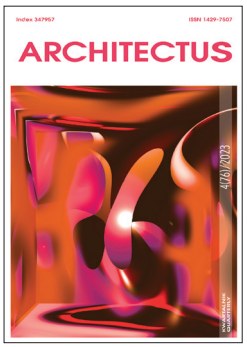

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Architecture of time: from motion picture to computer animation

Introduction

In terms of the classical architectural theory, form was defined as a static object exploring the potential of inanimate matter. The graphic representation of a static form was shown in two-dimensional image space using such means of expression as projecting, mapping, isometry or perspective, which imitated three-dimensional space. Changes in the ways of expressing architectural forms emerged with the progress of the industrial revolution and the exploration of film techniques by artists and architects at the beginning of the 20th century [1]. The forerunners of these developments were modernist architects of the Bauhaus School of Architecture, who experimented with motion picture techniques in search of a representation of architectural form in all dimensions, not only in space, but also in time [2]. They investigated the possibilities of expression of an architectural object, taking into account the influence of the observer's movement on the perception of form in space and time (discovery of kinaesthesia). They also explored possibilities of mutability of the architectural form by experimentation with dynamic states of spatial structure influenced by different inner and outer forces in time (discovery of kinematics and kinetics).

The Information Revolution of the 21st century forced rapid civilisation growth, defining the aims and directions of transformation, and creating phenomena such as virtual reality and the Internet [3], digital art and architecture [4], computer visualizations and animations [5]. The creators of the information age began to explore the world of digital media, video games, the Internet, and computer technologies. Artistic and architectural visions began to be formed by the aesthetics and content of the virtual world, creating the illusion of a four-dimensional real world.

Computer animations, which are a continuation of film techniques and allow the expression of the movement of the observer and objects in the context of space-time, appeared in the process of architectural creation as a result of using the potential of computer programs and their tools to visualize the mutability of spatial structures in time, heralding the birth of interactive and kinetic architecture. These simulations began to influence the shape of the built space, which was evident, for example, in the appearance of façades in the form of multimedia electronic screens displaying animated images [6]. There are more advanced technologies now, which allow one to simulate images as three-dimensional holograms, e.g. Leia Display System, creating the illusion of being in the real and transformable space-time [7]. Such solutions can be found in the CAVE project designed by Thomas A. DeFanti and Daniel Sandin, or i-CONE created by Martin Göbel [8]. Another important trend of the architecture of the information age is related to explorations of the interactions and mechanical movements of the elements of architectural objects, controlled by computer algorithms [9], for instance: Saltwater Pavilion designed by Kas Oosterhuis or V2Lab created by NOX. In such cases, architectural objects take the form of spatial structures that are integrated with smart networks that manage the flow of information and energy, and direct the movements and interactions between the various elements of these structures. In the near future, architectural forms will evolve from *structures with network* to *structures as network* [10]. It means that architectural objects will become the simulators of various dynamic states of spatial structures, which will enable their adaptation to changing environmental and functional challenges in time. The simulators will create a space of possibilities that will allow users to create and choose between different forms emerging in the process of simulating the changeability of architectural objects [11].

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State of research: the expression of architecture exploring the dimension of time

The formulation of a special and general theory of relativity by Albert Einstein had influence not only on the science at the beginning of 20th century, but also on the culture and art. Time and space were combined in the concept of four-dimensional space-time and related to the phenomenon of electromagnetism, which had its further consequences, which led to the creation of new theories in the field of not only physics but also the theory of the perception of reality by the human brain. Frank Wilczek compares this discovery to changing the way of seeing an image in painting from one fixed perspective to seeing it from different perspectives [12]. The change of perspectives causes the perception of the image to differ in many aspects between different points of view. This involves phenomena such as anamorphosis, which is the distortion of the spatial structure of an image by the movement of the observer in the metric field, and anachromosis – the modification of the colour of an image by the movement of a light beam while keeping its spatial structure unchanged. And it is precisely this variation in the perception of the image, resulting from the new concept of space in relation to time and movement, that has fascinated artists and architects most since the discovery of the theory of relativity.

