionally, the author acknowledges: the *'motion concept, the main characteristics of kinetic architectur*e' [48]. In this way, Korkmaz's considerations of kinetic architecture encompass not only elements that define kinetic architecture in general but also incorporate elements of 'adaptive architecture,' emphasising the building's interaction with external challenges. However, after analysis of realised cases of movable architecture, where Korkmaz primarily highlights the engineering solutions in the projects, he introduced a broader classification of kinetic buildings (Figure 32), wherein the first defined aspect lies in the goal with which the motion is applied: providing a starting form of the structure (portable, relocatable, demountable buildings) or adapting existing shapes (rigid forms and soft forms) [48]. In this way, the classification of kinetic buildings, based on the technical structural transformation, becomes synonymous with the typologization of deployable systems.

In his research Korkmaz focused attention solely on the category 'buildings with variable geometry or movement', which is characterised by motion where '*motion occurs after* *the geometry has been defined and the building used; the structure can adapt to future changes and modify its layout' [44].* In the first subcategory, referred to as *'Soft Forms of Building',* the author placed structures where motion is applied by additional elements that force the transformation of a structure made of flexible materials. Another subcategory comprises buildings consisting of elements capable of movements without the aid of additional elements, as the transforming structure itself comprises elements that *'span distances and support loads'* [48]. In this manner, Korkmaz's classification of deployable structures depicts them as a technical means through which kinetic architecture applies the principle of movement. This concept recalls Michael Fox's theory of Advanced Kinetic Architectural Systems [Figure 20], with the distinction that Korkmaz believes that the *'ways'* and *'means'* are dictated by the material characteristics of the structure, thus they could be considered as an integral tool for the realisation of kinetic architecture.

However, Korkmaz's concept represents an interesting aspect for this thesis chapter as an illustrative case of the term 'kinetic' used as an umbrella term. By defining motion as a foundational aspect of architectural kineticism in the initial stages of the first chapter, the author aimed to clarify the nature of movable architecture using the adjectives *'adaptable'* and *'responsive'*: *'kinetic architecture that creates adaptable spaces with physically kinetic form, thereby responsive to the changes in the set of pressures'.[48].* It indicates two facts: firstly, kinetic architecture cannot stand as an equivalent concept to non-static architecture, as the principle of motion is too extensive to be the sole defining characteristic of the entire concept. At the same time, it is sufficiently comprehensive to describe the broad spectrum of theories that analyse movable buildings from different points of view.

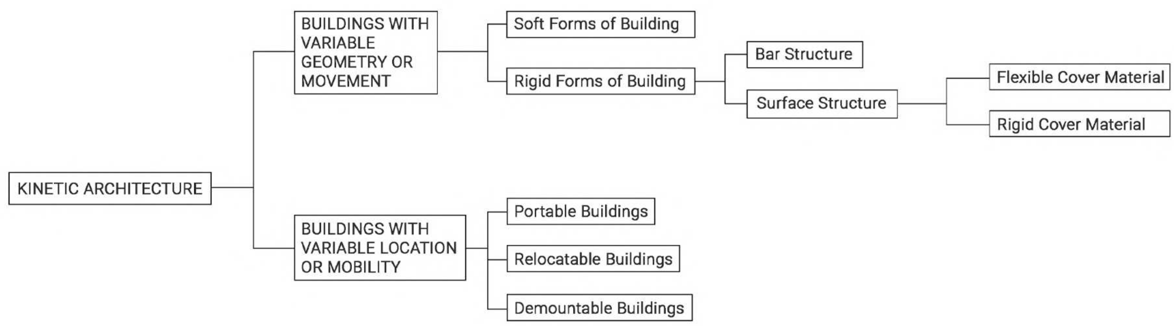


FIGURE 32

Classification of Kinetic Architecture proposed by Korkma. Fenci GE, Currie NG (2017) [44]

The 21st century witnessed a plethora of deployable structure classifications, emphasising the primary technical aspects of transformation systems, with some typologies based on the morphological aspects of kinetic architectural structures. One of those classifications was drafted by Architect Dr. Caroline Stevenson Rodriguez (Figure 33), considering in the first term the formal characteristic of transforming systems, which emerge as a resulting summary of the material configurations of each compound element. In his work, the researcher applies a synergetic approach:

'… where the combined action of the architectural components is considered to be far-reaching than the singular operation of the parts. In so doing, the nature of components and patterns is initially studied and then reinterpreted in the context of the entire form and the overall transformation.' [49].

In this manner, Stevenson portrays motion as an outcome of various elements facilitating the transformation of a kinetic mechanism, while simultaneously recognizing the crucial role of modularity and repetition of system elements embodied in the pattern organisation of a kinetic structure. According to the author, such structure communed of the identical kinetic system elements serves as a fundamental principle forcing the structure to transform. Another equally significant aspect that enables separated moving kinetic elements to function as a single integral machine is the synchronisation of movement. [49] In this context, the movement of a kinetic building or its components, perceived as a unified action by an observer, is the comprehensive outcome of functions performed by individual elements organised in patterns, working harmoniously according to a projected scenario of the motion. Simultaneously, the modular structure of this system imparts a high degree of flexibility, enabling the creation of varied structures using the same components.

In line with the majority of deployable architecture researchers [22], Stevenson underscores two types of deployable materials: *flexible and deployable*, while also introducing a third category, named *smart materials*. However her classification does not consider that typologisation. However, her classification neglects this division, focusing exclusively on morphological aspects of movable elements: *formal configurations (centric and linear)*, each characterised by various *types of movement* occurring in two or three-dimensional spaces *(spherical, circular tangential, radial, pivoting, monoaxial, biaxial, and multi-axial movements)* (Figure33). While the vertical axis of Stevenson's matrix incorporates the morphological characteristics of deployable structures as an integral system, classifying them based on physical transformation:

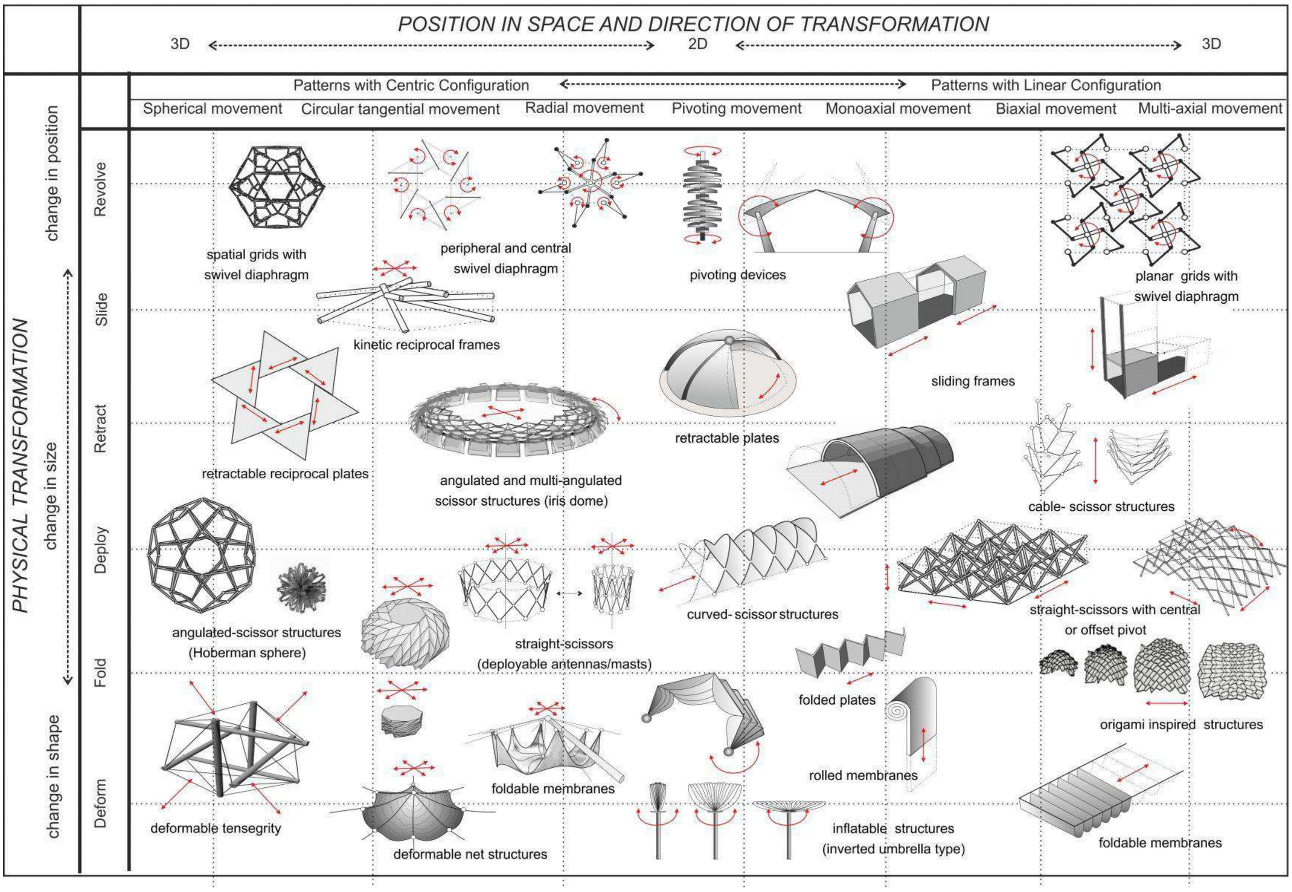


FIGURE 33

Morphological aspects and transformation strategies in kinetic architectural structures by Carolina Stevenson Rodriguez [49]

'Modifying size, shape and/or position results in a spectrum of transformations commonly found in contemporary examples of kinetic buildings. The main ones have been categorised in this paper as: deform, fold, deploy, retract, slide and revolve.' [49]

In terminological terms, Stevenson closely aligns with Korkmaz, employing the term "kinetic" as a synonym for deployable structure, and she extends this perspective, blurring the distinction between architecture and structure. Simultaneously, the author acknowledges the inadequacy of the motion principle as a determination point of kinetic architecture:

'Conceiving kinetic architecture goes beyond the mere integration of movable structures to predefined spaces; instead it entails the creation of transformable spatial experiences.' [49]

In this way, Stevenson sheds light on the capacity of kinetic architecture to generate a qualitatively new environment, transforming the same space multiple times and offering a novel dynamic experience. This interpretation opens the door to further discussions about the continuity of a transformable structure, shaped by its motion space on one side and influenced by user needs, external forces inducing motion, and building context on the other side. Perhaps, collaboratively generated by all these actors, a new dynamic environment, also described by Hilbertz as a responsive environment [40], could be a fundamental characteristic that distinguishes embodied architecture from non-static architecture.

Without delving deeply into the theoretical framework of deployable structures, as it is not the primary focus of this chapter, it is evident that the issue of classification remains a fundamental challenge for this field. As Fenci and Currie acknowledge in their article, which centres on the analysis of kinetic structure typology:

'... however, some are now obsolete due to progress in the field, others are misclassified and some are simply a list of deployable structures rather than an attempt to order according to specific criteria and thus of limited value in constructing a common vocabulary and understanding of this field.' [44]

However, the primary goal of this chapter remains to identify the place of deployable structures within the broader theory of non-static architecture. The first characteristic of deployable structure literature that should be acknowledged is the absence of a clear distinction between architecture and engineering. With a strong emphasis on the technical and material aspects of transformable systems, researchers equated the structure with the architecture itself, neglecting context, design, and space. This formalistic approach enables us to align deployable structures more closely with civil engineering and depict them as a means through which kinetic architecture can be realised. Referring to Sterk's triangle diagram, in which responsive architecture is depicted as the outcome of the interaction between three components: space, structure, and user's needs (Figure 27), the discussion of deployable systems is confined solely to structural components, neglecting dialogue with space and the user. Simultaneously, the principle of motion serves as a significant defining factor for kinetic architecture in the literature on deployable structures, with classifications primarily centred on attempts to analyse how motion is implemented in materials. Thus, it could be concluded that deployable structures serve as an intermediate field between non-static architecture and engineering, with a primary emphasis on the mechanisms enabling the transformation of structures.

2.2 INTELLIGENT BUILDINGS

The term 'intelligent' emerges as a relatively recent adjective among various non-static architectural terms employed in architectural literature, gaining prominence in the 1980s. This period was characterised by heightened discussions regarding the implementation of renewable energy sources, motivated by the two oil crises of 1972 and 1979 [50]. Another characteristic feature of this time was the proliferation of information revolutions, leading to the widespread use of personal computers. In their books ‘Intelligent skins’ (2002) Wigginton M. and J. Harris admitted:

‘The case for the intelligent building’ lies in the increasingly sophisticated demands for comfort which have accompanied the development of complex building forms and contents, with the consequent burgeoning of energy demand’ [50]

However, over several decades, the concept of intelligent building has undergone various stages of transformation; thus, the initial definitions focused on the application of automation, the rationalisation of resource use, and economic recoupment [50]:

- *‘Buildings which have fully automated building service control systems.’(Cardin, 1983) [50]*
- *‘Buildings which ‘provide information’ for an intelligent operator to act upon.’(Fagan, 1985) [50]*
- *‘An intelligent building combines innovations, technological or not, with skillful management to maximise return on investment’ (International symposium on Intelligence building in Toronto in 1985) [51]*

However, after 1985 the definition of intelligent building developed into the direction of adaptability to external forces:

- *Buildings which are ‘more than ordinarily responsive’ to changes in security, external environment, tenant demand and which offer shared tenant services. (Duffy, 1986) [51]*
- *The type of building which harnesses and integrates all levels of IT from data processing to environmental control and security. (David S Brockfield, 1989) [51]*

During the 1990s, the focal point of intelligence building shifted to the interaction between human beings and users. Bystrom (1990) from Shimitzu Co and Yasuyoshi (1993) from Mitsubishi Electric Corporation were among the first who placed the human being at the core of the intelligence building concept. They described the integration of personality with a building, connecting automatized offices and buildings with human mental activities. [52]

Group of architects DEGW (Duffy, Eley, Giffone, and Worthington) appeared to be one of the first intelligent building researchers who emphasised human interaction with buildings equipped with information technologies. Their research called Office Research into Buildings and Information Technology (ORBIT-1 in 1982-1982 and ORBIT-2 in 1985) examined how the information technology revolution reshaped office space standards [53]. In their 1998 book, 'Design for Change: The Architecture of DEGW,' the group introduced a definition of intelligent building, emphasising its self-learning capability to consider past experiences and adapt to evolving requirements: *'intelligent building is more responsive to user needs and has the ability to adapt to new technology or changes in the organisational structures.' [54]*. In 1998, Andrew Harrison, formerly the Global Head of Learning Environments for DEGW, emphasised that one of the core discoveries from ORBIT research was that buildings incapable of adapting to organisational changes and utilising information technology would necessitate substantial interventions such as refurbishment or even demolition. Taking into account this weakness in buildings, Harrison proposed that intelligent building have to include the aspect of 'responsiveness to change', defining it as:

'The intelligent building must respond to user requirements at a number of levels, relating to the life cycle of different building elements such as shell, services, scenery and settings.' [55].

Another theorist who criticised the technology-oriented concepts of intelligent buildings presented in the literature of the 1980s was Clements-Croome, having reviewed all existing definitions of intelligent buildings in 1997, he determined:

'The starting point for establishing a model of an intelligent building is people, because they determine the mind force of the building against which machines have to act' [56]

Based on DEGW's examination, Clements-Croome highlighted the gap between the requirements of users of intelligent buildings and the actual performance delivered by these structures. This led to the conclusion that intelligence in architecture should encompass flexibility. Moreover, the author argued that the concept of intelligence could be extended not only to a single building but to a cluster of them, enabling the distribution of communication and automation capacities [56], thereby intersecting with Sterk's responsive networks of building clusters [40].
Despite the shift in focus towards human needs, the definition of intelligent buildings in the theoretical literature of the 21st century continues to be a subject of discussion as this period witnessed further advancements in information technologies and their integration into buildings which also affected discussion around intelligence building. In this way, GhaffarianHoseini acknowledged in his 2013 paper that although the concept of intelligent buildings has been a model for decades, *'recent studies have argued that the concept of smart house is gradually entering our lives.' [57]*

Another significant aspect of the discourse surrounding intelligent building in the 21st century is its alignment with the issue of climate change, leading to an expansion of the concept towards sustainable design and energy-saving strategies. In Ghaffarianhoseini's (2013) study, the acknowledgment was made that the advancement of smart houses holds significant benefits in reducing energy consumption and minimising buildings' environmental impact. In this way. sustainability ought to be integrated as a core criterion in smart building development, aligning with creating a comfortable indoor environment and meeting users' needs through the application of automated technology. [57] The research conducted by Ochoa and Capeluto demonstrated that integrating intelligent technologies (active features) with early smart architectural design decisions (passive design strategies) enables buildings to achieve higher energy performance compared to when these strategies work separately. [57] In this manner, the authors concluded that the concept of intelligent buildings should encompass both of the aforementioned aspects:

'Intelligent buildings" are those that combine both active and passive intelligence, active features and passive design strategies, to provide maximum occupant comfort by using minimum energy' [58]

In the 21st century, the concept of intelligent building has shifted towards human-centricity, prioritising the creation of a healthy and comfortable living environment. Concurrently, the increasing concerns regarding climate change have propelled the theory towards sustainable architecture and energy harvesting technologies, aiming to reduce building footprint and energy consumption. Meanwhile, the developing information revolution shifts building intelligence to a more interconnected and data-responsive paradigm, capable of real-time adaptation and predictive maintenance.

The probable future of expanding the intelligent building concept could be seen in the pyramidal diagram (Figure 34), initially introduced by Harrison during the European Intelligent Building Study in 1999 and later adopted by Clements-Croome in 2004, stands as a symbol of the concept's evolution. Initially formulated until 2002, it aimed to illustrate an intelligent building as a comprehensive outcome of the development of information and communication technologies established in the 1980s, reaching a new level of advancements through mutual integration. The subsequent version of the pyramid, developed by Clements-Croome, highlighted intelligent organisational clusters as the next stage in extending the concept. According to the diagram, the next phase of the concept's evolution initiates with increasing building sustainability and achieving energetic self-sufficiency. Concurrently, with the acceleration of the informational revolution driven by artificial intelligence, intelligent buildings will be able to adapt to evolving needs and technological advancements. As it was admitted in the ORBIT research by DEGW group, the evolution of informational technologies may render obsolete buildings with a lack of sufficient adaptability. Consequently, it can be inferred that in the future, intelligent buildings are expected to converge with the concept of non-static architecture, wherein the latter would function as one of the system elements within the building's environment control system.

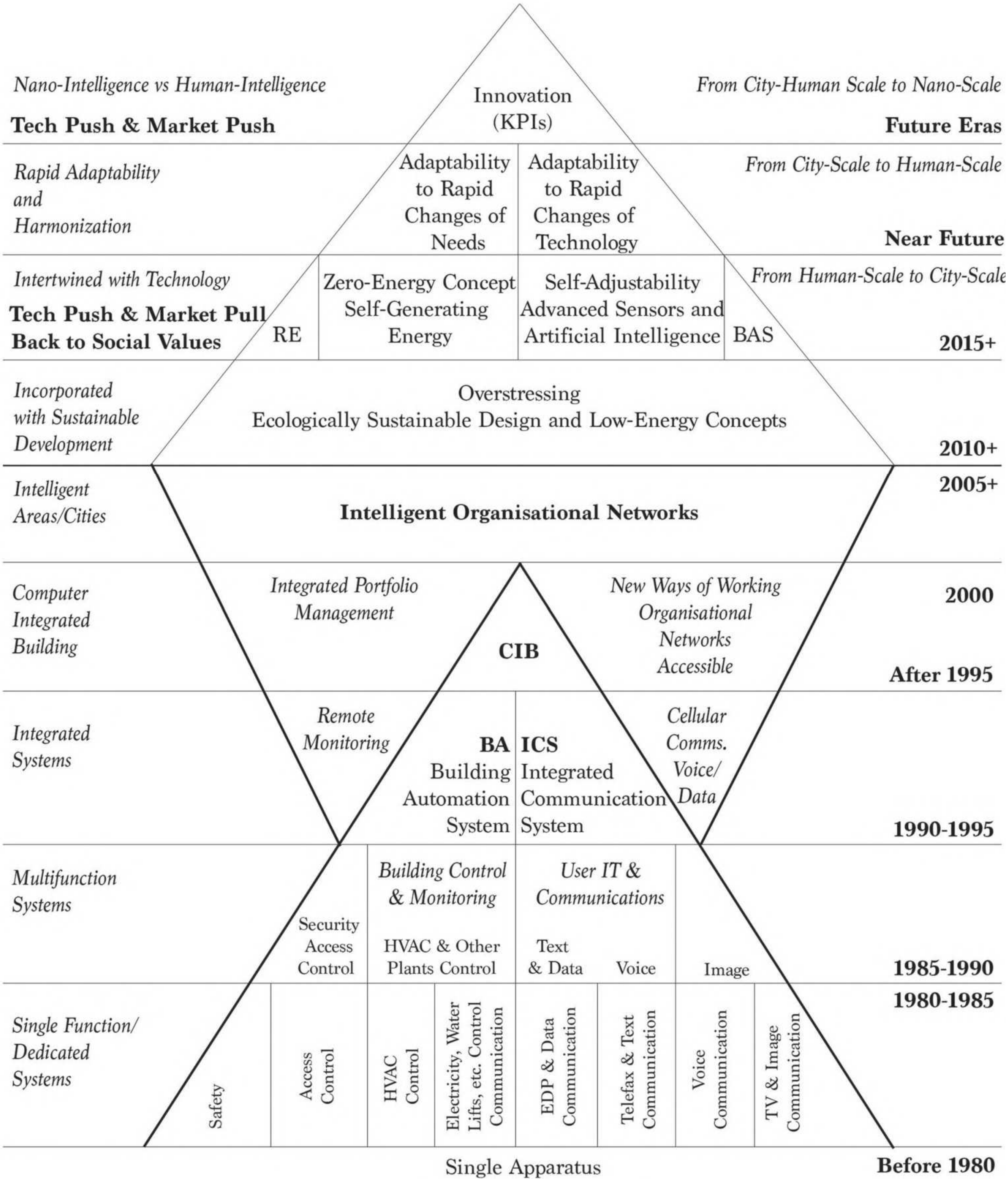


FIGURE 34 The intelligent building pyramid (Harrison 1999 and Clements-Croome, in 2004)

Despite the diverse interpretations presented in theoretical literature, the past decade has been marked by research aimed at summarising all materials related to determining intelligent buildings and identifying the key aspects shaping the concept at the current stage. Therefore, for instance, Ghaffarianhoseini, in his 2015 work, conducted a comprehensive review of the evolution of intelligent building terminology, delineating its key performance indicators across historical periods and proposing essential performance indicators that intelligent buildings must adhere to [51]. All 21 KPIs were divided according to the 4 categories: *smartness and technology awareness (1)*, related to the application of advanced intelligent technologies equipped with sensors and artificial intelligence and capable of further interoperation and upgrades; *economic and cost efficiency (2),* focusing on the rationalisation of resource, time, and cost management with the aim of boosting building productivity*; personal and social sensitivity (3)*, Related to creating a safe and convenient living environment that meets evolving user needs within a changing social and technological landscape*; environmental responsiveness (4),* referring to the use of renewable energy sources and energy-efficient systems to enhance ecological sustainability. [51] At the same time, another influential researcher, Clements-Croome, highlights three defining roles of intelligent buildings similar to Ghaffarianhoseini's KPIs, albeit without addressing the economic aspect:

'Addressing users' requirement in functional and sensory needs (1); utilising smart technology to enable security and monitoring to aid facilities management (2); being sustainable with viewpoints to energy, water and waste through incorporation of smart and appropriate green passive and active environmental design (3)'. [59]

In this context, the intelligent building emerges as an autonomous concept stemming from the intersection of architecture, informational and engineering technologies, and the societal and natural environment. Over the past decades, researchers have developed a comprehensive theoretical framework, conceptualising the integration of information and communication technologies into buildings, scrutinising real-world cases, and adapting theories considering practical experiences and changing social and technological demands. Concurrently, intersections exist between non-static architecture and intelligent buildings, prompting theoretical discussions on implementing motion principles within architecture.

The fundamental challenge arises from the demarcation between environment and architecture within the concept of intelligent buildings, wherein the emphasis is primarily placed on the internal living space, seen as the amalgamation of both active and passive means. [58] If aligning passive design solutions with architectural materials poses no significant contradictions, the segmentation of active tools like informational technologies, engineering, and adaptable systems into architectural and engineering categories becomes problematic. This way, the mobile components of the building integrate into a unified system, linking not only with engineering elements facilitating motion but also with the building's computational equipment and software responsible for calculating motion strategies and coordinating with other building systems. So, it resembles Fox's model of advanced kinetic architectural systems (Figure 20) previously seen in the chapter section on defining kinetic architecture, with the sole distinction being his emphasis on three components: structural engineering, sensor technology, and adaptive architecture, operating in alignment with one of four motion typologies and at least one of five mechanism types [30]. From this approach, two fundamental conclusions regarding kinetic architecture can be drawn. Firstly, within the advanced kinetic architectural system, the boundaries among these three components are conditional and subject to variation depending on the case. The system operates as an integral mechanism, simultaneously serving as a part of the building's intelligence, structure, and architecture. Secondly, the internal building environment, integrated by sensors within the building's control system and shaped by engineering and architectural components, transforms into a responsive environment as described by Hilbertz. [40] Hency, its physical characteristics and capacity to meet users' needs become the primary focus of the entire integrated kinetic system, while other factors such as energy efficiency, ecological impact, cost reduction, aesthetic design, etc., serve as secondary requirements, determining the boundaries within which the system can operate to create a convenient, human-oriented environment.

In their work, Khaled Sherbini and Robert Krawczyk (2004) aimed to distinguish between *responsive, kinetic, and intelligent* architecture, ultimately concluding that incorporating intelligent intelligence into movable buildings and their components leads to a novel architectural category named *'intelligent kinetic buildings*' by the authors. [60]

'Kinetic Architecture is not intelligent unless that the kinetic is a result of intelligent process. The tent is kinetic shelter that can be folded and transferred.' [60]

However, kinetics is categorised as one of the two types of responsive architecture based on the nature of its response: static or kinetic:

'A static external response can be in form of temperature, visual, audio, or/and light change. A kinetic response, on the other hand, comes in the form of movement.' [60]

Moreover, the authors classify kinetic architecture into five types based on the controlled mechanism: *direct control* (1), requiring direct manipulation by the user with energy output controlled solely by them; *input control* (2), necessitating an input device with sensors and a programmed system; *multi-input control* (3), involving multiple input devices where decisions are made according to programmed algorithms; *ubiquitous multi-input control* (4), consisting of autonomous systems coordinating with each other; and *intelligent control* (5), encompassing a self-learning capability within the controlled system [60]. The proposed model shares similarities with the adaptation levels outlined by Lelieveld C. M. J. L in 2007 (Figure 21), delineating the stages of technology integration into an adaptable system. Within this framework, the highest level of adaptation, labelled as "smartness," is defined by its inherent self-learning capability.

In this context, Sherbini and Krawczyk delineated the transition of kinetic architecture, furnished with sensors and advanced computational technologies capable of learning from experience, into a new category of buildings termed intelligent kinetic architecture. Herewith, the term "responsive" was employed by the author to encompass the entire category of non-static buildings, highlighting architecture's capacity to satisfy users' needs as a more fundamental aspect than just the principle of motion alone. Dividing responses into two types: *internal* and *external*, which encompasses two categories: *static* and *kinetic* (Figure 35)—Sherbini and Krawczyk utilised criteria akin to those employed by Frank Popper in 1968 to classify kinetic art (Figure 18), wherein they were identified as *spatial* and *non-spatial*. The inclusion of 'responsive' draws origination from Sterk and Fox's definition, wherein human interactions, through their requests, influence adaptive building components. However, a user represents only one facet intrinsic to non-static architecture, alongside elements such as context, engineering components facilitating motion, and the crafted internal environment. Furthermore, categorising the more broadly interpreted term 'kinetic' as a subordinate class within responsive architecture adds to the potential confusion within the terminology.

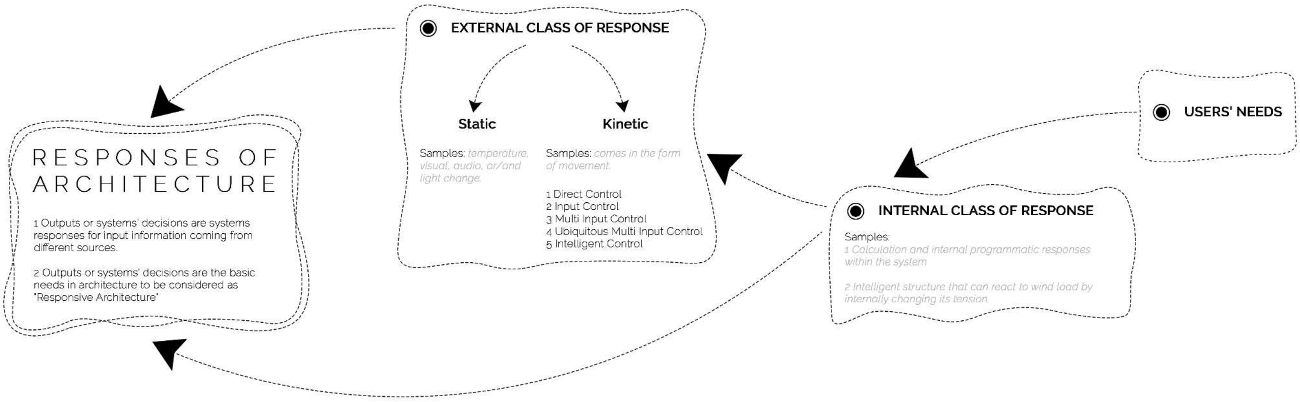


FIGURE 35

Classification of architectural responses developed on the base of the article of Sherbini and Krawczyk [38]

Asefi Maziar (2012), in examining the application of transformable building skins to enhance sustainable building performance, emphasised that adaptability is the inherent characteristic of intelligent construction [61].

'Intelligent systems are architectural spaces and objects that can physically reconfigure themselves to meet changing needs' [61]

In the case studies provided to illustrate smart skin implementation, the author described a comparable model proposed by Fox and Sherbini: sensor-derived information is analysed by a computational centre, initiating movements through kinetic components that result in changes to the internal environment.

A more specific subset within the broader scope of kinetic architecture, where intelligent building engages with non-static architectural concepts, is referred to as 'smart skins'. Given the important role envelope plays in the dialogue between observers and architecture, along with the inevitable cost increases associated with incorporating movable elements into buildings, it becomes evident that the majority of the implementation of motion principles in real projects has occurred within the sector of facade technologies. In the literature of the last decades, the building envelope has been portrayed as a barrier separating the inner environment from the external, protecting the building from heat loss or overheating [40]. This suggests that 'kinetization' and 'smartization' of the envelope present a more affordable means to enhance building energy performance, demanding fewer investments compared to deeply incorporating kinetic elements into the building's structure, which promotes the capacity for transforming the inner space. Wigginton and Harris (2002) provided a definition of smart skin, emphasising the aspect of system autonomy and meeting human needs:

'The intelligent skin is defined as responsive and active controller of the interchanges occurring between the external and internal environment, with the ability to provide optimum comfort, by adjusting itself autonomically, with self-regulated amendments to its own building fabric'. [50]

After analysing a substantial volume of literature on biomimetic building skins, Al-Obaidi, K.M., Ismail, M.A., Hussein, and Rahman (2017) identified the two other terms used equivalently to the *'smart': 'responsive' and 'adaptive'*, that extentds the terminological confusion inherent to non-static architecture theory to the field of buildings skins. According to the authors, the term *'smart'* was initially applied to describe envelope systems equipped with sensors and computational technologies, possessing a significant level of autonomy, sharing similarities with the concept of intelligence building. The term *'responsive skin'* is often employed interchangeably with *'adaptive building skin'* involving the implementation of computational technologies and self-learning capabilities. However, while the concept of smart envelopes primarily involves reacting to climatic triggers, a *'responsive skin'* extends its scope further, considering the environment within a broader definition of the context, evolving the same aspects as *'responsive architecture'*. [62]. In their terminological analyses, the authors admitted that *'adaptive building skin'* seemed to encompass wider scope compared to responsive systems as adaptability system aim to consider multiple parameters in the way to maximisie energy building performance: '*adaptive approach seeks to optimise functionality and waste reduction (i.e., energy consumption and availability of material resources).' [62].* Consequently, despite their distinct theoretical limitations, all three terms referring to building skins presuppose interaction with the environment through sensors and informational technologies, enabling motion.

FIGURE 36

Terminilogical limitations of 'Smart', 'Responsive', and 'Adaptive' building skins in the architectural literature according to Al-Obaidi, K.M., Ismail, M.A., Hussein, and Rahman (2017) [62]

The domain of smart building skins paves the way for another significant field in architectural theory known as biomimicry, which, in the light of the growing sustainable movement, has experienced a surge in interest over the past few decades. Wigginton and Harris (2002) likened adaptive facade system to human skin drawing a biological metaphor *'intelligent skin'* to illustrate epidermes's active role as a barrier safeguarding internal organs from external influences efficiently adapting to the warriors climatic conditions. According to theorists, likening the intelligent skin to the human organ should also illustrate its integration within the building's composition and other systems responsible for life circulation, contrasting the prevalent to *"chocolate wrapper' approach to building design so common in commercial architecture'.* [50] However, Wigginton and Harris extended the use of natural analogies, linking the building management system to the hypothalamus section of the human brain, emphasizing its responsive role to the external and internal triggers transferred through the nervous system. At the same time, according to the authors, learning abilities should be incorporated into the smart envelopes:

'Over time, the intelligent skin, with some of the characteristics of human intelligence, should develop an ability to learn, an ability to adjust and adapt, to cope with new situations, and an ability to anticipate the future.' [50]

Al-Obaidi, Ismail, Hussein, and Rahman (2017), after conducting an in-depth analysis of biomimicry in intelligent facade design, concluded that despite the broad range of potential nature-based implementations in architecture, most systems encounter limitations in adaptation. Their focus often shifts from addressing complex ecosystem problems to specific details. Authors acknowledged that, according to their proposed categories (Figure 36), *'most dynamic architectural systems are designed as responsive* *systems,' with only a few models classified as adaptive' [62].* When previous studies theorized mimicry in nature, suggesting methods and ideas, the latest approach focuses on incorporating smart materials into the facade system, capable of motion, relying solely on their physical characteristics, reducing or eliminating the need for conventional energy sources. [62] Given nature's inexhaustible potential as a model for various aspects of adaptable building skins, researchers developed a list of 10 design criteria for envelopes aimed at establishing principles of adaptability for facade systems:

'Biomimetic levels (1), Biomimetic Approaches (2), Biomimetic Classification (3), Methods and Tools (4), Mechanisms of Adaptation (5), Adaptive materials in nature (6), Biomaterials development (7), Adaptive behavior in building skin (8), Adaptive materials in architecture (9), Adaptive Systems (10)'. [62]

Concluding a comprehensive review of intelligent building literature and its association with principle of motion, it's evident that the concept of 'smartness' in architecture has significantly expanded over the past four decades, evolving alongside the widespread informational revolution and in response to emerging social concerns regarding climate, safety, and comfort standards. Although notable researchers in this field, like Derek Clements-Croome and Ghaffarianhoseini, have highlighted the lack of theoretical analyses, the intelligent building's theoretical framework today is marked by a well-established, comprehensive, and organized system of definitions, fundamental criteria, and aspects that define this field, especially when compared to the framework of each theory within non-static architecture. Hence, the four criteria of intelligent buildings can be identified as follows: *the utilization of computational technologies and monitoring systems with learning abilities (1); the establishment of a healthy and user-friendly environment (2); comprehensive sustainability measures aimed at minimizing the impact on the natural environment through passive and active design strategies (3).*

Over the last few decades, literature has increasingly emphasized adaptability as a fundamental characteristic of the intelligent building concept, functioning with passive design solutions to enhance building productivity and sustainability. One of the possible models describing the collaboration between building intelligent and non-static architecture has been introduced by Fox, where building motion is ensured with computational technologies and transmitted through engineering systems, forming one integral system compounding the three components. In such systems, the computational center, rather than the movable building elements themselves, serves as a crucial element, as the computer processes information from external sensors, calculates desired conditions, and devises the means and resources necessary to achieve them and subsequently initiate the motion. Furthermore, the characteristics of the information component—such as the control mechanism's capacity to consider multiple factors, the depth of its developed adaptation strategies, its self-learning abilities, and how it communicates with users—determine the features of an advanced kinetic system and its influence complexity on inner building environment. In such a system, motion is contextualized and characterized by several aspects: external stimuli (1) causing motion as it arrives from sensors; the input that initiates the motion (2), executed by building intelligence; the interaction with the user (3), managed by input control; and the purpose of the motion (4), wherein building intelligence primarily aims to create a healthy living condition for users in the most sustainable manner possible.

