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Integration Strategies of Motion and Construction Systems in the architectural design of kinetic buildings

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Abstract

Kinetic architecture focuses on the design of building elements that can change their shapes, positions, or configurations in response to environmental conditions or user needs, using mechanical, natural, or smart techniques while maintaining structural stability. The research problem was to investigate methods of integrating movement with construction Systems in the design of kinetic buildings to achieve functional, aesthetic, and sustainable outcomes. The study aimed to present a theoretical framework developed through a thematic analysis of previous studies, including factors of shared movement systems, construction methods, and ways of integrating them into the practice of kinetic building design. Common motion includes turning, opening, closing, folding, sliding, and deforming that are implemented using construction systems such as articulated bars, folded plates, cable structures, membranes, pneumatic systems, smart materials, and hybrid solutions. The integration of motion and structure varies, with most projects relying on mechanical, electrical, and computational systems to synchronize motion with structure, while intelligent and interactive systems enable adaptive performance through sensors or software. Control strategies range from direct control to indirect control as well as internal control that achieve dynamic and flexible buildings capable of environmental and interactive adaptation. In addition, integration into kinetic building systems adopts a responsive or non-responsive approach. The paper specifically examined the strategies of integrating movement and structure in contemporary dynamic pavilion projects. A descriptive-analytical approach was applied to extract the characteristics of ten real kinetic case studies. A comparative analysis of these characteristics revealed that modern kinetic architecture relies on a balanced integration of movement and construction technologies, using diverse integration methods and control systems to achieve flexible, interactive, environmentally responsive buildings capable of dynamically adapting to various variables, thus enhancing innovation and aesthetics, as well as functional performance.
Keywords: *Kinetic Buildings, Motion Techniques, Construction Systems, Integration Strategies, Automated and Non-Automated Response*

1. Introduction

The concept of kinetic architecture refers to a branch of architecture that involves the use of movable or dynamic components in a building or its structure to allow the elements of a building to move or rotate without affecting the overall structural stability [1] [2]. Kinetic architecture is characterized by the ability to change its shape and position, from the size of a single component to the entire building, in response to changing conditions. [3]. Adding movement to a building is essential, as it affects structural design, aesthetics, and performance. The physical properties of movement vary according to the type of kinetic building element (surface or volume), and the location where movement occurs in the structure (roof, floor, façade, etc.) [4]. Kinetic architecture represents more than just the movement of buildings. It also involves bridging the gap between nature and the built environment in terms of environmental fluctuations [5]. Moving elements in buildings can function as interactive systems, created mechanically or through the interaction of people, air, water, and other kinetic forces.

These kinetic elements are integrated in various ways based on user requirements and responses to the external environment [6].
Actual kinetic architecture consists of a number of interconnected elements, dynamic transition structures, joints, actuators, materials, and control systems to achieve strategies for transformation and movement control within the kinetic mechanisms that make up the structure of a building [7] [8]. Advanced kinetic architecture systems are interdisciplinary and arise from the intersection of fields such as adaptive engineering, structural engineering, and computing, making them inherently related to the performance of computational techniques [9]. Kinetic architecture equipped with advanced sensors and computational techniques capable of learning from experience represents a new class of buildings known as intelligent kinetic architecture. A well-designed kinetic structural system must meet three design requirements: it must meet all necessary spatial, functional, architectural, and structural requirements; it must be economically and structurally viable; and it must achieve the desired form for kinetic transformation. A key stage in the structural design of kinetic buildings is defining the basic design requirements and the movement structure. In the first stage, the design requirements are defined, including architectural, structural, and other design criteria that determine the shape and materials of the kinetic structure and the type of conversion required. The next stage, the movement structure, involves the basic geometric design of the kinetic system, including determining the system's initial dimensions and motion geometry. Following this, the number and type of actuators, as well as the shape and type of mechanism, are determined [10].
The above information highlights the importance of both movement and structure systems, as well as their integration, in the architectural design of kinetic buildings. Therefore, the second section of this paper reviews previous research on the integration of movement systems and construction techniques in the design of kinetic architecture. Accordingly, the third section presents the research problem, which canters on the need to develop a comprehensive concept for integrating movement and structure in kinetic buildings, thereby achieving aesthetic, functional, and environmental goals in contemporary architecture. Section four presents the theoretical framework for movement and construction systems and their integration into dynamic building design. This section explores strategies for integrating movement and structure in kinetic architectural designs and analyses how various control systems (mechanical, electrical, computer, and smart) can be employed to create dynamic, flexible, interactive, and environmentally responsive buildings, while enhancing both aesthetic and functional performance. Section Five explores integration approaches through real-world case studies of contemporary pavilion designs. Finally, the research concludes with findings and recommendations.

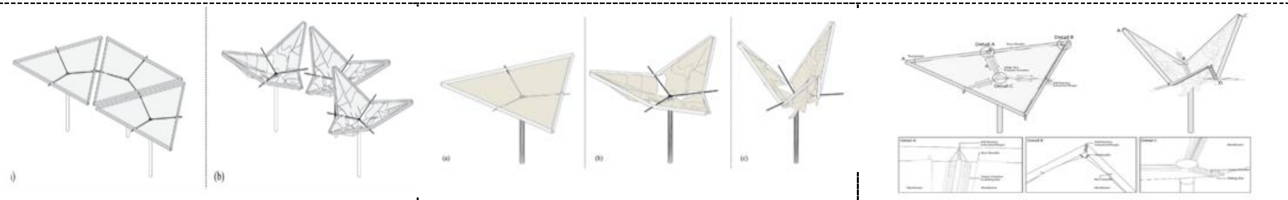
2. Literature Review

This section provides a review of previous studies on motion and construction systems and their integration in kinetic building designs.
Devi et al. examined kinetic technologies for kinetic buildings and classified kinetic structures that achieve climate response into integrated, independent, and discrete structures. They highlighted the use of multiple movement techniques such as folding, expanding, and shifting in shape or size through aerodynamic, chemical, magnetic, natural or mechanical means. The study focused on smart kinetic architecture, which is characterized by the ability to adapt and interact between moving components that operate independently without compromising structural integrity. Adaptive intelligent systems rely on sensors, centralized or decentralized control systems to achieve direct responses to environmental conditions. These responses are automatically activated by mechanically producing motion through actuators for aesthetic, functional, or environmental purposes, or in response to external environmental stimuli, within a time frame that may include scheduled changes on a daily or seasonal basis, or unscheduled changes that occur regardless of timing. The study provided examples of kinetic buildings (Figure 1) such as The Shed, which features a retractable shell that creates a hall that is controlled in terms of light, sound, and temperature when fully deployed over an adjacent outdoor courtyard. In addition, Al Bahr Towers used an automated exterior moving shading system, consisting of several canopy-like glass elements that automatically open and close depending on the intensity of sunlight to improve the climatic and functional performance of the building while maintaining its structural integrity [6].

The Shed | Al Bahr Towers

Fig. 1: Examples of kinetic buildings [6]

Kavuncuoğlu et al. pointed out that recent advances in building technology, robotics, computational design, and materials science have made it possible to design and manufacture practical and intelligent moving components for buildings. As a result, there has been a growing interest and demand for kinetic building systems and their applications. This demand is driven by the need for functional flexibility, adaptability to environmental conditions, sustainability, and improved structural performance. The study focused on the use of the Bricard mechanism as a structural component in the design of kinetic blinds (Figure 2), which provides significant advantages such as simplicity, lightness, and ability to control movement with a single motor. The Bricard linkage mechanism is a well-known type of motion joint in architecture and represents a mechanical mechanism based on only six elements and six three-dimensional moving joints. This design allows for precise control of the opening and closing of the canopy according to the changing needs of shading and protection [10].



Shift pattern for three canopy structures | Steps for transforming into the proposed Bricard linkage canopy structure | Detailed Drawings of the Canopy Structure

Fig. 2 : The Bricard mechanism as a structural component in the design of kinetic canopies [10]

Vazquez et al. focused on a digital workflow for the design of kinetic curtains based on the principle of binary stability, through a case study involving the shading of an office space. The study developed intelligent shading systems based on shape-shifting materials inspired by the mechanisms of plant movement (mimicking vitality). They introduced a new design strategy focused on integrating finite element analysis (FEA) software and daylight simulation, supporting the development of flexible and efficient shading systems without the need for complex mechanical mechanisms. A manual process was adopted as a prototype in preparation for the transition to intelligent operation at later stages. The research demonstrates the design of kinetic facades using flexible materials such as carbon fiber, allowing the panels to switch between two stable shapes without consuming continuous power [11].

Torres described the design of a portable, assembleable event stage based on folding structural systems using horizontal and radial scissor mechanisms to form a semicircle. The movable structure, as shown in (Figure 3), allows the stage platform to be deployed in a vertically oriented semidome. It consists of four components: the basic structure, the folding floor, the sawable arches, and the membrane. The system is based on a radially divided semicircle, with a fan-like radial sawing motion, and double scissor bows class. To achieve horizontal expansion of the basic structure, each beam is subsequently connected via a hinge at the ends of the beam that converges towards the central point, creating a fan-like opening motion. Load-bearing wheels were used to facilitate the movement of the beam, as well as hydraulic cylinders that provided the power required for deployment. The closure process is achieved through the mechanism of cables and pulley. The engineering exploration was carried out through digital modeling and gradient models to study motion and potential defects, with the aim of achieving a lightweight, stable and flexible structure [12].

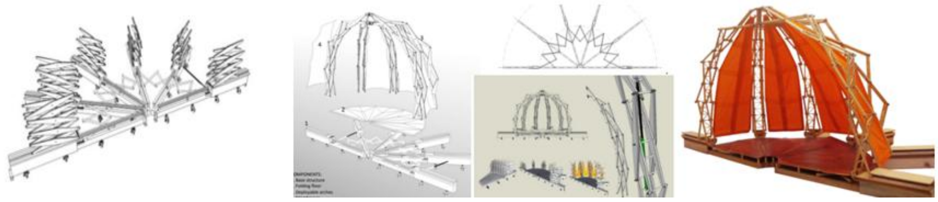


Fig. 3 : Design of a deployable stage based on the application of scissor-type structures [12]

Hussein et al. studied free-form convertible structures (FFTS), as promising solutions for creating flexible and adaptable structures (Figure 4) capable of freely changing their shape to meet diverse functional and aesthetic needs. The paper provides an algorithmic framework for designing, evaluating, and developing a prototype that achieves the required movement while overcoming certain design and technical challenges, improving efficiency, and reducing complexity and cost. These structures are based on the principles of dynamic kinetic architecture and are classified according to mechanisms such as spatial grid structures, scissor-like elements (SLEs), and pantograph systems. They combined multiple transformation modes such as curtains, beams, loops, and polyhedral shapes. The study reviewed previous models, including a double scissor structure that achieves multiple bends, and modified scissor elements that reduce the number of actuators and cost. The study classified the mechanisms and analyzed their effectiveness, and presented a prototype developed using Grasshopper 3D and Kangaroo 2 to evaluate performance in the simulation of transmitted shapes [13].