The space of possibilities is an operating simulation model of space-time, based on the exploration of mutability of basic features of its internal structures and transformation of its attributes by using algorithms of computer programmes. Time plays the key role in the space of possibilities. According to Brian Greene [13], to illustrate the structure of space-time, one can use the metaphor of a frozen river, in which space is a channel filled with ice, and time is a sequence of cut ice slices, following one after the other, like the frames of a motion picture. This metaphorical definition can be transferred to the description of an architectural model of the space-time in the meaning of a dynamic sequence of views of an architectural form, following one after the another with the observer's movement, or it can signify a sequence of dynamic transformations of a spatial structure under the influence of various forces acting on it in space-time.

According to Dean Buonomano's classification [14], there are two basic currents in defining the ontological nature of time, such as presentism and eternalism. In the concept of presentism, only the present is real. It means that the visualization of an architectural object in three-dimensional space in the present time is a representative image of form as an expression of *here and now*. The change of point of view along with the movement of the observer entails the need to create more images and simultaneously initiate new realities, because in the concept of presentism there are no such phenomena as *before and after*. Only the approach of eternalism, incorporating the concepts of past and future as well as *before and after*, enables the expression of space-time continuity by defining places in time, in other words, by spatializing of the time. The idea of eternalism is related to the perception of spatial structures as dynamic systems, being in motion and related to places in time. Motion pictures are the best representations of architectural objects because they imitate the way the human brain perceives and reconstructs the appearance of reality.

Finding an appropriate and stimulating way of expressing time in architecture is a certain challenge, because in the traditional understanding of architecture, the spatial dimension dominates over the temporal one. A similar situation took place in visual arts – in painting, which showed the real world or imagined by artists in static motionless pictures, existing outside of time or expressing at most the idea of abstract time.

Wassily Kandinsky, the vanguard artist representing abstract modern art at the beginning of 20th century introduced the concept of time to art theory. As he wrote in his book *Point and Line to Plane* [15], people believed for ages that paintings are only dipped in space, while music happens in time, which is contrary to scientific discoveries. The image is an act of taking place in time, both in the aspect of its creation by the artist and its perception by the observer. All elements of the paintings, from point to line to surface, are characterised by a specific length of time. Translation of visual composition into musical one, and vice versa, is possible because they constitute the unity, resulting from their physical wave characteristics (image – expression of light wave, music – sound wave) and from the similarity of wave propagation in space-time. Kandinsky, in the essay *On Abstract Theatre Synthesis*, postulated the necessity of integration of all arts "architecture, painting, sculpture, music, dance and poetry" [2, p. 104], and subordinating them to a common language of expression and common rules of composition in space-time.

Time and movement played the key roles in the theater performances of Oskar Schlemmer and Kandinsky, who were the creators of avant-garde performances on the theater stage of the Bauhaus School of Architecture. Schlemmer implemented the concept of an abstract performative show as an expression of constructivist dance, in which body movements, costumes and music represented dynamic harmony between man, space and time (e.g. *Figural Cabinet*, *Triadic Ballet*, *Yellow Sequence*, *Pink Sequence* [2]), and the concept of abstract theatrical synthesis based on the analysis of the elementary components of dance composition and choreography, which was to lead to the systematization of basic geometric forms and the principles of composition of motion pictures (e.g. *Form dance*, *Gesture dance*, *Space dance*, *Scenery dance*, *Box Promenade* [2]). These concepts were partly influenced by the art theories of Kandinsky, Paul Klee and El Lissitzky.

Kandinsky's theater performances, which are a manifestation of synthetic art that unites all fields of art, were created using such means of expression as abstract forms, colors, words, sounds, music and dance figures, stimulating all the senses of the performers and viewers of these performances (e.g. *The Yellow Sound*, *The Green Sound*, *Black and White*, *The Violet Curtain* [2]). Performances of this author showed the dynamic and time-varying nature of architectural forms, resulting from the movements of spatial objects, and the dynamic and time-varying nature of the perception of these forms, resulting from the movement of the observer. Kandinsky's artistic ideas, his

theatrical performances and motion pictures exploring the dimension of time had a significant impact on modernist architecture. In his performances, Kandinsky referred to three basic aspects of movement, such as kinaesthesia, manifested in body movements (dance), kinematics, expressed in the form of choreography of movement in the setting of a theater stage (choreography), and kinetics, which is an exploration of the forces and stresses associated with movement (dancing figures).