Nevertheless, kinetic architecture shouldn't be interchangeable term with smart building, as the principle of motion can be integrated into architecture without relying on information technologies. Sherbini and Krawczyk (2004) acknowledged that structures capable of transportation and reassembly could also be categorized as elements of non-static architecture. Therefore, the model of an advanced kinetic system represents one potential realization of non-static architecture, necessitating the integration of smart technology within the building. For instance, smart building envelopes made of materials capable of altering their form in response to environmental changes can facilitate motion without computational devices bringing the motion. However, these systems can simultaneously integrate with building intelligence, serving as both sensors and movable building components.

2.3 BIOMIMETIC ARCHITECTURE

Although architects have been using nature as a reference for building forms and structures since ancient times, the term *'biomimicry'* only appeared in theoretical literature in the middle of the 20th century. Michael Pawlyn (2019) acknowledged that this term was first introduced in 1962, preceding the term *'biomimetics',* which was coined by American engineer, and biophysicist Otto H. Schmitt in his doctoral thesis in 1950, where he was analyzing the octopus' nervous systems to build an electrinic device to mimic the propagatation of action potentials along nerve fibers [63,64]. Initially, the term *'biomimetic'* remained primarily used in medical and engineering research fields. However, during the 'Bionics Symposium: Living Prototypes - The Key to New Technologies' held in 1960 at the Air Force Base in Dayton, Ohio, US Air Force Major Jack Steele introduced the term *'bionics"* deriving its origin from the German *'Bionik',* which merges the German words *'Biologie' (biology)* and *'Technik' (technology)*. [65,66]. In 1970, the German zoologist Werner Nachtigall identified bionics as *'learning from nature for self-sufficient, engineerable design',* emphasizing a comprehensive approach in implementing natural references into design processes. [67]. Later, his book was translated into English, where the German term *'bionik'* was presented as *'biomimetic',* which can be interpreted as a merging of the two terms.

Chayaamor-Heil (2023) acknowledged that the term *'biomimicry'* seemed to emerge in the 1980s during the rise of the sustainable movemen, however its widespread adoption occurred after the publication of biologist and environmentalist Janine Benyus' book *'Biomimicry: Innovation Inspired by Nature'* in 1997. [64] In her work the author suggested the definition for *'biomimicry',* highlighting the importance of referencing not only visual images of nature but primarily the operational principles of biological organisms:

'A new discipline that studies natures best ideas and then imitates the designs and process to solve human problems'. [68]

In 2006, Benyus, alongside other colleagues, co-founded the Biomimicry 3.8 Institute, a non-profit organization focused on inspiring experts across different fields to learn from nature, aiming to create sustainable products, processes, and policies. [69] The organization's website states that *'biomimicry'* is a type of '*bioinspired design'*, a broader umbrella category that brings together approaches drawing upon biology as a reservoir of solutions (figure 37):

'While biomimicry is a type of bioinspired design, not all bioinspired design is biomimicry. An important factor that differentiates biomimicry from other bio-inspired design approaches is the emphasis on learning from and emulating the regenerative solutions living systems have for specific functional challenges.' [70]

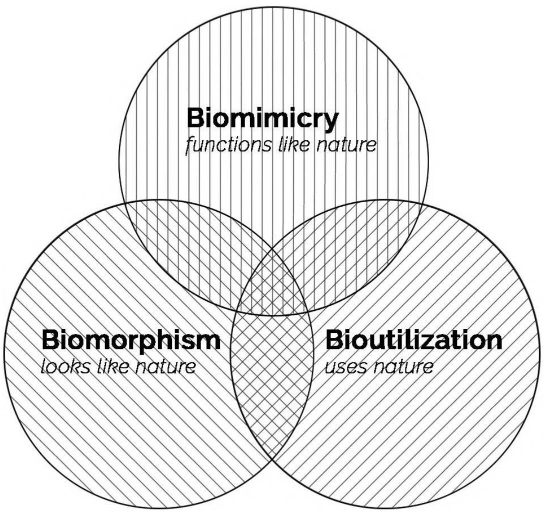


FIGURE 37

The diagram designed by Biomimicry 3.8 Institute illustration biomimicry as one of the bioinspired design types [70]

The Biomimicry 3.8 Institute distinguishes *'biomimicry'* from *'biomorphism'* and *'bioutilization*' based on how nature is integrated into design process. '*Biomimicry'* involves analyzing and emulating natural processes and strategies, while '*biomorphism'* primarily focuses on visually referencing natural forms. On the other hand, bioutilization exclusively involves applying objects from nature in a design or technology. [48] Founders of The Biomimicry 3.8 Institute identifie three fundamental elements of biomimicry: *emulate (1),* which involves researching and replicating natural shapes and strategies; *ethos (2),* a concept centered on designing to sustain life-supporting conditions; *(Re)connect (3),* an approach that views designed objects as extensions of natural interconnected systems. [70].

Despite the theoretics of biomimicry sharing common ground in determination of this term as multi disciplinary concept emulationing or inspirationing from natural process, strategies, interaction and system organistation in the design process, there are doubts in identification of the chalgengy type should be addressed. [66] While the Biomimicry 3.8 Institute portrays biomimicry as a design approach aligned with nature's sustainability [70], architect Badarnah (2017) narrowed this term to an architectural framework, defining it as an approach aimed at reducing environmental impact [66,71]. At the same time, Julian Vincent (2006) acknowledged that the benefits of utilizing *'biomimetics'* might not be immediately apparent in the short term, except in establishing new technical tools, and could potentially lead to unpredictable results.[50]. Thus, one can conclude that the multidisciplinarity, being one of the most significant characteristic of biomimicry, not only enables its application across various fields but also creates a challenge in its definition, as theorists narrow down the term within the confines of their specific research frameworks, thereby limiting its definition within their respective fields.

Nathalie Verbrugghe (2023) acknowledged that a goal of applying biomimicry is to advance current production technologies, aiming to utilize energy and resources more efficiently to decrease dependence on fossil fuels, which continue to be the primary source of waste [66]. Badarnah (2017) extends this approach to building envelopes by integrating it with building adaptation, proposing responsive building skins as a means to enhance resilience and sustainability through reduced energy usage and more efficient resource utilization. [71] Even though this concept shows parallels with the idea of intelligent buildings, the distinction between the two theories lies in biomimicry's focus on achieving sustainability through imitation of natural processes, while the latter concept primarily emphasizes creating a comfortable living environment. Hency, the biological evolution operates through the adaptation on the individual level of numerous organisms which employing methods such as mutation, recombination, and selection, these processes develop multifunctional strategies, aiming to fulfill not only individual needs but also those of their lineage. Thus, akin to architectural design, the final result of biological adaptation emerges as a compromise among various external demands, requiring organisms to consider them collectively rather than in isolation. [73] This suggests that advanced biomimetic architecture should not only integrate reimagined natural models and strategies but also prioritize the ability to adapt by learning from acquired experiences as a fundamental characteristic of biomimicry.

While the theory of intelligent building primarily engages with non-static architecture concerning responsiveness to human needs and external stimuli, biomimetic architecture interacts within the non-static realm focusing on adaptability, drawing parallels with biological adaptability. From biological point of view, the term adaptation is defined as:

'The evolutionary process whereby an organism becomes better able to live in its habitat or habitats' [74]

In practical nature-inspired architectural design, morphology and form seems to prevail as the most common characteristic adapted from nature, while mimicking natural strategies and processes defined by Benyus, Badarnah, and Vincent as distinctive features of biomimicry remain infrequently utilized in actual construction. Badarnah (2017) references the natural strategy of adaptation, which enables various species to survive in changing conditions, aiming to implement a similar approach in building design:

'Adaptation is the ability to maintain stable internal conditions while tolerating changing environmental conditions. In biology, it is called homeostasis—a fundamental characteristic in living organisms for survival.' [71]

The author identifies three adaptation means foubd in nature that can be applied in architectural design: *physiological(1),* which entails the original homeostatic response to an external stimulus; *morphological(2),* referring to the geometrical or structural changes of an organism; *behavioral (3),* describing the behavioral patterns of transitioning to a new environment with improved conditions. *[71].* Similar to nature, adaptation in architecture spans various temporal and spatial scales, with vernacular architecture illustrating long-term responses to climatic, resource, and socio-cultural influences utilising solely static architecture tools. [71] In this way, it can be concluded that adaptation in architecture extends beyond the confines of non-static architecture theories, operating not only within the bounds of individual buildings but also within their imaginated groups: architectural design traditions, styles, and approaches. Thus, adaptability is an attribute of kinetic architecture until the point it engages with the principle of movement within a specific building or a network of interconnected structures.

At the same time, certain theorists like Kuru (2019) [75,76] and Faragalla (2022) [77] underscore adaptability within the context of multifunctionality inherent in natural systems as a strategy to implement in facade systems. Considering the critical role of this building component in energy performance and its responsibility for 60% of heat losses occurring through facades, building envelopes can be designed to simultaneously fulfill numerous tasks:

Therefore, the multifunctionality of façades have become an important design goal for any sustainable building. In other words, adaptive façades would be able to perform several functions such as controllable insulation and thermal mass, radiant heat exchange, ventilation, energy harvesting, daylighting, solar shading, or humidity control.[77]

However, solely relying on adaptation cannot serve as the key characteristic classifying a responsive building skin as biomimicry, since kinetic envelope technologies can be an output of various theories proposing principles to generate responses to external environmental stimuli, as already evidenced in the previous section with the sample of intelligent skins. Faragalla (2022) delineates five types of adaptive facade systems: *Advance Intelligent Facade (1),* a smart system employing electromechanical devices detecting indoor and outdoor stimulus through sensors to generate a response; *Building Integrated Photovoltaic Facade (2),* a hybrid skin combining photovoltaic systems and thermal collectors, allowing the building envelope to both generate energy; *Kinetic Facade (3),* movable envelope system designed to react on environmental stimulus applying sensors and actuators; *Climate Adaptive Building Skins (4),* a dynamic facade adjusting its functions, features, or behavior as needed over time to enhance building performance, possessing adaptability, versatility, and evolvability; *and Biomimetic adaptive building skins (5)*, a facade type, adapts inspired by biology to enhance building performance with efficient strategies.[77] The classification faces challenges, chiefly the limitation of defining categories, as a category *'kinetic facades'* shares similarities with all four other groups, aligning this term primarily as a synonym for the overarching term *'adaptive skins*'. However, even with Faragalla's developed classification, evidence for biomimicry theory suggests its unique model of adaptability, inspired by natural processes and behaviors, distinguishing it from approaches derived from intelligent building or other architectural theories.

Kuru (2019) identified four levels of Biomimetic adaptive building skins: *scale (1),* determining a system size and containing such levels as *envelope (a), facade (b), facade component (c), and facade sub-component (d)*; *adaptability (2),* meaning facades responsiveness to environmental factors, functions, and stimuli; *biomimetics (3),* poinintg the application of natural strategies and process into architectural design, *performance (4*), measuring the effectiveness of operational strategies. [76] In this way, it can be concluded that a sole fundamental aspect distinguishing biomimetic adaptive skins from other types of adaptive facades is biomimicry itself.

Despite the fact that biomimicry received significant attention from architectural theorists in recent years, the focus has shifted towards environmental adaptability rather than multifunctionality [75,56]. Aysu Kuru (2020) acknowledged the potential for buildings to serve multiple purposes as a means of enhancing performance, drawing inspiration from nature's boundless reserve of ideas and strategies:

'Organisms have developed multi-layered structures (hierarchy) with diferent morphologies of basic components (heterogeneity) to achieve multifunctionality.' [75]

After examining a framework incorporating nature-inspired adaptation strategies, Kuru concluded that *'these strategies are mostly treated as individual components that serve a single function'* and subsequently formulated her own natural design principles for application in architectural design. (Figure 38) [75]

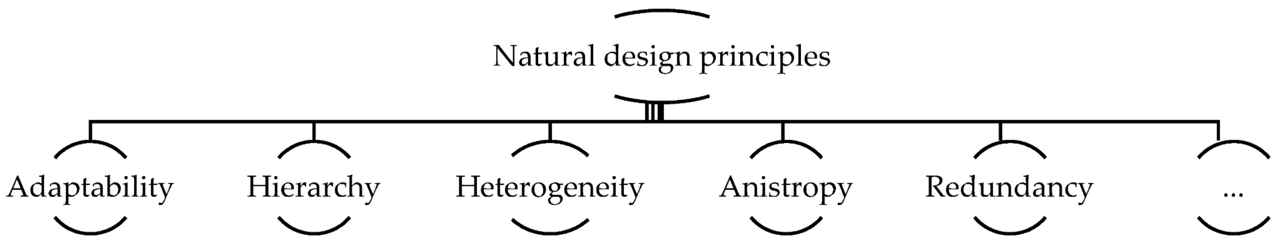


FIGURE 38

The natural design principles as an ever-growing classification, where the last item in the list presents continuity developed by Ausu Kuru [75]

Emphasizing the three key components of the suggested classification — *adaptability (1), hierarchy (2), and heterogeneity (3)* — the author maintains an open-ended approach to this biological process, indicating the potential use of other biological processes to achieve biomimetic multifunctionality. Regarding adaptability, Kuru emphasized the static nature and the inherent limitation in the ability to reconfigure itself, which were evident in the various realized projects featuring biomimetic adaptive building skins. In the context of biomimicry, *hierarchy (2)* is portrayed as an inherent characteristic of multi-level structures, enabling the development of diverse adaptation strategies across all scales, from nano- to macro-scale. A similar approach can be applied to architectural design:

'For example, building systems at a larger hierarchical level can host one function and its material at a smaller scale can host another.' [75]

Another fundamental natural design principle is heterogeneity, which refers to the varied quality or state, encompassing differences in geometry and content within a multidimensional structure. However, Kuru acknowledged that in nature, form, and function intersect, demonstrating that each natural form can be validated by its functions. In this way, heterogeneity can be implemented into architecture by incorporating various morphological shapes that encompass diverse functions. The author explains the work of this principle through the two slopes roof and eaves (Figure39):

'The roof itself functions as the top covering of a building and the eaves are the edges of the roof which project beyond the side of a building. The eaves function as shadings and through their geometric differentiation from the roof, the system becomes multifunctional.' [53]

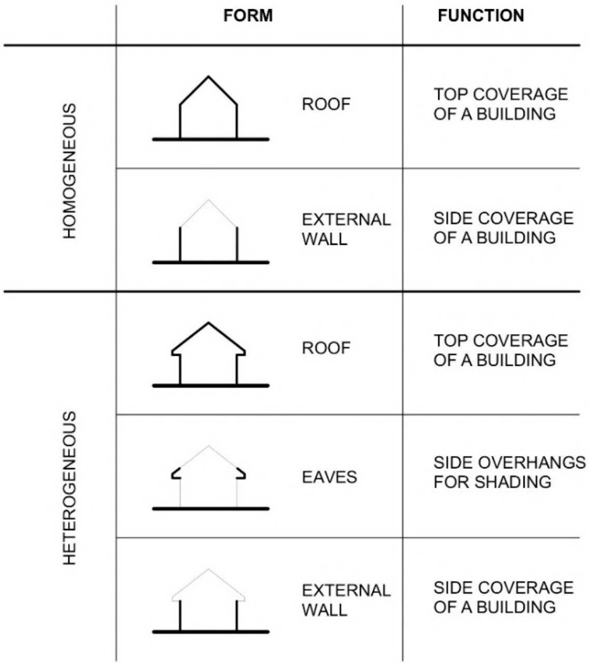


FIGURE 39

Heterogeneity in a conventional roof structure showing the heterogeneous forms of the rood and eaves by Ausu Kuru [75]

In one building, the two natural design principles of hierarchy and heterogeneity can interact, accommodating functions across its various elements positioned at different scales. For instance, within an existing hierarchical structure that combines elements of various scales, adjusting materials with nanostructured surfaces can introduce additional functions. Consequently, structural components assume heterogeneous forms within the hierarchical framework, adding extra functionality and enabling multifunctionality. [75] (Figure 40)

The implementation of biomimicry in architecture encounters challenges, primarily due to designers lacking knowledge in biology, moreover the abstraction phase draws as particularly difficult, where working with topics beyond designers' expertise poses significant hurdles. [66] To address those design issues, the line of biomimetic approaches were suggested by theorists [66,71,74,78]. Verbrugghe (2023) has systematized design strategies, outlining nine types, although most of them trace their origins back to the two fundamental approaches commonly presented in the design field: *bottom-up approach (or 'solution-based approach' or 'biology to design') and top-down approach (or 'problem-based approach' or 'design to biology') [66]* The distinguishing point between them lies in their starting points: the *'bottom-up approach'* begins with a projected biological strategy to resolve technical questions, whereas the '*top-down approach'* starts from the specific technical issue, aiming to resolve it through the implementation of natural strategies. [66]

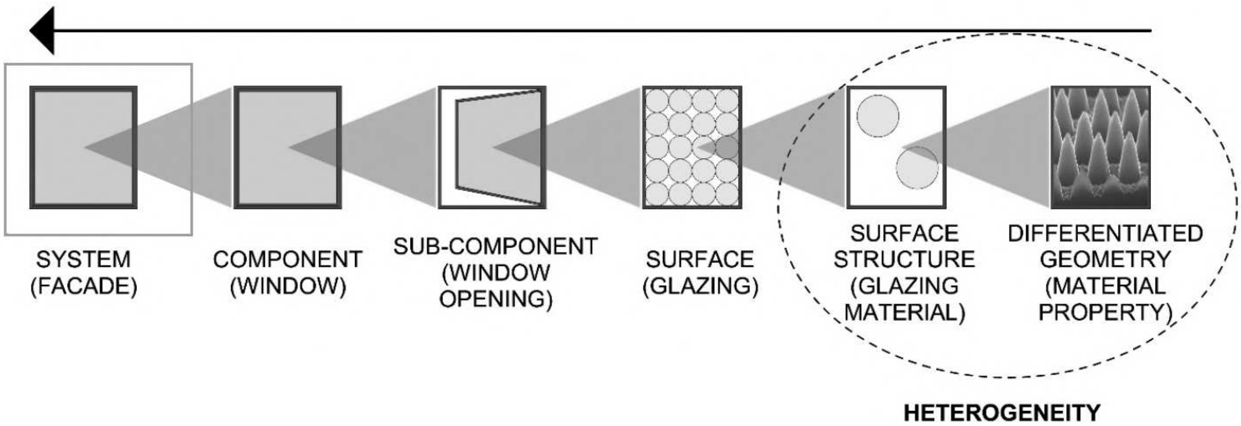


FIGURE 40

How buildings can achieve multifunctionality through integrating hierarchical building components with heterogeneous forms of material properties by Ausu Kuru. [75]

Kuru developed the *'Multi-Biomechanism approach,'* with the aim of introducing a method to achieve biomimetic functionality in adaptive building skins through the implementation of heterogeneity and hierarchy. The method referring to top-down approach and containing four stages: '*identifying a technical problem' (1),* involving identifying the best-case scenario and requirements through building performance simulation; *'selecting a biological solution' (2),* focusing on searching for biological solutions that satisfy the functional requirements established in the previous stage; *'achieving multifunctionality' (3)*, searching the biological mechanisms inherent to different scales and organizes them into a hierarchical system; *'developing a biomimetic strategy' (4),* transferring hierarchy and heterogeneity to functional and applicable materials, geometries, and configurations for the facade system. [66, 75]

Another theorist López emphasis the multifunctional feature inherent to biomimetic adaptation as natural solution are complex and highly responsive (2017), however the author turns light on adaptation inspired from plants as:

',Plants, because of their immobility have developed special means of protection against changing environmental issues (e.g. darkness, light, humidity, rainwater, fire, temperature, freezing, air movement or air quality). These adaptations develop over time and generations as a response to the ever changing environment'.

The author proposed a design method for adaptive building skins, presenting a reimagined bottom-up approach consisting of five stages, with the initial focus on examining biological reference. The approach initiates by identifying the *'climate context' (1)*, which holds the most influential power over plant behavior. The second step of the approach means searching an answer on the three questions regarding natural strategies: *what?(2.1)*, encompassing a comprehensive overview of adaptation strategies characterized by type, approach, and scale; *why?(2.2)*, aiming at identifying the primary challenges the building needs to address; and *how?(2.3),* focusing on the adaptive behavior resulting from the interaction of structure, morphology, and strategy. 'The first step*, 'identifying the climate context (1)',* and the second one, *'What? Why? How? (2)'* form the initial stage, named *'nature (I)',* aiming to identify the principles of natural adaptation. These principles are intended to be transformed into architecture in the subsequent phase of the approach, referred to as *'architecture (II)'.*The second stage comprises three steps: *'application ideas' (3)*, involving the development of an adaptation strategy that can be dynamic or static; *'innovation' (4)*, focusing at proving the enhanced energetic performance of the biomimetic envelope in comparison to traditional building systems; *'design concept generator' (5)*, applying the established principles into architectural design. (Figure 41) [66,78]

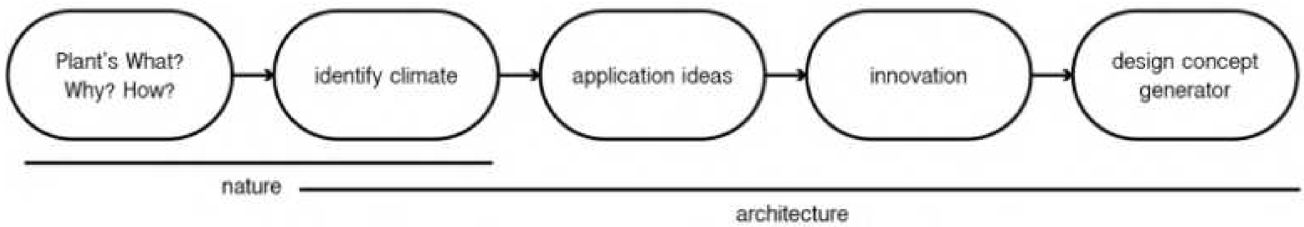


FIGURE 41

Plants to architecture approach developed by Lopez, compounding of the 2 stages: nature (I), including climate context identification (1), questions What? Why? How? (2); and architecture (II), consisting of the three steps: application idias (3), innovation (4), and design concept generator (5). [66,78]

Schleicher (2015) formulated the 'Push-Pull' method, focusing on translating plant movement into architectural design by employing a blend of bottom-up and top-down approaches. The approach contains the five steps: *kinetic movements (1),* involving seeking suitable adaptation role models; *identify biological nastic movements (2),* including examining the chosen kinetic movements to elucidate their functional mechanisms; *disclosing motion principle (3),* simplifying the identified relationships between principles to enhance design flexibility; *modeling bio-inspired mechanisms (4),* transforming the generalized motion model into biomimetic components using computational software to accurately mimic plant motion; *conceptualizing flexible* *component (5),* implementing and testing the resulting flexible component for practical usage and assessing its performance. [66,79]

In this manner, despite differences in initial points, all reviewed approaches—representative of bottom-up, top-down, and mixed method models—share similarities in the aspect of meticulously examining natural models to elucidate fundamental rules governing the functioning of adaptive systems. On the next stage, these determined fundamental principles must be conceptualized to allow for sufficient flexibility, enabling their translation into kinetic architectural elements to achieve the predicted result. Thus, biomimetic design is executed by emphasizing natural processes and strategies rather than merely mimicking form or employing natural materials straightforwardly.

Simultaneously, even though biometric design approaches primarily aim to assist designers in mimicking nature, these methods encounter certain challenges. Firstly, during the conceptualization step, simplification of the complex natural strategy into several fundamental points may result in inaccurate reproduction of biological principles, especially when designers lacking biological science knowledge might overlook fundamental elements. Secondly, the capacities of an adaptive architectural component to simulate natural processes are also limited in terms of material and technological frameworks. It can be acknowledged that as the complexity of the hierarchy increases alongside the expansion of heterogeneity across various scales, the technological complexity of the projecting element also rises. This escalation in complexity increases final costs and significantly heightens the risk of system breakdowns.

The multifunctionality inherent in natural adaptation processes constitutes an essential characteristic that biomimetic design approaches aim to emulate in adaptable building skins. Consequently, biomimetic adaptation in building skins differs from intelligent envelope systems in that bio-inspired facade systems primarily seek to offer a nuanced response to external stimuli through hierarchical multiscale kinetic systems. In contrast, intelligent facades prioritize addressing environmental complexity by efficiently meeting diverse requirements through calculated responses, optimizing resource usage. One of the most fundamental distinctions between these two building envelopes arises from the adaptation strategies employed in biomimetic skins, which stem from the intrinsic physical characteristics of smart materials and the initial design of responsive mechanisms. Consequently, biomimetic motion appears to be pre-programmed, autonomous, and uncontrolled, while the response of intelligent skins is derived from calculated outputs of computational systems, which can be managed by users and possess learning capabilities. As a result, intelligent skins are characterized by greater adaptability to user requests and unpredictable external stimuli, whereas building biometric envelope systems excel in multifunctionality and self-sufficiency. The potential fusion of these approaches in the design of kinetic facades could yield a novel system marked by multifunctionality and self-sufficiency, capable of conserving energy resources and equipped with advanced computational devices for enhanced user-oriented management.

In this manner, even nature has been an inspirational source for the architecture of ancient civilizations, the theory examining the translation into architectural design of natural forms, strategies, and the implementation of organic materials has been evolving for several decades. However, due to the limitations of traditional structural materials and engineering technologies, the mimicry of biological processes could not be seamlessly implemented into the building projecting. With the rise of the sustainable movement, which seeks ways to reduce the environmental impact of buildings, and the advancements in information and technology, biomimicry in its contaprary definition accepted within architectural theoretical circles [64, 66, 67-74, has become a research objective and has already developed a wide theoretical framework.

Upon a concise review of the literature regarding the adaptive aspect of biomimicry, it became evident that the emulation of natural strategies represents an alternative method for implementing the principle of movement. Consequently, the term *'adaptation'* [64, 74-79] has been predominantly selected to describe movable building components in various articles about biomimetic approach, aligning with the rules defining the theory of *'adaptable architecture',* especially its primary focus on motion strategies, its pricniples and organisation [31-33]. However, biomimetic adoprtation can be chararesid with the line of key characteristic: *sustainability though building performance amelioration (1), multifunctionality through hierarchical and heterogeneous systems (2), complex consideration of external stimules (3), and technical autonomy (4).* Considering organic mechanics as one of the most effective examples of energy management, bioinspired adaptation primarily aims to enhance building energy efficiency through the application of multifunctional and multiscaled systems. To achieve the system's capacity to respond to various stimuli simultaneously, designers address essential natural principles such as hierarchy and heterogeneity to simulate the functioning of biological organisms within technological limitations. Moreover, bioinspired adaptive envelopes aim to satisfy diverse requests from the external environment, making them multipurpose. Additionally, such systems attempt to utilize smart materials that react to changing environments by adapting their inner physical characteristics, rather than being set in motion by external forces.

This chapter section offers a concise overview of additional architectural concepts, each with its own research objectives that don't necessarily center on implementing the motion principle into architecture but often leverage it to achieve their primary goals. Alongside *deployable structures (1), intelligent buildings (2), and biomimetic architecture (3)*, this scope can encompass additional concepts such as modular architecture, sustainable architecture, parametric design, and more. However, motion isn't a pivotal factor in the aforementioned theories. When theorists and designers delve into motion within frameworks detached from kinetic principles, they frequently adopt approaches intrinsic to nonstatic architectural theories.

Despite each of the three reviewed concepts primarily focusing on the study of different fields, they contribute unique perspectives to implementing the motion principle in architecture, elaborating on the theoretical framework of kinetic architecture and introducing new aspects. For instance, *deployable structures* examines how motion can be transmitted through engineering systems, emphasizing the classification of kinetic systems based on their spatial characteristics. Consequently, *deployable structures theory* can be seen as a means through which kinetism is performed. Simultaneously, the *intelligent building concept* aims to integrate computational technologies into architecture to enhance the flexibility of living conditions and minimize the environmental impact of buildings. Within the intelligence framework, *adaptive architectural components* emerge as tools within an integrated system, as developed by Fox as *Advanced Kinetic Architectural Systems*, where motion serves as one of the three fundamental components alongside *structural engineering and embodied computation* [8]. The concept of intelligent buildings introduces the term *'responsive architecture',* illustrating how kinetic building components shape the internal environment and affect the users, establishing a self-contained system with three interdependent components, where intelligent building design serves as a mediator. On the other hand, *biomimetic architectural design* utilizes the term *'adaptability'* to redirect focus towards motion strategies and emphasizes multifunctionality inspired by biological processes and mechanisms.

Therefore, the various aspects and models concerning motion in architecture emphasized in the additional concepts reviewed in this chapter will be integrated with conclusions derived from non-static architecture theories seen previously. This integration aims to formulate a *comprehensive theory of kinetic architecture,* which will be developed in the next chapter section.

CHAPTER 3: CENTRIPETAL MOTION: COMPREHENSIVE THEORY ENCOMPASSING ASPECTS OF ALL NON-STATIC ARCHITECTURE THEORIES

Based on the analyzed concepts within non-static architecture, encompassing sections such as *'kinetic architecture' (1.1), 'adaptable architecture' (1.2), 'transformable architecture' (1.3), and 'responsive architecture' (1.4),* alongside additional theories addressing distinct research objectives but also concerning movable architecture: *'deployable structures' (2.1), 'intelligent buildings' (2.2), and 'biomimetic architecture' (2.3),* the forthcoming chapter will shed light once more on the initial issue raised regarding the lack of a theoretical framework and terminological confusions inherent to non-static architecture. [23,26,31,44,80,81] The primary issue resides in identifying the suitable umbrella term, emphasizing the decisive aspect of movable architecture, as presented in all theories of non-static architecture.

3.1 THE CRITERIAS OF NON-STATIC ARCHITECTURE THEORIES

3.1.1 KINETIC ARCHITECTURE

In reviewing the theoretical framework and definitions of kinetic architecture in the first section, it can be acknowledged that the *principle of motion*, with its broader physical and morphological interpretations, remains the most fundamental criterion defining this theory [23,28,29,30,44,81]. In his influential work, William Zuk (1970) remains one of the most fulfilling attempts at philosophizing kinetic architecture, seeking motion as a response to the influence of external forces:

‘Basic to the philosophy of kinetic architecture is the importance of being able to accommodate the problem of change. Under present architectural approaches, the form is likely to become obsolete from a functional point of view long before it becomes unsound and in need of physical replacement. The physical form should not straight jacket the constant change that is taking place in the set of pressures, creating an instability between pressure and form.’ [29]

In this manner, kineticism in architecture derives its originality from the contrast between *'kinetic'* and *'static'.* The historically formed approach of projecting the building environment as *'an ideal neutral space of Cartesian coordinates' [82],* as noted by Greg Lynn, has led to a divergence between architecture and other design fields that embrace an active contextual approach. Through an analysis of this aspect of architectural projection, the author introduces the term *'stasis':*

‘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.’ However, statics does not hold an essential grip on architectural thinking as much as it is a lazy habit or default that architects either choose to reinforce or contradict for lack of a better model. [82]

Laracuente takes this concept further by proposing *'kinesis'* as an opposition to *'stasis',* deriving its originality from the human sense of order embodied in the *'mythical definition of permanence itself grounded in legends and religious belief':*

‘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.’ [26]

The author aligns the emergence of architecture encouraging motion with the development of kinetic art, which began in the early 20th century, itself inspired by the introduction of animation in the 19th century:

‘Kinetic art and architecture both descend from animation, which in turn comes from chronophotography, a consequence of morphology, that itself derives from painting.’ [26]

Thus, *'kinetic architecture*' emerges as a concept primarily defined by motion and heavily reliant on the interpretation of motion's boundaries. Within theoretical literature, it serves as a broad term encompassing various architectural adaptabilities. For instance, it is referenced in Zuk’s *'Kinetic Architecture' [28]* and Frank Popper’s *'Origins and Development of Kinetic Art.'* Additionally, it operates within complex architectural systems that transmit motion through the application of supplementary technologies, as seen in Fox’s *Advanced Kinetic Systems [30]* and *the various classification of deployable structures. [22, 27]*

3.1.2 ADAPTABLE ARCHITECTURE

From the second chapter section concerning the representation of adaptability in architectural theory, it can be inferred that this term distinguishes itself from the previous one by placing focus on the *environmental aspect*. External stimuli, as forces that set structures in motion, are considered in almost every definition of adaptable architecture. [31, 32, 33] This theory primarily emphasises the motion as a building capacity estebleshed though strategy, containing diverse level of adaptability [33], limits of interference in the building structure [32]. Furthermore, biomimetic design, describing movable architectural components, operates within the term *'adaptability',* shifting focus towards the multifunctionality and multilevel nature of responsive architectural motion. [71,73-77]. This highlights the significance of a *motion strategy* as the second fundamental aspect of adaptable architecture. Lee (2012) elucidates this concept in his thesis by presenting a comprehensive definition of adaptable architecture based on a review of theoretical materials within the field. Within this examination, key aspects are identified:

'Adaptable architecture: buildings that are planned to be easily altered or modified to fit changing functions or external conditions, before or after occupancy.' [23]

Furthermore, the author examined the purposes in which the term was utilized within theoretical literature, observing that adaptability was predominantly applied to social and economic contexts. (Figure 42) The social rationale denotes the inherent ability of a building, its components, or clusters to adapt across various scales: *individual/household scale (1), community/organizational scale (2), and societal scale (3).* Social needs primarily address changing household dynamics and activities while seeking solutions for homes and community spaces to evolve with shifting requirements. While the economic purpose refers to achieving financial profit through the implementation of adaptable strategies, thereby expanding the building's functionality. [23]

3.1.3 TRANSFORMABLE ARCHITECTURE

The third section of the chapter explored the theoretical boundaries of the concept of transformable architecture, concluding that the *resulting outcome* manifests in alterations to the building's inner or outer characteristics. [34-39] Moreover, transformability is more frequently associated with *morphological characteristics* such as dimensions, shape, and appearance rather than inner features [35-37]. Additionally, some definitions mention the presence of *actuators and movable engineering systems*, which enable and transmit motion [23,36,38]

Regarding rationales, social together with aestetic purpose forms more then two thirds of transformable architecture application. (Figure 42). Aesthetic reasoning primarily pertains to the diverse variability achievable through layout transformability, fostering a novel living environment experience. The social function of transformability operates across various levels, ranging from shaping individual household living environments with features like sliding partitions to a macro level, where adaptable spaces cater to changing family structures, address disaster recovery needs, and accommodate the evolving preferences of an aging population. [23]

3.2.4 RESPONSIVE ARCHITECTURE

The comprehensive concept discussed in the fourth chapter section emphasizes simultaneously two aspects of architectural motion: the *external stimuli* triggering the building's reaction and the *resulting response*, influencing both the changing environment and the user. Furthermore, the primary focus of responsive architecture lies in the *interdependence between architectural elements on the one side, the active environment, and the user on the other side. [23,40-43]* The resulting interaction between these components forms an *autonomous cycle* characterised by its rhythm and the mutual influence among its elements and abling of progressive development, forming an *evolutionary environment. [40]* Responsive architecture also considers the potential to extend architectural responses across entire building clusters, suggesting a model where the movement of each structure is coordinated and capable of learning [39]. The primary focus of these concepts revolves around meeting the changing needs of users, which initiates architectural responses but is simultaneously influenced by the dynamic environment. "Furthermore, the terms *'responsive architecture'* and the associated *'responsive skin'* are commonly used in theoretical literature, particularly in relation to intelligent buildings, which explores how buildings adapt to changing external stimuli to maintain a stable internal living environment [60, 62].

According to Lee [23], the use of responsive architecture in recent theoretical literature in 32% of the worlds is inherently linked to *environmental rationales*, encompassing two aspects: *climate and site conditions.* (Figure 42). The responsive strategy aims to enhance a building's energy performance and improve its sustainable characteristics by responding to surrounding stimuli stemming from changing climates or site configurations. Similar to the previous concept, social rationales operate at three scales: *individual, community, and societal levels.* The distinctive aspect from the previous concept at the individual level is a greater emphasis on fostering building energy performance and user control rather than focusing solely on functional or structural building organization.