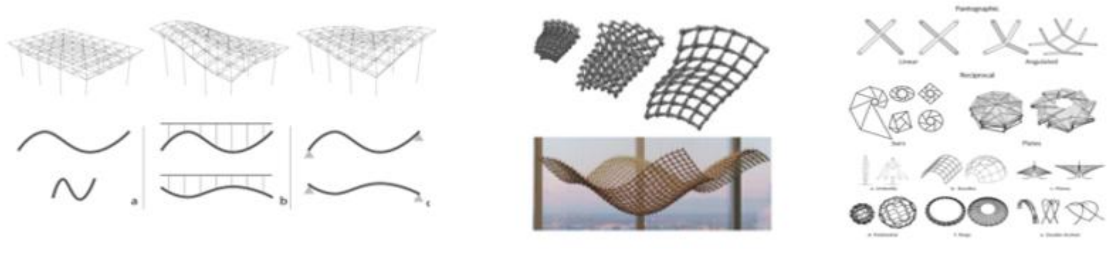


Fig. 4 : free-form transformable structures [13]

Fenci & Currie addressed deployable structures that have the ability to transform into multiple configurations along predefined and secure paths, facilitating movement and assembly, and promoting sustainability. These structures fall into two main categories: deployable and detachable/reconfigurable structures, with a greater emphasis on the former. The study referred to Merchan's (1987) classification of moving structures, including: vertical structures (elements that bear tension or pressure, such as scissor mechanisms), surface structures (continuous surfaces made of rigid plates or flexible materials), inflatable structures (depending on gas or liquid pressure), and telescopic structures (sliding tubes for volume adjustment). The study also cited Gantz's classification, which includes: planar structures such as scissor mechanisms, two-dimensional panels (including non-deformable membranes such as origami), cable and membrane systems (disassemblable and reconfigurable), pneumatic structures (air-filled or air-supported), tensile structures, and retractable roofs. and spatial structures, where structural weight is neglected during deployment and can be used on the ground or in space [14].

Jeong et al. highlighted the importance of interdisciplinary design in developing effective and sustainable adaptive facades that can effectively enhance a building's energy performance through intelligent adaptation to sunlight, thereby improving indoor user comfort. The study emphasizes the integration of architectural design and mechanical engineering to achieve flexible and reliable solutions using advanced technologies such as switchable connections and cable control systems. A prototype of a system called "KineticSKIN" is designed and built to intelligently redistribute solar energy and enhance indoor comfort. This was achieved by integrating performance-based architectural design with daylight simulation and mechanical motion analysis through an interdisciplinary approach that combines architecture and mechanicalism. The study focused on the development of switchable connections and cable control systems to achieve accurate and efficient movement. In addition, it emphasizes the importance of exploiting solar radiation for energy sustainability while providing user control over light levels, views, and other parameters, as shown in (Figure 5) [15].

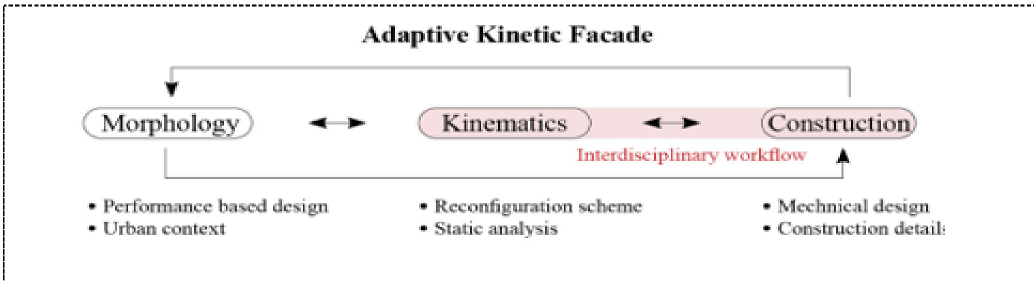


Fig. 5 : KineticSKIN design process with interdisciplinary workflow [15]

The "KineticSKIN" is adaptive kinetic facade system starts with a unit consisting of two folding wings as shown in (Figure 6), the angles of which can be adjusted to balance light gain or shading according to seasonal changes. Several prototypes were developed: the first flexible TPU material was used but was weak against wind loads; the second was fold-restricted used rubber layers; the final prototype is based on a dual cable system, which provides high precision and stability. The system allows multiple units to be connected to a single motor , which reduces the number of motors and reduces the visual effect. The folding motion is controlled by winding the cable. The simulation results showed an improvement in indoor lighting distribution, reducing excess light in summer while increasing illumination in winter [15].

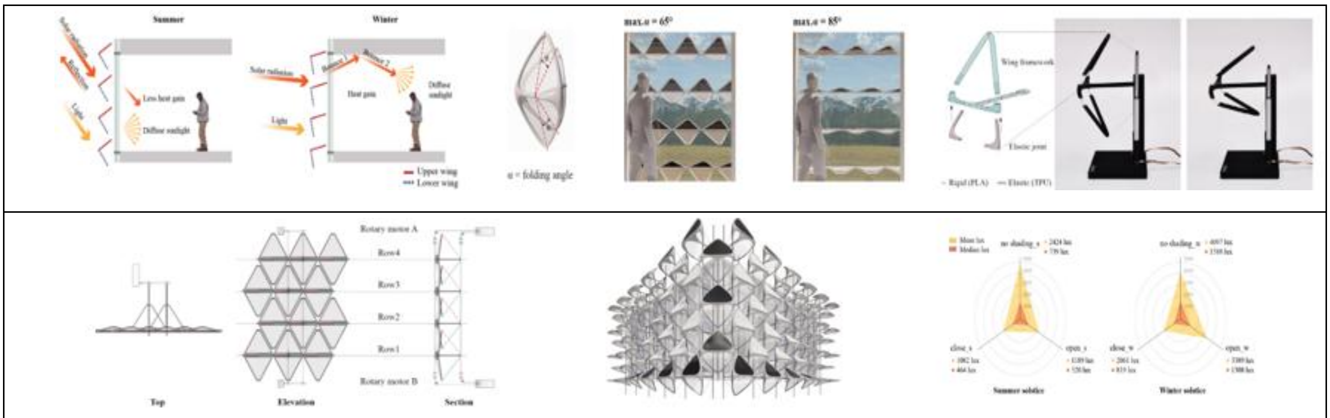


Fig. 6 : The "KineticSKIN" adaptive kinetic façade system with a unit comprising two foldable wings[16]

Table 1 shows a comparative analysis of previous studies

Table 1 : Comparative analysis of previous studies

Study	Key Points	Knowledge gaps	What will be addressed in the research
Davey et al	The use of smart motion technologies in architecture achieves an effective climatic and functional response through integrated systems that self-interact with the environment without compromising structural integrity.	Focus on limited applications for certain buildings. Lack of generalization to other types of structures.	A comprehensive study of the classifications of movement techniques in architecture. Assess the environmental performance and climate response of a wider range of structures.
.Kavuncuoğlu et al	Technological advancements in robotics, computational design and materials science have enabled the development of intelligent and flexible kinetic components in architecture, where the Bricard mechanism stands out in kinetic shading systems for its ability to move smoothly and precisely control using a single motor, enhancing adaptation to environmental conditions and improving the functionality and sustainability of buildings	Focus on one type of mechanism. Lack of focus on integration with multiple intelligent systems.	Analyze the integration of multiple motion mechanisms with intelligent systems in design. The study of the response of structures to various environmental conditions.
Vázquez et al	The Torres study shows that the use of a folding structure with scissor and radial mechanisms to spread a half dome flexibly and stablely, while incorporating hydraulic cylinders and wheels to facilitate movement, allows for a lightweight and flexible platform that can be assembled and transported, with the ability to effectively control the opening and closing.	Use of specific materials only. Failure to study long-term performance.	Evaluate various kinetic materials and solutions. Studying the impact of continuous environmental adaptation on performance.
Torres	The use of a folding structure with scissor and radial mechanisms to spread the half dome flexibly and stablely, while incorporating hydraulic cylinders and wheels to facilitate movement, enables a lightweight and flexible platform that can be assembled and transported, with the ability to effectively control the opening and closing.	Focus on temporary structure only. Failure to study sustainable performance or environmental adaptation.	Study of permanent and temporary deployable structures. Performance and sustainability analysis.
Hussein et al.	Freeform convertible structures provide flexible and adaptable solutions, relying on scissor and mesh mechanisms to change shape freely, while improving efficiency and reducing complexity and cost through a digital simulation design.	Focus on prototyping design without extensive actual application. Lack of focus on integration with smart systems:	Develop verifiable prototypes Intelligent control integration of convertible structures
Vinci and Corey	Deployable structures provide a flexible and sustainable solution, with the ability to safely transform into multiple configurations, and their classification includes scissor, surface, inflatable, telescopic, and pneumatic structures, facilitating movement, assembly, and reconfiguration.	Focus on theoretical classification. Lack of practical practical examples.	Testing and evaluating deployable structures in practice. Integrate the classification of structures with real-world applications.
Jeong et al	The development of adaptive facades such as "KineticSKIN" is based on an interdisciplinary	Limited number of prototypes.	Develop scalable models.

	design that combines architecture and mechanical engineering, enabling precise and efficient movement of folding modules, while optimizing the distribution of interior lighting and the utilization of solar energy, enhancing the interior comfort and sustainability of the building.	Lack of long-term performance study of interfaces.	Studying the long-term performance of adaptive interfaces.