The invention of the cinematograph at the end of the 19th century contributed to the creation of a new branch of art – film, which is the expression of motion pictures in real time. Further technical inventions of the 21st century (CGI, computer-generated images, 3D–5D images) expanded the possibilities of artistic expression of film narrative. Technologies related to the information revolution also had a significant impact on contemporary architecture, allowing one to its spatial trap, in which time existed only in the sense of presentism (*here and now*). Thanks to computer animations, it is possible to show a static architectural form as a continuous process of discovering its phenomenon by the observer in time, and in the case of dynamic forms of changing shape as a continuous sequence of moving images without losing the integrity and complexity in their perception in the sense of eternalism (*before and after*). It means that it is now possible to fully implement the concept of time spatialization in architecture and create structures that seek inspiration and explore the dimension of time, i.e. the so-called *time-based architecture*.

The development of digital technologies and architectural software allows to overcome the limitation of man's perception and analogue film techniques based on recording about 24 frames per second. Computer animation makes possible the registration of changeability of the architectural object without any frame rate limitations, because digital simulations operate in the space of bits and not in the space of the images. In computer simulations we are dealing with a category of liquid animated architecture that can be experienced in an infinite space-time continuum and can be seen at any selected moment by stopping the time of the simulation. Spatial simulations are based on different 3D software of computer animation, e.g. Autodesk Maya, Lumion, 3ds Max, Rhinoceros, CATIA, ArchiCAD, Artlantis, SketchUp, Bryce, taking advantage of the potential of digital visualizations and special effects of these programmes.

Research goals and methods

The aims of the research were to determine how time can be presented in architecture and how it can influence the shaping of architectural forms, and what means of expressing the dimension of time are most useful in architectural design. The research was based on a critical analysis of architectural visions exploring the time dimension from the modernist revolution [2], [16] to the information revolution [4], [10], [17], [18], and on a comparative analysis of contemporary trends in shaping dynamic time-varying forms, representing kinetic architecture.

The architectural forms in space-time were analyzed in different aspects of structuralism, according to which all existing objects exist in a network of structures [19]. Two basic types of network have been distinguished, the first related to the functioning of the object in its spatial context, and the second to the functioning of the object itself without its interactions with the context. The first network of structures describes the mutual relations between the observer, the object, and space-time. The process of time spatializing was examined by analyzing the observer's movement and its impact on the expression of architectural objects in space-time (kinaesthesia). The second one defines the interrelations between the elements of objects, the forces within them and space-time. These relations were investigated based on the analysis of movements and mutability of structural elements, the actions of forces and their influence on shaping of the spatial structures (kinematics and kinetics). Subsequently, binary oppositions (e.g. statics vs. dynamics, immobility vs. mobility, static image vs. motion pictures) were defined, which became the basis for a more complete analysis of the architecture exploring the time dimension, referring to different degrees of mutability and dynamics of spatial structures and related to different means of artistic expressions.

Research results: concepts of spatialization of time and their impact on the expression of architectural forms

The contemporary search for the expression of architecture, exploring the dimension of time, is a continuation of the concept of Kandinsky, who explored the potential of motion pictures as the best means of expressing the observer's movements and the dynamic transformation of an architectural object in time. The difference between past and present explorations lies in the choice of other means of expression, i.e. the transition from performative theater performances to computer animations, which are virtual simulations of the mutability of spatial structures over time.

The simulations refer to the four space-time dimensions and address a wide range of mutability of spatial structures. In the course of the research, the following types of architecture were distinguished, exploring the dimension of time, in conjunction with different types of simulations of movement and mutability of spatial structures over time:

– kinaesthetic architecture: simulations of the observer's movement and mutability of the spatial structures' perception,

– kinematic architecture: simulations of mutability of the states and geometries of the spatial structures,

– kinetic architecture: simulations of mutability of the shapes and forces affecting the forms.