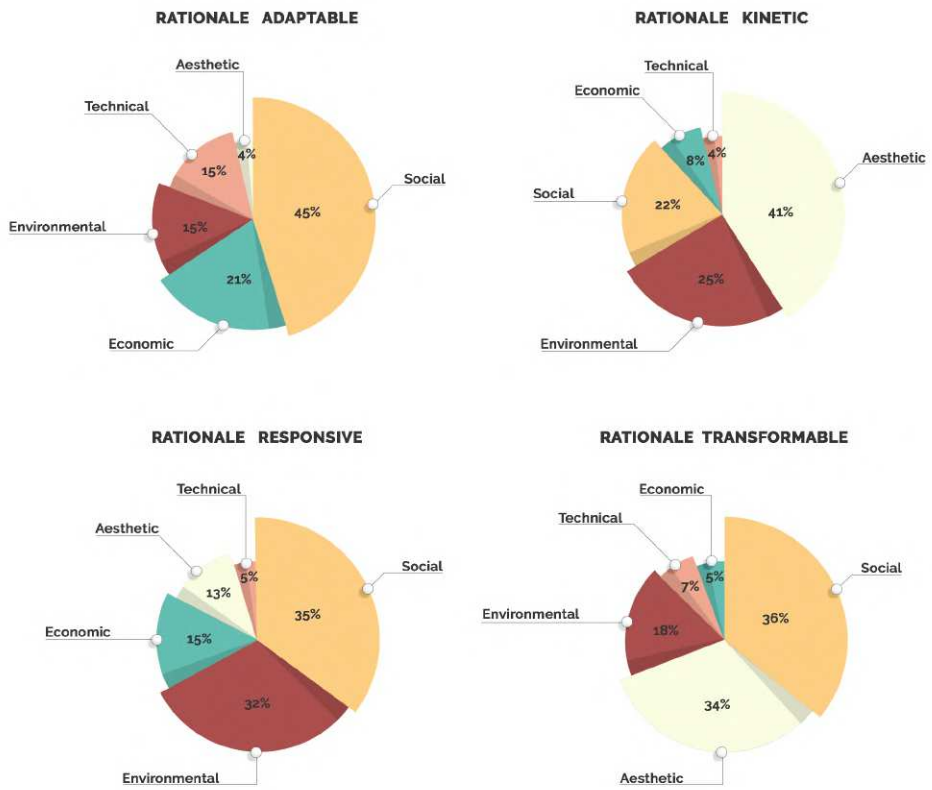


FIGURE 42
Comparison of Rationales by Terms: Adaptable, Kinetic, Responsive, Transfombale by Joshua David Lee [23]

3.2 THE CRITERIAS OF ADDITIONAL CONCEPTS ENCOMPASSING ELEMENTS OF NON-STATIC ARCHITECTURE

3.2.1 DEPLOYABLE STRUCTURES

Deployable structures can be defined as *a field of structural engineering* dedicated to examining *kinetic systems that initiate and transmit architectural motion.* The scope of this theory is primarily focused on motion itself, often neglecting accompanying aspects such as the *changing environment, users' needs, the resulting outcome and ect.[44-49]* In cases where theories connect the deployable system with general architectural concepts, the term *'kinetic'* is regularly applied, primarily emphasizing the capacities of movable systems. [44,48,49] Fox integrates deployable structures as a foundational element within Advanced Kinetic Architectural Systems, defining means and ways through wich kinetic architecture is performed. [30] (Figure 20) The literature on deployable systems offers various classifications, categorizing structures based on *deployable material characteristics (flexible, deployable, smart), types of movement, and number of movement axes (monoaxial, multiaxial) and used dimensions (2D and 3D). [44,48,49]*

3.2.2 INTELLIGENT BUILDING

The theory of intelligent buildings emerges as a self-sustaining field of research at the intersection of architecture, computational technologies, and structural engineering, aiming to to develop adaptable internal building environments that efficiently and sustainably meet user needs. In this way, the use of movable architectural elements within the framework of smart building design shifts the focus of non-static architecture towards addressing concerns related to *environmental sustainability and energy performance monitoring*. To integrate the concept of building smartness into the expansive realm of non-static architecture, theories utilize the term *'kinetic'* to shed light on the general motion capabilities of elements [60], and *'responsive'* to underscore their connection with an adapting environment [60]. However, the term *'adaptability'* is utilized more frequently, particularly in the context of intelligent building skins, to emphasize the smart envelope's *capability to delineate various models of changeability in response to a dynamic environment.* Beyond mere functionality, intelligent buildings prioritize *user-centric design*, engaging with occupants not merely as participants but also recognizing their needs as integral to the *purpose of enabling architectural adaptability*. Moreover, the concept of intelligent buildings delves into the *control management aspect*, advocating for responsive systems equipped with *self-learning abilities.*

3.2.3 BIOMIMETIC ARCHITECTURE

Similar to the preceding concept, biomimicry emerges as a substantive field incorporating architectural design, biology, and structural engineering, with a focus on studying, rethinking and implementation of natural process into architectural design. [68-73, 75-79] *Adaptive building skins* serves as an intersection point of the biomimicry and non-static architecture. [71,75-78] Biomimetic approach shares similarities with kinetic architecture seeking *origins of architectural motion into natural changeability*, however taking this way farther and highlighting *multifunctionality* inherent to the various natural processes. [73,75-77] As a way for adaptable systems to reach multi purposeness, the biomimicry proposes to address the *multi levelness organisation and formal heterogeneity*. [75]

3.3 THE KINETIC CHRONOLOGICAL MODEL OF THE FIRST LEVEL

3.3.1 KINETIC AS AN UMBRELLA TERM FOR NON-STATIC ARCHITECTURE THEORIES

In this summary highlighting non-static architectural concepts *(kinetic, adaptable, transformable, and responsive)* it becomes evident that they collectively prioritize motion as a fundamental aspect within their theoretical literature. While all these theories, apart from kinetic theory, share a common explore additional dimensions related to the application and performance of this principle in architecture, kinetic theory uniquely perceives *motion as an independent and self-sufficient phenomenon*. As discussed in the initial segment of the chapter's sixth section, *'kinetic'* is a term commonly used in architectural discourse to delve into the *philosophical underpinnings of architectural motion or as a general descriptor for systems facilitating motion transmission.* Consequently, '*kinetic'* architecture serves as *an umbrella term encompassing all theories concerned with how motion principles manifest in architecture.* It is also used *interchangeably with 'non-static architecture'.*

As kinetic architecture emerges as a comprehensive label encompassing all non-static architectural theories, the inherent theoretical propositions of each concept can potentially be amalgamated into a unified, *overarching kinetic theory.* This synthesis could establish generalized criteria and facilitate their hierarchical organization, drawing from the collective insights of these diverse architectural perspectives.

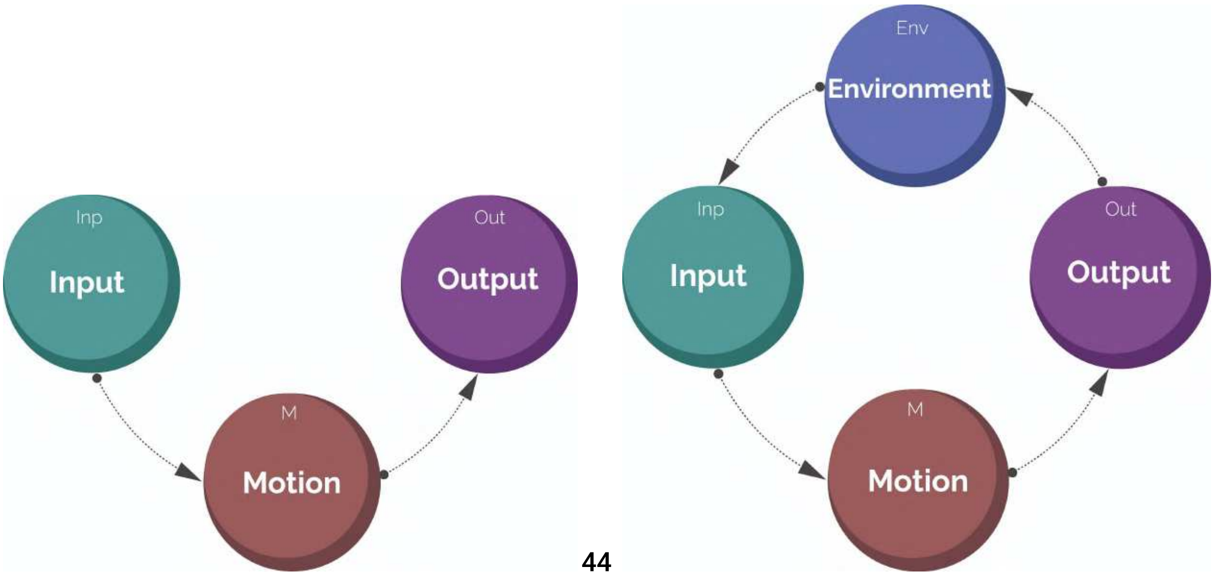
3.3.2 MOTION AS A CENTRAL ASPECT OF KINETIC ARCHITECTURE (PERMANENT CRETERIAS OF KINETIC ARCHITECTURE)

The challenges in developing a system that describes all criteria for kinetic architecture are not solely rooted in their identification, but also in their systematization. Various aspects of motion exhibit distinct characteristics, natures, originalities, and roles within the performance of architectural motion principles. Consequently, organizing all identified criteria requires a structured system-forming principle, and in the context of motion, employing a *chronological order* can effectively categorize kinetic architectural criterias. Motion itself can serve as both the starting and zero-coordinate point in this categorization. This approach facilitates the grouping of all aspects into three overarching global categories: *input (1),* preceding motion, *the motion (2)* itself*, and the output (3)* that represents the motion impact. (Figure 43) This conceptualized model aligns with the concept of responsive architecture, emphasizing the self-dependence of architectural motion from its surroundings, depicting it as a cyclical process. For a comprehensive understanding, the *environment (4)* must be integrated as a fourth category within the chronological model of kinetic architecture, influenced by the output of architectural motion and generating requests referred to in this model as input.The category of *'environment' (4)* encompasses various elements, including but not limited to the inner microclimate, external climate, the physical appearance of buildings, users themselves, and more. In reality, it emerges as a complex system comprising numerous structural elements that may have limited self-connection, but in the context of architectural motion, it forms an intricate integrated environmental system, producing a request *(input)* and enabling a kinetic system to respond.

In this manner, broader categories of kinetic architecture can be delineated as follows:

1. *Input - the trigger that a kinetic architectural system takes into account to initiate the process of architectural motion.*
2. *Motion - the change occurring within the kinetic architectural system due to external stimuli, and it is intended or projected to happen within that system;*
3. *Output - the effect caused by architectural motion, essentially denoting the changes occurring outside the kinetic system but directly attributed to its motion;*
4. *Environment - a conceptualized group of objects interconnected solely by their capacity to interact with a kinetic architectural system.*

The resulting kinetic chronological model, composed of four interconnected categories *(input, motion, output, environment)* (Figure 44) , establishes a closed cyclic process that, in turn, exhibits *general characteristics typical of integrated systems as a whole*, rather than inherent in each individual element separately. However, even in this simplified form without further subcategorization, the model encounters an initial challenge in representing kinetic systems, as described by Zuk as '*Dynamically self-erecting structures'* capable of a singular motion and irreversible disassembly. This challenge can be addressed by introducing the *first typology criteria of kinetic systems: cyclical (1),* signifying the ability to repeat motion, and *one-time (2),* characterised by singular motion. In the latter case, the kinetic system transitions from a kinetic object to a static state, losing its capacity for further motion by realizing its potential motion into kinetic action.



43 44

FIGURE 43, 44

The open cycle (Figure 43) and the repeatable cycle of the projecting Kinetic System motion depicted through Kinetic Chronological Model (Figure 44)

The indicated criteria such as *input (1), motion (2), output (3), and environment (4)* can be considered permanent criteria as they are inherent in each object of kinetic architecture. These aspects span from assembled and disassembled temporary structures to multifunctional intelligent building envelopes capable of self-learning. However in the such generalised form Kietic The chronological model cannot be considered complete as it fails to clarify the relations between different criteria and typologies indicated in the previous chapters. Moreover, it does not offer a diverse range of models within kinetic architecture. Hence, there is a necessity for further detailing of the Kinetic Chronological model.

3.4 THE KINETIC CHRONOLOGICAL MODEL OF THE SECOND LEVEL

3.4.1 DETAILING ENVIRONMENTAL CRITERIA WITHIN THE KINETIC CHRONOLOGICAL MODEL

The suggested portrayal of the *environment category* appears to encompass a wide array of objects grouped under this overarching label, creating a nebulous collection lacking specific emphasis and necessitating further elaboration. The paramount focus should be on discerning the *user* as a unique element in the kinetic architecture system due to its subjectivity and intelligence. Responsive architectures offer various models of interaction between users and kinetic systems. These models often position humans in a dual role: *as the primary source of requests for such systems and as the ultimate recipients of their responses* [40]. Placing the *user* at the focal point *between input and output,* they become an autonomous element within the active environment. However, not all kinetic architectural systems directly cater to human requests. Instead, they predominantly respond to environmental changes via sensors, facilitating architectural motion when these internal or external conditions deviate from the projected ones. Consequently, *interactions between users and kinetic mechanisms* can manifest both *directly and indirectly.* The necessity of a user's constant interaction as an integral part of kinetic systems remains a subject of debate. Kinetic systems can be engineered to respond to triggers that may not directly address human requirements. Yet, even when a kinetic architectural element is designed, perhaps, to respond primarily to natural stimuli for aesthetic purposes, humans retain the potential to intervene in the architectural motion by adjusting or halting the kinetic mechanism. In this way the *user* should be marked as *a permanent component* of the kinetic chronological model.

The Intelligent Building concept explores the integration of computational technologies to optimize the comfort within *a building's living space* [50, 57, 58, 62]. Furthermore, the theory emphasizes the safeguarding function of building, portraying its envelope as a barrier that separates the internal microclimate, with its specific physical conditions, from the fluctuating external environment. Consequently, building *microclimates* emerge as the secondary component within the *environmental category*, able to interact with *input triggers* and *be influenced by the kinetic component's motion*. However, it's important to note that not all kinetic architectural components are designed regulate the internal building microclimate, hency, this component should be considered a *temporary element* within the *kinetic chronological model.*

Additionally, the connection between buildings and their *external context* is extensively explored through theories like intelligent building design and biomimetic architecture, often within a *sustainable design approach.* Much like the consideration of the internal microclimate, the *outer context* can be regarded as *a third composite element of environmental criteria* as it can be directly influenced by the movement of kinetic components, abling to cool the building, reflect sunlights, and ect. The outer context, within its scope, emerges as a comprehensive category amalgamating various subclasses such as outdoor climate and building contexts, both may be substantially impacted by the kinetic structure. Additionally, it encompasses subcategories like the local social-cultural landscape, which, solely in limited instances, may experience sufficient influence from building structures. However, in most cases, the *outer context* functions not only as a subject of influence but predominantly as a continuously changing environment, generating triggers that affect both *users and the inner microclimate*, thereby enabling the kinetic system to respond. Unlike the *inner microclimate*, the outer context consistently participates in the *kinetic chronological model,* even in situations where the kinetic system is intended solely for influencing the inner building environment. This occurs because the structure hosting movable architectural elements remains an integrated part of the *surrounding context*, thereby impacting the kinetic building system.

In this manner, the environmental category can be further detailed into three interdependent components: *the user (1),* a distinct and permanent element within the kinetic chronological model, possessing subjectivity and direct interference capability in the movable architectural mechanisms; *the inner microclimate (2),* a temporary subclass representing the specific conditions of the building's internal environment; and *the external context (3),* a complex and enduring class amalgamating diverse categories surrounding building itself (Figure 45). More frequently, the *external context (3)* serves as an environment generating new requests for the kinetic mechanism, both directly and indirectly. As kinetic architecture continues to evolve, additional subcategories integrated into the kinetic cycle could be included in the environmental criterial of the model. However, at present, it's evident that these new subcategories will likely stem from further elaboration and segmentation of the *outer context class (3).* Nevertheless, the requirement for any newly indicated aspect of *environmental criteri*a to play a role within *the chronological kinetic model - either as a generator of new stimuli for motion or as one of the affected objects by the kinetic system -* will remain consistent. The internal microclimate, in conjunction with the external context, could mold what's referred to as a *'responsive environment.'* As integration between humans, kinetic mechanisms, and the surrounding context deepens, this responsive environment might evolve into what Wolf Hilbertz termed the *'evolutionary environment'* in the future. [40]

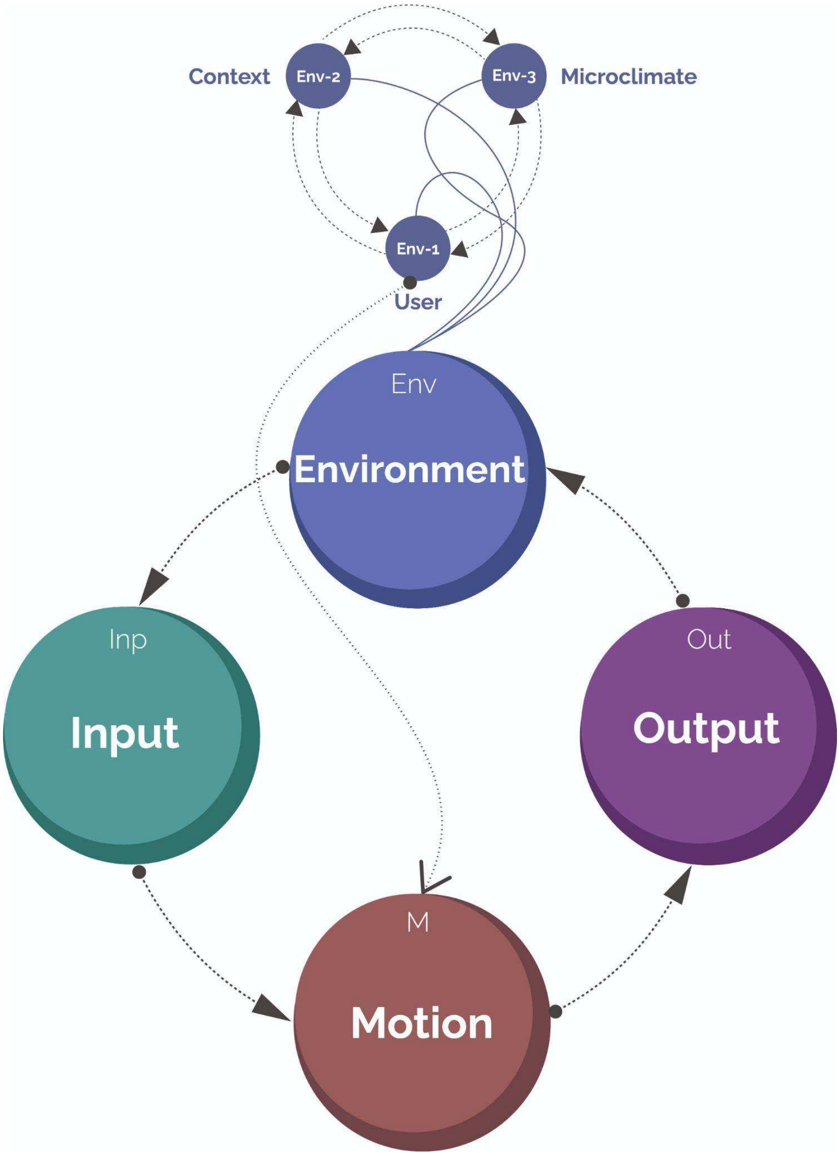


FIGURE 45

The Kinetic Chronological Model with detailed environmental aspect

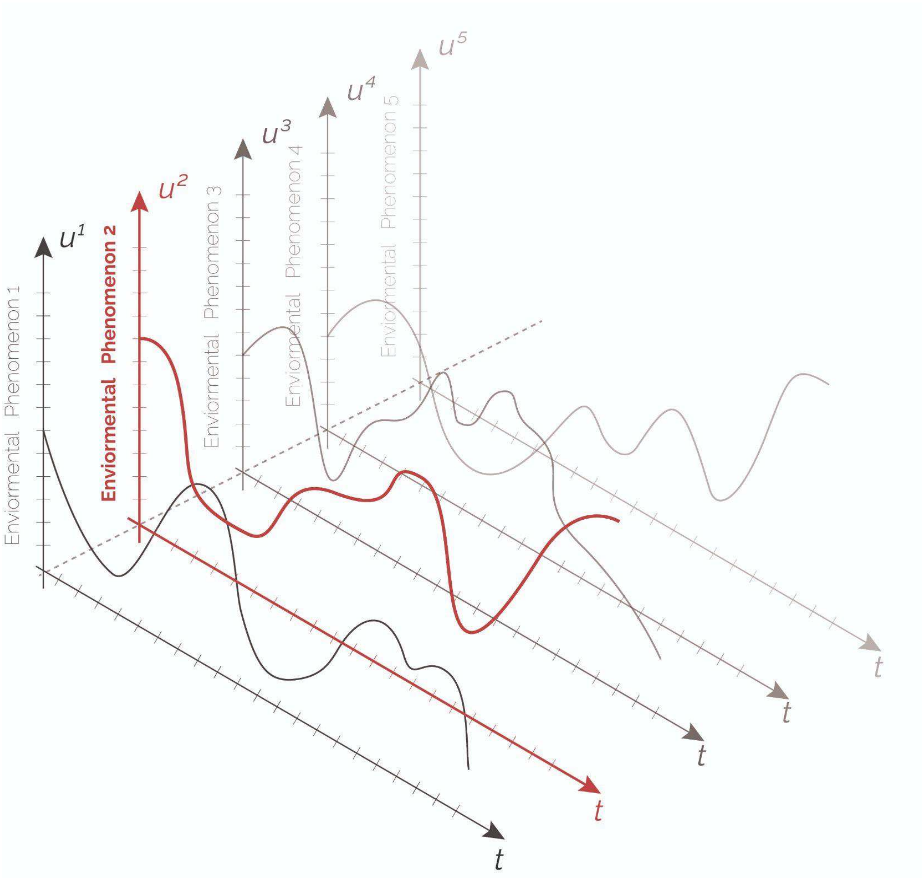
3.4.2 DESIGNER ASPECT WITHIN THE KINETIC CHRONOLOGICAL MODEL

The drafted chronological model delves into the human role as users of kinetic mechanisms, initiating requests, and as recipients impacted by the motion in architecture. However, the human's pivotal role *as designers of the kinetic system itself* has long been overlooked, despite their capacity as creators dictating essential functions, structures, and other facets within the envisioned kinetic architectural system. In this manner, the *designer (D.1)* ought to be included as an individual component within the model, serving as the initial branch, aiming to demonstrate that the projection solutions adopted during the projection phase hold the capacity to decisively shape the entire kinetic system throughout its operational cycle.

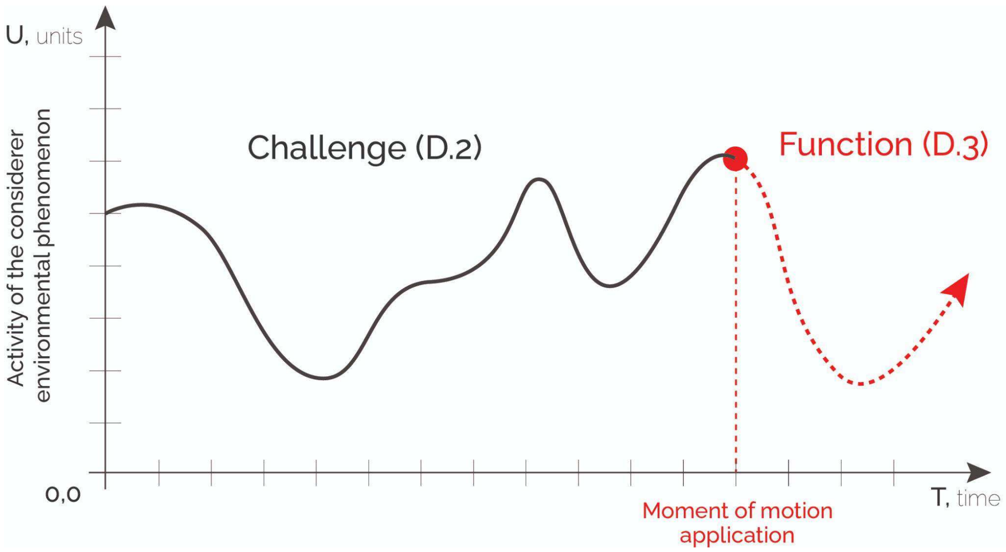
The incorporation of a kinetic system into buildings necessitates stimuli projected to engage with movable mechanisms, stemming from the external environment detailed in the preceding section. Consequently, the designer must discern the phenomena occurring within the external environment, capable of impacting the building. This occurrence need not exclusively pertain to environmental phenomena tied to climate change; rather, its scope extends to encompass broader definitions, such as human or social needs. In this context, *designers (D.1)* of the kinetic system must identify a *challenge (D.2)* arising from the building environment that requires interaction with movable architectural elements.

In such scenarios the identification of a challenge follows a process similar to selecting a single graphic from a multitude displayed on a multi-coordinate system, the X-axis represents a time period, while the Y1, Y2, Y3 axes denote the activity of a phenomenon measured in units inherent to it. Within this framework, a phenomenon may find characterization with numerous parameters; for example, sunlight may be defined by the solar constant, colour temperature, sunshine duration, solar altitude, and radians (Figure 46.1).

However, the application of the kinetic system aims to bring about a shift in the trajectory of the function describing the activity of such a phenomenon. This transformation in the environmental phenomenon's activity represents a *function (D-3)* that kinetic architectural systems aspire to accomplish. (Figure 46.2) If the kinetic system aims to achieve multifunctionality, it can be depicted as a series of shifts occurring within a set of grafs of functions. The aspect of multipurposeness will be further examined in subsequent sections.



46.1



46.2

FIGURE 46

The graphs depicting the activity of the Environmental Phenomena considered by the Kinetic Architectural System and selected by the Designer (Figure 46.1) alongside the predicted changes, which can be defined as a Function (3) of the Kinetic Architectural System (Figure 46.2)

Applying a similar approach as seen in functional graphs, the impact of a *kinetic component's purpose (D.3)* on *input, motion, and output* categories can be meticulously described. However, the motion's occurrence entails more components than merely determining the considered environmental phenomenon impacting the kinetic component *(Challenge (D-2))* and the projected effect resulting from enabling the motion of that mechanism *(Function (D-3))*. Primarily, the kinetic architectural system must establish *parameters defining the range within which it can respond to the considered environmental phenomenon.* For instance, within the context of a kinetic facade regulating the indoor microclimate, when the indoor temperature surpasses the optimal range for human comfort, the adaptive building skin initiates the ventilation mechanism. In this scenario, the boundaries of comfortable temperature conditions function as the *limits (D.4)* for the kinetic envelope, prompting the initiation of the kinetic response. Hence, these *limits (D.4)* delineate the parameters of the considered natural phenomenon that enable the initiation and completion of motion of the kinetic system. (Figure 47) In other words, the limits of the activity of the controlled environmental phenomenon influence the *input (In)* of the kinetic mechanism, guiding its transition, and on the *output (Out)*, determining when the motion of the architectural component should cease. Thisы resolves the challenge of translating the parameters of the considered environmental phenomenon into the realm of the kinetic system, as it now possesses markers within which it must operate.

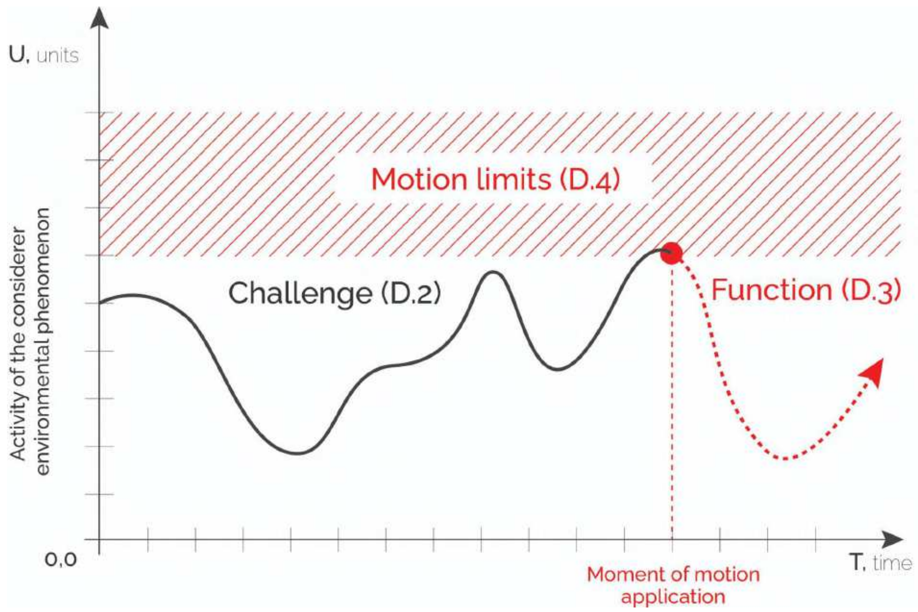


FIGURE 47

Limits of the Kinetic Architectural Systems, depicted on the function graph illustrating the activity of the considered environmental phenomenon.

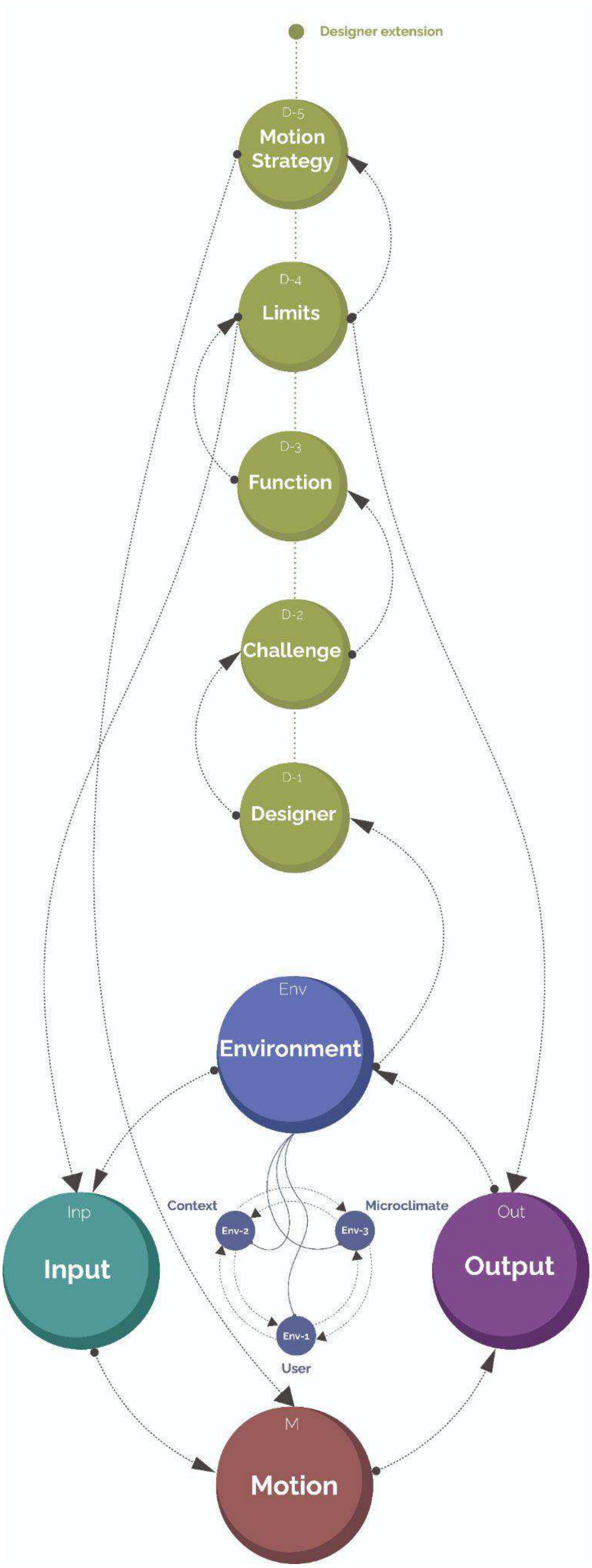


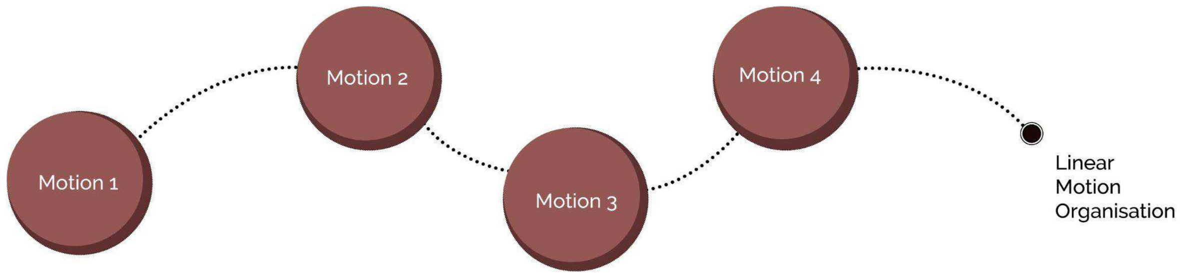
FIGURE 48

The Kinetic Chronological Model with the added designers' branch

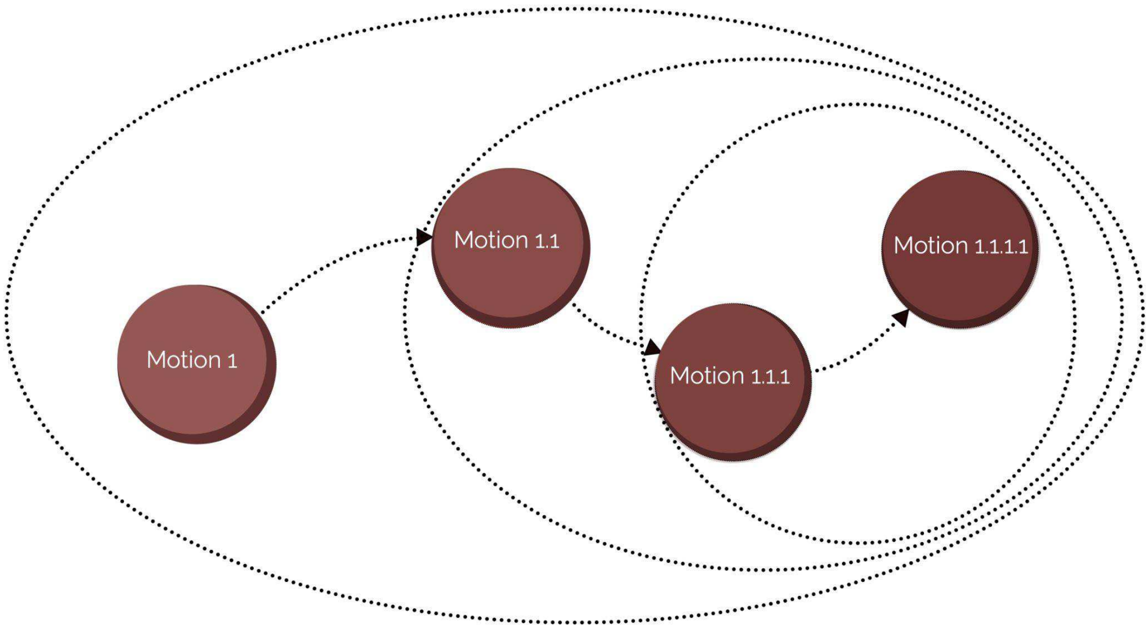
3.4.3 MOTION STRATEGY OF KINETIC CHRONOLOGICAL MODEL

However, while limits establish boundaries, they do not define the characteristics and organization of architectural motion itself. Therefore, a set of criteria directly linked to implementing motion principles into materials, as discussed in sections 1.6.1 and 1.6.2 and reflected in Table 1, can be consolidated into a category termed *'motion strategy' (D.5).* Applying the hierarchical principle inherent in biomimicry, this approach can be extended to *motion organisation (D.5.1)* of the Kinetic Architectural Systems, resulting in further classification based on the internal arrangement of kinetic components. This categorization allows for the definition of *linear systems (D.5.1.1),* where architectural movable elements are equal and non-overlapping, and *multi-level systems (D.5.1.2)*, where kinetic components are interdependent and divided on separated levels. Nevertheless, the movable component has the capacity to assimilate characteristics from both types, amalgamating into a new category termed as *complex systems (D.5.1.3)*. While *liniear systems (D.5.1.1)* align with a horizontal arrangement, *multi-level (D.5.1.2)* organization signifies an evolution into depth, spanning several levels, *complex systems (D.5.1.3)* encompass attributes from both dimensions. (Figure 49) Furthermore, it's viable to identify components where motion solely applies to a singular structural element; yet, this can be considered a specialized form of linear structure.