The comparative analysis of previous studies reveals that each study was limited to a specific strategy for kinetic construction. Practices in kinetic architecture have applied different methods and approaches to achieve the integration of movement and structure. Accordingly, the research problem in this paper can be identified as the lack of comprehensive knowledge about the strategies of integrating systems of construction into kinetic buildings. The research aims to identify these strategies in kinetic design theories and applications, and to investigate them in contemporary kinetic pavilion practices. Data from the kinetic pavilions were then collected, analyzed, and the results drawn to reach conclusions that illustrate general trends in the development of kinetic architecture.

3 . The Research Problem, Aim and Methodology

Based on previous studies, the research problem focuses on the need to build a comprehensive conception of integrating movement and construction in kinetic buildings to achieve aesthetic, functional and environmental goals. This research aims to identify the strategies of integrating movement and structure in kinetic architecture designs, and recognise how different control systems (mechanical, electrical, computer, and intelligent) are employed to achieve dynamic, flexible, interactive, and environmentally responsive buildings. To achieve this goal, this paper presents a theoretical framework derived from the thematic analysis of the theory and practices of kinetic architecture, highlighting common movement, construction methods, and ways to integrate them into kinetic construction practices.

Finally, the framework indicators were examined in a case study of ten contemporary pavilion designs. The criteria for selecting cases can be traced back to the following:

1. It was designed by different architects in diverse areas.
2. These cases represent contemporary trends in kinetic architecture, demonstrating a clear innovation in the integration of movement and construction.
3. Sufficient documentation is available to describe cases including official websites and academic publications.

The paper adopted a qualitative descriptive approach in analysing a set of ten case studies of contemporary kinetic pavilion buildings. The results were statistically evaluated using percentages in a comparative analysis of movement types, construction systems, integration strategies, and control methods.

4. A Framework for Integrating Motion and Structure in Kinetic Architectural Designs

The theoretical framework aims to present motion and construction systems in kinetic architecture. It identifies their integration strategies and highlights their roles in shaping buildings capable of adapting to changing conditions. Movement systems is defined in terms of the types of movement required in buildings, construction systems outlines structures and systems that support this movement, and integration strategies result from responsive or unresponsive control methods that coordinate both movement and structure.

4.1. Types of Motion Methods

In the context of architectural design, motion is simply a means of changing position.[4]. Building motion is one of the methods of form-making and serves as a means of expressing architectural ideas. Dynamic motion involves the integration of technologies within buildings, where transformable mechanical structures change according to climate, need, or function [16]. Dynamic motion affects architectural form-making methods, compositional patterns, and structural and design techniques. It enables the creation of sustainable architectural configurations that adapt to climate conditions while meeting indoor environmental standards. Producing dynamic architectural forms requires the integration of construction techniques, lightweight and adaptable materials, as well as advanced control systems [17]

Following Stevenson's classification, the types of transformations occurring in kinetic architecture, as illustrated in (Figure 7), are deformation, folding, deployment, tensioning, sliding (translation), and rotation. Deployable structures do not necessarily conform to a single type of transformation; rather, they may result from a combination of two or more transformation types [14][18]

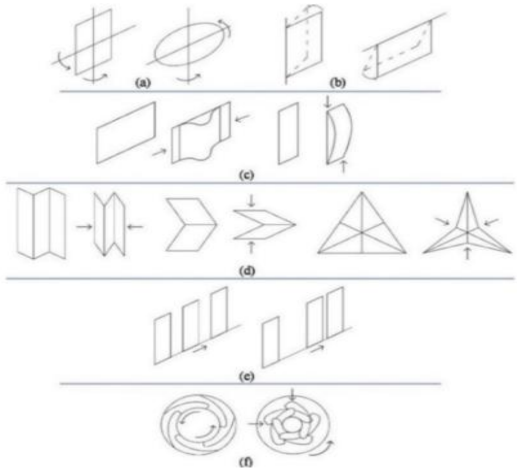


Fig. 7 : Movement Types: (a) full rotation; (b) oscillatory rotation; (c) deforming; (d) folding; (e) sliding; (f) hybrid [18]

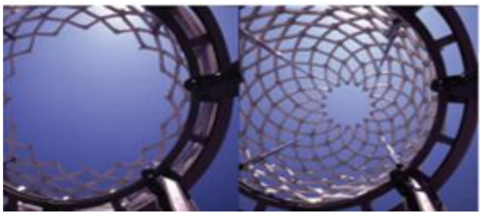
4.2. Types of Construction Systems Based on Motion Methods

Construction techniques for shaping moving surfaces vary widely. Escrig and Korkmaz emphasized the importance of distinguishing between deployable and demountable structures which helps to achieve a more accurate functional understanding. [19]. These structures can be classified into specific categories based on various criteria, such as the type of structural element within the assembly, its mobility, the joints that connect it, the geometric and kinetic properties of the system, as well as their applications in specific engineering fields. Kinetic structures that move through rotation, sliding, folding, or deformation can be grouped into the following categories:

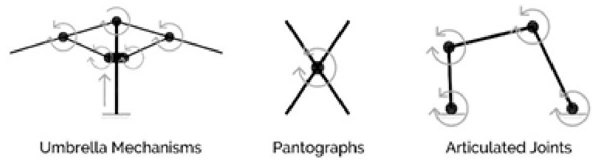
4.2.1. Construction Systems Based on Articulated Bar (Hinge) Motion

These structures consist of bars and joints, which can be used in single units or arranged in a network (pantograph). They carry loads through structural elements subjected to tension, compression, or bending (Figure 8) [20]. For example, Hoberman's Iris Dome is composed of elements connected via joints, which are essential structural components in kinetic systems. Motion is typically enabled through two-dimensional or three-dimensional mechanisms. These mechanisms use various types of joints to transfer force and motion and to connect elements together. Joints are defined according to the type of connection between elements.

There are kinematic double joints, classified as simple or complex. In complex double joints, linear or point contact occurs between elements, and they are usually employed in intricate designs. Architectural applications often utilize rotational, sliding, spherical, cylindrical, helical, or planar joints[21][22].



Hoberman's Iris Dome[21][22]



Schematic description of Bar Structures [20]

Fig. 8 : Construction Systems Based on Articulated Bar (Hinge) Motion

The scissor mechanism is considered one of the fundamental units of kinetic structural systems. Scissor-Like Elements (SLEs) are characterized by a pair of rigid bars (straight or angled struts) connected at their intersection by a rotational joint [20]. In the case of straight bars, the joint is located either at the midpoint of the metal bar or at its end; whereas in angled bars, the system includes single-angle scissors with a single intermediate joint [23].

4.2.2. Construction Systems Based on the Folding of Flat Sheets

These structures consist of continuous surfaces (Figure 9) in which some parts endure only tensile forces. This category includes structures made of rigid panels or flexible materials, where folding can occur in both types depending on the type of connections between elements. Folded structures differ in their geometric form, the type of base on which they are implemented, the performance method, the way stiffness is formed, their function and position in the building, and the materials from which they are made [24].

The term "folded structure" refers to a folded form of surface-based constructions in architecture, including structures derived from elements that create a folded system through their spatial interrelationship [25]. Examples include folded structures formed from flat folded surfaces, such as those in the three types shown in the figure 9: Linear Additions, Combination of Additions, and Radial Additions [24][25].

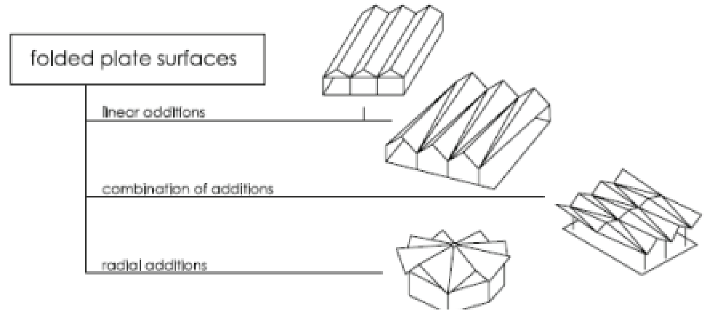


Fig. 9: Folded plate surfaces [25]

4.2.3. Construction Systems Based on Tension and Stretching of Cable and Membrane Structures

This type relies on cables or flexible membranes to carry loads and shape the structure. Cable-and-pulley systems are important construction techniques used to produce movement and achieve structural stability and final form, [8][14][19]. Membrane and cable structures depend on tensioned cables and stretched fabrics to achieve stability and their final shape, with the cables distributing the loads and fixing the tensioned membrane. In this technique, membranes only achieve stiffness and stability under biaxial tension.

Frei Otto classified membrane structures according to a movement matrix: some systems have a supporting structure that remains fixed during movement, while in others, the supporting structure moves along with the membrane [20]. A remarkable example of kinetic architectural structures using primarily flexible devices is the retractable roof built in 2006 at Kufstein Fortress in Austria by Kugel + Rein (Figure 10). Combinations of rigid and flexible devices can form hybrid systems such as deployable tensile structures [8].

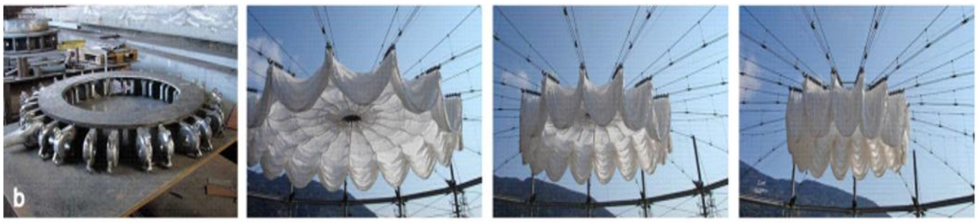


Fig. 10 : The retractable roof built at the Fortress Kufstein, Austria by Kugel + Rein[8][9]

4.2.4. Construction Systems Based on Shape-changing Using Inflatable and Pneumatic Membrane Structures

This category includes pneumatic structures that rely on air to form and support the structure. There are three main types of pneumatic systems: (a) air-inflated structures, (b) air-supported structures, and (c) compressed-air structures with integrated deployment mechanisms [8][14][20]. One example is the Floating Theatre (Figure 11) designed by Yutaka Murata and engineered by Mamoru Kawaguchi. The theater was formed using three high-pressure inflated tubes connected to a single-layer membrane. This structure is considered deformable and can change form through folding or expansion [8][14]

Fig. 11 : Floating theatre [8][9]

4.2.5. Construction Systems Based on Shape-changing Using Smart Materials

Smart materials play a crucial role in kinetic walls and adaptive, interactive building façades due to their intrinsic properties, which allow them to change their physical or morphological characteristics in response to environmental or electronic stimuli without an external energy source [26]. These materials possess extraordinary capabilities to alter their mechanical, electrical, or visual properties, their internal structure or configuration, and/or their functions to achieve desired behaviors [8]. They can

convert energy in response to environmental stimuli or computer-controlled inputs [20] and have the unique ability to "re-member" and return to a pre-defined shape when exposed to a specific trigger [17]. Smart materials operate across different scales, including sensors and actuators functioning as independent systems [27].
An example of smart material application is the ShapeShift project (Figure 12) designed by Manuel Kretzer, which features rapidly responsive kinetic membranes reacting to climatic conditions, especially sunlight, to provide intelligent shading using electroactive polymers (EAPs). ShapeShift explores new possibilities for architectural embodiment and "organic" kinetics. EAPs are polymer-based actuators that convert electrical energy into muscle-like motion, changing their shape accordingly. In the field of active materials, EAPs stand out due to their high deformability, rapid response, low density, enhanced flexibility, and lightweight properties[21][28].