Kinaesthetic architecture: simulations of the observer's movement and mutability of the spatial structures' perception

Kinaesthesia is related to the perception of the position of parts of the human body relative to each other and the movement of the whole body in the context of its spatial settings. The kinaesthetic sense of the human brain, which

determines the motor coordination of a man, is responsible for the way in which a human being is involved in relations with spatial settings. Every man is characterised by the specific kinesphere [20], which determines the individual way of moving. There are essential differences between people in this matter, resulting from age, height, or weight of their bodies, which influence on the speed of movement, horizon of view and perception of the space. The interpretation of architecture in the aspect of kinaesthesia emphasises the importance of dynamic perception of space in connection with man's movement as the most natural way of describing it. Therefore, the visualization of an architectural object shown as a static image of an architectural form in perspective is far from the way in which a person perceives the space. Only animation of images is capable of expressing the fluxion and continuity of seeing, characteristic for human brain. Furthermore, spatial simulation allows the architect to better control and verify design assumptions regarding the shaping of the architectural form.

Computer animation as a means of expression can be used to show an architectural object from the point of view of a moving man. It is an extension of the film technique in which the camera follows the observer's movement in space. The computer simulation of the observer's motion is created around a transit path, a kind of wormhole that can take many shapes and forms; for example, it can be straight or curved, horizontal or vertical, open or closed, linear or looped, single-level or multilevel. Transit paths are most often associated with communication in the urban and architectural spaces, such as streets, passages, promenades, corridors, galleries, ramps, or stairs, which determine the possible ways of the observer's movement in space and determine the directions of insight into this space.

The following important features of the architecture of time have been defined in terms of the phenomenon of kinaesthesia, which influence the degrees of mutability of the perception of spatial structures:

– transit path geometry,

– dynamics of the observer's movement along the transit path,

– orientation and position of the human body in space,

– dynamics of space flow along the transit path.

The basic elements of the observer's movement animation focus on the issues of the geometry of transit paths and the dynamics of the observer's movement. The geometric shape of the path plays an important role, because the sequence of intersection lines in the architectural perspective passes differently depending on whether the path is straight or curvilinear. Another important factor is whether the observer is moving along a horizontal or vertical path, since a change in elevation affects horizon line shifts, and the extent to which panoramic views open and close. The speed of the observer's movement also has a significant impact on the perception of space. A person moving on foot perceives space differently from, for example, a person driving a car. In contradiction to showing form only from selected static viewpoints in traditional architectural perspectives, simulations of the observer's movement in the virtual world allow to see a form as a dynamic event taking place in the space-time continuum and to better understand the interrelationships between a man, form and its spatial context (Fig. 1).

The transit path as a kind of wormhole, forming around a moving observer both in the real and virtual world, reveals important aspects of human perception related to the mental representation of the directions of space and their binary oppositions (e.g. forward or backward, up or down, right or left movement), and the sense of orientation and position of the human body in space (e.g. being in space open or closed, inside or outside an architectural object). In the process of creation of the spatial structures, many architects take into account the way a moving observer perceives space, and the dynamic game of openings and closings in architecture is addressed not so much to a static observer as to an observer in motion. For example, in SANAA's house in a Plum Grove [21], the irregular perforation of the walls of the house creates visual connections between its various internal spaces, as well as opening views to its external surroundings. The complexity and richness of these views, as well as the mutual visual interpenetration of internal and external spaces, can only be experienced in the situation of a moving observer.

Simulating the observer's movement in space is not only a tool supporting the conscious creation of an architectural form as an event in time, but also a way of thinking about the dynamics of the space itself. Architects often subordi-