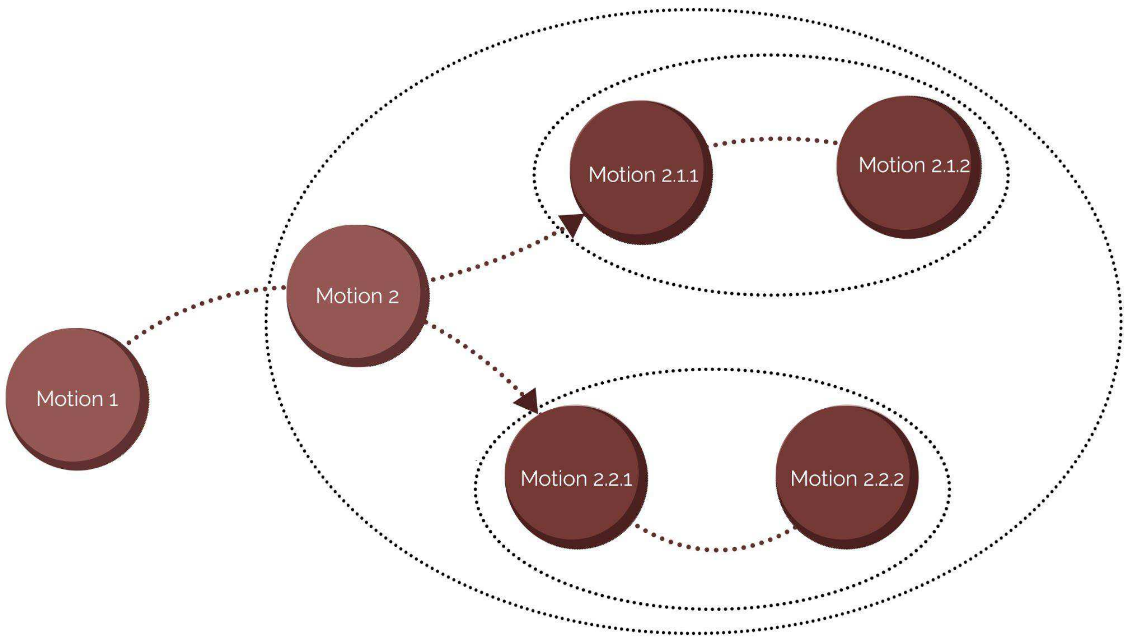
Other equally significant criteria for kinetic components can be explored in the works of Michael Fox [30], which delve into the *ways (D.5.2)* and *means (D.5.3)* necessary for the performance of kinetic architecture. The initial criteria depict the physical transformation within a kinetic element, whereas the final one pertains to the engineering elements facilitating motion transmission. Nevertheless, delving deeper into these criteria encounters a succession of challenges, which will be expounded upon in subsequent sections.



49.1



49.2



49.3

FIGURE 49

The classification of Kinetic Architectural Systems based on the organization of motion: linear (D-5.1.1), multi-level (D-5.1.2), and complex systems (D-5.1.3).

In the classification of *spatial motion (D.5.2.1)*, the primary focus should be on recognizing that motion is a relative process. Consequently, it is essential to establish the principle that in its classification, motion must be considered within the context of changes occurring in the new form of the kinetic component respectfully to its initial state. As each motion can be characterized by a motion vector, architectural motion can be analyzed in terms of the axis that directs the transmition. In the classification of deployable structures proposed by Carolina Stevenson (2017), the typology of movable systems is based on the *direction of transition* and the *spatial organisation* of movable elements. Stevenson introduces the primary division of architectural motion based on the number of utilized planes during the transmission: 2D and 3D. The subsequent level of classification involves dividing deployable structures based on the directions through which transmission occurs.

An intriguing aspect of this classification is its adaptability, allowing motions to exhibit traits that blend seamlessly with neighboring criteria, resulting in the absence of rigid boundaries between the identified categories. As a consequence, all motion types are sequenced in the 3D-2D-3D order. The simplest structures, operating within two planes using pivotal motion, find themselves centrally placed in this arrangement. Meanwhile, the most complex systems in terms of motion organization are placed at the edges of this classification. Consequently, motion types follow an order: *spherical (D-5.2.1D-1), circular tangential (D-5.2.1D-2), radial movement (D--5.2.1D-3) , pivoting (D-5.2.1D-4), monoaxial (D-5.2.1D-5), biaxial (D-5.2.1D-6), and multiaxial (D-5.2.1D-7) movements.* This classification constructs a narrative of architectural motion, commencing with self-directed vectors confined within circular trajectories, which then evolve into linear mono-vector variations, progressively acquiring and developing additional axes. Moreover, this categorization, rooted in the distinct features of deployment directions, extends its implications into the delineation between three and two-dimensional classifications. Thus, *spatial motion (D.5.2.1)* can be classified based on the *direction of transformation (5.2.1D)* into six indicated types *(D.5.2.1D-1 - D.5.2.1D-6)* (Figure 50).

Furthermore, Carolina Stevenson employs the parameter *of physical transformation (D.5.2.1T)* to describe the conversion of deployable structures within a space. This commences by modifying the structure's form, primarily found in constructions utilizing flexible materials, advances towards adjusting the size of the deployable element, and concludes with repositioning, predominantly involving rigid systems. Continuing the same approach applied in the *transformational directions (D.5.2.1D)* classification, the author devised a new gradient for the motion parameter of *physical transformation (D.5.2.1T)* that blurs the boundaries between distinct categories, *encompassing deform (D.5.2.1T-2), fold (D.5.2.1T-3), deploy (D.5.2.1T-4), retract (D.5.2.1T-5), slide (D.5.2.1T-6), and revolve (D.5.2.1T-7).* Nevertheless, this classification system was originally devised exclusively for deployable structures. In the realm of kinetic architecture, a domain that encompasses a wider array of movements, there arises the necessity to incorporate supplementary classifications like *assembling (D.5.2.1T-1)*. This category embodies the intricate evolution of form, frequently culminating in the total collapse of the structure. Furthermore, there exists the facet of *transmission (D.5.2.1T-8),* symbolizing the definitive relocation or reorientation of the kinetic structure. Thus, *spatial motion (D.5.2.1)* can be classified based on the *physical transformation (D.5.2.1T)* into six indicated types *(D.5.2.1T-1 - 5.2.1T-8)* (Figure 50).

Furthermore, the proposed classification delineating architectural *spatial motion (D.5.2.1)*, grounded in its *transformational directions (D.5.2.1D)* and *physical transformation (D.5.2.1T),* remains open-ended, allowing for continual adjustments as engineering progresses, introducing a plethora of new materials and kinetic systems. As observed in the classification of deployable structures, varied methodologies can be employed to systematize architectural motion. The proposed classification primarily accentuates the intrinsic nature of motion itself, refraining from encompassing the nuanced characteristics of the mechanisms employed in transmission, delineating it as a distinct category.

As previously acknowledged, the domain of *non-spatial motion (D-5.2.2)* encompasses a wide range of changes that occur within systems without the involvement of physical displacement or movement in physical space in mirco levele relationally to the human scale. Theoretical discourse, by and large, tends to omit comprehensive analysis of this category of kinetic structures, often prioritizing examination of *spatial motion (D-5.2.1).* Consequently, a more detailed classification becomes imperative. One fundamental criterion for classification involves the nature of anticipated physical changes within kinetic systems. Frank Popper (1968), in his study of kinetic art, highlights various manifestations of non-spatial kinetic art: *shifts in color, alterations in luminosity, variations in texture, and changes in transparency [38]*. Here, the focus predominantly resides on the resultant effects of motion rather than the intricate process itself.

Thus, the classification should primarily center on the nature of the process that facilitates changes within the kinetic system. The decision can be derived from the *nature of the process* occurring within the component: all changes may exhibit *a physical nature (D-5.2.2.1),* not altering the chemical composition of the structural material, or a *chemical nature (D-5.2.2.2),* resulting in the formation of new substances with distinct chemical properties. The lack of comprehensive theoretical literature on non-spatial motions contributes to the inadequacy of such a classification, leaving ample room for further research and classification in this field.

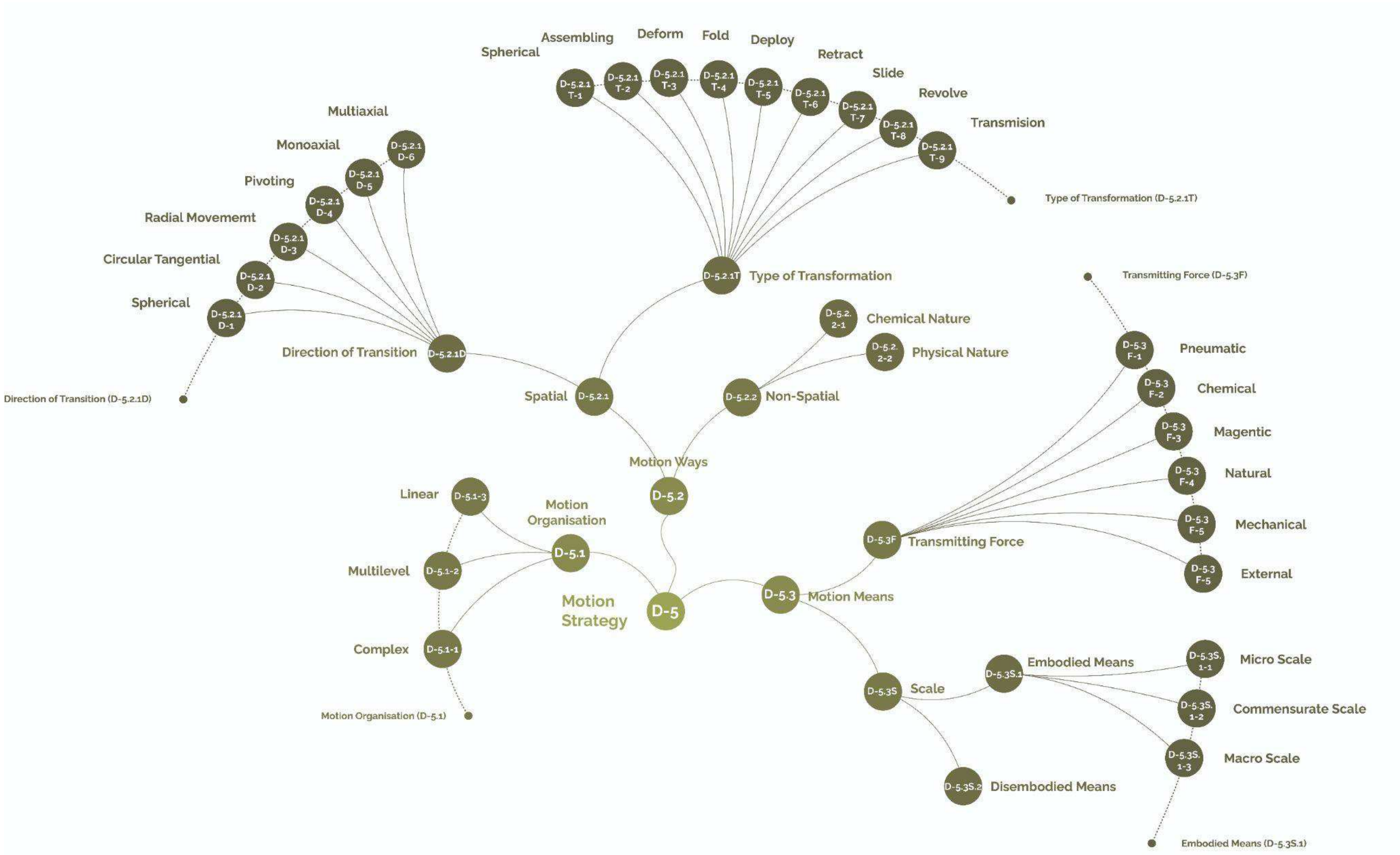


FIGURE 50: Deep Classification of Motion Strategy (D-5) within the Kinetic Chronological Model

To further elaborate on the architectural motion categories previously referenced—*organization (D.5.1)* and *ways (D.5.2)*—for the facilitation of kinetic system movement, it becomes crucial to integrate engineering components that directly enable transitions. These components, falling under the category labeled *'means (D.5.3),'* align with Fox's Kinetic Advanced Architectural Systems. [52] In the case of the *means (D.5.3)* the theoretical literature offers an extensive array of classification options, primarily drawn from the domain of deployable structures. Initially, Fox classified all means based on the characteristics of *force transmitting (D-5.3.F)* the motion: *pneumatic (D-5.3.F-1), chemical (D-5.3.F-2), magnetic (D-5.3.F-3), natural (D-5.3.F-4), mechanical (D-5.3.F-5). [8]*. Nevertheless, this categorization was initially tailored for the autonomous transmission of motion within integrated kinetic advanced systems in buildings. However, its application becomes limited in the context of portable or demountable structures where the need for external force is generally prevalent. Thus, the inclusion of the *external (D-5.3.F1-6)* classification within the building schema becomes essential to encompass structures reliant on external force for motion transmission. (Figure 51)

In addition, the categorization of *motion means (D-5.3S)* can be contingent upon their scale concerning the considered architectural structures. Principally, those domains where architectural kinetics are orchestrated by external instruments, exemplified by structures with dynamic positional alterations, merit distinctive classification. Such instances fall under the category of *disembodied means (D-5.3S.2)*, distinguishing from the remainder. Conversely, other instances find alignment in a separate class as *embodied means (D-5.3S.1),* seamlessly integrated directly into the structure hosting the kinetic mechanism. As the foundational point in this classification, the building hosting kinetic structure was considered. Subsequently, the mobile embodied *motion means (D-5.3S1)* may be devided on *micro scale (D-5.3S1-1),* wherein the kinetic element assumes the role of a structural constituent within the building. It is equally applicable at a *commensurate scale (D-5.3S1-2)*, signifying an autonomus structure that either occupies a substantial portion of the hosting building or embodies the building itself. Furthermore, at the *macro scale (D-5.3S1-3),* a scarcely observed circumstance, theoretically examined by Sterk in the responsive network diagram, portrays a scenario where a singular building functions exclusively as a constituent within a globally coordinated architectural response taking place within the cluster [41]

In this manner, the *motion strategy (D-5)* encompasses various categories, including *motion organization (D-5.1)*, which determines how movable elements are organized within a kinetic system; *motion ways (D-5.2),* defining the method by which motion can be performed; and *motion means (D-5.3),* through which *architectural motion (M)* occurs. Thus, by determining the three criteria, which stem from the motion limits of the considered environmental phenomenon, the *designer (D-1)* may indirectly influence *architectural motion (M).* Within the Kinetic Chronological Model, the *Design branch (D)* plays the role of the conceptual dimension, projecting the actual environment of the kinetic system, reimagining it, and adapting the kinetic system for interaction with its *surroundings (E).*

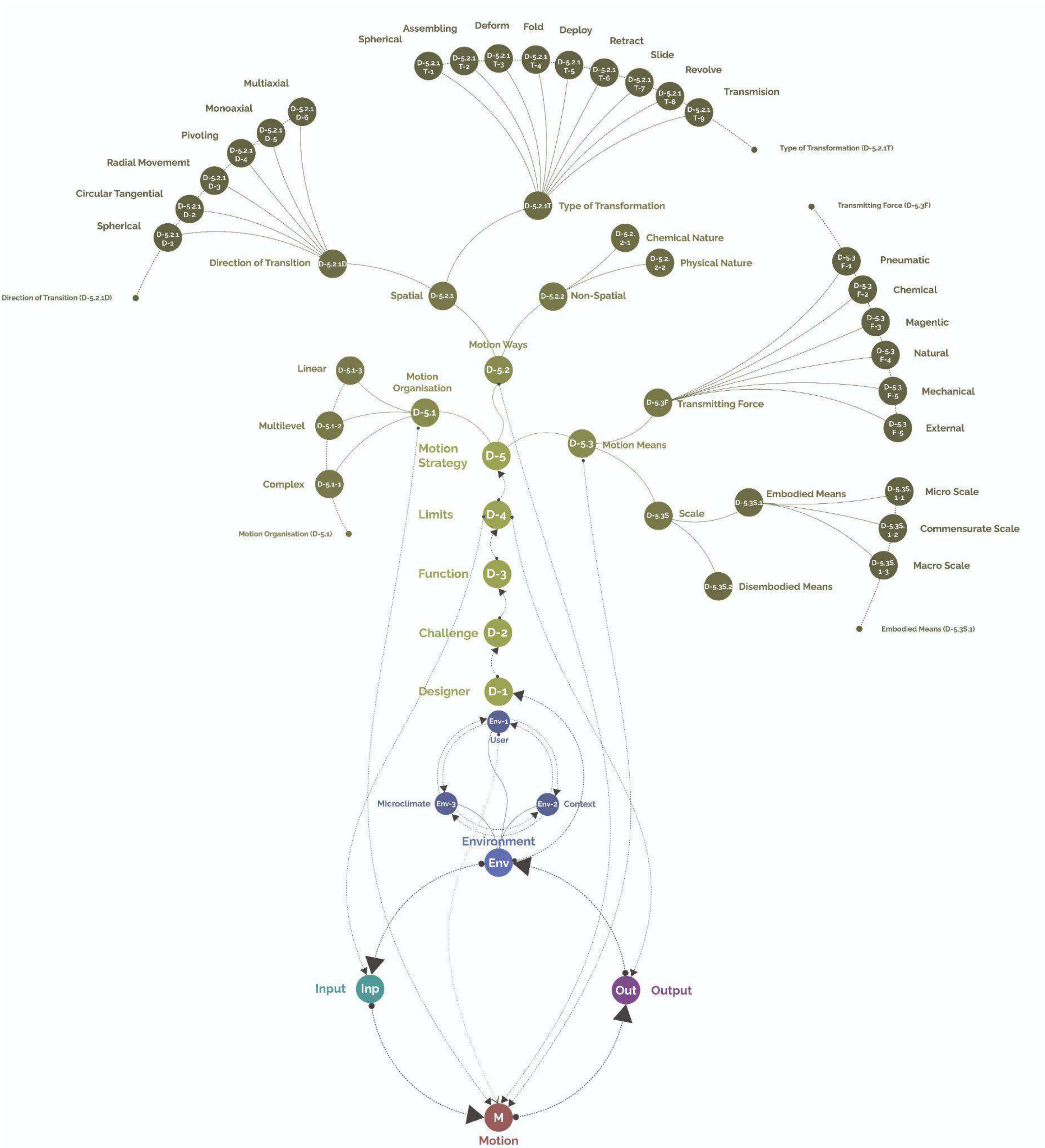


FIGURE 51:

The Kinetic Chronological Model with Completed Designer Branch and Motion Strategy Classification

3.4.4 INTPUT OF THE KINETIC CHRONOLOGICAL MODEL

In the framework of the Kinetic Chronological Model, the *input (In)* assumes a pivotal role as a propelling force for the kinetic system, delineated by the limits of the considered *environmental phenomenon (D-4)* and the ongoing processes within the *environment (E)* of the structure housing the kinetic system. As elucidated in section 3.4.2, the fundamental role ascribed to input (In) within the Kinetic Chronological Model is exclusively confined to the facilitation of motion. In this capacity, it assumes the characteristics of an actuator, responsive to external stimuli and exerting force to instigate alterations in the kinetic architectural system. The classification of input primarily hinges on the character of the force employed to initiat alterations in the Kinetic System, specifically in terms of *adaptability (In-Ad)* to external stimuli. In adopting such an approach, the gradations of adaptation, articulated by Lelieveld, Voorbij, Poelman (2007), can be utilized for the categorization of actuators [33]. However, the challenge of extending the specified categories to a more detailed level of *input criteria (In)* within the Kinetic Chronological Model arises due to the blending of input and output in the classification proposed by the authors.

Thus, the first category, *'flexible' (In-Ad-1)* is determined as an *'action is in direct control of the user, which means that the component doesn't have the ability to change itself. The components of the building are changeable, with an external force'.* Within the parameters of the input criteria, it has the potential to encompass *input (In)* systems that exclusively enable motion through manual user control, thereby rendering the input manually manageable. As an instance of such kinetic systems, sliding shutters can be aligned with this particular category.

The second suggested class *'flexible' (In-Ad-2)* is defined as *'active building component will give a set reaction to a specific change; the action must be undertaken by the user or environment'.* In this manner, it functions as the most straightforward category and can be applied to input that cannot measure the activity of the considered environmental phenomenon, solely possessing two static regimes, one of which initiates motion. As anticipated, the output of such a system may be constrained to just one type of response.

The third type, *'dynamic' (In-Ad-3)* is determinated as '*architecture can give different output on a certain input. The action-reaction relation is not a closed relation. More possibilities and settings are possible within one system. These possibilities are bordered and set in advanced'.* In this manner, dynamic input entails actuators utilizing computer technologies; however, the connection between specific activities of the considered environmental phenomena and the type of motion is pre-programmed.

The fourth kind of adaptability, *'interactive' (In-Ad-4)* according to the authors, is characterised by *'ability to have a two-way conversation with the users and/or its environment. A dialogue is set up between the user and the system. An integrated system is needed for interactive relations'.* When applied to the Input category, this class needs to include actuators comprised of computers capable of establishing feedback with the user or environmental phenomenon through the utilization of sensors. Thereby *'the behaviour and reactions are set by the programmer'.*

The fifth group, *intelligent (In-Ad-5)*, is described in the work as *'not only if it accepts natural language input rather than just specific commands, but also if it allows the user to take initiative. If the system adapt itself to the users' interests and interaction preferences and works cooperatively with the user to accomplish specific goals with the use of additional sources of knowledge to meet the needs of the user'.* Thus, intelligent input refers to computer-manageable actuators characterized by the ability to operate with data originating from the environment and the capacity to adapt the work method to the to users' experiences.

The last, the sixth criteria, named *smart (In-Ad-6)* is determinated with *'ability of self-initiative. The smart system is completely integrated in the life and behavior of the users and environment. The system is self-learning'.* When extrapolated into the input adaptation criteria classification, it encompasses the input system integrated with building intelligence, thereby forming an integrated system with the capacity for self-learning based on the obtained data from the input and output experiences of the Kinetic System.

In this way, the proposed categorization of input systems encompasses a myriad of actuator types, enabling them based on their varying levels of *adaptability (In-Ad)* to the changes within the considered environmental phenomenon. This facilitates the organization of a diverse array of structures, spanning from uncomplicated ones managed through manual control to intricate kinetic systems endowed with the ability to engage in self-learning processes.

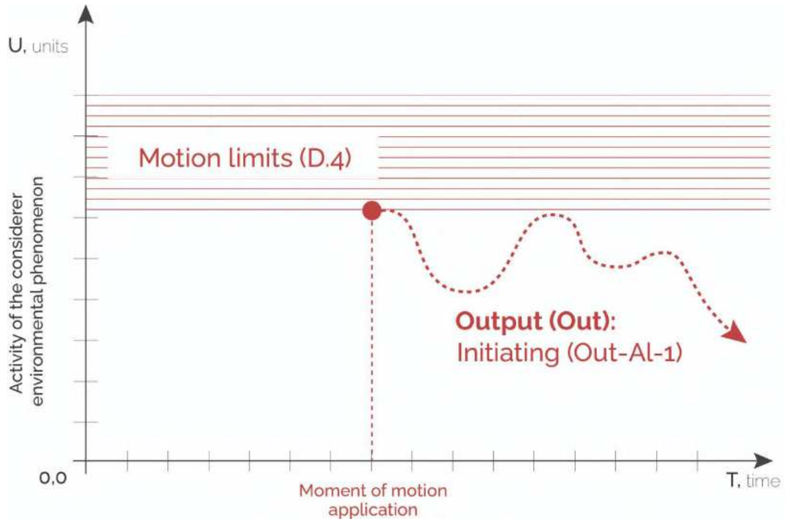
3.4.5 OUTPUT OF THE KINETIC CHRONOLOGICAL MODEL

While the Kinetic System's *Input (In)* predominantly manifests as force, the *Output (Out)* navigates into a less materialistic category known as changeability, occurring within the activity of the considered environmental phenomenon. These transformations can be depicted as a change in the functional path of the activity, occurring after the initiation of architectural motion, absolutely similar to the *Function (D-3)* demonstrated in Figure 46.2. The key distinction lies in the fact that while Function (D-3) is associated with projection alterations, the *Output (Out)* directly reflects changes occurring in real life, which, in most cases, differs from the predicted results (Figure 52)

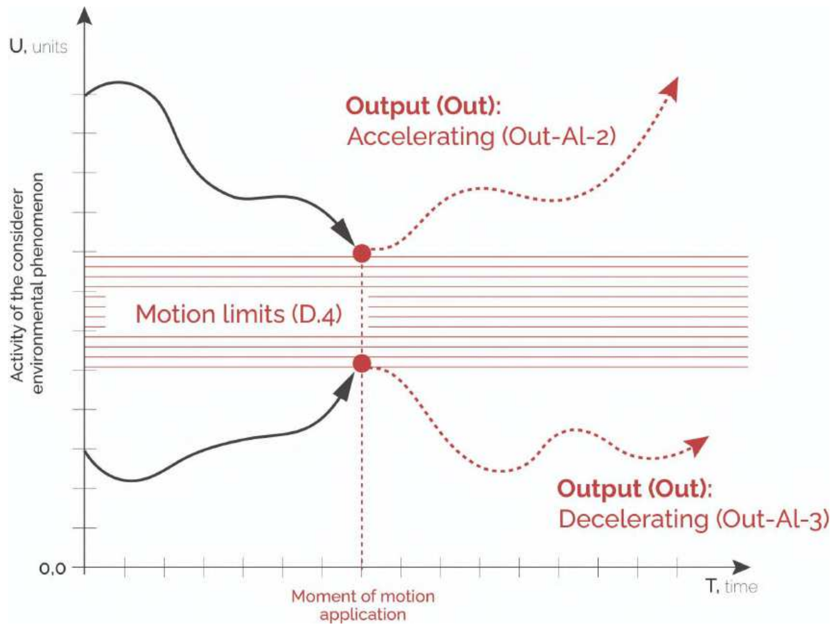
Henceforth, the predominant *Output (Out)* criteria within the Kinetic Chronological Model can be subjected to additional classification grounded in the nature of activity alterations (Out-Al) transpiring within the parameters of the contemplated environmental phenomenon. Continuing the graph-based approach, the sequence of transformations unfolds as follows: *Initiation (Out-Al-1)*, wherein architectural motion (M) causes the commencement of activity in the considered environmental phenomenon; *Acceleration (Out-Al-2),* where the kinetic system's motion propels the amplification of the activity in the environmental phenomenon; *Deceleration (Out-Al-3),* marked by the gradual slowing effect on the impacted process; and *Termination (Out-Al-3),* wielding the capacity to bring the activity of the environmental phenomenon to a complete standstill (Figure 36.1-36.3).

FIGURE 52

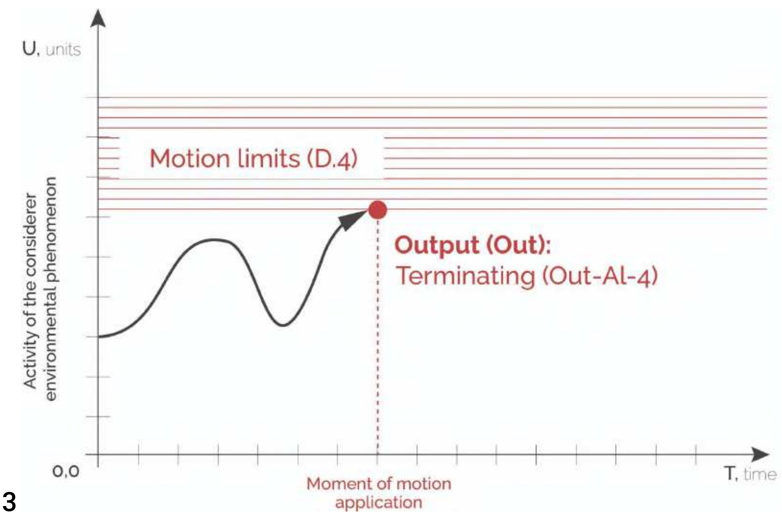
Comparison of predictable changes occurring in the activity of the considered environmental phenomenon reflected in the category Function (D-3) and real transformations depicted through the category Output (Out)



53.1



53.2



53.3

FIGURE 53.1-53.3

The classification of Kinetic System output is based on the nature of activity alterations in the considered environmental phenomenon: Initiating (Out-Al-1) - Figure 53.1, Accelerating (Out-Al-2) and Decelerating (Out-Al-3) - Figure 53.2, and Terminating (Out-Al-4) - Figure 53.3.

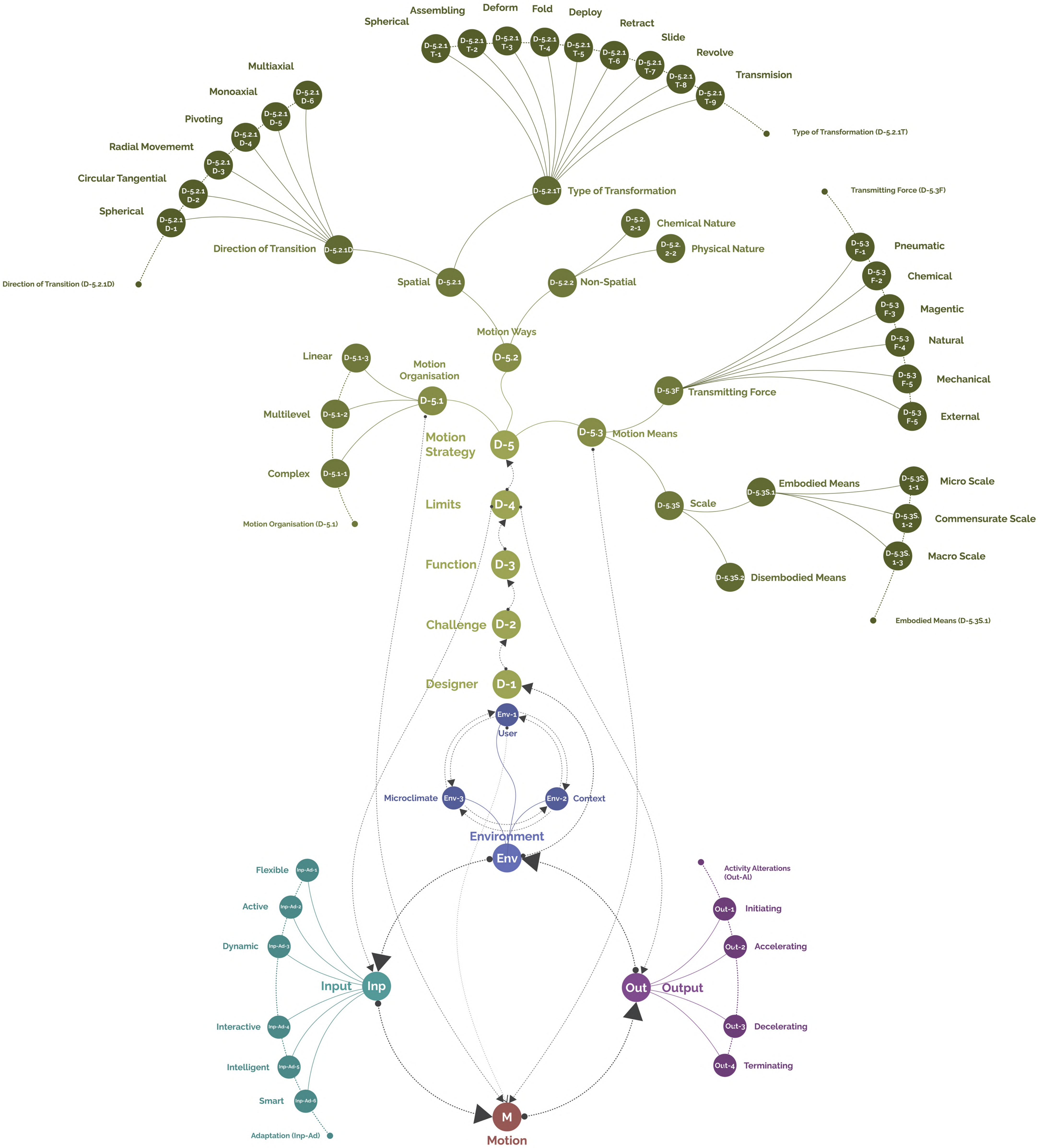


FIGURE 54
Completed Kinetic Chronological Model of the 2nd level

3.4.6 MATRIX OF CRITERIA OF KINETIC-CHRONOLOGICAL MODEL WITH THEIR DEFINITION

Criterias of Kinetic Chronological Model						**Line index**	**Definition**
Criterias of the 1st level	Criterias of the 2nd level	Criterias of the 3d level	Criterias of the 4th level	Criterias of the 5th level	Criterias of the 6th level		
Input						In	The force considered by a kinetic architectural system to initiate the architectural motion process.
	Adaptatiion					In-Ad	The classification criteria for Kinetic System input emphasize the categorization of actuator systems based on their level of adaptability to changing parameters of the considered environmental phenomena.
		Flexible				In-Ad-1	The input adaptation class is directly manageable and set into motion through manual control by the user.
		Active				In-Ad-2	The input adaptation class responding directly to the specific changes or actions undertaken by the considered environmental phenomenon and is characterized solely by two static regimes. One of these regimes facilitates motion of the Kinetic System, while the second one maintains it in static conditions.
		Dynamic				In-Ad-3	The input adaptation class, utilizing computer technologies, offers a wide variety of settings; however, it is limited in its variability, as all motions for predicted changes in the activity of the considered environmental phenomenon are projected and programmed beforehand.
		Interactive				In-Ad-4	The input adaptation class encompasses computer-based actuators that enable interaction with the user and/or the environment through sensor systems. However, the response to requests is limited to pre-programmed variations.
		Intelligent				In-Ad-5	The input adaptation class pertaining to actuators managed by computers, distinguished by their capability to interact with data stemming from the environment and the adaptability to adapt the response to users' experiences.
		Smart				In-Ad-6	The input adaptation class, integrated with building artificial intelligence, is capable of self-learning, self-regulation, and further development based on the received data from the input, output, and monitoring of activity changes of the considered environmental phenomenon.

Motion						M	The alteration taking place within the kinetic architectural system in response to external stimuli is intended or planned to occur within that system.
Output						Out	The dynamic changing effect in the activity of the environmental phenomenon streaming directly from the ensuing architectural motion and exerting an influence on the Kinetic System environment.
	Activity Alterations					Out-Al	The alterations within the activity parameters of the considered environmental phenomenon are established in units of measure per unit of time and occur after the initiation of architectural motion.
		Initiating				Out-Al-1	The category of output alterations, architectural motion acts as the instigator, igniting the initiation of activity in the considered environmental phenomenon.
		Accelerating				Out-Al-2	The output alteration class, where architectural motion results in the diffusion of activity within the considered environmental phenomenon.
		Decelerating				Out-Al-3	The output alteration category, where architectural motion induces a deceleration in the activity of the considered environmental phenomenon.
		Terminating				Out-Al-4	The output alteration class, where architectural motion brings about the suspension of activity in the considered environmental phenomenon.
Envionment						Env	The conceptualised ensemble of objects interconnected exclusively by their ability to interact with a kinetic architecture system, meaning influence the kinetic system or be influenced by it. The primary role of the environment is as a source of the considered environmental phenomenon, which the kinetic system is projected to take into account.
	User					Env-1	The individual having the ability to impact the kinetic system or be influenced by it, possessing subjectivity and the capacity for direct involvement in the movable architectural mechanisms.
	Context					Env-2	The conceptualized group of objects located outside the Kinetic System, capable of encompassing the considered environmental phenomenon, or objects and related processes that impact the phenomenon or are influenced by it. In the last case participation occurs indirectly within the Kinetic Cycle.
	Microclimate					Env-3	The internal state of the structure accommodating the Kinetic System, delineating the features of the inner milieu and the constituent elements of structural systems.
Design						D	The process of the Kinetic System development, aiming to determinate its fundamental characteristics of the

Designer					D-1	The individual or individuals tasked with designing a kinetic system, defining its key characteristics, and aiming to establish interactions between the Environment and the Kinetic System.
Challenge					D-2	The phenomenon or process, determinated with a designer, occurring in the environment of the Kinetic System enables its reaction and is projected to be considered by this system.
Function					D-3	The predicted changes that may occur within the activity of the considered environmental phenomenon after the application of an architectural motion.
Limits					D-4	The numerical range of units of activity of the considered environmental phenomenon, within which the kinetic system initiates architectural motion.
Motion Strategy					D-5	The group of the projected traits that define the fundamental features of the Kinetic System though which architectural motion finds its performance.
	Motion Organisation				D-5.1	The categoty of the motion strategy, dictating the internal hierarchy of motion elelmts within the system.
		Linear			D-5.1-1	The category of motion organization, distinguished by the horizontal hierarchy of movable architectural elements, where all elements are placed in the one order levele and structurally independent.
		Multilevel			D-5.1-2	The classification of motion organisation, marked by a vertical hierarchy and a multilevel organization of structurally integrated movable elements. Meanwhile, each level exclusively houses a singular component engaged in motion.
		Complex			D-5.1-3	The classification of motion organisation, characterized by a hierarchy extending into depth and width, encompassing both structurally autonomous and integrated movable elements. This amalgamation integrates features from both linear and multilevel organizational types.
	Motion Ways				D-5.2	The categoty of the motion strategy, elucidating the spatial trajectory of its transformative processes.
		Spatial			D-5.2.1	The class of motion way, involving transformations in the structure of the Kinetic System taking place within the context of the human scale, thereby leaving the transformation process visible for the human observation.
			Direction of Transition		D-5.2.1D	The class of the spatial transformation, specifying the spatial vector of the occurring alteration within the Kinetic System.