Fig. 12 : the ShapeShift project [17]

4.2.6. Unique Hybrid Kinetic Construction Systems

These technologies combine more than one kinetic building system within a single structural mechanism. A notable example of this is canopy structures, which are considered hybrid systems because they integrate the principles of articulated structures and cable membrane structures. These systems typically consist of a central mast (fixed part) that supports a folding membrane structure [23].
The classification of kinetic canopy structures is generally divided into three main categories [29]: kinetic membrane structures, kinetic rigid rod structures, and kinetic rigid plate structures. One of the most well-known examples is the kinetic parachutes at the Prophet's Mosque in Madinah, Saudi Arabia (Figure 13), which were installed in the mosque's courtyard in 1992. These awnings combine functionality, climatic (shading and ventilation), symbolic and aesthetic dimensions, representing one of the earliest large-scale applications of kinetic canopy structures in contemporary Islamic architecture [8] [30].

Fig. 13 : The kinetic umbrellas at the Prophet's Mosque in Medina [30]

4.3. Strategies of Integrating and Combining Motion with Construction Systems in Kinetic Buildings

Strategies that integrate movement with construction systems enable the kinetic system to become an integral part of the building, both functionally and structurally, rather than an addition. In other words, they refer to how motion interacts with the building's construction method, structure, materials, and systems to perform a specific purpose (environmental, aesthetic, interactive, functional, etc.), rather than merely providing decorative movement. The strategies of integration between motion and the structural system can be defined according to the following variables:

4.3.1. Types of Integration Systems

Integration methods can be implemented through various control systems, including mechanical, electrical, computational algorithmic, intelligent, manual, natural, and others. A control system is a device or a set of devices that manages, commands, directs, or regulates the behavior of other devices or systems [31]. These systems control the movement of the structure through the structural design of the building itself [32].
Any mechanical system requires an energy source to operate (Marcin Brzezicki, 2024), which may come from other energy sources as well. These can be natural sources such as gravity, solar energy, or wind energy [8]; or other means of motion to perform the kinetic structural solution, such as thermal, electrical, mechanical, pneumatic, hydraulic, biological, chemical, or magnetic energy [8][20].
In computational and digital integration, digital technologies and software are used to design and control the kinetic system. Software systems manage the movement of kinetic parts, such as dynamic façades, operable surfaces, or environmentally responsive elements. Advanced computing provides the capability to respond to changing environment [28].

The use of embedded computational systems within the building structure is increasingly present in contemporary envelope proposals. They can be employed to collect, process, and intelligently utilize information to control structural behavior and regulate internal comfort conditions [8]. One notable example is the interactive kinetic wall of the Aegis Hyposurface project (Figure 14), designed by Mark Goulthorpe of dECOi Architects. It consists of a mechanically moving surface that expresses motion through computer control methods, computational design, and digital fabrication techniques. [8][31]

Fig. 14 : The Aegis Hyposurface project [31]

4.3.2. Methods of Control and Management in the Integration of Motion and Construction Systems

Methods of motion control vary, as the operation of movement can be directly performed by the user (manual operation), automatically through sensors and computer systems, or a combination of both human and automated control. Motion control mechanisms represent a central aspect of properly designing and constructing movement according to the constraints and challenges associated with kinetic operation, such as human and environmental interaction.

Computer-based control systems that manage the movement of kinetic elements consist of a central processing unit (CPU), software systems, sensors, programs, and actuators. Sensors detect environmental changes or user interactions, while the software executes actuator movement based on sensor inputs. The CPU manages communication between sensors, software, and actuators [1]. Automated control systems in kinetic construction consist of the following components:

Inputs: Represented by sensors and various input methods, providing different information about the surrounding environment. There are five input methods: manual input, sensors, detectors, pre-existing internal information, manual programming, and the internet. [31][32]

Control Units: Represented by the computer responsible for decision-making and issuing commands, receiving information from input systems, and buffering actuators that move the structure [31][32]

Sensors: Sensing technology is used as a computer-based control mechanism to accommodate and respond to changing needs. They are widely applied in adaptive architecture to provide data for automatic adjustments. Sensors can interact with the environment and detect conditions inside and outside a particular adaptive building, enabling movement. Not all architectural kinetic systems respond directly to human requests; many respond primarily to environmental changes via sensors. These devices collect information from the physical environment, such as wind speed, temperature, light levels, air pressure, air quality, and noise levels, and provide data for dynamic environments [27][33]

Smart sensors operate in four areas. They perceive individual comfort at different times of the day and year, detect changes in building function or use, monitor changes in occupant characteristics, and track variations in annual average outdoor weather conditions [27] .

Three methods of motion control can be classified as direct control, indirect control, and internal control, as follows:

Firstly: Direct motion control: In this category, motion is directly actuated by one of the multiple energy sources (Figure 15) including electric motors, human power, or biomechanical changes in response to environmental conditions or user preferences. An example of this is a glass roof with a simple rotation system that can be applied to produce multiple geometric configurations. The motor is directly controlled to achieve three-dimensional transformation resulting from a single sliding movement [3][34][35] .

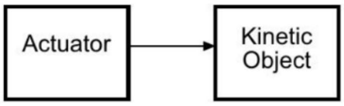


Fig. 15 : Direct control diagram [3][35]

Direct control may occur through human intervention, such as manual operation, where users retain the ability to adjust or stop the architectural movement mechanism. [9][36] An example of this is the Sharifi Ha House in Tehran, Iran (Figure 16), which represents a flexible modern residential design consisting of three movable boxes employing rotation techniques to achieve dynamic façades that adapt to weather conditions and the functional requirements of the floor plan according to user needs. This allows the adjustment of indoor light levels while providing formal flexibility that overcomes site constraints and narrow façades. The three rotating rooms remain closed when the outside weather is cold but can be rotated up to 90 degrees to optimize sunlight. All of this can be executed with a single button press via manual user control [6][32]

Fig. 16 : The Sharifi Ha House in Tehran [32]

Secondly- Indirect motion control: It occurs when the control system is separated from the motion operator through sensors and detectors (Figure 17). Motion is indirectly triggered via a sensing and feedback system. The control process begins with external inputs being received by the sensor, which then transmits a signal to the controller. The controller sends operational instructions (on/off) to the energy source to activate movement. Indirect control represents an individual autonomous response to a single stimulus. [3][34][35].

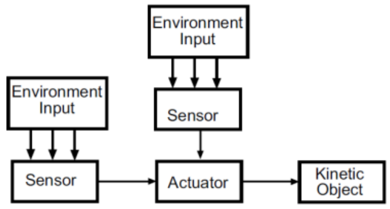


Fig. 17 : Indirect control[3][35]

In kinetic architecture, software systems collect environmental data, such as temperature, light intensity, sun orientation, and wind speed, then analyze this data using programmed algorithms and issue commands to the control systems. This integration of computational techniques has enhanced kinetic systems, where computer control is fully integrated via location-sensing devices connected to the architectural elements. It has increased adaptability in kinetic buildings, as modern movable panels routinely incorporate sensors and actuators that respond to environmental factors, such as sunlight, temperature, and user interactions [3]. Indirect control systems can be classified into the following types:

a – Ubiquitous Responsive In-Direct Control: In this type, motion results from multiple pairs of independent sensors and actuators functioning together as an interconnected network. The control system requires a predictive and self-adaptive feedback algorithm. Responsiveness and adaptability are achieved through the integration of sensors and actuators as individual elements, opening the door to the development of more intelligent kinetic systems (Figure 18). An example is the kinetic wall shown in (Figure 18 - left) which acts simultaneously as both structure and envelope—a rigid yet flexible membrane or cladding system that can be used either as a temporary structure or integrated into an existing one. The system is essentially an assembly of basic cellular designs. To facilitate movement by allowing each panel to be individually controlled relative to its adjacent panels, a cable is suspended at the rear side of the two vertical members of each cell [3][34][35].

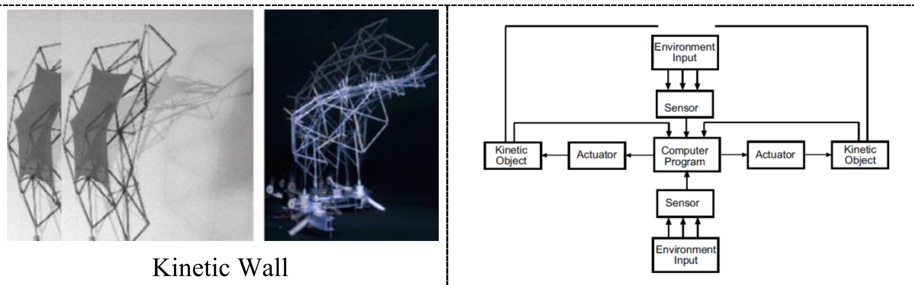


Fig. 18: Ubiquitaire responsive indirect control [3][35]

b– Interactive and Responsive In-Direct Control: In this type, the basic system for operating motion is similar to that of the indirect control system (Figure 19). However, the controller may make decisions based on inputs from multiple sensors and then issue an optimized command to the power source in order to activate the motion of a single element (Figure 19 - right). For example, a large deployable tent system (Figure 19 - left) can be integrated into multiple stable structural configurations, incorporating a distributed sensing system that responds to natural lighting conditions [3][34][35]. Another example of interaction with light is the design of a roof canopy for an outdoor plaza at the Central Market in Abu Dhabi (Figure 20a). The designers created a kinetic shading system that functions as an operable network. In its covered configuration, the shading roof resembles a hollow canopy. Each complete unit actually consists of multiple openings operated by a single motor arm.