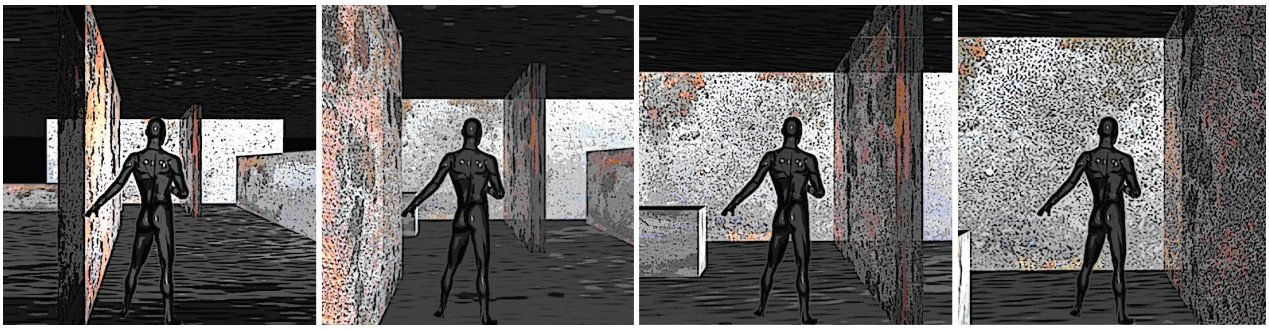

Fig. 1. Kinaesthesia: simulation of the observer's movement – a sequence of selected viewpoints in the space-time continuum (drawings by A. Kwiatkowska)

Il. 1. Kinestezja: symulacja ruchu obserwatora – sekwencja wybranych punktów widzenia w kontinuum czasoprzestrzennym (rys. A. Kwiatkowska)

nate the spatial composition to the transit path, being the original core of the concept, which determines the form of the object and generates the flow of space and events that take place along the path. For example, the Möbius House, designed by UN Studio [22], expresses the flow of space along the Möbius strip, creating a looping space-time corridor and affecting the observer's movement inside the house. Another example of a form of space flow defined by a transit path is Daniel Libeskind's The Spiral Extension [22]. The body of this object follows a deconstructed dynamic staircase, which is its central core and determines its shape.

Kinematic architecture: simulations of mutability of the states and geometries of the spatial structures

Kinematics describes the geometry of motion in terms of the position and trajectory of an object or its components in space-time without taking into account the mass and forces acting on the object. Kinematic analysis of spatial structures involves the dynamics of changes in their geometry over time, enabling the simulation of the mutability of their shapes and the control of the transformation processes of architectural objects.

Each form is created by setting in motion some element of space, for example, a point, line, plane, or solid. This movement determines the process of transformation of the spatial structure from the germ to the final shape of the form. As was described by Paul Klee:

All pictorial form begins with that sets itself in motion […]. *The point moves* […] *and the line comes into being – the first dimension. If the line shifts to form a plane, we obtain a two-dimensional element. In the movement from plane to spaces, the clash of planes gives rise to body (three dimensional)* […]. *A summary of the kinetic energies which move the point into a line, the line into a plane, and the plane into a spatial dimension* (after: [23, p. 6]).

In the process of creation, the transition from a one-dimensional to a three-dimensional geometric form is tantamount to simulation of the movement of its components. This is due to the phenomenon of the structure of space and the ways in which its geometric representation is expressed. Spatial continuity is realized in a smooth transition from a point through a line and plane to a solid. In Kandinsky's analysis of the geometric composition of dynamic space-time systems [15], a point is defined as the form with the smallest temporal extension and infinite connection possibilities in *n*-dimensional space. In architecture, a point is the result of the intersection of multiple planes, e.g. the sharp end of a solid, while in music it corresponds to a single sound. A line is the trace of a point's movement along a linear track toward infinity. The length of the line is an expression of the extension of the form in time. Linear forms and structures in architecture are equivalent to lines in painting and note lines in music. A plane is created by the movement of the line towards infinity in a direction other than itself. A field is part of the plane bounded by lines. A solid is formed by the movement of a plane in a direction other than it designates, defining the space inside and its external complement.

The following important features of architecture of time have been defined in terms of the kinematics phenomenon, manifested in the mutability of the geometry of spatial structures under the influence of real or apparent movement:

– exploration of the dynamism of the geometry of the spatial structure,

– expression of variation of geometric rhythms,

– exploration of depth in architecture,

– expression of mutability of chiaroscuro exposure of the architectural form,

– exploration of the mutability of acoustic space.