		Spherical	D-5.2.1D-1	The direccrion transition class, involves a three-dimensional movement pattern reminiscent of a sphere, granting the Kinetic System the freedom to rotate in any conceivable direction.
		Circular tangential	D-5.2.1D-2	The direccrion transition class, characterised by movement along the circumference of a circle, maintaining a tangent relationship with the circle's curvature.
		Radial movement	D-5.2.1D-3	The direction transition class, pertaining to motion of elements extending outward or inward from a central point
		Pivoting	D-5.2.1D-4	The direccrion transition class, involves rotation of the structural elelemrs around a fixed point or axis.
		Monoaxial	D-5.2.1D-5	The direccrion transition class, denoting movement of components of Kinetic system along a single axis.
		Biaxial	D-5.2.1D-6	The direccrion transition class, involving the movement of structural elements within the Kinetic System along two distinct axes.
		Multiaxial	D-5.2.1D-7	The direccrion transition class, encompassing the movement of structural elements along multiple axes, allowing for versatile and simultaneous directional changes.
	Type of Transformation		D-5.2.1T	The class of the spatial transformation, delineating the physical alteration in both form and material of the Kinetic System as architectural motion unfolds.
		Assembling	D-5.2.1T-1	The category of transformation type involving systems capable of structural assimilation, leading to the temporary collapse of the shape with the potential for repeating this process.
		Deform	D-5.2.1T-2	The classification of transformation type encompassing structures that change their form in an unrestrained manner and have the ability to be reassembled into their original configuration.
		Fold	D-5.2.1T-3	The class of the transformation type, characterized by structures made of flexible materials that can wrinkle or crease coming into contact with themselves.
		Deploy	D-5.2.1T-4	The class of the transformation type, comprised of mechanisms constituted with rigid elements connected by pivoting joints that can be compacted back to their original undeployable condition.
		Retract	D-5.2.1T-5	The class of the transformation type, including systems consisting of planar rigid elements that can be pulled back or folded in, stacking one on top of the other.

			Slide	D-5.2.1T-6	The class of the transformation type, including structures that move entirely from side to side in continuous contact with a surface.
			Revolve	D-5.2.1T-7	The class of the transformation type, embracing systems whose structural elements can rotate or orbit around the axis.
			Transmisison	D-5.2.1T-8	The category of transformation type is characterized by systems with a variable location without compromising their structural integrity. Consequently, during this type of transformation, all points of the Kinetic Structure remain stable within the inner system, while the structure itself changes its position.
	Non-Spatial			D-5.2.2	The class of motion way, ecompassing alterations in the Kinetic System that occur within a micro-scale context in relation to the human scale. Consequently, an observer may exclusively engage with the outcomes of the undergone transformation.
		Physical Nature		D-5.2.2.1	The category of non-spatial transformations occurring on the micro scale, specifically associated with changes in form without alterations in material properties.
		Chemical Nature		D-5.2.2.2	The category of non-spatial transformations occurring on the micro scale, intricately connected to changes in the material properties of the structure, potentially entailing the engagement of physical transformations.
Motion means				D-5.3	The category of the motion strategy, involving the engineering elements that constitute the Kinetic System and facilitate the architectural motion.
	Transmitting force			D-5.3F	The class of the motion means, comprising their categorization based on the nature of force, facilitating the transmission of movable elements.
		Pneumatic		D-5.3F-1	The class of the transmission force of motion means, pertaining to the use of compressed air or gas to initiate and control motion, reling on the pressure and flow of air or gas to achieve mechanical effects.
		Chemical		D-5.3F-2	The class of the transmission force of motion means, Involving the utilization of chemical reactions as a means to induce controlled movement of the Kinetic system.
		Magnetic		D-5.3F-3	The class of the transmission force of motion means, Relating to the manipulation of magnetic fields to drive motion in the Kinetic System,s utilizing the principles of magnetism to control and guide movable elements.
		Natural		D-5.3F-4	The class of the transmission force of motion means, characterized by the integration of natural forces—inherent forces present in the system's environment—to induce motion within the Kinetic System.

				Mechanical		D-5.3F-5	The class of the transmission force of motion means, Involving the application of mechanical components such as gears, levers, and other and systems to generate and control motion within the Kinetic System.
				External		D-5.3F-6	The class of the transmission force of motion means, Concerning the incorporation of external sources or influences to initiate and regulate motion within the Kinetic System.
			Scale			D-5.3S	The category of motion means, incorporating their classification based on their spatial dimension relative to the hosting structure.
				Embodied means		D-5.3S.1-1	The category of motion means scale, involving movable elements of Kinetic Systems directly integrated into the structural system of the hosting structure.
					Micro scale	D-5.3S.1-1	The category of embodied motion means characterized by a significantly smaller scale of the Kinetic System relative to the structure hosting it.
					Commensurate Scale	D-5.3S.1-2	The category of embodied motion means, distinguished by a relatively equivalent scale of the Kinetic System concerning the structure that hosts it. Consequently, in such instances, the Kinetic System has the potential to evolve into the structure itself.
					Macro scale	D-5.3S.1-3	The category of embodied motion means identified by a relatively substantial scale of the Kinetic System concerning the structure that accommodates it, thereby integrating the building as a constituent of a significantly larger ensemble.
				Disembodied means		D-5.3S.2	The category of motion means scale, including systems that facilitate the motion of the Kinetic System without being integrated into the structural organization of the hosting building.
Criterias of the 1st level	Criterias of the 2nd level	Criterias of the 3d level	Criterias of the 4th level	Criterias of the 5th level	Criterias of the 6th level	**Line index**	**Definition**
Criterias of Kinetic Chronological Model							

TABLE 2 THE CRITERIAS OF KIETIC CHRONOLICAL MODEL

3.4.7 INTELLIGENT ASPECT WITHIN THE KINETIC CHRONOLOGICAL MODEL

Incorporating *intelligence* into the kinetic system can not only expedite the responsive process but also fundamentally alter response generation, necessitating adjustments in *the kinetic chronological model.* The primary function of the unique computational center is to gather data generated at various stages of the kinetic mechanism's response: first, at the *input stage* by absorbing information about external conditions; next, during *the motion* itself by monitoring the transmission of the kinetic mechanism; and finally, at *the output stage* by controlling the influence of architectural motion on the surrounding environment.

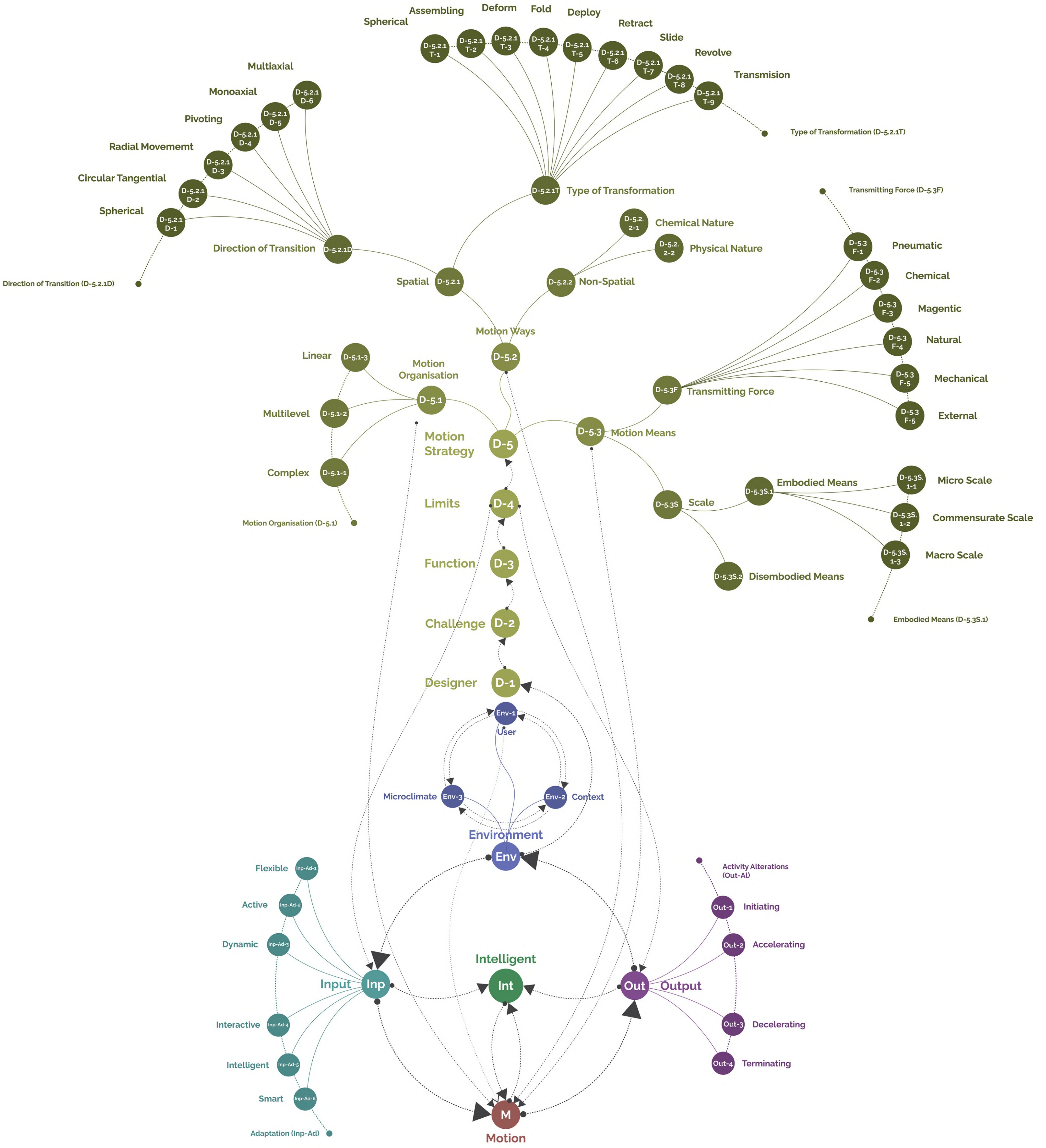


FIGURE 55
Kinetic Chronological Model of the 2nd level with the integrated Intelligent Criteria

3.4.8 LIMITATIONS OF THE KINETIC CHRONOLOGICAL MODEL AND ITS POTENTIAL APPLICATIONS.

Whether the resulting Kinetic Chronological Model enhances the complexity and versatility of Kinetic Architectures is illuminated in a new perspective. Primarily, it highlights that architectural motion is contingent upon the surrounding context, including the potential presence of a user, the concept emanating from the fundamental principles of architecture, which are inherently designed by humans and for humans. This revelation opens a pathway to another crucial criterion often overlooked in contemporary theoretical literature: the role of a designer, a person shaping the foundations of the future Kinetic System, that had been already review in the section 3.4.2 Designer Aspect within Kineitc Chronological Model. The majority of characteristics and principles of the Kinetic System are determined by the designer during its projection phase, encompassing aspects such as motion organization, motion pathways, and motion mechanisms. This enables the creation of a diverse typology of kinetic systems, ranging from simple manually controlled shading, movable walls, or transported temporary structures to complex multifunctional intelligent building envelopes. The reverse side of this feature in the proposed classification is the opportunity it presents to describe and analyze, with a uniform approach, a wide array of kinetic systems characterized by variable features. In this manner, the potential implementation of the Kinetic Chronological Model leads, firstly, to a significant design variability, and secondly, to a varied research classification, both guaranteed by the systematic approach to architectural motion.

Additionally, the chronological principle, according to which all criteria of kinetic architecture are organized, portrays architectural motion as a process—an act unfolding over time. This approach enables the demonstration of causal relationships between the kinetic system and its surroundings, encompassing the context, building, and user through inputs and outputs. Furthermore, the resulting process is not confined solely to a closed cycle; instead, it is characterized by a multilevel hierarchy and by the extensive design extension, defining the fundamental properties of the evolving Kinetic System. These complex systems allow for flexibility in further adjustments and classifications, rendering them open-ended and relevant for the ongoing development of kinetic architecture. In this manner, further modifications can illustrate the pinnacle of kinetic architecture, propelling it to a new level.

Simultaneously, Kinetic Chronological Systems confront limits truces their origin from their basic characteristics. One of the most fundamental constraints arises from the evolving landscape of contemporary technologies and societal demands. As technologies integrate further into kinetic architecture and new social requests emerge, the kinetic model may undergo changes, echoing the narrative of the Intelligent Building Pyramid, which doubled in size over a five-year period. Future transformations may impact the model at a deep classification level, such as expanding motion means influenced by new smart materials. Additionally, the model may experience changes in the number of fundamental criteria, as seen in the case of the intelligence aspect, necessitating the incorporation of a new temporary element into the closed kinetic cycle of the first level. In both cases, the complex model will require further detailing, resulting in an increased number of criteria.

The second limitation arises from the generalization of the environment aspect, which categorizes objects broadly, primarily shifting focus to architectural motion itself. Even though the division of the environment into three criteria—user, context, and surroundings—captures a portion of the complexity, it overlooks the broader spectrum of social-cultural, natural, and other global processes that can influence the kinetic system. Consequently, the Kinetic Chronological Model neglects sustainability requirements, impacting the incorporation of a significant portion of kinetic systems. In this way, the Kinetic Chronological Model is generally limited in reflecting and clarifying the processes occurring within the environment of the hosting building. A more detailed and extensive exploration of the environment aspect will necessitate further in-depth research into the objectivity of social, cultural, environmental, economic, technological, and other fields.

However, the broad discourse on sustainability was not completely ignored within the model. The biomimetic approach to architecture, in particular, considered sustainability implementation primarily through the multifunctionality of the Kinetic System, achievable via the multifunctionality and hierarchy.

At the same time, the third limitation of the resulting model aligns with the sustainability discourse and is related to proofing the technological complexity in pursuit of achieving precise results. As evident from the proposed classifications of input or motion means based on the utilized technological level or intelligence implementation, the general characterization of the kinetic system involves the complexity of the utilized technologies. This complexity may lead to increased costs in design, construction, maintenance, repair, and utilization of the Kinetic System, which may not always result in a rational allocation of resources. For each considered environmental phenomenon and kinetic system, the interdependence between technological complexity and cost efficiency can be depicted through a functional graph, where the X-axis represents the amount of costs and the Y-axis represents efficiency (Figure 51). Initially, with the increase in kinetic system efficiency, the impact on the considered environmental phenomenon will grow. However, there is a point where the graph of the environmental phenomenon will plateau, overlapped by the growing line of the kinetic system performance. Beyond this point, further technological complexity does not lead to cost efficiency. In this way, the Kinetic Chronological Model cannot conclusively demonstrate the rationality of technological advancements in designed Kinetic Systems and this choice would be calculated separately. Therefore, the model is limited in suggesting technological implementations for specific cases, and its predictive function is restricted.

FIGURE 56
Dependence between technological complexity of the designed Kinetic System and cost efficiency

Moreover, the Kinetic Chronological Model can be utilized not only as a tool for researching and systematizing existing kinetic systems, but it may also offer an alternative approach in designing kinetic systems. As a design method, it employs a top-down approach where the problem or challenge of the environmental phenomenon under consideration serves as the starting point, shaping the configuration of the Kinetic System. This stands in contrast to a bottom-up strategy, where the proposed design solution emerges as the primary idea, reversing the roles of the task and the tool, even though the underlying challenge still needs to be addressed.

In contrast to the methodologies delineated in Section 2.3, the Kinetic Chronological Model diverges by eschewing an end pound of the design process exclusively at the phase of kinetic mechanism formulation. Rather, it encourages further exploration into how the configuration of the kinetic system will transform throughout the progression of architectural motion. Hence, it enables a designer to perceive the kinetic system not only as a static object but to encompass its dynamic shape evolution, considering kinetic architecture as a continuous process.

Secondly, the Kinetic Chronological Model emphasizes wide variability, accommodating a broad spectrum of characteristics within the kinetic system that can be adjusted to assess performance. Ideally, the model can be conceptualized as a manageable algorithmic approach, consisting of several sequential stages. It commences with the designer, followed by the determination of basic characteristics that can be regulated and fine-tuned in this stage to achieve optimal performance through the emulation of architectural motion. In this manner, by experimenting with different characteristic combinations, the designer may arrive at the final output embodied in the configuration of the designed Kinetic System. And the systemised criteria framework facilitates a comprehensive analysis of design elements, assisting designers make informed decisions during the planning and conceptualization stages.

Thirdly, the design approach guided by the Kinetic Chronological Model can be characterized by a multidimensional analysis, incorporating all fundamental aspects of kinetic architecture. This design method considers the contextual surroundings impacting the kinetic system and being affected by it as a source for the considered environmental phenomenon. Additionally, it incorporates the human aspect in two roles: as an observer and user of the system and as its designer. This dual perspective allows the depiction of a person as a final stakeholder in any kinetic mechanism. Moreover, the technological aspect is integrated at each stage of the kinetic system's projection, enabling a designer to formulate solutions that determine the basic engineering traits of the Kinetic System. Thus, the Kinetic Chronological Model facilitates a holistic approach to the design process, ensuring a nuanced understanding of the intricate interplay between these diverse elements.

Simultaneously, the next chapter presents a sample of Kinetic System projection guided by the resultant Kinetic Chronological Model to showcase the design potential of such an approach.

CHAPTER 4. FORMING MOTION: ALGORYTHMIC FORMED KINETIC FACADE TO ELEVATE ENERGY PERFOMANCE

4.1 THE DESIGN METHOD BASED ON THE KINETIC CHRONOLOGICAL MODEL

The final chapter of the thesis aims to examine the design potential of the resulting Kinetic Chronological Model drafted in the previous chapter through its transformation into an architectural design method and its implementation into the design of the Kinetic System. The identified criteria of Kinetic Architecture will be utilized for the further conceptualization of the Kinetic System, as it has already been acknowledged as one of the most significant potential contributions of the resulting model to the architectural theoretical framework. Its systematization and organization have mainly analyzed aspects of non-static architecture, consolidating them into a single classification model, which serves as a comprehensive resource for features to be implemented in the design of kinetic architecture. In this way, the classification system describing the architectural motion process must be adopted into the top-down method of design.

The impact of the design phase on the Kinetic System's performance has already been acknowledged in the preceding chapter, given that the traits of the Kinetic System take form in the early stages of the design process. Consequently, the depiction of the kinetic system should strive for optimal coherence, encompassing all potential scenarios the design mechanism might confront during its operation. This approach is more inclined to refrain from introducing an entirely novel method but rather to persist in the same rationale that underpins the conventional top-down approach. The innovation of the proposed design method lies more in its motion simulation, enabling an understanding of the form transformation at all stages of architectural motion. It incorporates further adjustments within the projecting Kinetic System to enhance performance. In this manner, the Kinetic Chronological Model results in a new type of extended top-down method, characterized by a robust controlling mechanism that compels the designing kinetic system to accommodate various requests.

4.1.1 THE PREMIER CONCEPTUALIZATION PHASE

4.1.1.1 IDENTIFICATION OF THE CONSIDERED ENVIRONMENTAL PHENOMENON

The design of the Kinetic System revolves around discerning the environmental phenomena, whose impact on the hosting structure should be within the realm of manageability for the kinetic system. As already acknowledged in section 3.4.1, the environment within the Kinetic Chronological Model is considered as a conceptualized group of objects responsible for generating new requests for a Kinetic System and creating a context within which architectural motion occurs. In this way, the considered environmental phenomenon may have various natures: being a climate process, changes occurring within the building microclimate or the building structure itself, or social requests arising from the need to adjust building functionality.

The principal inquiry arising at this stage pertains to the building's capacity to effectively manage the considered phenomenon while utilizing the rational value of the source. While kinetic architecture holds the potential to resolve numerous issues, the implementation of architectural elements enabling motion demands precise consideration of the required resource. The costs associated with enabling architectural motion, encompassing aspects such as energy, materials, and system complexity, can potentially overshadow the anticipated benefits of integrating the kinetic system. Therefore, the selection of the considered environmental phenomenon signifies the premier conceptualization and modeling, with the aim of analyzing whether the implementation of architectural motion can yield the optimal outcome.

4.1.1.2 PREMIER CONSEPTUALISATION OF THE KINETIC SYSTEM

The initial conceptualization of the drafting of a kinetic system during the testing phase of the considered architectural motion encounters a series of inherent challenges, for instance those encountered in the implementation of biomimetic design [66, 71, 75, 78]. The scarcity of knowledge and practical cases in addressing specific issues may lead to erroneous conclusions regarding the ability to manage precise phenomena with particular types of kinetic structures. In such instances, referencing cases with similar mechanisms responsive to analogous stimuli can help mitigate the risk of error. Thus, the identification of the considered environmental phenomenon coincides with the examination of case studies and the primary exploration of potential types of kinetic mechanisms that could be implemented to manage the manageable environmental phenomenon.

However, a kinetic structure can be designed to interact simultaneously with various environmental phenomena, serving as a multifunctional system. In such cases, the designer encounters additional challenges related to the capacity of the mechanism to address numerous tasks and the issues inherent to the internal organization of the kinetic system, aiming to integrate different kinetic elements into one multi purpose system. As discussed in Section 2.3, this design challenge can be addressed through a multilevel organization, where each level of the system is designed to fulfill a specific function. Furthermore, achieving multifunctionality in the projected system necessitates a more comprehensive level of conceptualization where the designer has to join referented systems into the one functional mechanism.

The primacy of determining the considered environmental phenomenon's impact on the form of the Kinetic System, conversely, the priority of the second category over the first one aligns with the discourse presented in architecture since the beginning of the 20th century: "form follows function," or the alliance of function to shape. In the majority of cases of kinetic architecture application, the movable elements have to broaden the building’s functionality, proving the paradigm proposed by modernist architects. However, in projects where the primary goal is an enrichment of the building's appearance, the considered environmental phenomenon is usually selected specifically to meet the requirements of the architectural form. In this way, both categories, Identification of the environmental phenomenon, and the primary conceptualization of the Kinetic system can serve as an initiating point in the draft of the movable architectural mechanism. Hence, the approach originating from the Kinetic Chronological Model provides freedom to the designer and considers these two steps as interdependent. Moreover, the architect may return to the phase of the primary conceptualization of the Kinetic System in the subsequent steps, revisiting it an indefinite number of times during the further examining of the considered environmental phenomenon.

4.1.1.3 FUNCTION OF THE PROJECTING KINETIC SYSTEM

The second stage of the design approach aligns with the eponymous stage of the Kinetic Chronological Model - Function (D-3) and involves determining the changes occurring in the parameters that depict the activity of the considered environmental phenomenon after the application of architectural motion. This category involves conceptualizing the effects that a projecting Kinetic System may have on its surroundings, typifying these effects within the same category as the Output (Out) category: initiating, accelerating, decelerating, or terminating. Visualization of the impact on the environmental phenomenon stems directly from the step involving its determination and requires an understanding of the general characteristics and capacities of the system to adjust to the influence of the projecting Kinetic System.

Thus, this stage of the design requires a deep examination of the nature and the scale of alterations occurring after the transformation of the projecting Kinetic System.

4.1.1.4 LIMITS OF THE ARCHITECTURAL MOTION

In the third phase, the limits of future Kinetic System motion have to be determined to provide a numerical definition of the activity of the environmental phenomenon within architectural motion that has to initiate and interact. Similar to the previous stage, the limits arise from the fourth criterion of the Kinetic Chronological Model (D-4), which involves strong associations with the alterations that have to occur within the environmental phenomenon, serving as the requisites for the Kinetic System.

In this way, the all four steps form the one sense block named as the Premier Conceptualisation aiming to define and examine the the environemntal phenomenon and define general idea of the Kinetic Systemadapting according with the clarifying nature of the considered environmental phenomenon to provide material for the further elebaration of the Kinetic System itself. (Figure 57) This block can be characterized by two entry points, signifying the initiation point, which can be applied in either of two places: either in the determination of the environmental phenomenon or in the primary conceptualization of the Kinetic System.

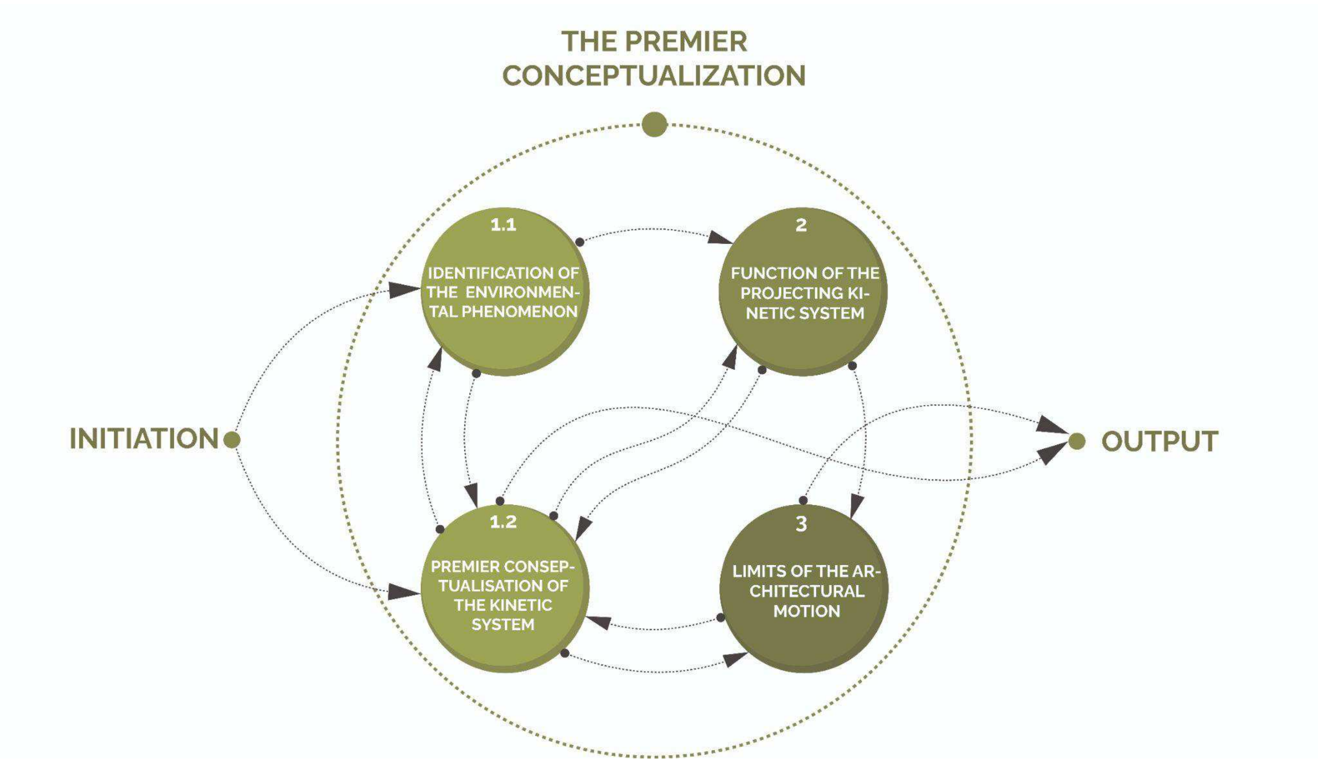


FIGURE 57
The Premier Conceptualization Block of the design approach originated from the Kinetic Chronological Model

4.1.2 MOTION PROJECTION

At the point when the considered environmental phenomenon is determined and analyzed, and the model of the projected kinetic system is presented in the form of preliminary drafts, the ways through which the kinetic system interacts with the outer environment should be defined to describe the way how architectural motion can occur. This intermediate point in the design method, between the initial conceptualization and the projection workflow of the kinetic system, requires the designer to address a series of questions: how alterations occurring within the considered environment may initiate architectural motion, determining whether the motion process will be self-controlled and self-regulated, and assessing how changes in the kinetic elements will impact the environmental phenomenon. To each of the dedicated questions, one component of the system motion projections corresponds.

The projection of the kinetic system necessitates the utilization of elaborations resulting from the previous phase, as presented in the initial conceptualization of the Kinetic System, and involves the examination of the considered environmental phenomenon. The designer is tasked with projecting a kinetic system that interacts with the outer environment. As demonstrated in the Kinetic Chronological Model, the movable architectural mechanism interacts with the considered environmental phenomenon in two moments: at the moment of motion initiation and when architectural motion affects the activity of the considered environmental phenomenon. Therefore, the designer should conceptualise a mechanism responsible for considering environmental alterations and initiating motion. Additionally, the designer must address the impact that the kinetic system should have on the activity of the considered environmental phenomenon.

Futhermore, in addition to the initiation sensors, the contemporary kinetic system can incorporate a facility responsible for monitoring architectural motion and leveraging past adaptation experiences, regulating the transformation process to achieve better performance. In the case of the utilization of information technologies, as already demonstrated in Section 3.4.7, the implementation of computational technologies may significantly influence the performance and speed adaptation of the Kinetic System. However, this advancement comes at the expense of increased costs. Simultaneously, information technologies ameliorate the system's capacities for dialogue with a user. In this way, in addition to the method of interaction between the user and considered environment, at this step of the design process, a designer should also focus on the system's capabilities of self-learning and regulation of occurring motion and interaction with a human.

In this manner, the elaborations produced in the second phase of the design method have to integrate the outcomes resulting from the examination of the considered environmental phenomenon into the model of the kinetic system. The objective is to adapt it for integration with the considered environment, including the user. Furthermore, it marks the first phase in the design method where the designer can contemplate projecting the system as a process, intrinsic with inputs and outputs, and explore how the motion is regulated by the system itself. Therefore, the step of kinetic system motion projection culminates in a detailed model of the kinetic system, complete with actuators and characterized by the effects that should impact the considered environmental phenomenon. That model further has to be detailed with the subsequent projection of the kinetic system in the next design phase.

4.1.3 KINETIC SYSTEM PROJECTING PHASE

In this manner, the designer, in the second phase, must delve into the details of the fundamental characteristics of the Kinetic System, aligning them with the categories of the Motion Strategy (D-5) criteria of the Kinetic Chronological Model, and determining the physical characteristics of the projecting Kinetic Model and the way it can interrect with the considered environmental phenomenon. As the definition progresses, these characteristics must be further applied to the resulting primary concept of the Kinetic System to elevate it to a new level of detail. Thus, the organizational structure of the criteria in the second design phase will bear similarities to the first, as it encompasses parts related to further in-depth research and the drafting of a model that can be adjusted with developments from the initial primary research.

Analogously to the Premier Conceptualization Phase, the Projecting phase aligns with the criteria of the Kinetic Chronological Model, particularly emphasizing the Motion Strategy, encompassing the elaboration of motion organization (1), motion pathways (2), and motion mechanisms (3). It involves selecting the necessary characteristics of the projected Kinetic System. Similarly to the previous stage, the projection process can commence from any of the indicated three points and return to this phase an unlimited number of times. Consequently, the outlined design process does not prescribe a strict path, affording the designer the flexibility to alter the sequence of solutions to pursue. This establishes the design method more as a list of points to address rather than a rigid set of instructions to strictly adhere to.

4.1.3.1 ORGANISATION OF THE KINETIC SYSTEM

The crucial aspect in the process of projecting the kinetic system is the determination of its inner structure, requiring the definition of how motion-enabling components are organized to form a single integral mechanism. In this point, a designer should conceptualize the fundamental characteristics of the inner structure organization of the drafting kinetic system, choosing between mono and multi-functionality, and deriving from this decision a linear, multilevel, or even a complex structure. Thus, at this point, the Kinetic System should acquire a volume, as the two preceding steps are related to the features of the individual movable elements, while the step of projecting the order of the kinetic system allows the creation of an inner skeleton where the drafted kinetic components will be placed. In this manner, this step of the projection aims to yield the defined principles of the inner organization, which can then be embodied in the modell.

The definition of the kinetic system's organization serves as a good initial point for the entire projection process, acting as a connection between the conceptualization and projection stages. Depending on the complexity of the designed kinetic system, a designer may draw inspiration from nature, which contains numerous instances of movable and adaptable elements, or refer to already constructed kinetic systems. However, the complexity of designing a Kinetic System may necessitate examining specific features that a designer aims to achieve by the end of this organizational projection step, increasing the research component of the draft workflow.

At the same time, the inner order of the Kinetic System can be determined later, following the specification of the characteristics of the movable elements or adjusted based on determined features of the internal elements to enhance their efficiency in performing the primary function. Hence, similar to the previous phase, the design method allows for great variability in ways to develop the Kinetic mechanism, with a focus on the specific points that a designer should address in working on the system.

4.1.3.2 MOTION WAYS OF THE KINETIC SYSTEM

The determination of motion ways plays a pivotal role as one of the two stages responsible for evolving the movable elements of the kinetic system and isintricately intertwines with the kinetic means design step. Therefore, the primary objective at this stage in kinetic system design is to identify spatial or non-spatial architectural motions capable of altering the activity of the considered environmental phenomenon. The planning of architectural motion is strongly linked to the nature of the considered environment and requires the utilization of essential knowledge about its activity to design an architectural motion that will serve as a catalyst, changing environment action. In this scenario, the designer may delve into the classification of the Output (Out), where various effects (Out-Al) of the movable mechanism on the considered environment are delineated. Moreover, the designer should concentrate predominantly on the boundaries of architectural motion, defining the parameters within which it must initiate and conclude its action. These limits need to be translated in some way into the language of the structure, for instance, through the control system or smart materials. Thus, the principal objective of this step can be framed as the projection of the contraction capable of bringing alterations into the environmental phenomenon activity.

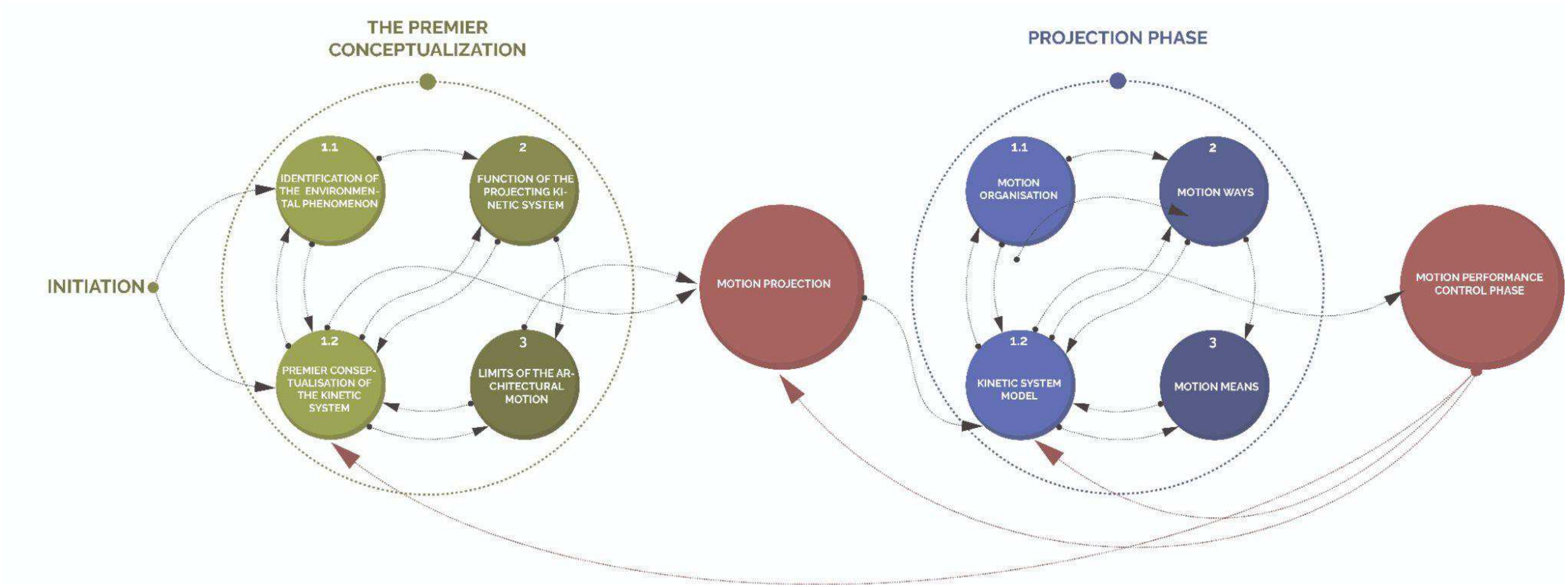
The planning of the architectural motion cannot be initiated without the diving into the great variety of the movable architectural elements classification, starting from the first level of the decision on spatial and non-spatial and finishing with the clarification of the number of axes through the motion is performed or the nature of force enabling physical or chemical transformation into the kinetic system.