Macro-mod folding tents

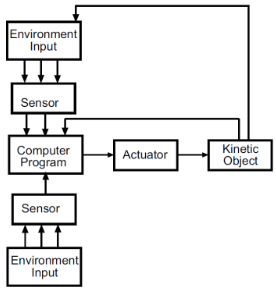


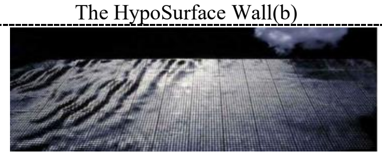
Fig. 19 : Responsieve indirect control[3][35]

Responsive indirect control is also exemplified in the HypoSurface Wall designed by Mark Goulthorpe of dECOi Architects (Figure 20b). The project consists of an interactive mechanical surface that deforms in real time in response to various environmental stimuli, including sounds, human movement, weather conditions, and electronic data. The HypoSurface is composed of an array of actuators, each receiving positional information via a high-efficiency bus system combined with a set of electronic sensors. An example of interaction with sound is the Sljivancanin Sound-Responsive Wall (Figure 20c), which is made of cellular components that respond to different stimuli by opening and closing cells that absorb sound and emit light. Another example is interaction with wind, represented by the Super Cilia Skin (Figure 20d), a tactile and visual system inspired by the beauty of grass swaying in the wind. It consists of an array of computer-controlled actuators mounted on a flexible membrane. The visual qualities of the surface change significantly depending on weather conditions and the time of day.[31]

A roof canopy for an outdoor plaza at the Central Market(a)

The HypoSurface Wall(b)

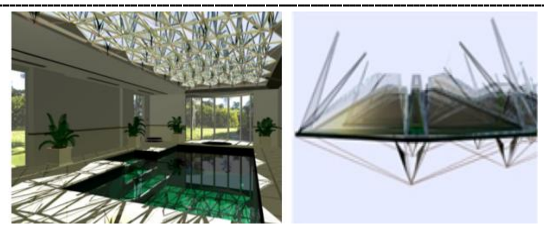
The Sljivancanin Sound-Responsive Wall(c)

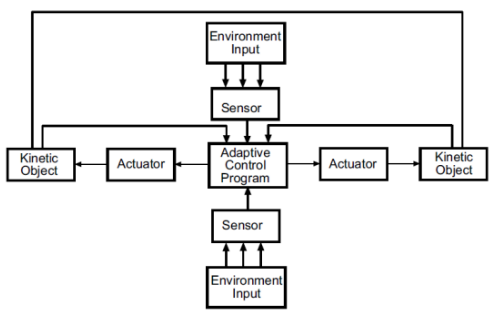


The Super Cilia Skin(d)

Fig. 20 : Examples of Interaction with Environmental Stimuli[31]

c- Heuristic, Interactive and Responsive In-Direct Control: At this level, movement relies on either individual or collective responsive actions that are capable of self-adaptation (Figure 21). The systems learn through successful experimental adaptation to enhance overall performance within a dynamically changing environment. An example is the use of an interconnected system of individual windows that operate together to optimize thermal comfort and daylighting conditions. Each unit consists of eight individual panels that slide along four straight tracks toward the center of the frame, creating an open configuration. The system maintains structural stability throughout all stages of deployment of the individual units. One corner of each unit contains a single cable attached to an electric motor, which actuates the deployment of the entire unit by sliding this joint toward the center. Integrated control is achieved through a set of localized sensors attached to each panel [3][34][35].





Responsive Skylights

Fig. 21 : Heuristic Responsive In-Direct Control[3][35]

Thirdly- Control systems can also combine both direct and indirect methods: An illustrative example can be found in interactive envelopes or façades that employ smart materials, such as the Flare-façade system (Figure 22). The Flare dynamic façade is a modular system that can be installed on building façades or any wall surface, creating a "living skin" that enables the building to interact with its surroundings. It is composed of a series of uniform metallic flake units capable of tilting, directly controlled by computer systems to generate variable surface patterns, producing three-dimensional mechanical animations. Alternatively, the flakes can be controlled individually by pneumatic cylinders to generate changing surface patterns. Furthermore, control can be achieved through sensor systems located both inside and outside the building, which transmit their data to the Flare system, enabling indirect interaction and response.[8][17][30]

Fig. 22 : The Flare-façade system[17]

Fourthly- Internal control: depends on the intrinsic structural properties within the system itself, which contribute to defining or transferring motion between components. This category includes deployable and movable kinetic construction systems (Figure 23).. These systems have the capability for mechanical movement within the structure but do not incorporate a direct control device or active control mechanism. An example is the Folding Egg, a prototype foldable paper-like structure demonstrating internal control. It is made from low-cost recyclable material and forms a three-dimensional, foldable, and stable structure [3][34][35]

The Folding Egg

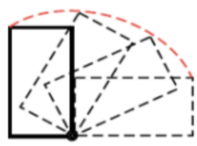


Fig. 23 : Internal control diagram [4][35]

Smart materials capable of independent movement fall within this internal control approach, as their composition provides them with a form of mechanical autonomy. This means that their intrinsic material structure endows them with "embedded microscopic properties" that enable large-scale kinetic behavior, which is programmed during fabrication.

4.3.3. Types of response automation in kinetic construction systems

Kinetic construction systems vary in their response to external stimuli, ranging between:

a. **Irresponsive Integration**: including kinetic buildings do not automatically react to the surrounding environment. They are operated manually, via buttons, or through pre-programmed schedules that are not linked to real-time input from environmental conditions or user interaction. These systems differ in their movement timing, which ranges from non-automated to automated:

Firstly- Non-automated movement is operated based on user intervention without present timetable.

Secondly- Predefined (automated) movement determines motion timing and patterns in advance. It is pre-programmed and scheduled according to the preset timetable.

b. **Responsive Integration**: including kinetic buildings respond directly to environmental changes or user interactions through intelligent control systems and sensors. Responsive architecture is defined as a shape-changing building that moves and reacts based on external factors, enabling interaction with the environmental conditions and user activities. [26] . Such systems often include mechanical units that control the movement of elements according to environmental data or user needs [18]. Responsive kinetic construction systems differ in their timing of response, which ranges from non-automated to automated:

Firstly- Non-automated Response: Movement is interactively operated either manually by the user or pneumatically with the wind. In this case, elements move directly without motors, sensors, or control systems.

Secondly- Adaptive and Real-time Automated Response: Movement adjusts according to environmental changes, user activities, or functional requirements. Feedback mechanisms, such as sensors, monitor environmental outputs adapt the structural movement accordingly. In this approach, motion and construction systems are integrated in buildings that dynamically adapt to environmental or functional conditions, requiring a fully integrated combination of architectural design, mechanical systems, and responsive technologies. Such buildings often include moving parts, self-reconfiguring components, or elements that adjust their positions in real time. This results in immediate, interactive, and responsive motion, where building components react directly to environmental stimuli—such as light, temperature, wind, or sun orientation—or user inputs. Examples include smart interactive roofs, walls or façades that rely on sensors and control systems such as motors and softwarein which a façade opens automatically under strong sunlight, or a roof opens in response to improving weather [7][35] .

5. Exploring the integration of kinetic structural systems for contemporary exhibition pavilions

In the following sections, the paper presents descriptive analysis of kinetic structures of ten case studies of contemporary kinetic pavilion designs.

5.1. Serpentine, A Capsule in Time (2025) in London, United Kingdom, designed by Marina Tabassum

It is a lightweight rectangular wooden structure (Figure 24) designed as a temporary exhibition pavilion, filled with semi-transparent panels to enhance a sense of community. It diffuses and immerses light upon entering the space, forming a vaulted enclosure with tunnel-like domed ends composed of four separate arched units. The pavilion incorporates a distinct architectural kinetic mechanism, represented by one of the capsule elements capable of movement, which can be repositioned to alter the spatial configuration of the pavilion. The motion relies on an underground hydraulic mechanism responsible for shifting part of the structure (the roof or capsule) by a precise distance (approximately 1.4 meters) [37][38][39].

The analysis of this pavilion reveals that its movement is based on direct control, where the operation is non-automated. The capsule or roof is manually activated when needed, primarily to provide shaded space accommodating up to 200 people during events. The kinetic structural system's response is therefore non-automated, as the pavilion's movement does not occur automatically in reaction to sensors or direct user interaction, but rather through manual operation of the hydraulic mechanism when required—for instance, during events—to move the capsule or roof

Fig. 24: Serpentine, A Capsule in Time[37][39]

5.2. Kinetic Pavilion at the Radíč Chateau (2024) in Radíč-Sedlčany, Středočeský kraj, Czechia designed by Huť Architektury Martin Rajniš

The pavilion incorporates wooden columns and a transparent wooden roof composed of 16 movable panels(Figure 25). This mechanism allows the pavilion's appearance to be transformed into different configurations while also enabling adaptation to environmental conditions through the opening and closing of the panels. The panels operate via a lifting and rotational mechanism along a circular track through a hinged system, indicating the presence of operable supports controlled by mechanical joints. Steel cables connect the roof elements to provide balance and stability against external forces, preventing frame deformation during panel movement.