Architects are aware of the importance of these relationships and often look for the best formal means of expression to convey the dynamism of the spatial structure and the kinetic energy trapped in it. Revealing the geometric forming lines and stress lines in the structure itself is not always possible, but their signs can be seen in abstract sketches of architectural objects drawn by Daniel Libeskind, Peter Eisenman, Bernard Tschumi and Lebbeus Woods [24]. Generative design tools are best for projection of motion and time in architecture, in the sense of generating real or apparent simulations of the mutability of states and geometry of spatial structures that express the so-called kinematic architecture (Fig. 2). Generative forms are characterized by machine learning and algorithmic intelligence resulting from information management using

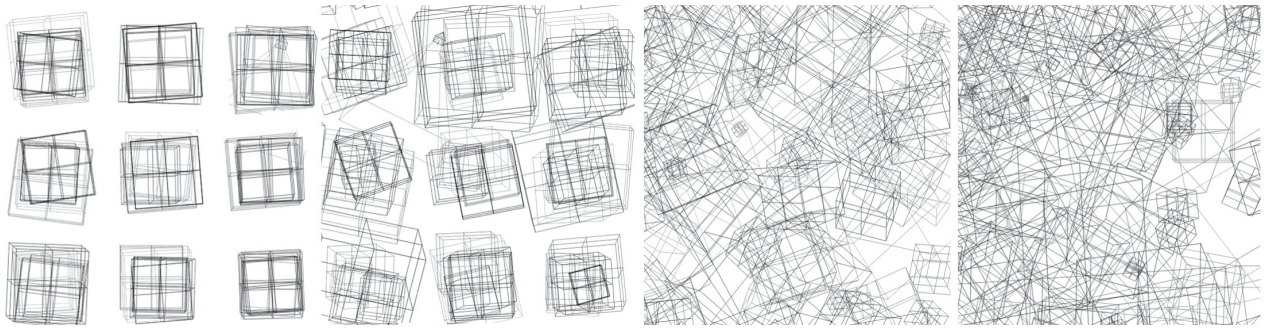

Fig. 2. Kinematics: simulation of the movement of cubes and projection of the mutability of the geometry of the spatial structures – a sequence of selected frames in the space-time continuum (drawings by A. Kwiatkowska)

Il. 2. Kinematyka: symulacja ruchu sześcianów i projekcja zmienności geometrii struktur przestrzennych – sekwencja wybranych klatek w kontinuum czasoprzestrzennym (rys. A. Kwiatkowska)

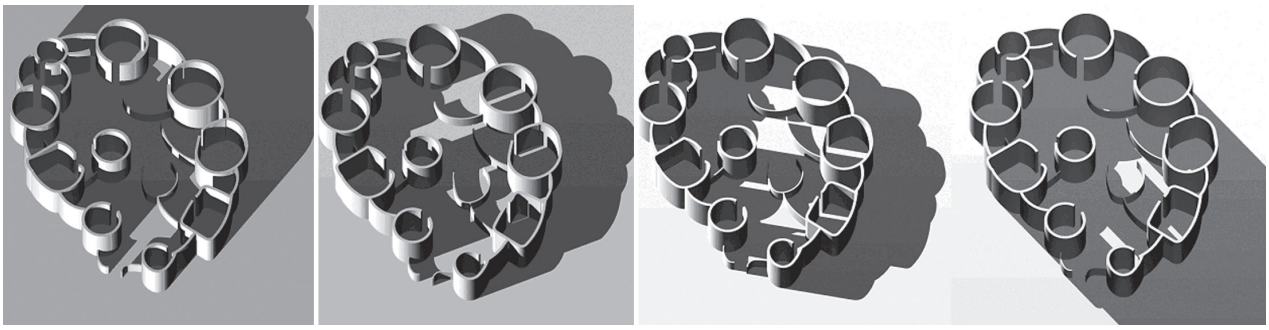

Fig. 3. Kinematics: simulation of time-varying chiaroscuro projection and projection of the mutability of the geometry states of spatial structures – a sequence of selected frames in a space-time continuum (drawings by A. Kwiatkowska)

Il. 3. Kinematyka: symulacja zmiennej w czasie projekcji światłocieniowej i projekcja zmienności stanów geometrii struktur przestrzennych – sekwencja wybranych klatek w kontinuum czasoprzestrzennym (rys. A. Kwiatkowska)

various computational models. Their shapes and geometry are the result of the mathematical operations used. These forms are defined by three basic parameters: […] *initiator (starting form), generator (set of copies and mutations of the starting form) and rule (algorithm for ordering the structural elements of the starting form)* [11, p. 101].