4.1.3.3 MEANS OF THE ARCHITECTURAL MOTION

This phase of the design should result in determining the type of force that enables architectural motion and, additionally, its scale relative to the hosting structure. The designer must understand through what technologies the selected architectural motion can be transmitted. It may require a review and further adjustments of the motion method if the designer cannot identify the most suitable means of motion transfer. While working on the mechanism facilitating the alteration of the Kinetic System, the designer should develop a functional prototype of the model. This prototype serves as the sole way to control the capacities of the motion means.

4.1.4 MOTION PERFORMANCE CONTROL PHASE

When the computational model of the Kinetic System is completed, it should be tested for interaction with the considered environmental phenomenon, with changing parameters of input to ensure that the model of the Kinetic System initiates motion within the functional limits. This testing also allows the designer to control the output produced by the simulated architectural motion. In cases where the output does not align with the planned function, the designer should conduct further testing to collect more data, aiming to identify and adjust specific parts of the Kinetic System model.



The design approach originated from the Kinetic Chronological Model

FIGURE 45

4.2 DETERMINING THE FUNDAMENTAL CHARACTERISTICS OF THE PROJECTED KINETIC SYSTEM

The modern kinetic envelope systems often encounter challenges related to visual comfort, as they are typically constructed using solid materials aimed at isolating the building's interior microclimate from external influences. While incorporating motion principles into design projects can provide identity and character to the building, the implementation of such systems is often limited to the specific project for which they were designed. Attempting to integrate a kinetic system into an existing building, such as during the reconstruction of a residential structure, may disrupt the architectural appearance already in place.

Therefore, the adaptability of kinetic building envelopes is often constrained by their initial design. To address this limitation, it is essential to minimize visual interference with the host structure, making them applicable to various buildings and structures. This could be achieved through the development of design technologies capable of generating kinetic envelopes based on specific building configurations and contexts. Such a framework should respect the existing architectural appearance while incorporating transparent and flexible materials, allowing observers to appreciate not only the kinetic system but also the architecture of the host building. Ultimately, achieving this goal requires computational design tools that capture the architectural character, rhythm, form, and order of the building.

The design section of the thesis will attempt to explore the potential of kinetic systems constructed from 'light elastic materials' such as textiles, fibers, membranes, etc. Their fundamental characteristic is physical flexibility, enabling them to be seamlessly implemented into any existing form. The following chapter will review instances where elastic materials have been applied in kinetic architecture.

Another goal for the architectural design part is the creation of an algorithmically driven envelope characterized by the ability to adapt to the changing configuration of the hosting building. This algorithm will aim to serve as the prototype for the previously described generative design tool, with the potential to achieve a sufficient level of adaptability, abling to suggest an optional soolurions.

Finally, while the drafting system can be multifunctional, performance calculation is not the primary target for the design part. However, the resulting Kinetic system must undergo performance testing. Therefore, environmental phenomena such as solar activity and the issue of building overheating will be considered, as these are common functions of Kinetic systems.

4.3 THE BRIEF REVIEW OF THE EXISTING ADAPTIVE ENVELOPES

4.3.1 TEXOVERSUM INNOVATION CENTER. 2023. Allmannwappner + Menges Scheffler Architekten + Jan Knippers Ingenieure

The collaborative effort of Allmannwappner and Menges Scheffler Architekten, along with engineering input from Jan Knippers Ingenieure, gave rise to a woven facade design inspired by textile construction. Unlike the typical use of fabrics in architecture, where they are primarily employed in interiors or as supplementary elements for facades, this building's facade breaks away from uniform textile surfaces. Instead, it showcases interwoven triangular modular elements crafted from carbon and glass fiber threads. [85] This leads to a unique exterior covering marked by fluctuating patterns of solid areas and empty spaces in different sizes. Menges Scheffler Architekten partner Achim Menges acknowledged:

‘The fibre facade is an integral part of both the architectural expression of the building as a textile research and innovation centre and the environmental engineering and related indoor comfort strategy of the project’ [85]

Texoversum's facade features triangular panels, each measuring approximately four meters in width and 1.5 meters in height, produced through a groundbreaking robotic winding process developed at the University of Stuttgart. Comprising five distinct panel types with the same triangular outer shape, these panels exhibit slight variations to function as corner pieces and create varying-sized openings at the center. [85]

59

60


FIGURE 59, 60

59: Texoversum Innovation Center, Northeastern Facade. [87]

55: Texoversum Innovation Center, Northwestern Facade. Photos taken by Brigida González. [87]

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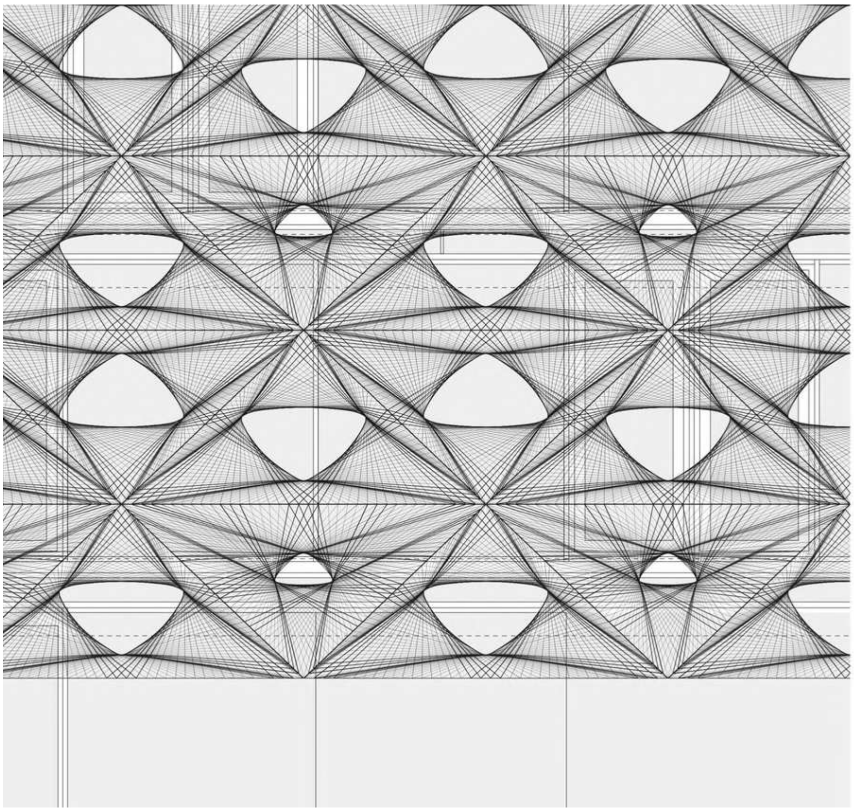
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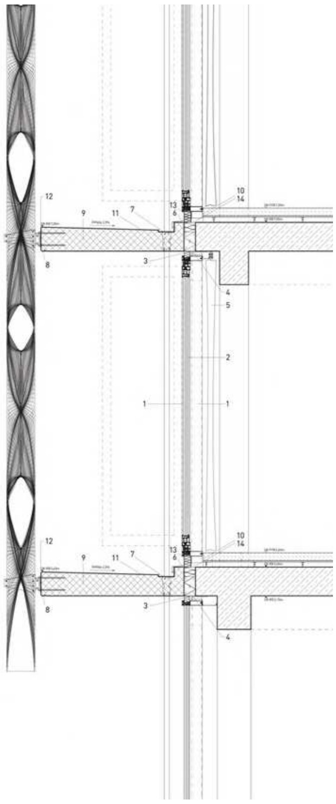


FIGURE 61, 62

61: The woven facade of the Texoversum Innovation Center: detailed drawing of the layout component. [87]

62: The woven facade of the Texoversum Innovation Center: detailed section drawing. Designed by Allmannwappner, Menges Scheffler Architekten, and Jan Knippers Ingenieure. [87]

The Texoversum facade exemplifies an innovative technology with the capacity to revolutionize the construction industry. This intricate structure was digitally designed and is constructed using carbon fibres meticulously wound by robotic processes. Menges Scheffler said:

'Fibrous filaments are freely placed between two rotating winding scaffolds by a robot.During manufacturing, a lattice of white glass fibres is generated, onto which the black carbon fibres are placed where they are structurally needed.' [85]

Drawing inspiration from natural networks found in entities such as spider webs, beetle wings, and palm leaves, the resulting fiber structures are remarkably lightweight yet exceptionally robust, requiring minimal material. This not only conserves resources but also facilitates the transportation and assembly of the components. [86]

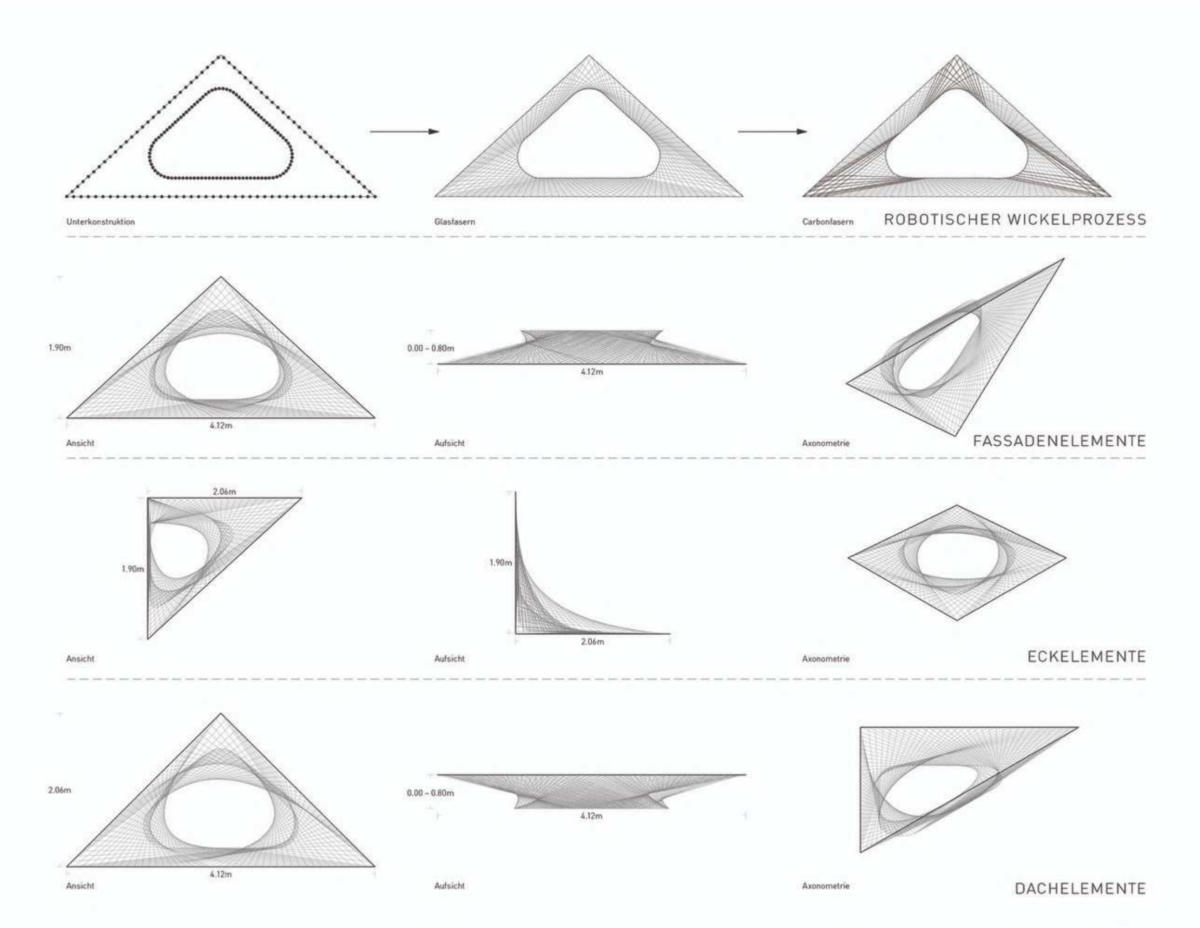


FIGURE 63

The structural component of the woven facade of the Texoversum Innovation Center, Projected by Allmannwappner, Menges Scheffler Architekten, Jan Knippers Ingenieure [87]

Menges Scheffler acknowledged the way in which the creation of such a technological envelope had become possible::

'The distinctive facade design is a result of the deep integration and careful negotiation of intended architectural expression, the traces of the unique materialization process, and the specific materiality of the filaments…. As the design, engineering, and fabrication processes are fully digital, we were then able to collaborate closely with the consulting engineers on the

project from the outset. We shared design and simulation models with an increasing level of detail, so steering our design intent by iteratively integrating structural engineering, building physics, and robotic fabrication in the project's advancement' [88]

In this manner, Texoversum emerges as a unique result of the close collaboration between engineers and architects, introducing an entirely new technological and multidisciplinary approach to designing the building envelope. The concept of elastic adaptive facades produced through digital applications appears to be a prospective research topic in the near future.

4.3.2 THE THEME PAVILION EXPO YEOSU. 2012. SOMA Lima

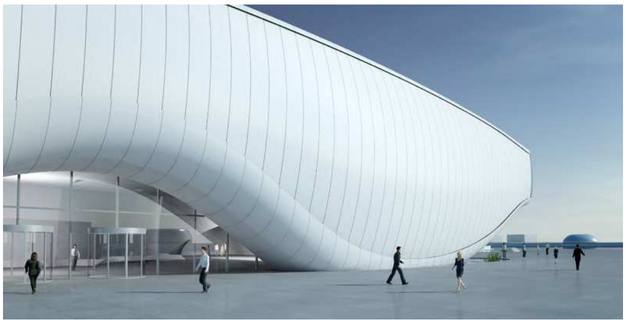
64  65 

FIGURE 64, 65

64: The kinetic facade of the theme pavilion Expo 2012 Yeosu in the closed condition. [90]

65: The kinetic facade of the theme pavilion Expo 2012 Yeosu in the opened condition. Projected by soma ZT GmbH, the kinetic facade was designed by Knippers Helbing GmbH. [90]

Winning first place in an open international competition in 2009, the thematic pavilion now stands as a vibrant addition to a newly revitalized promenade within an existing harbor. Its state-of-the-art facade technology imbues it with fish-like characteristics, utilizing glass fiber-reinforced polymers (GRPF). [89] The incorporation of these dynamic lamellas within the building's exterior demonstrates how biological movement mechanisms can be seamlessly integrated into architectural design:

'The integration of the moving lamellas within the building's skin was inspired by a research project at the ITKE University Stuttgart that investigates how biological moving mechanism can be applied in an architectural scale.' [90]

The innovative kinetic facade, developed in collaboration with engineering consultants Knippers-Helbig of Stuttgart, aligns with bionic principles, showcasing the EXPO's innovative and ecological approach. In contrast to virtual and multimedia displays, this analog kinetic facade, integrated into the Pavilion's architecture, creates memorable experiences through the choreography of wave-like patterns during the day. At night, LEDs embedded in the lamellas enhance the visual impact, illuminating adjacent surfaces.

Constructed from glass fiber-reinforced polymer, the kinetic light facade combines technical innovation with dynamic presence, effectively conveying the Expo's aspirations in a captivating way.

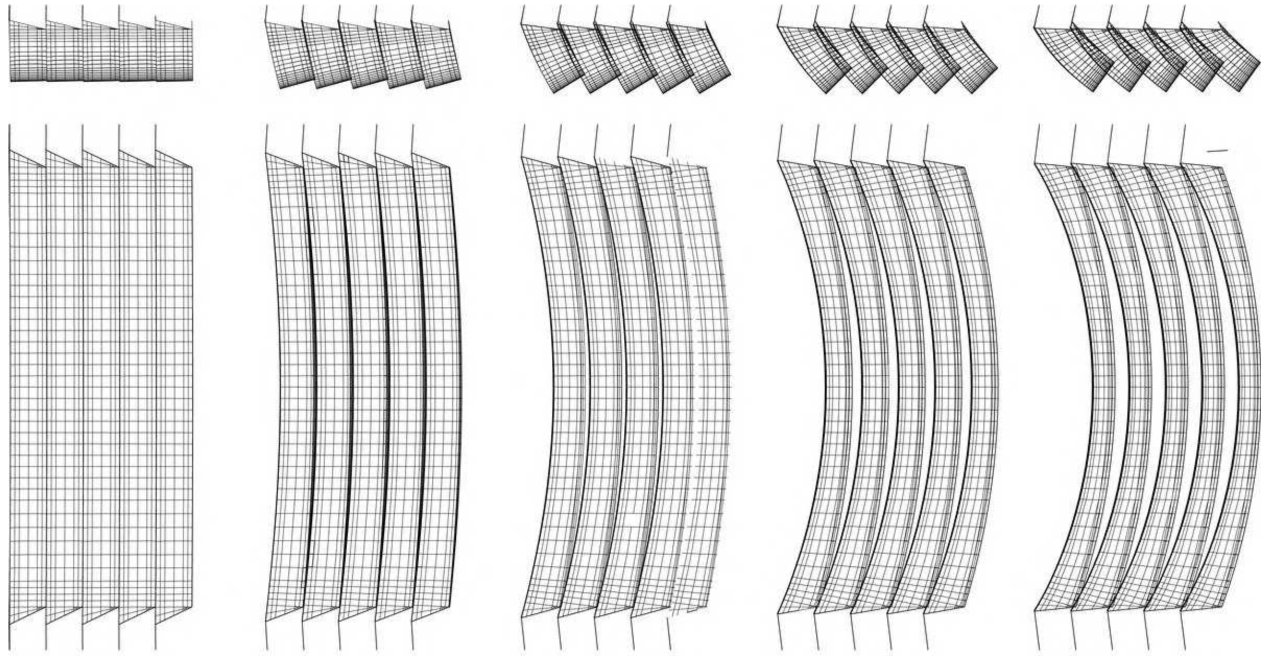


FIGURE 66

Kinetic lamellas of the Expo Pavilion facade, rotating from closed to 60° opening. Detailed drawing (https://www.iaacblog.com/programs/parametric-skin/)

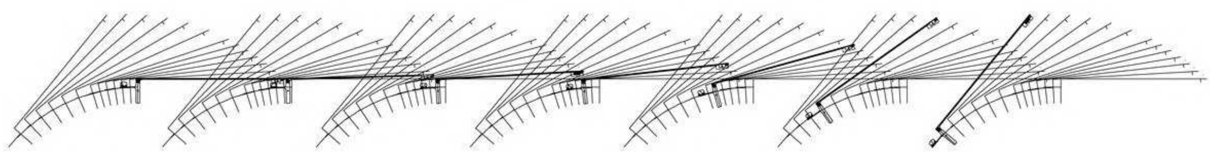


FIGURE 67:

Kinetic lamellas of the Expo Pavilion facade movement from closed to 60° opening cut through the middle of a lamella. (https://www.iaacblog.com/programs/parametric-skin/)

'It is a combination of natural and artificial elements, like plants or fields of solar collectors and piezoelectric halms, which produce light when moved by the wind. The topographic lines of the roof turn into lamellas of the kinetic media façade' [90]

Thus essence, the Thematic Pavilion at Expo Yeosu combines architectural ingenuity, technological innovation, and ecological considerations to deliver a captivating and environmentally conscious experience.

4.3.3 KINETIC WALL AT THE VENICE BIENNALE. 2014. Barkow Leibinger

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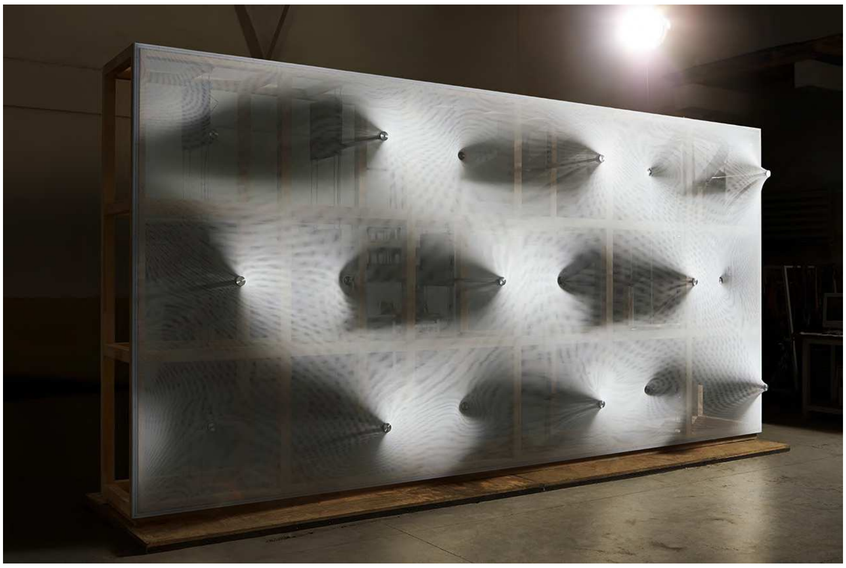
89 

FIGURE 68, 69

68, 69: Kinetic Wall at the Venice Biennale drafted by Barkow Leibinger. Photo taken by Katie Watkins [91]

Barkow Leibinger's Kinetic Wall, showcased at the 2014 Venice Biennale's Elements of Architecture exhibition, stands out in the Wall Room for its innovative design and forward-thinking approach. Positioned alongside a 17th-century Dutch house, the Kinetic Wall represents a convergence of past and future, symbolizing the impact of digital technologies on architectural elements.

'Surface (wall) movement is activated by a series of motorized points which extend and retract that transform an elastic (stretched) translucent synthetic fabric into a topographical section of peaks and valleys. This movement transforms the exhibition visitor's corridor between the "Kinetic Wall" and the adjacent (glass) partition wall into a differentiated arch-like space' [91]

Although the practical applications of this technology may not be fully apparent, the malleability of the fabric, as demonstrated in Johannes Förster's video, showcases its potential. The Kinetic Wall's 3-dimensional transformations draw attention to the possibilities beyond the fabric skin, hinting at broader implications for the future of architectural design and interactive spatial experiences:

'Kinetic Wall offers an alternative future, an architecture that is materially and spatially dynamic of both natural and synthetic/recycled materials,' [89]

Thus, Barkow Leibinger, through the AR (augmented reality) object Kinetic Wall, explores the transformation potential of elastic materials.

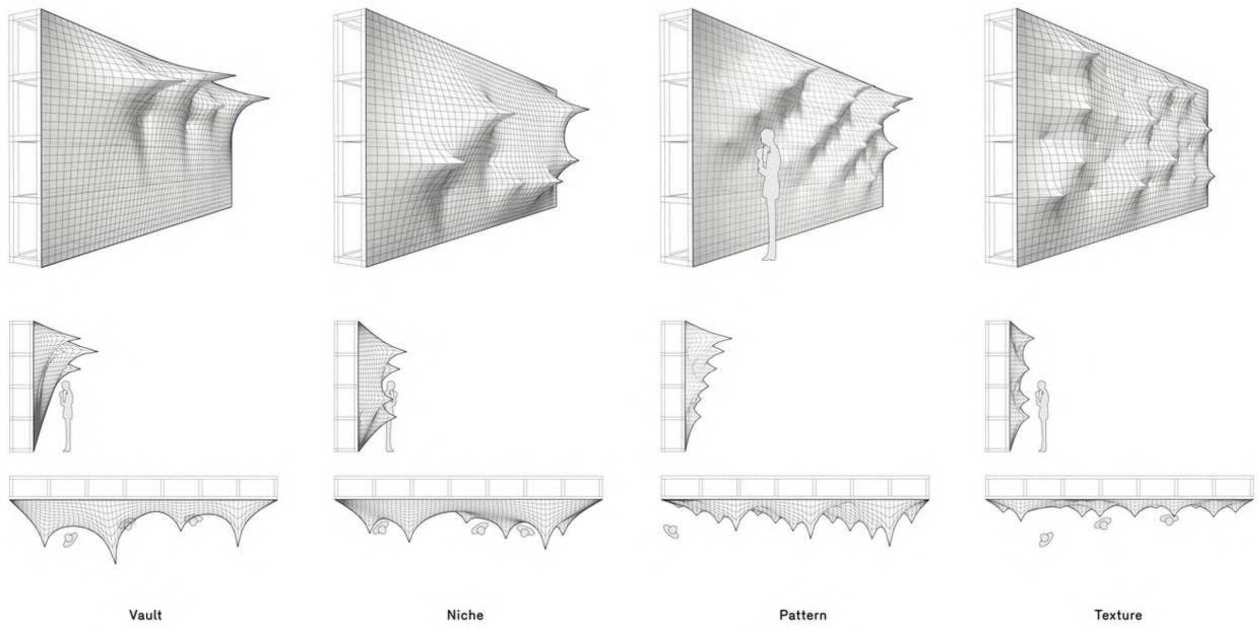


FIGURE 70

Configurations of the Kinetic Wall at the Venice Biennale drafted by Barkow Leibinger. [92]

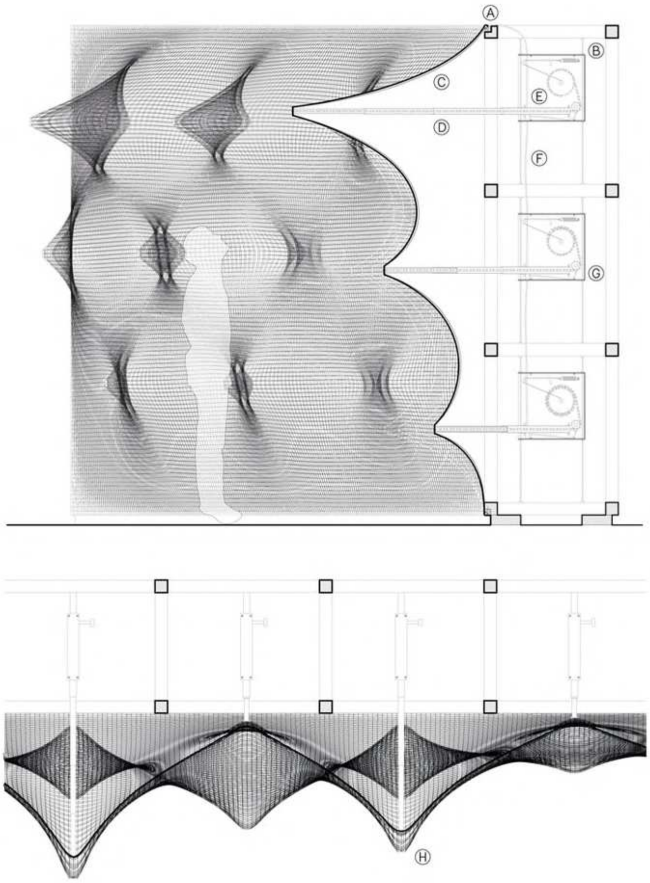
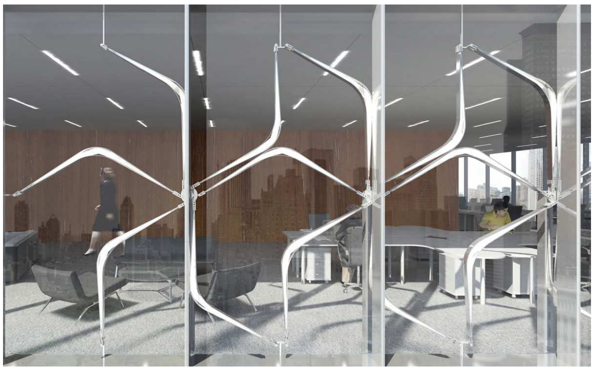


FIGURE 71

Sections of the Kinetic Wall at the Venice Biennale drafted by Barkow Leibinger. Legenda: A - revolving mounting profile; B - CNC milled laminated wood; C - two layers of gridded elastine; D - telescoping rod; E - 24V motor; F - electric cable; G - programmable activator; H - conenction cable. [92]

4.3.4 SHAPING FACADE. 2017. Jin Young Song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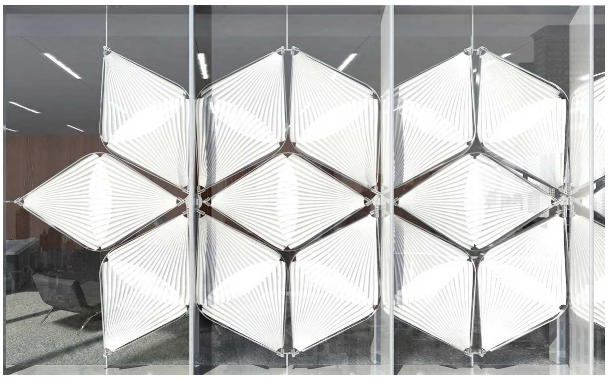
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FIGURE 72, 73

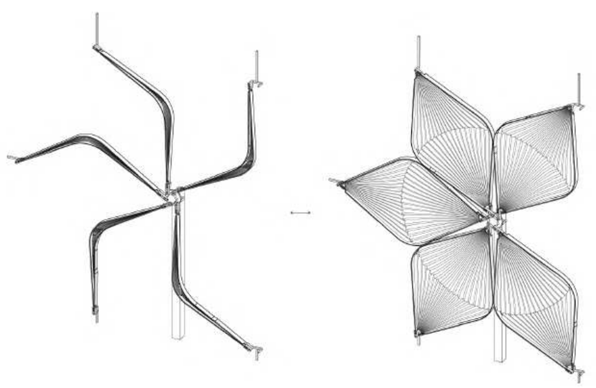
Shaping facade designed by Jin Young Song and Jongmin Shim and gained the 1st prize in the international competition Laka 2018:

72: The shaping facade in the closed condition [93]

73: The shaping facade in the opened condition. [93]

The Snapping Facade is an architectural competition project designed by Jin Young Song and Jongmin Shim from the University at Buffalo, State University of New York. It achieved the first prize in the Laka 2016 architectural competition. The project focuses on utilizing elastic instability as the driving force for the Kinetic envelope.:

'Snapping Facade suggests an alternative approach for the design of dynamic facade systems that use a "snapping-induced motion" to open and close apertures, providing shading for the building. The prototype explores using weakening-induced bands tied within the elastic threshold which, produce "snap" deformation with minimal stimulus. Traditionally, unstable movement within the building construction is considered as an undesirable occurrence but, the Snapping Facade aims to harness the characteristics of elastic instability by applying it as an opening and closing mechanism using the embedded energy within the materials.' []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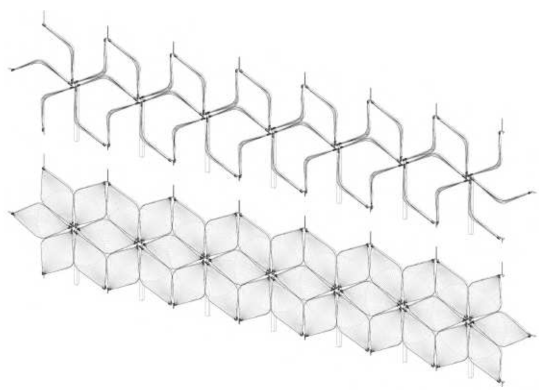
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FIGURE 74, 75

Opening and closing of the shaping facade: of the single element (74), and the wall (75) [93]

4.4 THE KINETIC WOWEN FACADE PROJECTION

4.4.1 DESIGN PREPARATION

4.4.1.1 THE PREMIER CONCEPTUALISATION OF THE KINETIC SYTEM: THE FUNDAMENTAL PRINCIPLES

In the initial phase of conceptualization in the design process, the focus lies in identifying the essential characteristics integral to the projected Kinetic System, which serve as envisioned goals for the culmination of the design process. Furthermore, these specified principles can serve as evaluating markers for the success of the draft output, guiding the adjustments of the responsive envelope.

In the context of the thesis, the design phases aimed to develop a Kinetic System algorithm capable of operating with changeable input data parameters and applicable to a wide range of scenarios. The *adaptability (1)* to the hosting wall configuration emerges as one of the most fundamental criteria for projecting Kinetic Woven Facades. The minimum requirement for adaptability is the ability to accommodate projecting envelopes on the most common types of external hosting envelopes: curtain walls and walls containing traditional window apertures. The algorithmically generated skin should be able to fit both fully glazed walls and solid walls with a characterized order system. However, the criteria for adaptability may not include walls with a different form from vertical surfaces. Additionally, the adaptability of the hosting will, in fact, determine the geometry of the structural segments of the projecting kinetic system. In this wat the more comolcated form of the single structural unit can significantly restrict the adaptability of the Kinetic Facade.

The second selected criterion arises from the statement mentioned in the previous section 4.2 regarding the choice of the considered environmental phenomenon to achieve the maximum possible efficiency of the projecting Kinetic System. This is reflected in its *multifunctionality (2.1),* capable of satisfying numerous requests. One possible approach is to attempt to implement two or more functions into one movable element, which may result in difficulties with performance control, as the motion of one element can influence the second one, requiring a more in-depth examination of the correlation of the two considered environmental phenomenon activities. An alternative approach is *a multilevel organisation (2.2)*, involving the integration of the movable architectural element on two levels in terms of the motion organization of a projecting Kinetic System. Such an approach will necessitate the design of the second movable element; however, the calculations for the kinetic system's performance will be much simpler to calculate. In this way the criterias of mulifinctionality and hierarchical organisation will be considered as the fundamental pricnoples fo the developing Kineric Woven Facade.

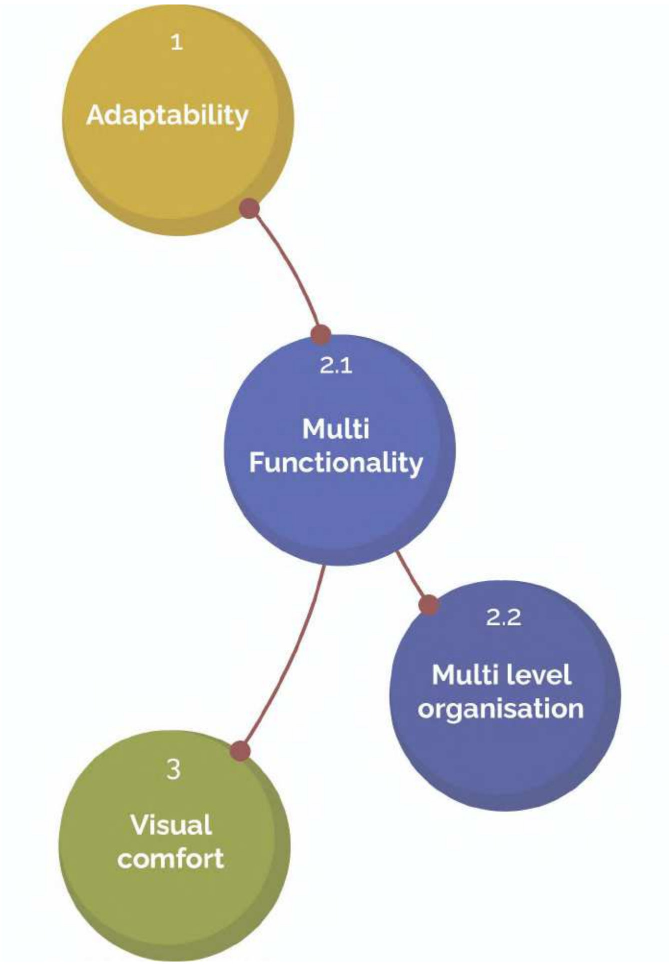


FIGURE 76

The fundamental principles of the Kinetic Woven Facade: Adaptability (1), Multifunctionality (2.1) through Multilevel organisation (2.2), Visual comfort (3)

Additionally, the previously acknowledged plan to examine the capacities of the elastic knitted facade to fulfill functional requests for decreasing solar gain results in the third aspect, referred to as *visual comfort (3)* for observers of the external building appearance and the users' view from the window.