The movement of the panels in the kinetic pavilion is controlled by an automated system remotely managed via electronic controls, which implies the use of electric motors to actuate the panels. Being reliant on automated systems and computer control, this movement may follow pre-set schedules while sometimes responding interactively in real time to environmental conditions. The control is based on intelligent software and algorithms that precisely determine the timing and direction of panel movement The feedback system integrates the computerized control system, which manages panel movement with high accuracy, and the surrounding environmental variations such as light, temperature, and wind. This system relies on sensors that continuously monitor environmental conditions and transmit data to the computer system, which processes the information and makes appropriate decisions to move the panels in a smart and interactive manner.[40][41]

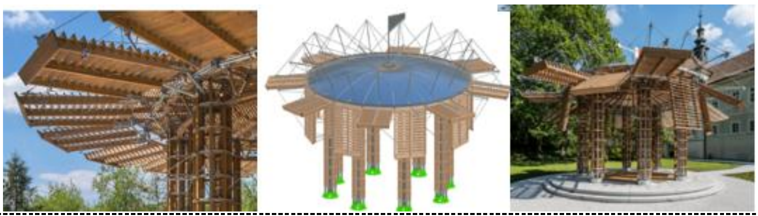


Fig. 25: Kinetic Pavilion at the Radíč Chateau[40][41]

5.3. The UAE Pavilion at Expo (2020) in Dubai, United Arab Emirates designed by Santiago Calatrava

The roof design reflects the movement of the falcon's wings during flight (Figure 26). Sustainable elements, such as photovoltaic panels, are integrated into the roof structure, animating the entire building when the 28 mechanically articulated wings, made of Fiber-Reinforced Plastic (FRP) and Carbon Fiber-Reinforced Plastic (CFRP), are deployed. The wings rotate at angles of 110° and 125° and vary in three lengths, each supported by multiple control points. The rotation is managed by 46 specialized synchronized hydraulic actuators, relying on hinges at the steel rib bases, which allow the wings to pivot smoothly. The movement is governed by custom-developed software, operated by nine computers controlling over 2,000 points across the pavilion. The system collects and analyzes data from sensors to make precise operational decisions. This setup allows for pre-programmed, meticulously scheduled movements, based on solar, wind, and shading studies using sensor inputs, implemented through 3D simulation modeling. Due to the large size and heavy weight of the wings, deployment relies on up to three synchronized hydraulic cylinders, which operate precisely to prevent uneven motion that could cause structural cracks within the pavilion itself.[42][43]

Fig. 26: The UAE Pavilion at Expo[42][43]

5.4. The Indian Pavilion at Expo Dubai, United Arab Emirates (2020) designed by CP Kukreja Architects

The Indian Pavilion (Figure 27), is a four-story structure was conceived in a trapezoidal form. The design represents India in motion, capturing the transformative aspects of the country by bringing this dynamism to the façade. The architect chose to express this through a kinetic façade composed of rotating elements—a mosaic of movable panels. The façade consists of 600 individual metal modules mounted on a large steel framework with modular steel components that are recyclable.

The movement of these modules during the day produces dynamic patterns across the façade. Pre-programmed sequences allow the modules to form specific patterns, which can be adjusted according to sun orientation at the push of an internal button, functioning similarly to an automated curtain system. The modules can also respond to environmental conditions, such as sun direction or heat. The rotation and movement of the modules are controlled via gears, axles, and electric motors, which individually rotate each unit. Digital programming is used to generate patterns and display sequences based on environmental conditions or visual presentation requirements. Additionally, sensors are incorporated to enable certain movements to respond to light intensity and solar conditions, further enhancing the interactive and adaptive qualities of the pavilion façade.[44][45]

Fig. 27: The Indian Pavilion at Expo Dubai[45]

5.5. The Polish Pavilion at Expo Dubai – United Arab Emirates (2020) designed by WXCA

The Polish Pavilion at Expo 2020 Dubai, a three-story structure (Figure 28), employs a modular wooden box structure surrounded by kinetic aluminum units. These units flutter naturally and automatically with the wind, without the use of motors or control systems, evoking flocks of birds in flight or leaves fluttering in the breeze—a motif that is also repeated in the pavilion's interior. The units are arranged in a regular geometric grid, occasionally forming radial patterns. They appear suspended in a manner that allows individual or collective movement, such as swaying or slight rotation around their connection points. This movement implies the presence of flexible or rotating joints between the unit and its supporting element. Tension cables or thin wires are used as key components for suspending or supporting the units, enabling the kinetic behavior while the anchor points and primary supporting structure remain fixed.[46][47]

Fig. 28: The Polish Pavilion at Expo Dubai [47]

5.6. The New Zealand Pavilion (2020) in New Zealand designed by Jasmax

The designer focused on integrating a kinetic façade made of a unique architectural mesh called Kaynemaile, a lightweight double-layer system that animates the exterior appearance of the Pavilion (Figure 29). It was designed to create a striking liquid-like effect, which can ripple and move interactively in response to an audible pulse emanating from the building. The "digital pulse" effect integrates motion and sound into a fully immersive sensory experience. This effect extends beyond the building façade, covering the interior walls and reaching the river hall, enhancing the sense of a pulsating flow unifying the entire pavilion. A sequence of digital animated waves is programmed alongside a synchronized sound system, making the rhythmic pulse appear to ripple across the shiny exterior mesh.

Sensors distributed along the path detect the presence or movement of visitors, sending this data to a central system via WatchOut, which analyzes it and generates appropriate responses, including lighting, sound, digital ripples, and other effects. The central control system ensures synchronized multimedia output with movement, lighting, and even real water effects. The mesh is fabricated as a single piece, supported by angled metal frames (painted steel or aluminum) and installed with top fixation and bottom tensioning to achieve the desired wave form. The black mesh is supported from behind, with prominent frames at the top. Its structural function is to carry and shape the mesh, while the base and bottom roof, finished in glossy black metal or polished aluminum, serve both aesthetic and structural purposes, supporting the lower edges of the façade.[48][49]

Fig. 29: The New Zealand Pavilion [48][49]

5.7. The Dancing Pavilion (2016) in Brazil designed by Guto Requena Studio

It is an interactive pavilion for temporary use,. The pavilion features an interactive architectural appearance, showcasing the integration of architecture with advanced technology (Figure 30). The exterior of the metallic envelope consists of various colors suggesting diversity and reflecting the vibrant spirit of the country. The outer cladding consists of 824 square metal panels measuring 87 × 87 cm, each containing 500 rotating circular mirrors with a diameter of 60 cm at the center of the panel. These mirrors rotate fully in the horizontal direction and open and close, producing continuously changing patterns and visual effects under sunlight.

External systems (software, sensors, motors) were used, where the discs are rotated mechanically by electric motors controlling the individual motion of each disc via a small stepper motor. Sensors inside the building capture music and the movement of dancing people. The data collected by the sensors are processed by a computer program to activate the motors, thereby animating the mirrors on the façade and creating dynamic movement of the panels. The kinetic system—from mechanical gearing to software—represents an advanced integration of architecture, precision mechanics, electronics, and interactive programming (cyber-architecture). The pavilion, known as the Dancing Pavilion, exemplifies a sophisticated type of kinetic construction technology, with mechanisms belonging to the category of single-axis movable façades driven by small motors. The hybrid technologies in the Dancing Pavilion combine a fixed steel structural system forming the supporting frame with an external cladding of metal panels incorporating mechanical-electrical motorized units that allow precise control of movement.[50][51]

Fig. 30: The Dancing Pavilion`[50][51]

5.8. Madrid Umbrella Pavilion, Expo 2010, in Shanghai, China (2014) designed by 3Gatti

A facade system of operable steel canopies was designed to provide shading for the glass façade during summer while allowing more daylight penetration in winter (Figure 31). When fully extended in a flat position, the canopies block most of the sunlight and protect the interior from strong winds. However, daylight can enter the building when the canopies are partially or fully opened. In such a configuration, the canopies create an attractive star-shaped pattern and are designed to be non-resistant to wind loads, which prevents structural stress in the event of hurricanes. The architects employed perforated Corten steel to form the surface of each canopy, in addition to the infill panels between them. Each canopy is operated manually through a simple mechanical pulley system, which eliminates the need for motors, sensors, or computerized control. This design allows visitors to open and close the canopies. The pulley mechanism acts as a manual kinetic device that moves each canopy via a spring-loaded central hinge [52][53].

Fig. 31: Umbrella façade of madrid-pavilion [52]

5.9. One Ocean – Thematic Pavilion for Expo, Yeosu (2012) in South-Korea, designed by soma architecture

The theme of Expo 2012 was "The Living Ocean and Coast", which was represented by the One Ocean Pavilion (Figure 32). The pavilion features a kinetic façade design inspired by biological motion mechanisms. The façade integrates moving lamellae into the building envelope, operating through a system of repetitive joints that emulate the motion of fish gills and the overlapping of fish scales. More than one hundred lamella-like panels are installed, allowing sequential opening and closing movements that generate wave-like patterns across the entire façade, visually simulating the dynamic motion of the ocean. The lamellae are actuated by rotational mechanical joints and axes, driven by servo motors positioned along both the top and bottom edges of each panel.

The kinetic system consists of 216 servo actuators, all coordinated through a centralized computer-controlled unit. This unit continuously receives feedback from the actuators regarding each panel's position and performance, using embedded sensors. Such feedback is essential for coordinating the movement and producing the intended dynamic façade patterns. The system is adaptive, responding to environmental conditions such as wind, temperature, and solar radiation—for example, the façade automatically closes when wind speeds exceed 12 m/s. Notably, the movement is not solely derived from the mechanical joints but also from the inherent behavior of the material itself. The lamellae are fabricated from GFRP (Glass Fiber Reinforced Polymer), a smart and flexible material capable of achieving a range of motion patterns. The material's unique physical properties—high tensile strength combined with low bending stiffness—allow for large reversible elastic deformations under axial stress. This property enables the façade elements to morph fluidly, reinforcing the biomimetic concept of the pavilion [7][18][54][55].

Fig. 32: One Ocean – Thematic Pavilion[55]

5.10. Milwaukee Art Museum "Quadracci Pavilion (2001) in Milwaukee, Wisconsin, USA designed by Santiago Calatrava

The design of the Quadcopter Wing Pavilion is inspired by the wings of seagulls soaring over Lake Michigan (Figure 33), creating a visual and structural harmony with the surrounding site. The pavilion primarily functions to welcome visitors and host temporary art exhibitions within the Milwaukee Art Museum. The structural formation mimics a bird's skeletal anatomy, creating a kinetic framework with operable wings that can open and close, allowing interior space expansion, panoramic views of the lake, and adaptive sunlight framing. The signature wings of the museum, known as the Burke Brise Soleil, represent the architectural crown of the building and function as a movable solar shading system. Each wing spans 217 feet and is composed of 72 rectangular steel fins with a constant cross-section of 330 mm, rigidly connected by steel spacers and mounted on a 48-degree inclined mast axis. Both wings are supported by rotating columns linked to all the fins. These columns are further reinforced by the main building structure.