The manifestation of geometric rhythms in architecture by exposing regular spatial intervals, delineated by rhythmic surface divisions or accented by the rhythmic order of columns, is a kind of time measuring, giving the space dynamism and setting it in motion. An example of such a dynamic composition is the Grapevine Vibrational project by GT2P [25], which is an expression of the real mutability of the geometry of spatial structures, referring to the pattern of a dense avenue of trees, expressed in the form of overlapping systems of trellises, vibrating under the influence of the wind and creating a kind of space-time passage, measured by a specific rhythm of the spacing of the pillars and the mutability of the geometry of the grids of the trellises under the influence of the blowing wind. The simulation of the variation of the geometry of spatial structures based on rhythmic intervals is particularly visible in parametric algorithmic design. For example, the concept of Wave Interference by GT2P [25], which is an expression of the apparent mutability of the geometry of structures, defined by mathematical equations interfering with the parameters of spatial units, refers to the illusion of rhythmic movement of waves on the surface of an object.

The exploration of depth in spatial composition is another means of expression of motion and time in architecture. There are various possibilities of exposing depth, for example by creating a linear structure (passage, gallery, corridor), defining two places in time: *here and now* – the point where the observer stands, and *before and after* – the point on which the observer focuses his or her attention distant in time (forward or backward movement) or through the perforation of the walls (puncture, hole, opening in the wall), allowing for confrontation and manifestation of the distance of the foreground – *here and now* from the background visible through the opening – *before and after*, and also by manipulating the sharpness of vision or blurring the shapes of objects, suggesting their distance in time and space. Experimenting with the sharpness of the perceived architectural form is a very impressionistic means of expression, the potential of which can be seen in the Blur Building project by Diller & Scofidio [26]. The depth of architectural space is shown by the contrasting sharpness of the pier in the foreground and the fog-blurred building in the background. Computer animations are the best tools for visualizing the spatialization of time in concepts that explore the linearity of structures, play with the opening of objects to the context or or play with the sharpness of objects' contours.

Consideration of the time-varying exposure of the chiaroscuro of an architectural form often lies at the origin of the way of shaping and sculpting the tectonics of its spatial structure, as well as the manner and degree of perforation of the solid itself. In the creative process, computer simulation of a solid's exposure to sunlight is the best tool for analysing and controlling design decisions in terms of shaping the form, allowing to track dynamic changes in the perception of its plasticity and spatiality (Fig. 3). The project of the Louvre in Abu Dhabi, designed by Jean Nouvel [22], is a very impressive example of simulation and modelling of spatial structure in search of the dynamic projection of light and shadow and the geometric pattern of the dome's surface, the perception of which varies over time with the change of the angle of inclination of the sun's rays during the day.

The exploration of the acoustic space through a specific way of shaping the surfaces of architectural interiors and the conscious creation of acoustic effects associated with it (e.g., echo, resonance, amplification or silencing of sound) is the creation of architecture immersed not so much in space as in time, because the propagation and reflection of sound waves are temporal events. The idea of designing an architectural interior as an expression of the sonic potential of a space is similar to composing a piece of music, the essential components of which are the dynamics of the loudness of sounds, rhythmics, i.e. the ordering of the sequence of sounds in time, as well as melodics and colors related to the pitch and timbre of sounds. Computer simulation of the propagation and reflection of sound waves from the surface of an architectural object allows to verify how the geometry of the spatial structure affects the characteristics of the acoustic space in its interiors, including

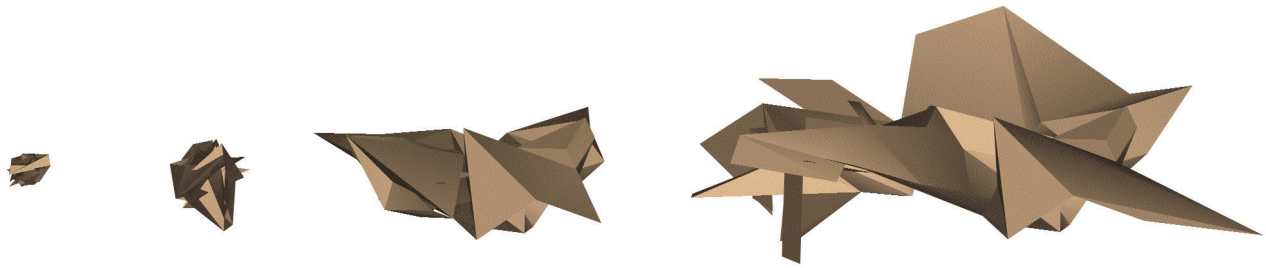

Fig. 4. Kinetics: simulation of the mutability of shapes of a growing spatial structure over time – a sequence of selected frames in the space-time continuum (drawings by A. Kwiatkowska)