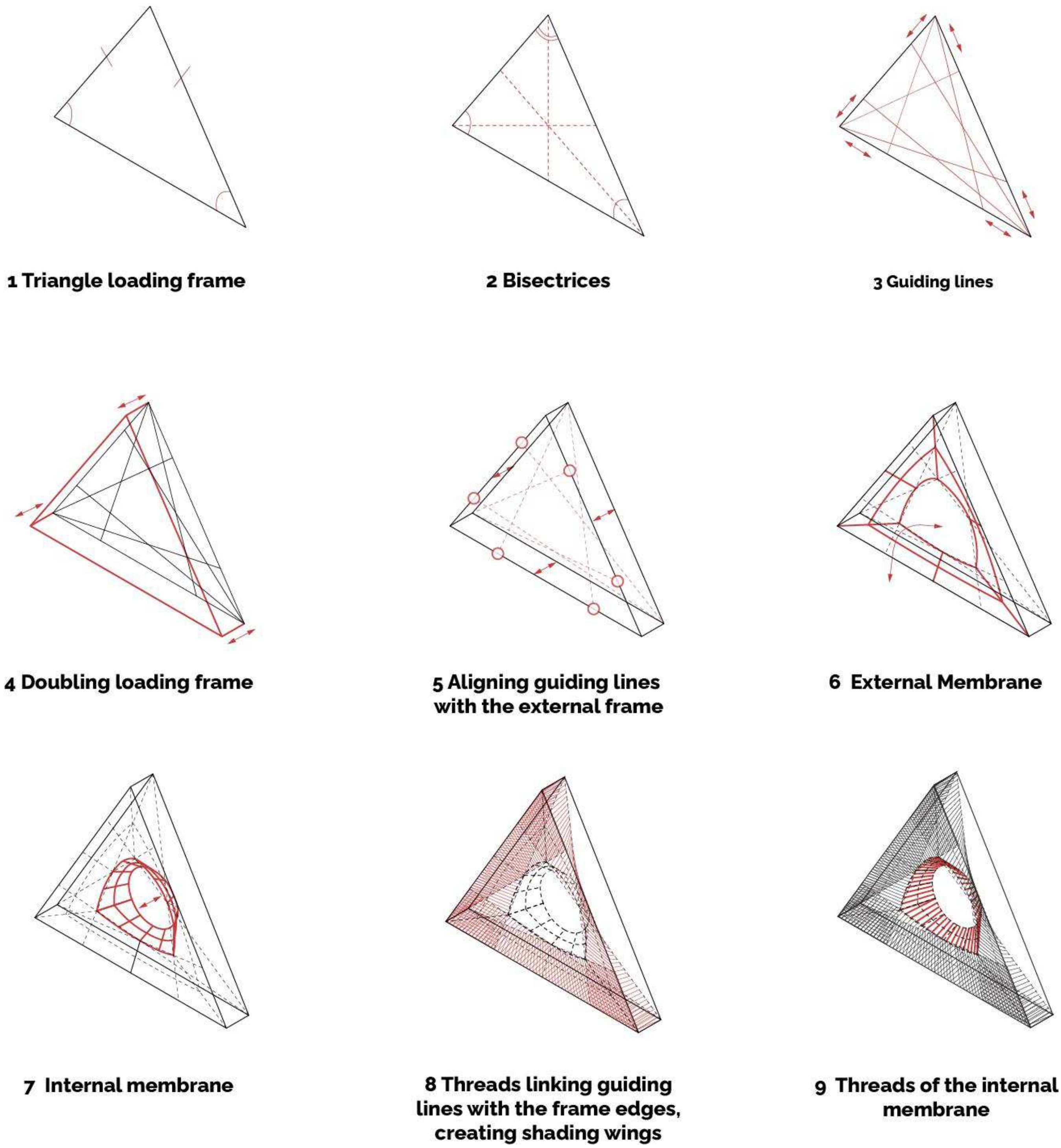
In this manner, the three indicated fundamental principles: adaptability (1), multifunctionality (2), multilevel organisation (2.2), and visual comfort (3) will become the key characteristics of the projecting Kinetic System.

4.4.1.2 THE MOTION PROJECTION OF THE KINETIC SYSTEM

To enhance the adaptation capacities of the Kinetic Woven Facade, the *triangular-shaped segment* has to be considered as the structural units of the responsive envelope, as this form enables coverage for all types of vertical hosting walls, including curved ones (Figure 77.1) To simplify the technological means involved in performing architectural motion, the most straightforward type of transformation has to be implemented: *sliding* (D-5.2.1T-7). This allows the elastic fibers to deform together with the sliding guiding lines (Figure 77.2-3). The guiding lines will be constructed *along medians*, linking the triangle vertex with the front edge. In this manner, each segment will have three pairs of guiding lines. However, to resolve the issue of overlapping pairs of the directing lines, each pair has to move in different planes. Therefore, the triangle frame has to be duplicated to form the *rails*, to which one end of the guiding lines will be linked (Figure 77.4-5). At the end of these steps, the supporting skeleton of the facade segments is formed (Figure 77.5).

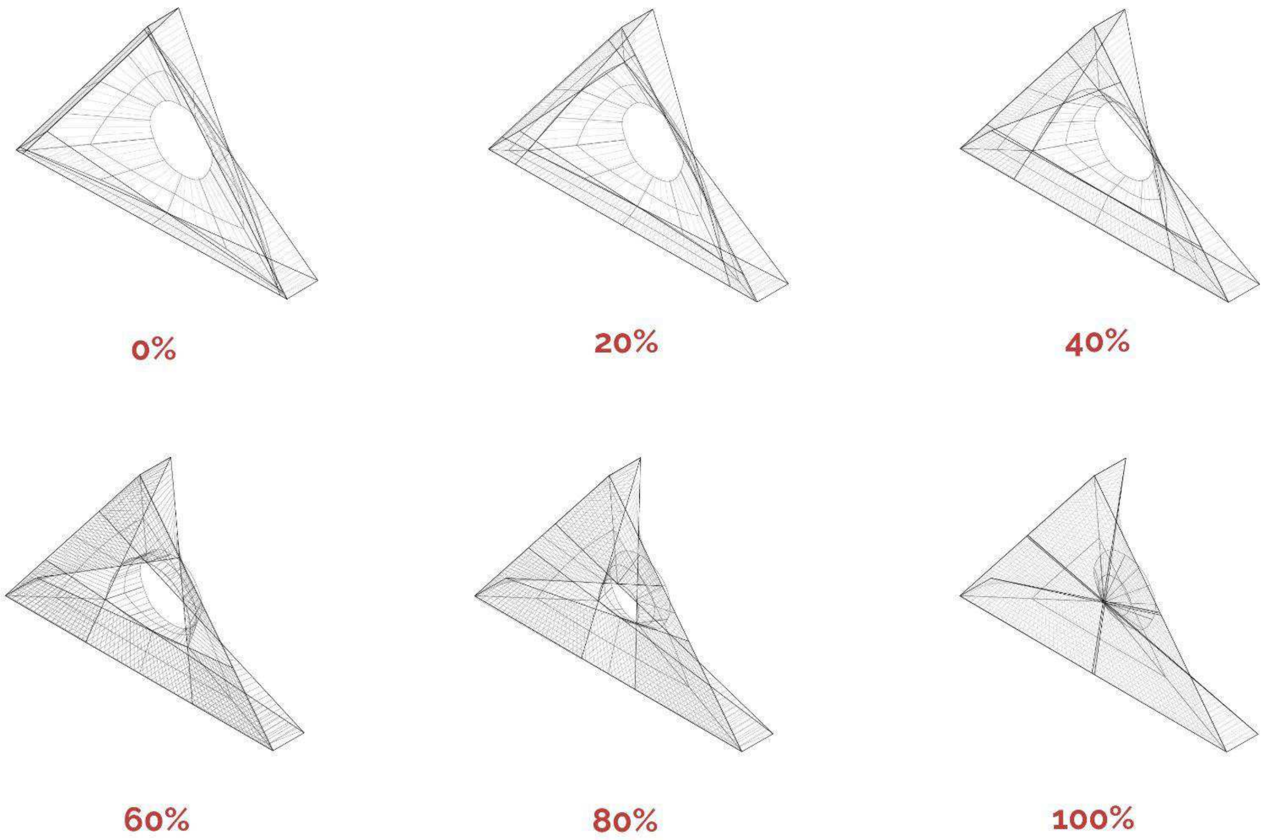
The next step involves the application of *a transparent membrane* tightly adjacent to the wall, which can be divided into inner and external sections, *bordering* together with the *curv*e formed through the points of intersection between guiding lines (Figure 77.6-7). This step results in the construction of the *fiber shading wings* by aligning the guiding lines with the edges of the triangle framework using fibers (Figure 77.6-7). The final action is required to align the curve of the membrane border with the membrane *attachments to the wall,* also using *fibres*. In this way, the sliding guiding lines facilitate the deformation of the elastic fibers and the membrane.

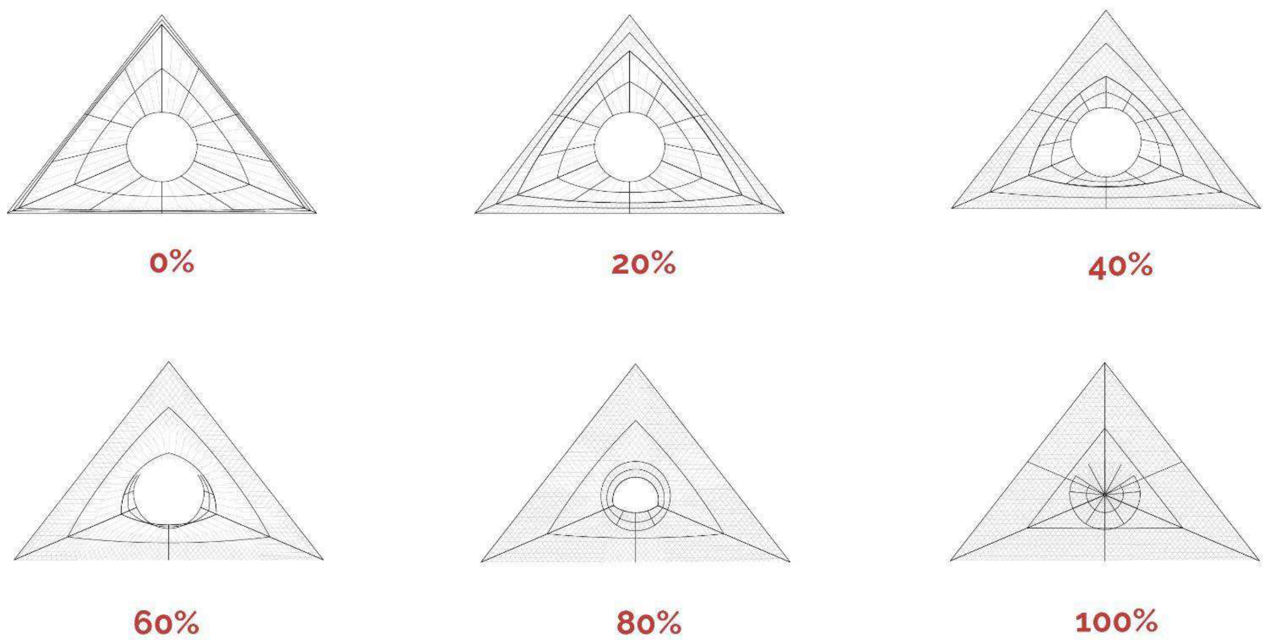
Thus, the Kinetic Woven Facade can be considered closed when the guiding lines are maximally close to the position of the projection of the triangle median (Figure 78 - 100%). The opening condition means the configuration when the guiding lines come maximally close to the triangle edges (Figure 78 - 0%).



FIGURES 77

The evolution of the Kinetic Woven Facade shape





FIGURES 78

The movement of the segment of the Kinetic Woven Facade

4.4.1.3 THE KINETIC SYSTEM PROJECTION WITH COMPUTATIONAL TOOLS

The algorithm generating the Kinetic Woven Facade has to be developed with the tools of the computational design such as a Rhinoscense's plugin Grasshopper, providing a great variability in the already instilled tools and diverse library of the plugins. The all key elements constructed on the differentblocks of the algorithm are represented on the figure 79 in the chronological order of construction. And the graph on figure 80 reflects the sense blocks of the Grasshopper code and the link between them, while the nextt Figure 81 provide the script itself with the small windows of the visualisation, illustrating the intermediate results.

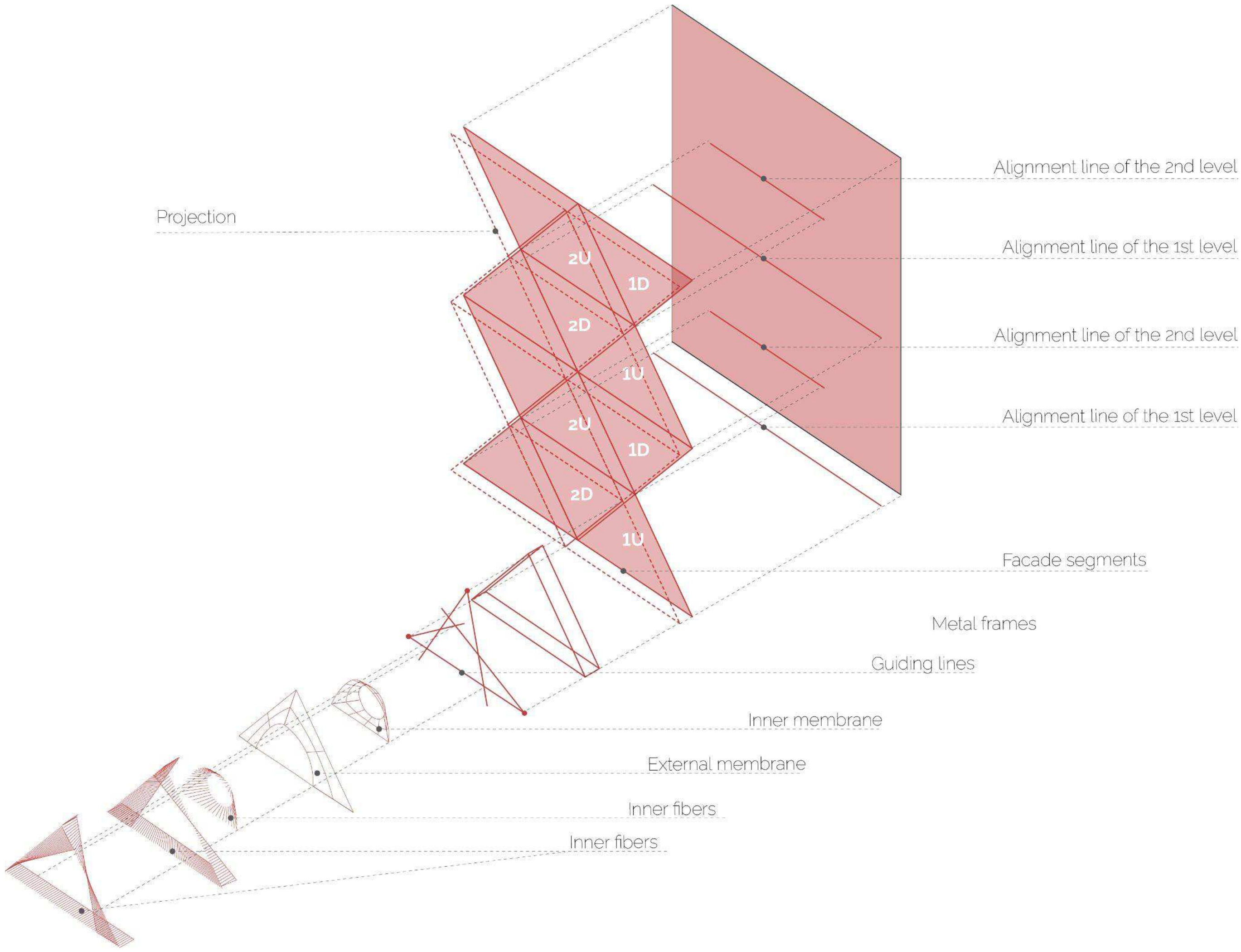


FIGURE 79

The structure of the conceptual model of the Kinetic Woven Facade

Consequently, the algorithm utilizes input data, which includes the curve indicating the surfaces of the hosting wall, and a set of parameters that regulate various aspects of the Kinetic Woven Facade. These parameters may include the gap between fibers, the approximate step dimension of the grid, and others. Additionally, the input block accommodates parameters for regulating facade openings, such as the percentage of the guiding line opening and the ratio of the dimension of the circle hole to the entire height of the triangle segment. The data in this block determines the fundamental characteristics of the developing Kinetic Facade.

Another block under the name 'Primary Processing' constructs the alignment line of the 1st and of the 2nd level, forming the grid of the future facade. Moreover, this block also performs primary calculations, the results of which are utilized in the subsequent steps of the algorithm. The main data in the form of the alignment curves is then transmitted to the next stage, where the facade is segmented with the triangle elements, indicating the projection of the future Kinetic Woven facade's grid.

All triangle tiles constructed in the 'Facade Segments' step can be divided into four types: 1U (indicating the first stock with the distinguishing vertex rotated up), 1D (indicating the first stock with the distinguishing vertex rotated down), 2U, and 2D. Once the segments are completed, they are projected onto the plane, indicating the position of the guiding lines rails. As a result of the operations in these two functional blocks, the outcome represents a set of triangle surfaces that are further utilized.

For the construction of the guiding lines, the triangle surfaces and their projections are utilized. For each triangle vertex, the script indicates a front edge, based on which the median can be initially constructed and then transformed into the guiding lines. At the end of the described functional block, the script provides an output in the form of two sets of curves. These curves are then intersected to obtain points where guiding lines overlap each other, determining the boundary edge between the inner and external membrane.

On the next step, the designed guiding lines, the frame edges, and the membrane borders are sorted according to their position with respect to the apertura. If the hosting walls include openable windows, the membrane is attached in a different way for the fragments located in front of the windows. After all the information is sorted, it is applied to construct the described two types of membranes, which themselves serve as output information that can be exported into Rhinoscense.

In parallel, the guiding lines are divided into points based on the indicated gap between the fibers, sorted according to their closeness to the frame edges, to which they will be linked to form fibers. Consequently, the resulting output in the form of lines is adjusted according to the given fiber thickness and can also be exported into Rhinoceros.

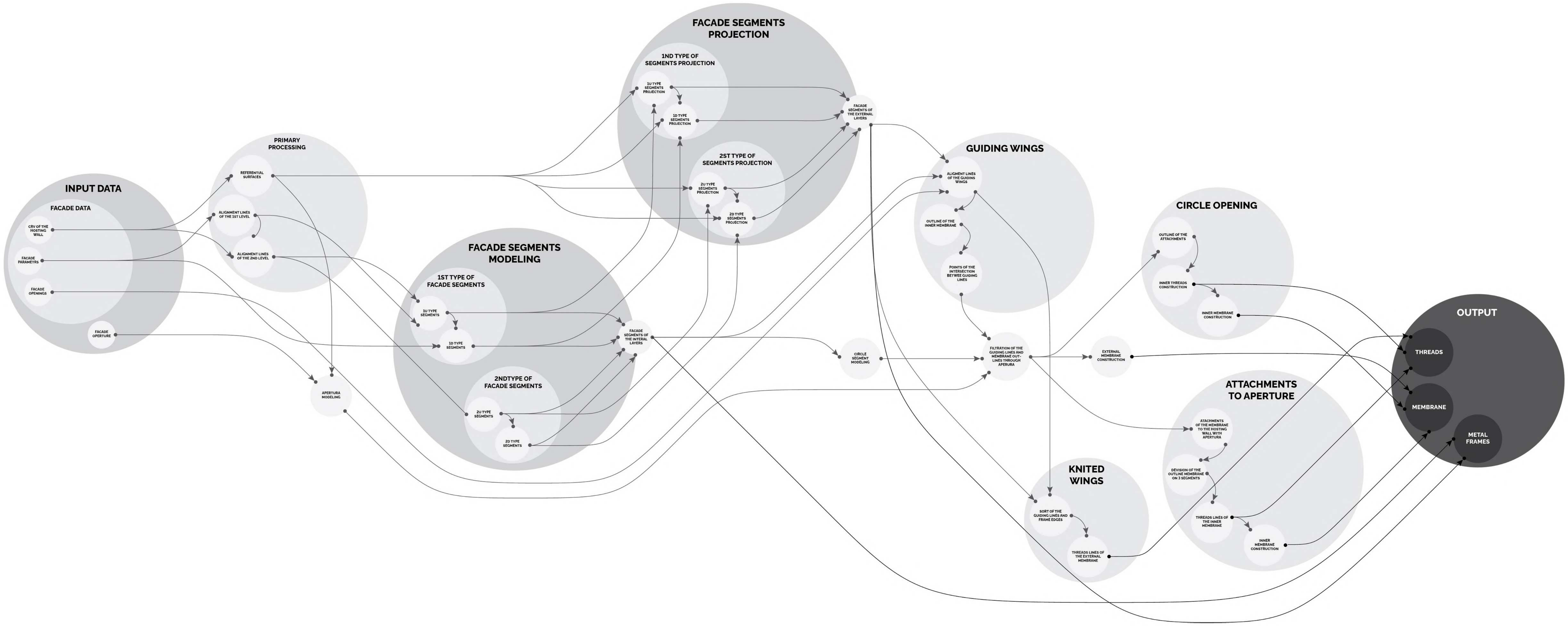
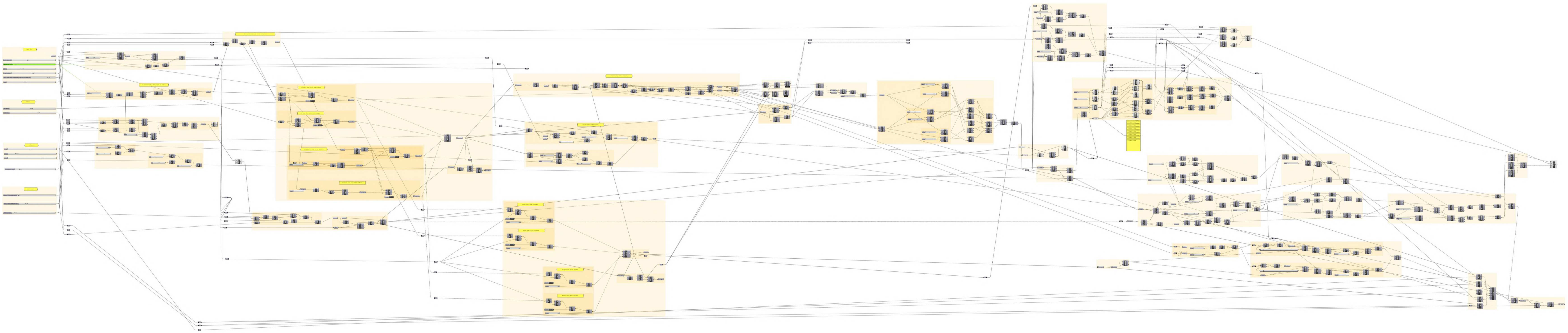
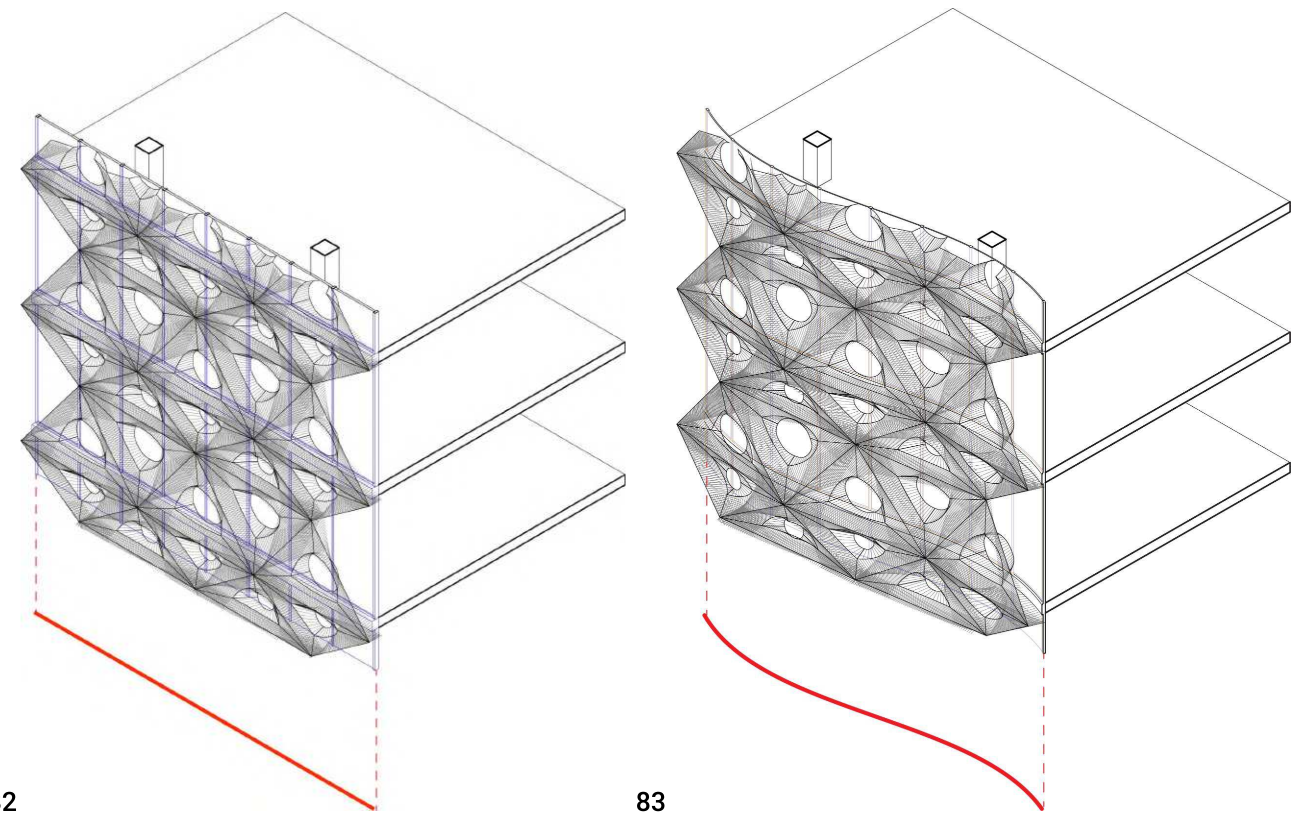


FIGURE 80
The diagram illustrating the primary functional blocks of the Grasshopper algorithm responsible for constructing The Kinetic Woven Facade. This construction is based on the input configuration of the provided building's facade



4.4.1.4 RESULLT EVALUATION

The resulting output of the generating algorithm has to be evaluated according to the criteria outlined in Chapter Section 4.4.1.1: Adaptability, Multifunctionality through hierarchical organization, and Visual comfort, using samples of hosting walls with various configurations.



82 **83**

FIGURES 72 and 83

The adaptability of the designed envelope to the shape of the hosting building's external wall:

82: The Kinetic Woven Facade applied to the linear wall;

83: The Kinetic Woven Facade applied to the curvilinear wall.

Figures 82 and 83 demonstrate the application of the Kinetic Woven Facade on both linear sections of hosting curtain walls and curved envelopes. The division of triangle segments allows to algorithmically generated facade to adapt to envelopes of diverse geometries.

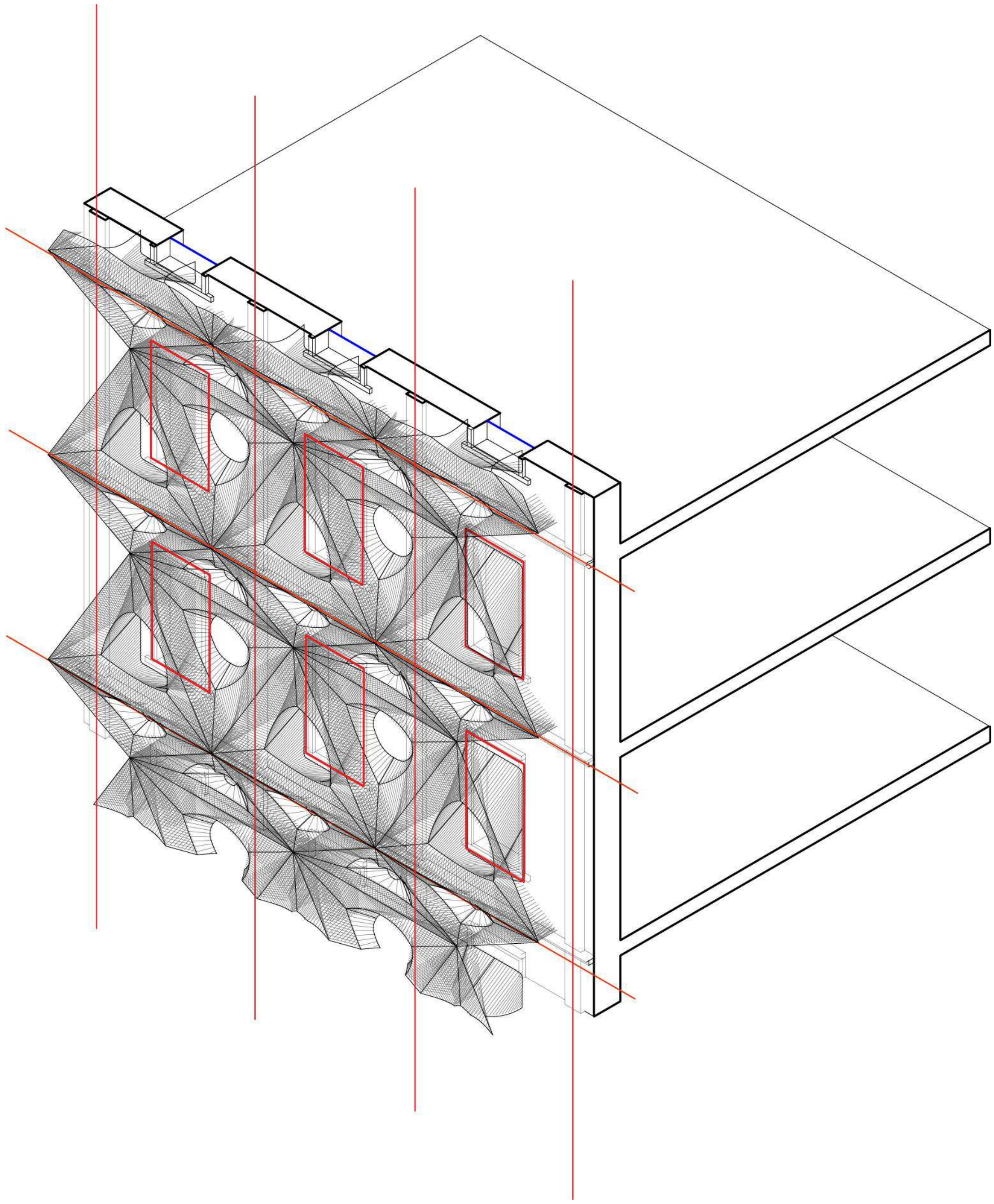
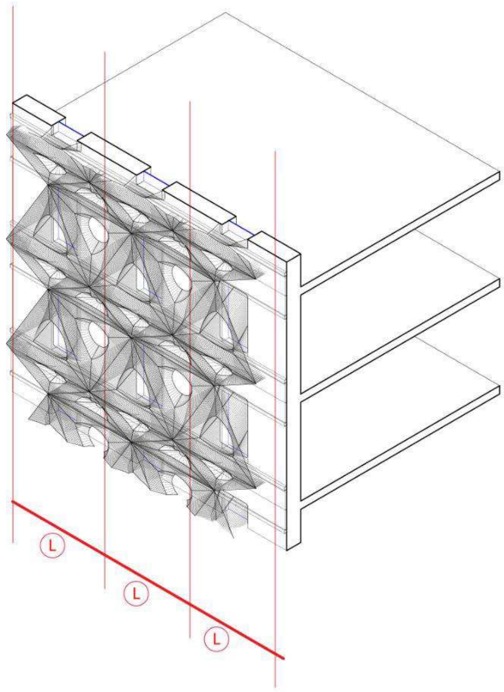


FIGURE 84

The adaptability of the Kinetic Woven Facade to different types of hosting building apertures.

Figures 84 showcase the application of the Kinetic Woven Facade to a solid wall featuring openable windows and an established order system. The use of a specialized membrane that aligns precisely with the frames of the existing apertures, coupled with the flexible grid of the Kinetic facade allowing for segments of varying heights, enables the responsive envelope to be implemented on walls while retaining the possibility of window openings and highlighting the formed facade order system.



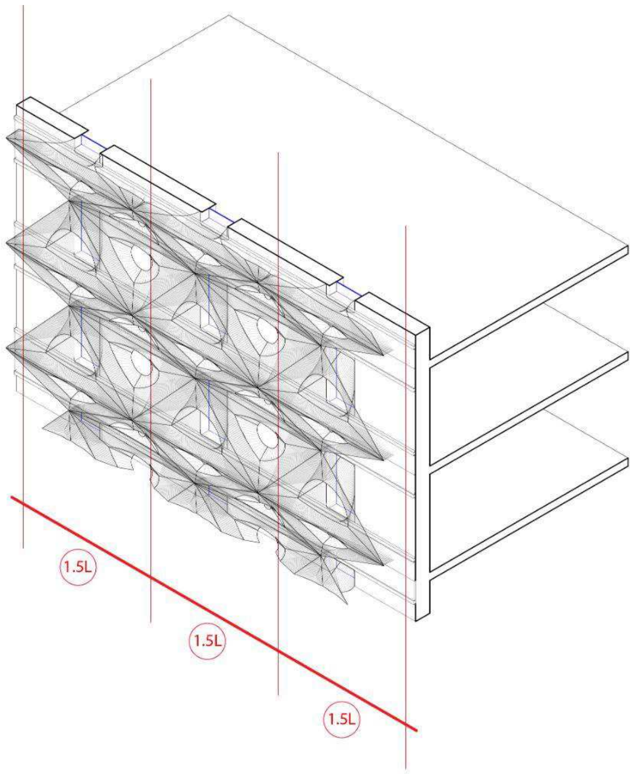


FIGURE 85

The adaptability of the developing Kinetic Woven Facade to the vertical grid of the hosting building.

Figure 85 reflects how the Kinetic Woven Facade can be scaled in the horizontal dimension by adjusting the gap between windows. This flexibility in the horizontal grid allows the resulting responsive envelope to adapt to varying configurations.

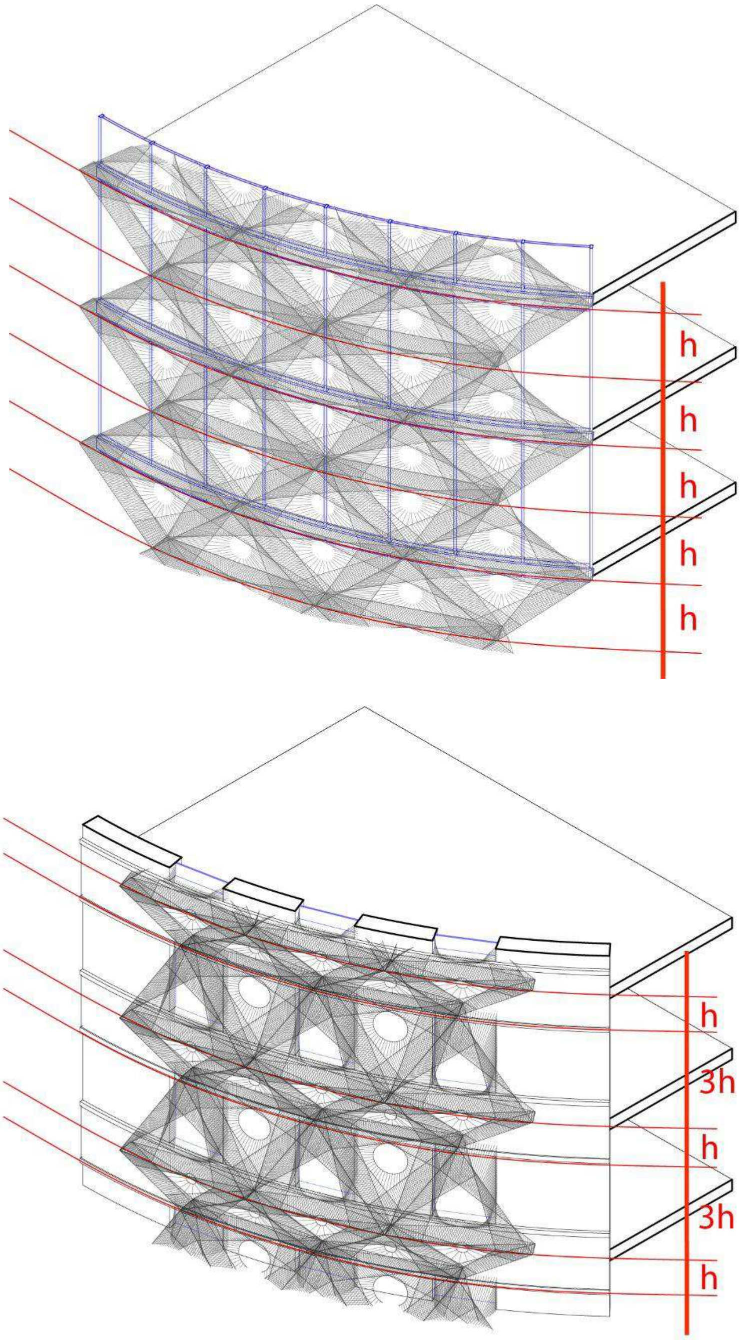
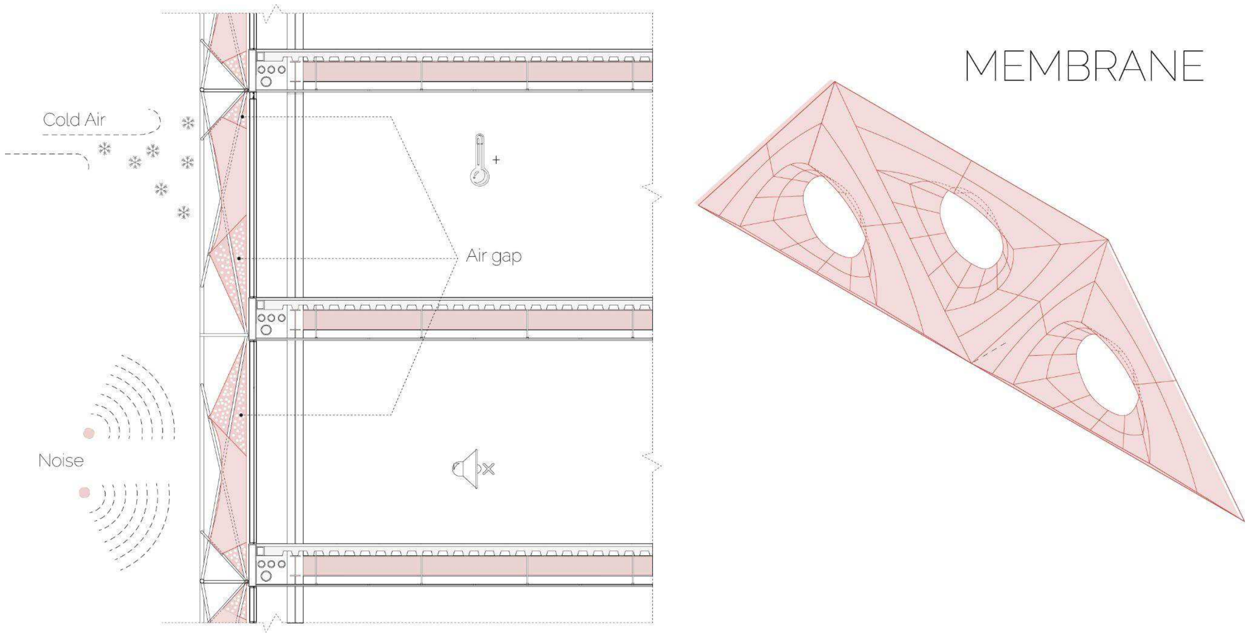


FIGURE 86

The adaptability of the projecting Kinetic Woven Facade to the horizontal grid of the hosting building.