A total of 11 pairs of hydraulically driven actuators, computer-controlled, rotate the columns 90 degrees to fully open or close the wings. The system incorporates cylindrical and helical joints within the hydraulic arms and gear rings, ensuring synchronized wing motion, which takes approximately 3.5 minutes to complete a full cycle of opening or closing. Ultrasonic sensors installed on the fins continuously monitor wind speed and direction, providing real-time input to a computational control system. When wind speeds exceed 23 mph for more than 3 seconds, the wings automatically close. This enables the system to adapt dynamically to wind conditions, sunlight, and shading requirements, making the pavilion responsive to its environment while maintaining aesthetic and functional performance[56][57][58][59].

Fig. 33: . Milwaukee Art Museum "Quadracci Pavilion [58]

6. Results:

The paper relied on analyzing the descriptions, images and videos of the ten case studies (available on the Internet) to extract the specificity of structural-kinetic integration in their designs, as clarified in Table 2.

Table 2: The results of applied motion types, construction Systems, and the integration strategies between them in the case studies of kinetic pavilion

Indicators of Integration Strategies in Kinetic Structures			Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Type of Movement	Sliding (Displacement)	Parallel Sliding	●									
		Vertical Sliding										
	Rotation			●	●	●	●		●			
	Sliding and Rotation Combined											
	Opening and Closing			●	●				●	●	●	●
	Folding				●					●		●
	Deploying				●							●
	Extension and Contraction											
	Deformation	Rolling										
		Bending / Torsion									●	
		Expansion										
	Oscillation, Swinging, or Vibration						●					
	Wave Motion							●			●	
	Other											
Construction Systems	Construction Systems s Based on Hinged-Bar Movement			●	●		●				●	●
	Construction Systems Based on Folding Flat Sheets									●		
	Construction Systems Based on Cable and Membrane Structures			●				●				
	Construction Systems Based on Inflating and Deflating Membrane Structures											
	Construction Systems Based on Smart Materials										●	

	Unique Movable Construction Systems (Hybrid)			●				●	●				
Integration Strategies between movement and Construction Systems	Types of Integration Systems	Mechanical		●	●							●	●
		Electrical			●	●	●		●	●		●	●
		Algorithmic/ Computer-Based			●	●	●		●	●		●	●
		Intelligent (Smart)			●	●	●		●	●		●	●
		Hydraulic		●		●							●
		Manual		●							●		
		Natural						●					●
		Other											
	Methods of Control and Management in the Integration between Movement and Construction Systems	Direct Control of Movement		●		●	●	●			●		
		Indirect Control of Movement	Indirect Responsive Control (Ubiquitous)		●				●			●	
			Indirect Responsive and Interactive Control		●	●	●		●	●		●	●
			Indirect Responsive, Interactive, and Inferential Control			●	●						
		Internal (Autonomous) Control				●						●	●
	Types of response automation in kinetic construction Systems	Irresponsive Integration	Non-automated movement of the kinetic structural system	●							●		
			Pre-programmed (automated) movement of the kinetic structural system		●	●	●					●	●
		Responsive Integration	Non-automated response of the kinetic structural system					●			●		
			adaptive and instantaneous re-sponse of the kinetic structural system (Real-time		●	●	●		●	●		●	●

- **Results of the types of motion in the case study of the kinetic pavilions**

The results presented in Table 3 and (Figure 34) indicate that the most commonly used movements in kinetic pavilions are 50% rotation and 60% open/close. They reveal that these movements are the most effective and flexible for various architectural uses such as spatial shifting or daylight control and ventilation. Then, folding is less than 30%, deploying is 20%, and wave-like motion and oscillation/swing are less common at 10%, usually associated with symbolic or artistic projects. Some types of movement are rare or almost unrepresented – such as stretching/contracting or twisting – reflecting limited application compared to rotation and opening/closing.

Table 3: Results of the types of motion in the case study of the kinetic pavilions.

Movement Type		Numbers of cases to which the values apply	Percentage
Sliding (Displacement)	Parallel Sliding	1	10%
	Vertical Sliding	0	0
Rotation		2,3,4,5,7	50%
Sliding and Rotation Combined		0	0
Opening and Closing		2,3,7,8,9,10	60%
Folding		3,8,10	30%
Deploying		3,10	20%
Extension and Contraction		0	0
Deformation	Rolling	0	0
	Bending / Torsion	9	10%
	Expansion		0
Oscillation, Swinging, or Vibration		7	10%
Wave Motion		6,9	20%
Other		0	0

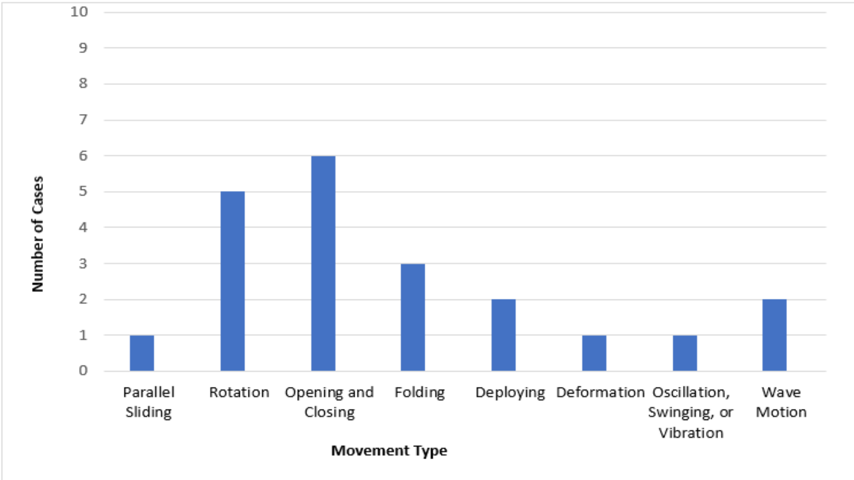


Fig. 34: Results of the types of motion in the case study of the kinetic pavilion.

- **Results of construction techniques in the case study of the kinetic pavilion**

Results of movement-related construction systems in the kinetic pavilions under investigation are clarified in Table 4 and (Figure 35). Articulated bar mechanisms are the most prevalent at 50%, appearing in most cases involving rotation or folding. Folding planar structures are less frequent, and appear in 10% of projects featuring movable surfaces or facades. Smart materials are rarely used. They implement in only 10% of systems that integrate environmental response or self-operation.. Unique or hybrid construction techniques are applied in 30% of cases that require innovative and unconventional solutions.

Table 4: Results of construction techniques used in the case study of the kinetic pavilions

Types of Construction Techniques Based on Motion Methods	Numbers of cases to which the values apply	Percentage
Construction systems Based on Hinged-Bar Movement	2,3.5,9,10	50%
Construction systems Based on Folding Flat Sheets	8	10%
Construction systems Based on Cable and Membrane Structures	2,6	20%
Construction systems Based on Inflating and Deflating Membrane Structures	0	0
Construction systems Based on Smart Materials	9	10%
Unique Movable Construction systems (Hybrid)	1,5,6	30%

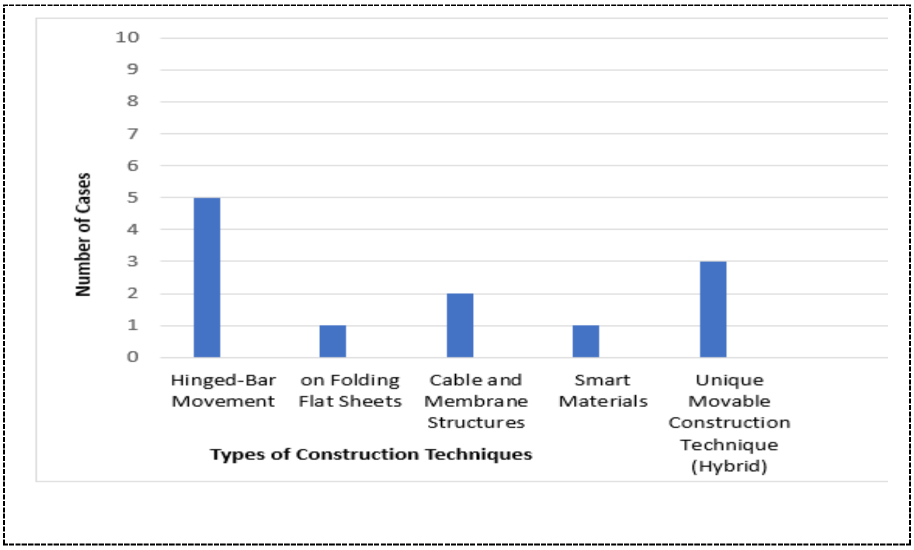


Fig. 35: Results of construction systems in the case study of the kinetic pavilion

- **Results of integration systems between motion and construction in case studies of kinetic pavilions**

The integration systems applied in constructing kinetic pavilions depend mostly on mechanical, electrical, and computational systems as clarified in Table 5 and (Figure 36), which required direct operation or digital control. In some cases, intelligent systems were used, using sensors or interactive software to adapt the movement to environmental conditions or user circumstances. Integration using manual interaction was less common at 20%, and natural interaction also appeared in 20%, which indicates the feasibility of harnessing natural forces to move parts without mechanical or electrical control. Some projects have used multiple integration approaches (mechanical + electrical + algorithm) to achieve precise and synchronous movement, reflecting multiple levels of integration in complex architectural projects, with 80% of cases using more than one type of integration system.

- **Results of control systems between motion and construction in case studies of kinetic pavilions**

Results related to control methods in Table 5 and (Figure 37) indicate the integration of the movement with structure using direct control was applied in 60% of cases, which means that many designs have controlled the movement directly, often mechanically or electrically. Responsive indirect control, which relies entirely on the independent response of the system without user intervention, appeared in 30% of the cases. (Figure 37) shows that indirect, responsive and interactive control was adopted in 70% of cases, where the system reacts quickly to environmental or user changes. 20% of cases, reflecting AI-driven or system-derived control. Internal control of the system, where the control is fully embedded in the system, was also present in 30% of cases. Furthermore, multiple indirect control methods were applied simultaneously in 30% of cases. In 20% of cases, there were two cases that combined indirect control and internal control, and one case combined the three types direct , indirect control and internal control.

- **Results of response type in case studies of kinetic pavilions**

The results in Table 5 and (Figure 38) also highlight the prevalence of responsive integration in kinetic pavilion. Non-responsive integration in kinetic construction techniques shows that there are instances of non-motorized structural system movement at 20% for predefined skeletal movement (mechanism) at 50%. On the other hand, cases representing responsive integration range from non-motorized skeletal system response at 20%, to the real-time adaptive response of the (automated) structural system at 70%. In addition, some cases combine compensatory and non-responsive integration, which represents 50%.

Table 5: Results of integration systems between motion and construction in the case studies of kinetic pavilions.

Types of Integration Systems	Numbers of cases to which the values apply	Percentage
Mechanical	1,8,9,12,15,16	60%
Electrical	1,2,9,10	40%
Algorithmic/ Computer-Based	2,3,4,6,7,9	60%
Intelligent (Smart)	2,3,4,6,7,9,10	70%
Hydraulic	1,3,10	30%
Manual	1,8	20%
Natural	5,10	20%

Methods of Control and Management in the Integration between Movement and Construction Techniques Systems		**Numbers of cases to which the values apply**	**Percentage**
Direct Control of Movement		1,3,4,5,7	50%
Indirect Control of Movement	Indirect Responsive Control (Ubiquitous)	2,6,9	30%
	Indirect Responsive and Interactive Control	2,3,4,6,7,9,10	70%
	Indirect Responsive, Interactive, and Inferential Control	3,4	20%
Internal (Autonomous) Control		3,9,10	30%
Types of response automation in kinetic construction Systems		**Numbers of cases to which the values apply**	**Percentage**
Irresponsive Integration	Non-automated movement of the kinetic structural system	1,8	20%
	Pre-programmed (automated) movement of the kinetic structural system	2,3,4,9,10	50%
Responsive Integration- automated	Non-automated response of the kinetic structural system	5,8	20%
	adaptive and instantaneous response of the kinetic structural system (Real-time	2,3,4,6,7,9,10	70%

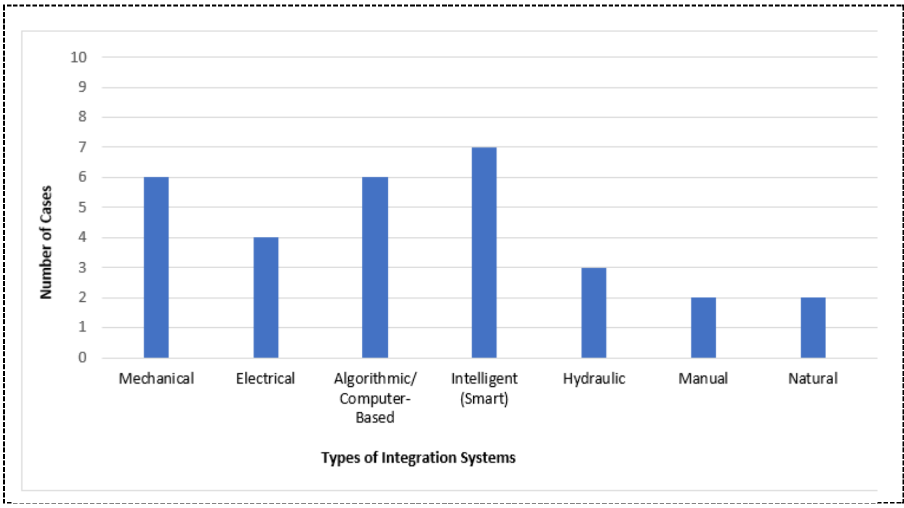


Fig. 36: Results of Integration Systems

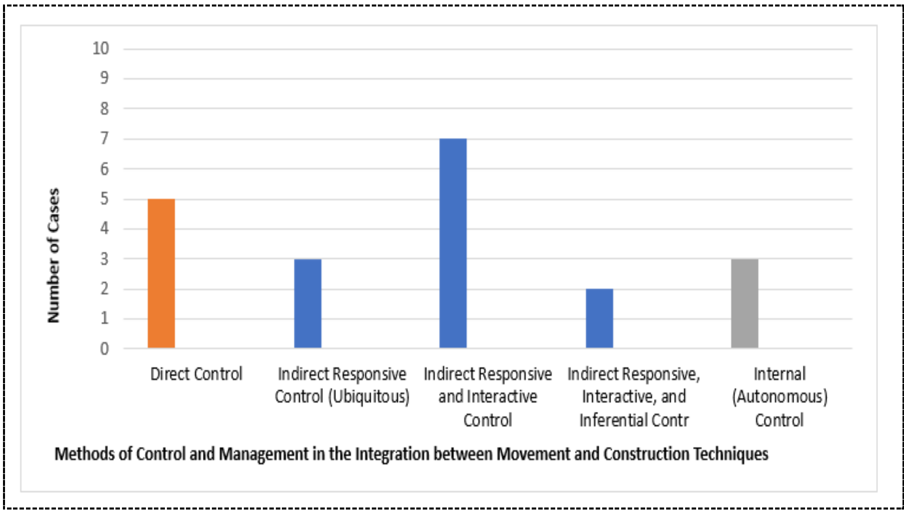


Fig.37: Results of Control and Management in the Integration between Movement and Construction Techniques

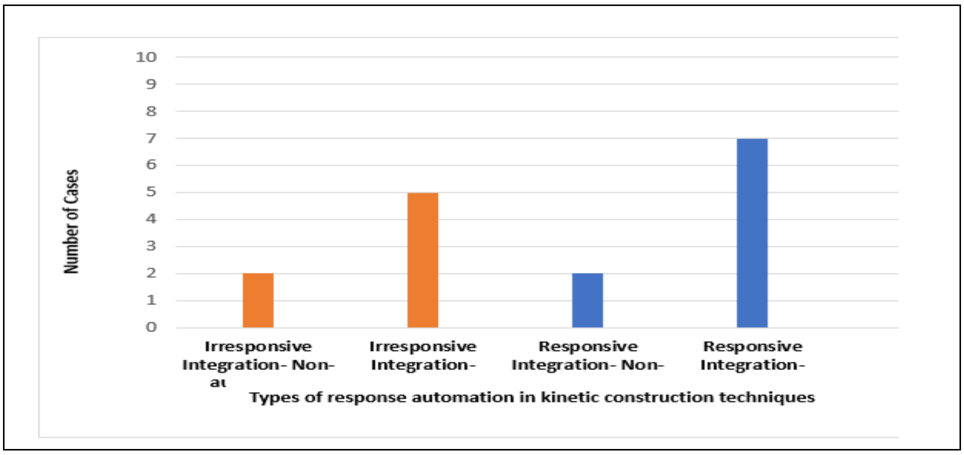


Fig. 38: Results of response automation in kinetic construction techniques

7. Conclusion:

The study proposed a theoretical framework defining movement types, construction systems, and their integration strategies in the design of kinetic buildings. Common kinetic design concepts include expansion and transformation in both volume and shape, as well as opening and closing movements. The main movement types were defined as deformation, folding, deployment, tension, sliding (displacement), and rotation. Deployable structures do not necessarily correspond to only one type of transformation; they may result from a combination of two or more. Regarding construction systems related to movement, the paper identified hinged bar structures consisting of bars connected by joints, folded planar sheet structures comprising continuous surfaces, cable and membrane structures inflatable and pneumatic membrane structures, smart material-based structures, and unique or hybrid kinetic systems which combine more than one construction technique to achieve innovative or multifunctional kinetic solutions.

Integration strategies, or the ways of combining movement and construction systems, ensure that the kinetic system becomes a fully functional and structural part of the building rather than an add-on. Integration systems can be achieved through mechanical, electrical, computational, intelligent, manual, natural, or other control systems. Movement control strategies may be operated directly by users (manual operation), automatically via sensors and computer systems, or through a combination of human and automated control. These are categorized as direct control, indirect control, and internal control. Kinetic construction systems vary in their capability to response to external stimuli. They are characterized by having either irresponsive integration, in which movements of the system occur automatically or non-automatically without responding to any external interaction, or responsive integration, wherein buildings have automated or non-automated responses to environmental changes or user interaction via control systems and sensors.

Analysis of movements and construction systems in contemporary kinetic pavilion projects shows that:

- the most common and effective motions are rotation and opening/closing. These provide high flexibility for adjusting interior and exterior spaces, controlling lighting and ventilation, and allowing direct or semi-automatic response to environmental conditions.
- Hinged-bar structures were the most widely used, especially for rotational or folding motions.
- Folded planar sheet techniques were applied in projects requiring specific movable surfaces or façades.
- Smart materials played a crucial role in systems relying on environmental responsiveness or self-actuated motion.
- Unique or hybrid techniques were employed in projects requiring innovative and unconventional architectural solutions.

The integration strategies between motion and structure in kinetic pavilions reveal that:

- They were applied using direct or indirect digital control to achieve precision and effectiveness.
- Intelligent systems, including sensors and interactive software, were used to enhance the system's ability to react rapidly to environmental changes or user interactions.
- Natural integration applied in cases where environmental forces drive movement without mechanical intervention.
- Most projects implemented more than one type of integration system, reflecting multi-level control for precise and synchronized motion.
- The results of the responsive ability of kinetic pavilions indicate a clear diversity in the degree of integration between building kinetic systems, their environment, and their functions. Some projects rely on non-responsive integration, where structural systems move in a non-automated manner or follow a pre-defined motion without directly responding to surrounding conditions. In contrast, responsive integration is futher applied, where kinetic systems react dynamically to the real-time environment or user inputs, either through non-automated interactive response or automated adaptive response. Additionally, some projects adopt a hybrid approach, combining pre-planned irresponsive motion with adaptive response, reflecting a trend toward integrating multiple strategies to achieve precise, synchronized, and environmentally adaptable movement.

In general, the results indicate that contemporary kinetic architecture relies on precise integration strategies to incorporate types of movement, construction systems, integration methods, control systems, and response patterns to achieve multiple functions, including aesthetics, sustainability, user interaction, and symbolism, while maintaining dynamic adaptability according to the environment, users, and other variables. This integration makes architectural projects more flexible, innovative, and effective.

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