Figure 86 illustrates how the Kinetic Woven Facade can be adapted to the hosting wall with equal or different gaps between aligned lines of the hosting wall aperture. This adaptability of the projecting envelope is achieved through the implementation of a parameter that determines the ratio between the aligned lines of the 1st and the 2nd level of the kinetic facade.



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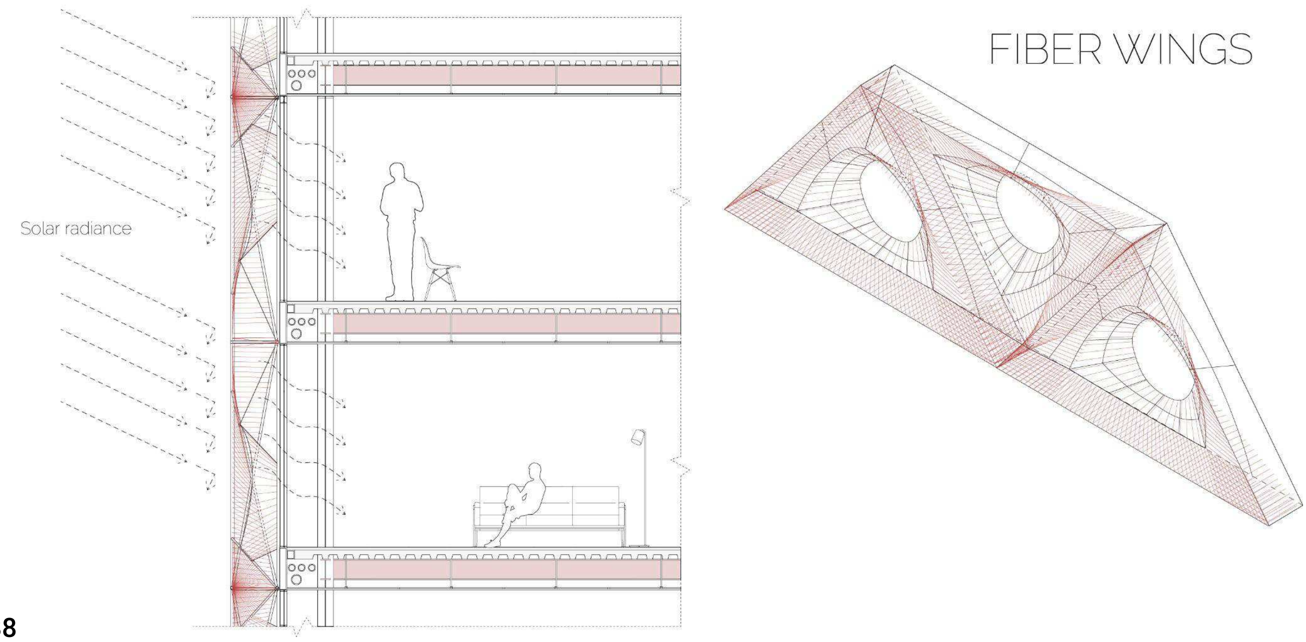


88

FIGURE 87, 88

The multifunctionality of the developing Kinetic Woven Facade is organized through various structural elements, serving different purposes:

87: The transparent membrane enables noise reduction, particularly in the case of curtain walls, and minimizes heat loss by securely attaching to the building and covering the entire external surface;

88: The movable woven wings allow for opening and closing based on the solar pat

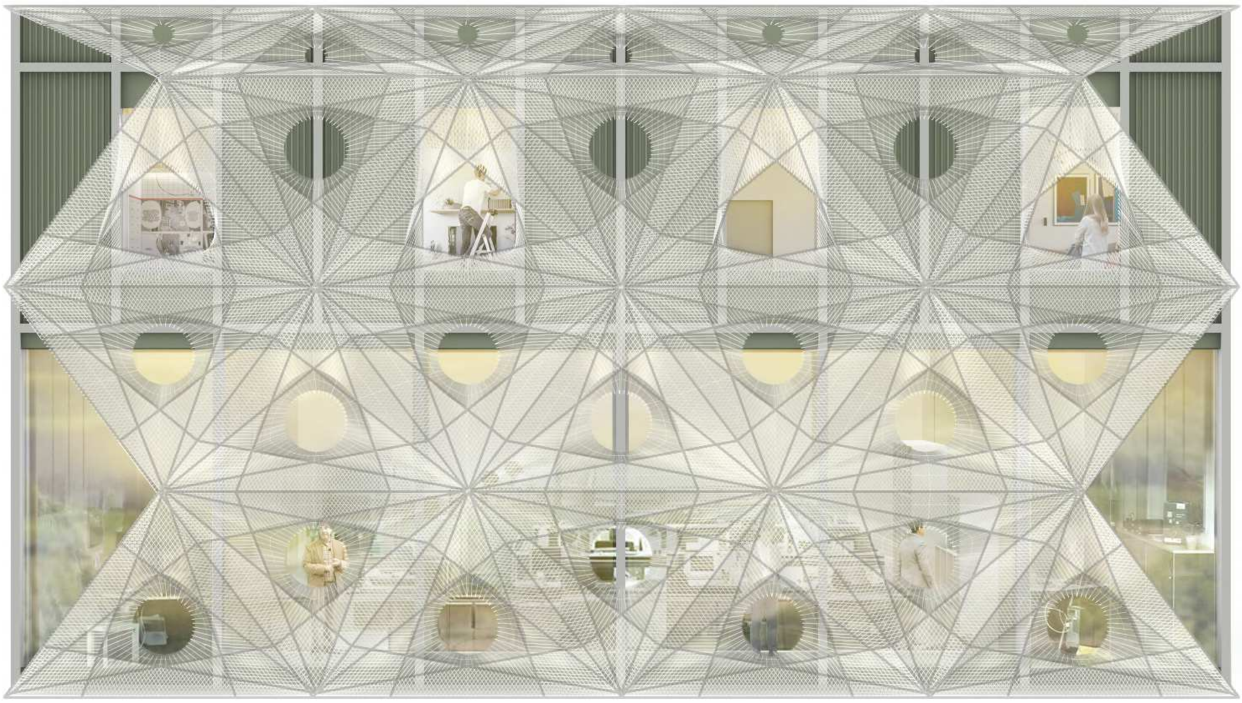
Figure 87 demonstrates the capability of the 1st structural element of the Kinetic Woven Facade transparent membrane to minimize the interference of external noises into the inner building space and partially protect the windows from heating losses. This is achieved as the membrane fits tightly to the wall, leaving no gaps and maintaining an air pocket between the hosting wall and the external membrane surface.

Figure 88 represents fiber wings, serving as the 2nd structural element of the Kinetic Woven Facade and enabling shading by diffusing direct sunlight, thereby protecting the inner building space from overheating.

Figure 89 Showcasing minimum visual interference for inner observation, the thin fibers do not obstruct the panoramic view from the windows, making the Kinetic Woven Facade more visually pleasant compared to other kinetic systems that utilize solid materials.

Figure 90 illustrates the visual comfort of the Kinetic Woven Facade for external observers, as the architectural elements remain readable through the thin fiber grid and membrane. However, the inhabitants of the building can be unconcerned about privacy, as the projecting responsive envelope partially obscures what is happening in the windows.

89.1



89.2

FIGURE 89

The visual comfort of the Kinetic Woven Facade for both internal (85.1) and external observation (85.2)

4.5.1 THE ENERGY PERFORMANCE CHECK OF THE DRAFTING KINETIC ENVELOPE

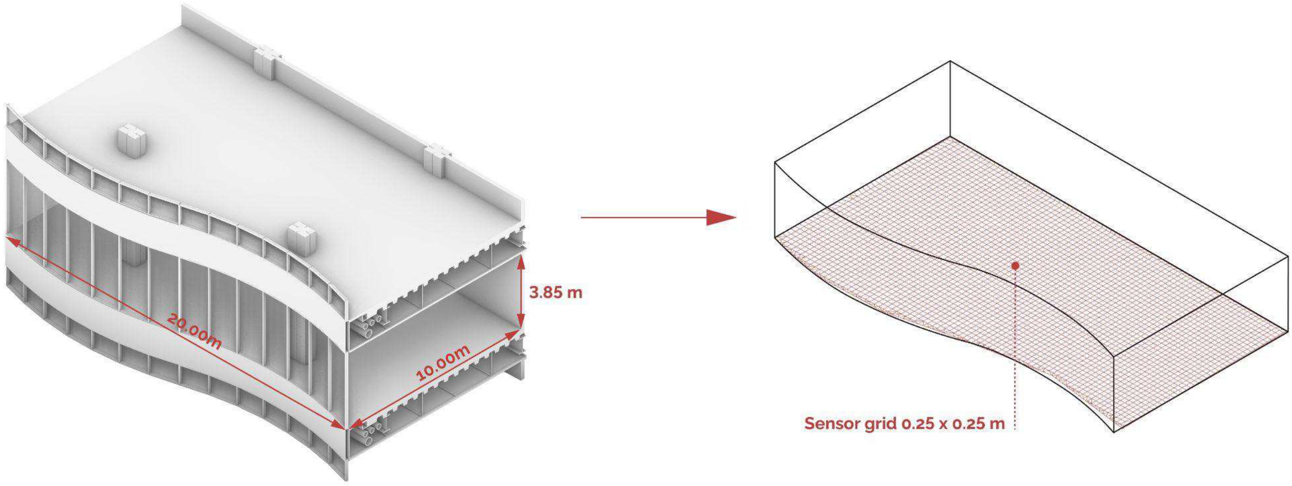


FIGURE 90

The simplified building model used for the calculations of the annual daylight

As planned, the Kinetic system needs to be tested for its ability to control daylight using weather simulation plugins for Grasshopper, such as Ladybug and Honeybee (Figure 91). These plugins allow checking the resulting facade for energy performance. Since the projecting envelope involves complex geometry, the simulation will be conducted on a relatively small-scale part of the building envelope, including the curtain wall, to mimic the room. The floor of such a room will be treated as a calculation surface divided into a grid with variable dimensions, ranging from 0.25 m for simulations without the implementation of the Kinetic Woven Facade to 1 m where the responsive envelope was employed. The simulating room windows face south with the location in Milan, Italy.

The results of the running simulation without the kinetic system implementation can be seen in Figure 92, where most of the floor surfaces are affected by direct sunlight. However, with the implementation of the Kinetic Woven Facade opened on 50% (Figure 93), the difference becomes visible, as the zone permanently heated by daylight is located solely behind the open hole between fiber wings. Moreover, when the Kinetic system is closed at 100%, as depicted in Figure 94, the red zones indicating permanent daylight disappear completely. From the calculations, it can be concluded that Woven Facades are capable of protecting the inner building space from overheating, despite appearing more transparent than traditional solid material openings.

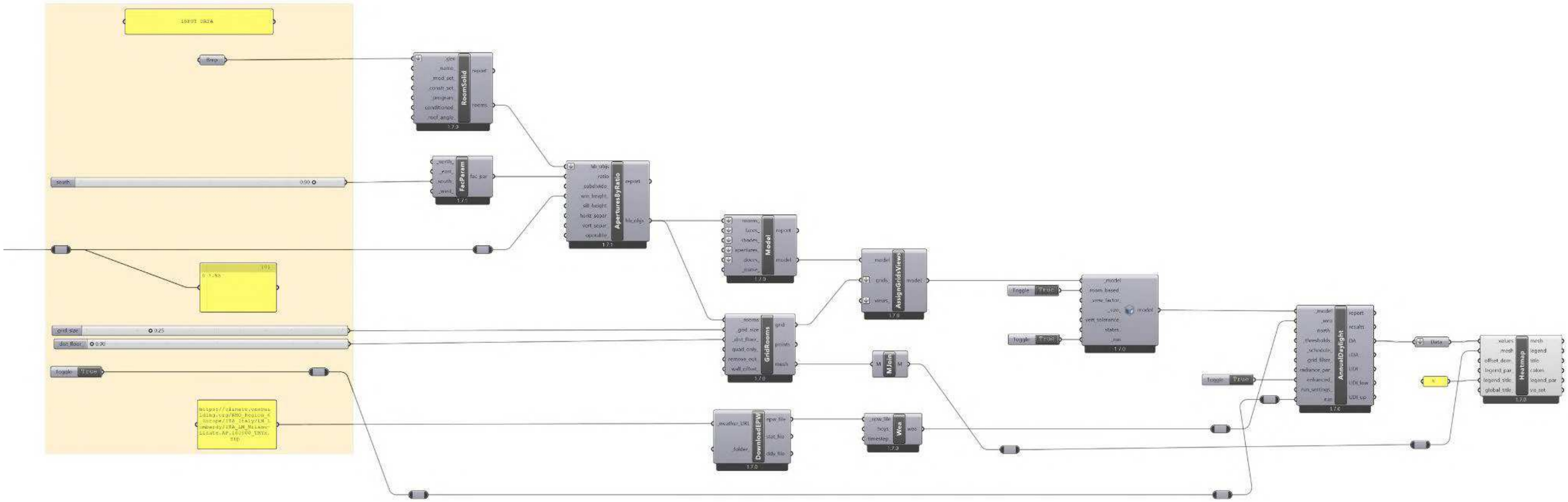


FIGURE 91

The Grasshopper algorithm with application of the Plugins Honeybee and Ladypub to calculate the daylight

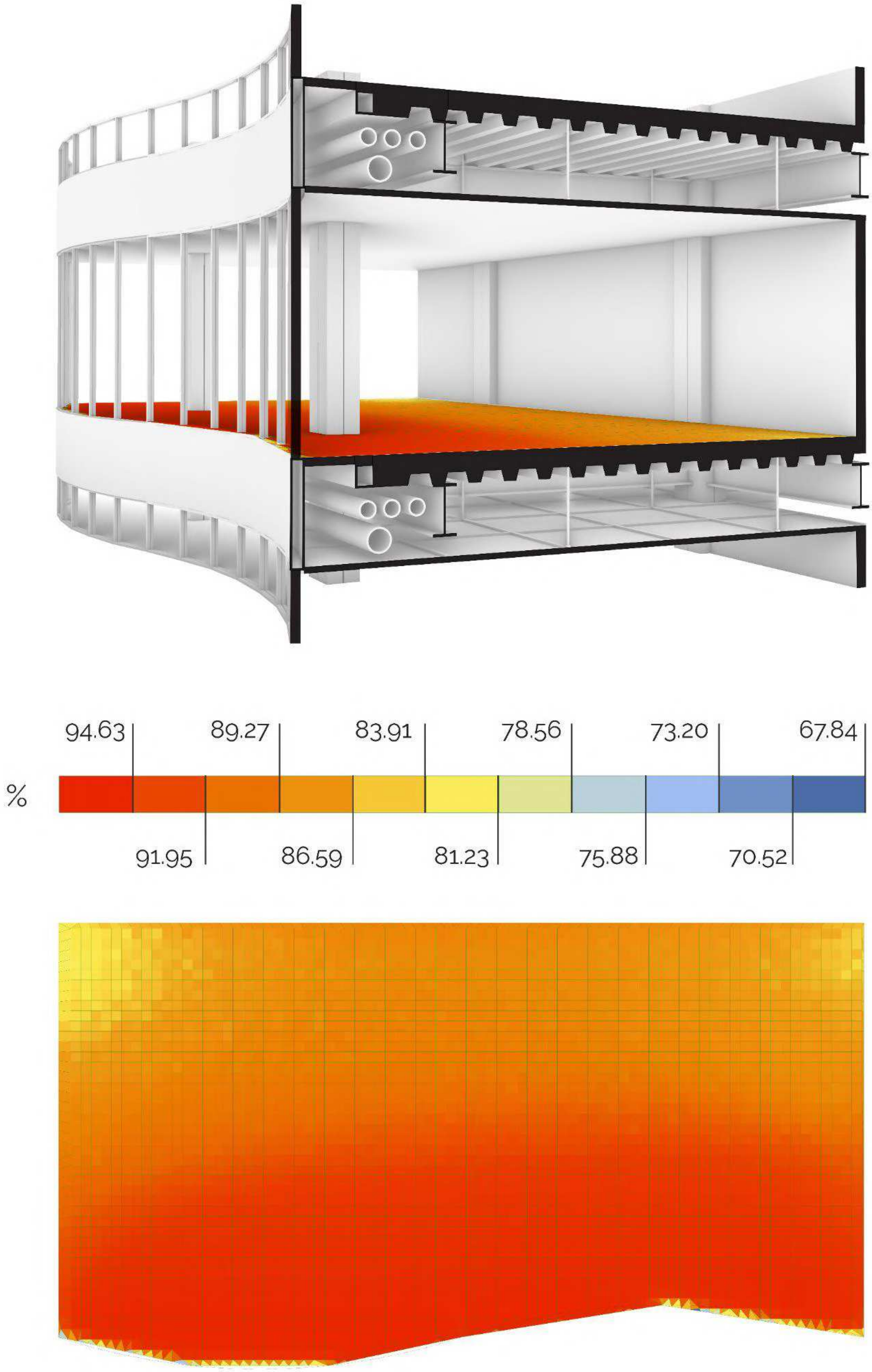
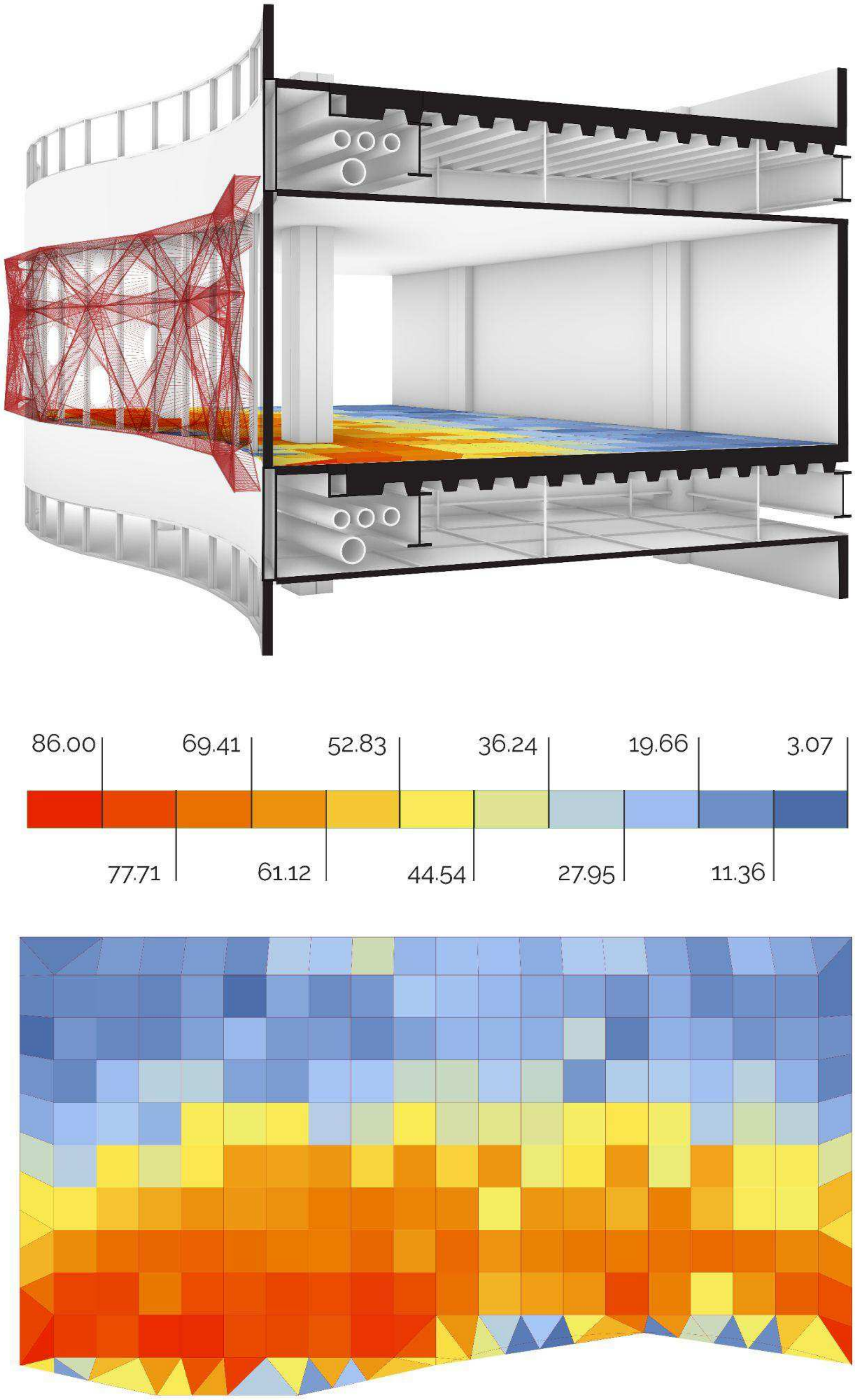


FIGURE 92

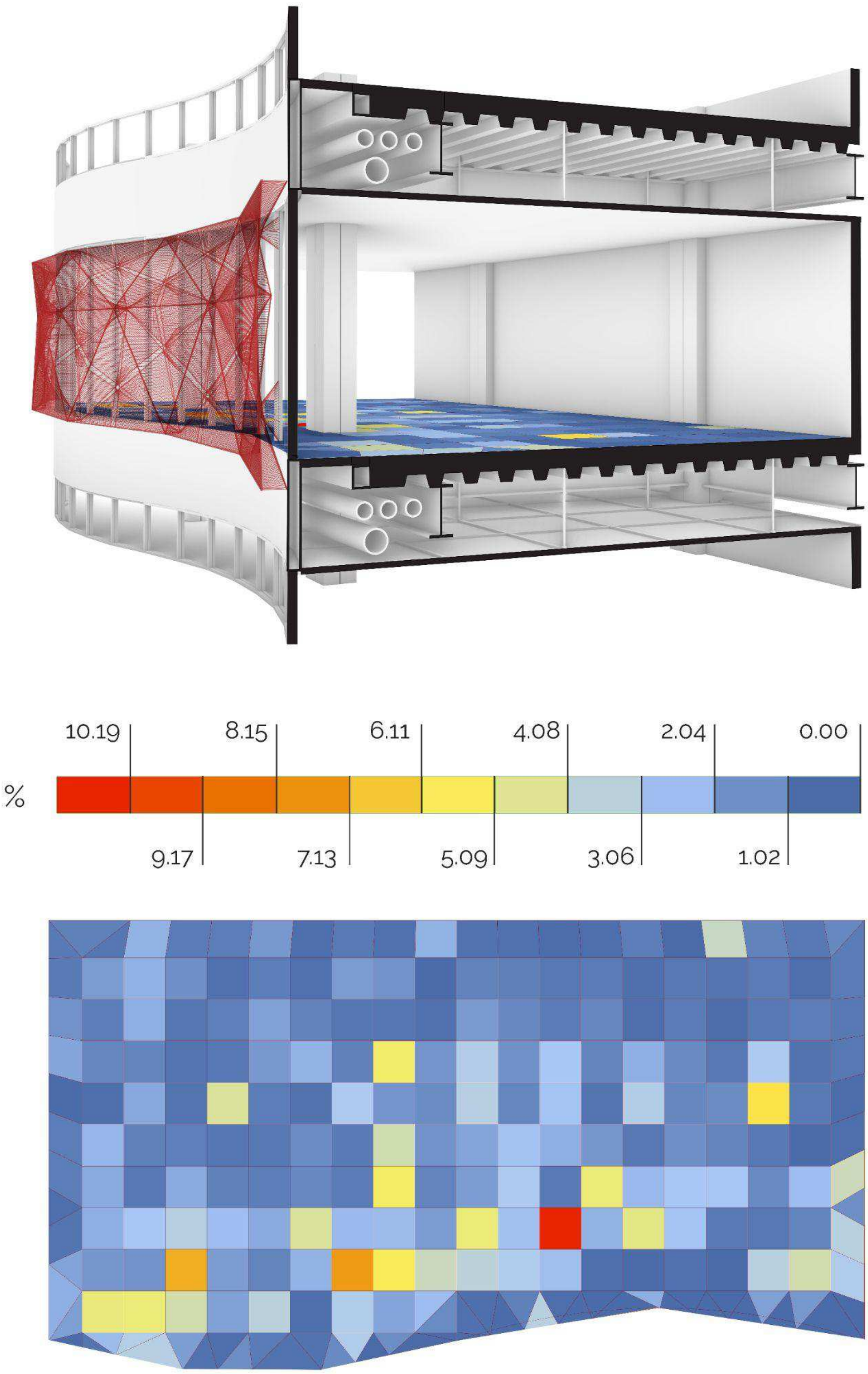
The results of the calculation of annual daylight depicted on the section of the building used for running simulations: the output before the application of the Kinetic Woven Facade

93



FIGURE, 93

The results of the calculation of anual daylight depicted on the section of the building used for running simulations: The results after the application of the partially closed Kinetic Woven Facade (50%).



FIGURES 94

The results of the calculation of annual daylight depicted on the section of the building used for running simulations: The results after the application of the completely closed Kinetic Woven Facade (100%).

4.5.2 THE STRUCTURAL DEVELOPMENT OF THE KINETIC WOVEN FACADE

The Kinetic Woven Facade is comprised of three main components: a metal loading structure, including frames, guiding lines, and anchoring elements to the hosting wall; a PTFE membrane; and fiberglass threads (Figure 95). The metal loading structure serves as the foundational framework, providing support, stability, and the necessary infrastructure for the kinetic elements. It includes frames defining the overall structure, guiding lines responsible for the movement of the kinetic elements, and anchoring elements securing the facade to the hosting wall. Guiding spokes are implemented with a pneumatic mechanism allowing them to increase and decrease in length, moving along metal rails.

Fiberglass threads are seamlessly integrated into the membrane, enhancing its tensile strength and providing additional structural support. These threads contribute to the overall durability of the facade, ensuring resilience and longevity. The combination of the metal loading structure, PTFE membrane, and fiberglass threads results in a dynamic and responsive architectural element capable of adapting to changing environmental conditions and user preferences. The innovative use of pneumatic mechanisms adds an extra layer of sophistication to the facade's functionality, allowing for controlled and dynamic adjustments.

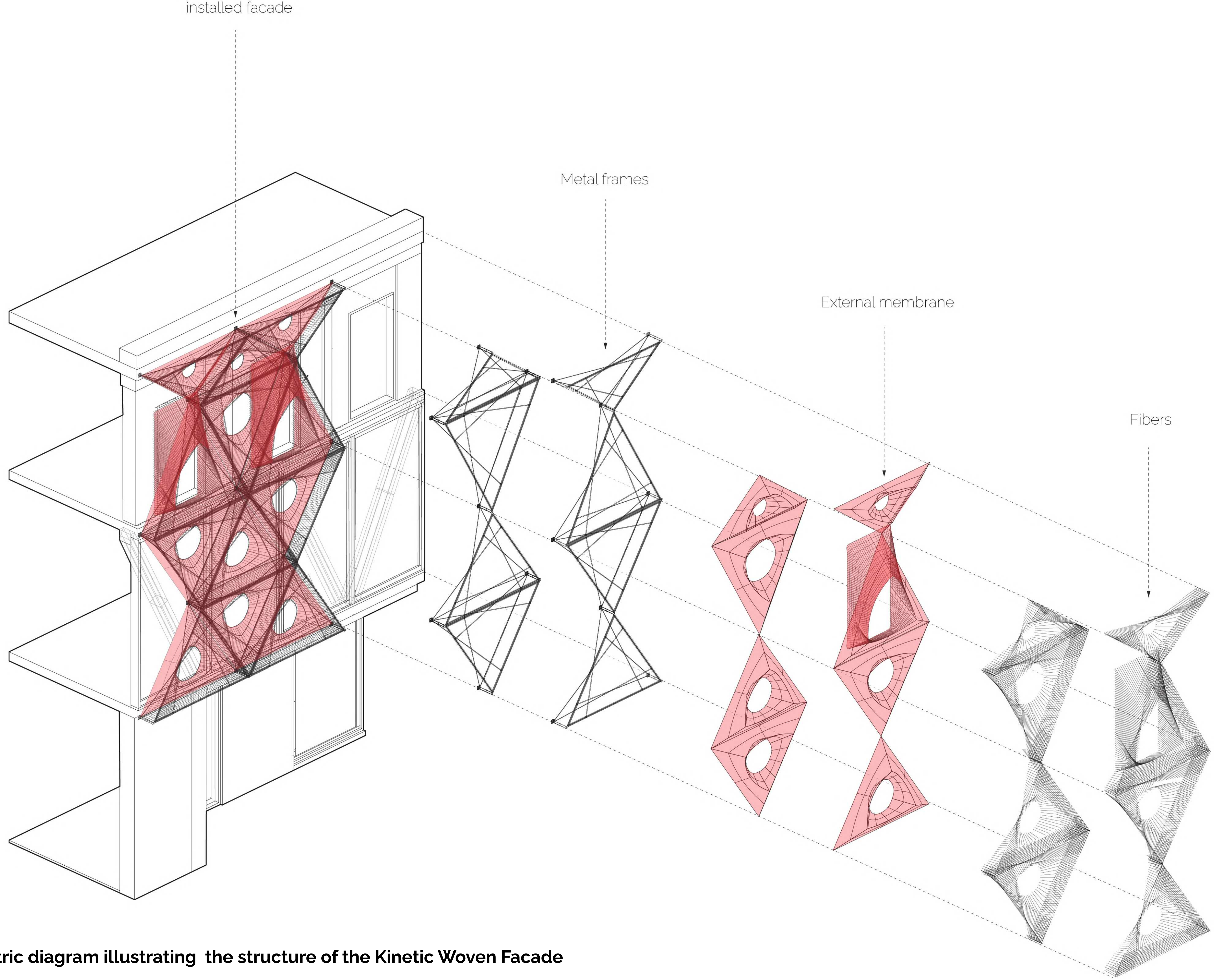


FIGURE 95
The axonometric diagram illustrating the structure of the Kinetic Woven Facade

4.5.3 THE DESIGN POTENTIAL OF THE KINETIC WOVEN FACADE WITH INTERACTION IN DIFFERENT URBAN CONTEXTS

In addition to its highlighted functional applications, the Kinetic Woven Facade showcases significant design potential and adaptability. This versatility is not confined to contemporary architecture; it extends to the reconstruction of buildings within mixed urban contexts. In such environments, where a diverse historical fabric replaces a singular historical urban structure and buildings from different eras coexist, the Kinetic Woven Facade finds a niche for its innovative design.

The transparent fiber facade distinctly accentuates the building's exterior, aligning itself with the facade grid. The slender fibers ensure minimal interference with the visual appearance of the hosting building, allowing its architectural features to remain prominent. The Kinetic Woven Facade thus becomes an elegant and adaptable design element, contributing to the revitalization and harmonization of urban spaces with varied historical layers.

Moreover, the kinetic components of the facade unfold, creating dynamic patterns reminiscent of origami, resulting in a living, breathing entity. The interplay of light and shadow on the surfaces introduces depth and complexity. The use of materials such as PTFE membrane and fiberglass threads provides a level of transparency, fostering a captivating interaction with natural light. This transparency transforms the facade's appearance during the day, as sunlight filters through, casting intricate patterns within the building interior. Thus, the Kinetic Woven Facade can be implemented alongside modern materials like electrochromic smart glass, creating a remarkable visual effect of color change with the motion of the fiber wings and the sun's path.

In summary, the Kinetic Woven Facade's aesthetic appeal lies in its ability to create a visually dynamic and responsive architectural element. The interplay of light, movement, and adaptive design contributes to a modern, engaging, and aesthetically pleasing facade that transforms the building into a unique and memorable structure.

THESIS CONCLUSSIONS

Concluding this thesis, the research embarked on an exploration that began with an extensive review of the theoretical landscape surrounding architectural concepts like *'kinetic architecture,' 'adaptive architecture,' 'transformable architecture,'* and *'responsive architecture.'* These concepts, all gravitating towards the central theme of architectural motion, were approached from distinct perspectives, yielding varied yet converging conclusions, each encompassing various aspects intrinsic to the performance of architectural motion. Expanding the purview, the research delved into other concepts, such as *'deployable structures,' 'intelligent building,' and 'biomimetic architecture,'* which, while focusing on different research subjects, acknowledged the pivotal role of architectural motion within their frameworks. Scrutinizing relevant publications provided insights into fundamental criteria, offering a nuanced understanding of the contextual occurrence of architectural motion.

These identified aspects served as the theoretical foundation for constructing the Kinetic Chronological model. The model sought to intricately weave these criteria into a cohesive cycle, investigating how the specified criteria of kinetic architecture could harmoniously coexist with the progression of the Kinetic System. The resultant theoretical model seamlessly integrated these criteria into a complex system, portraying the self-dependence of diverse aspects and categorizing them based on their influence on motion performance.The Kinetic Chronological Model, thus developed, serves as a solution to the existing theoretical disorganization and the ambiguity prevalent in contemporary literature on non-static architecture. It remains an open-ended multilevel typologization model, holding substantial potential for further refinement and adaptation as kinetic architecture continues to evolve.

Nevertheless, the derived theoretical model encompasses substantial design potential, integrating elaborated and conceptualised extensions that manifest as design solutions initiated during the project's inception, shaping the subsequent performance of architectural motion. The design methodology originating from the resultant Kinetic Chronological Model can be characterized as an expanded top-down approach. This methodology diverges from other approaches by its emphasis on the execution of architectural motion, monitoring architectural transformation at three pivotal junctures: during the input and initiation of the transition, throughout the motion itself, and ultimately, at the output phase, impacting the envisaged architectural motion.

The resulting design method was applied to practical design, focusing on exploring the design potential of elastic materials in the development of responsive envelopes. The unique characteristics of these materials offer solutions to challenges inherent in contemporary kinetic facade systems, such as adaptability to various building walls and visual comfort. The goal of maximizing adaptability in designing kinetic envelopes led to the development of an algorithm based on the Grasshopper plugin for Rhinoceros. The resulting workset can generate a Kinetic Woven Facade based on input data that reflects the configurations of the host building and the parameters of the Kinetic Facade.

The algorithmically driven kinetic elastic facade aims to protect the interior building environment from overheating and fully adheres to the primary principles of the projected Kinetic System: adaptability (1), multifunctionality through hierarchical organization (2), and visual comfort (3). Additionally, the facade's performance was tested using climate simulations based on the LadyBug and HoneyBee tools for the Grasshopper plugin. The simulation results illustrate the effectiveness of the light Kinetic Woven Facade in reducing annual daylight exposure.

Undoubtedly, the complex performance of the resulting facade necessitated consideration of additional parameters for climate simulation, including solar radiance and energy balance. However, the organized simulations primarily aimed to assess the elastic material's capacity to resist overheating. The final results clearly demonstrate the significant potential of kinetic elastic envelopes in mediating the building's interaction with the surrounding environment. Furthermore, the Kinetic Woven Facade inherently possesses significant design potential owing to its elastic fibers and transformative characteristics.

THE TABLE OF THE FIGURES

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