Il. 4. Kinetyka: symulacja zmienności kształtów wzrastającej struktury przestrzennej w czasie – sekwencja wybranych klatek w kontinuum czasoprzestrzennym (rys. A. Kwiatkowska)

the determination of the loudness, rhythm and timbre of sounds. In turn, the acoustic characteristics alone, without original knowledge of the appearance of the space, make it possible to estimate the distances and heights of the interior of a spatial structure and to reconstruct its geometric shapes. The idea of designing an architectural form as an expression of its aesthetic and sound qualities implements Kandinsky's postulate about the necessity of creating a unity of visual and acoustic space, that is, a synthesis of architecture and music. Such a unity of sensory effects can be found in the interactive installation Edit Sp(l)line, designed by NOX Architects for the freshHtwoOexpo pavilion [22], in which the exhibition path is combined with real-time animation and a dynamic and expressive projection of lights, sounds, vibrations and shapes.

Kinetic architecture: simulations of mutability of the shapes and forces affecting the forms

Kinetics defines the activity of objects under the influence of various forces, describing their static and dynamic states. It defines how an object and its components work under the pressures of internal and external forces. Kinetic analysis is the basic tool for describing the flow of data and energy in a spatial structure, allowing the control of the operation of the structural system and the simulation of the movement of an object or its parts, as well as the mutability of shapes over time.

Kinetic forms are the expression of forces that interact with architectural objects and generate the movement of entire objects or their components, affecting the variation of their shapes or positions in time and space. The interaction of forces can be taken into account in the form creation phase in search of the best shape expressing specific forces and stresses, or it can be a kind of *modus operandi*, i.e. the basic way of functioning of a form moving in real time. According to Kandinsky's concept [15], composition in painting or architecture means the organization of living forces that reveal themselves in the form of tensions resulting from the pressure of forces on materials, which determines the shape of painting or architectural forms. Computer simulations allow to verify the impact of various external and internal forces on matter, as well as to study their impact on the mutability of the shapes of spatial structures (Fig. 4). While in the virtual space there are no restrictions with regard to the creation of moving architectural objects, in the existing reality – the implementation of such concepts is associated with many difficulties, resulting from the laws of physics (e.g. the principles of thermodynamics, the law of friction, the influence of wind, etc.) and with high operating costs associated with increased energy consumption needed to keep the objects in motion. In the near future, due to the use of intelligent technologies and lightweight materials in construction, it will be possible to go beyond the existing limitations of kinetic forms. Intelligent spatial structures of the information age will be able to move, transform and change their shapes under the influence of acting forces in real time.

The evolution of forms in 21st century architecture, expressed in the transition from stable to dynamic structures, reinforces the idea of time-based architecture, i.e. architecture exploring the dimension of time. Form as an artefact, characterized by an invariable, stable structure, is replaced by form as an event, revealing itself in space as an interactive and time-transformable structure [27]. The basic tools for the creation of dynamic kinetic forms, related to the simulation of the mutability of shapes and the forces acting on them, focus on the problem of controlling the flows of energy and information in spatial structures by encoding, controlling and interacting with them.

The following tools for creating architecture of time have been defined in terms of the phenomenon of kinetics, which have a significant impact on the mutability of the shapes of spatial structures and the movement of their components:

– coding of internal "living forces" affecting the spatial structure,

– interactive control of the flow of energy and information in the spatial structure,

– responsiveness and transformation of spatial structures under the influence of external forces.

The coding of kinetic forms is based on algorithmic design, i.e. on the development of a set of instructions defining the mutability of architectural objects in a certain time under the influence of acting internal forces, using such programming languages as text editors of architectural programs (e.g. Python, Java, C#, Ruby, etc.) or object-oriented visual scripting languages (e.g. Grasshopper 3D, Autodesk Dynamo, Rhino, Visual Basic.NET Revit, etc.). The forces

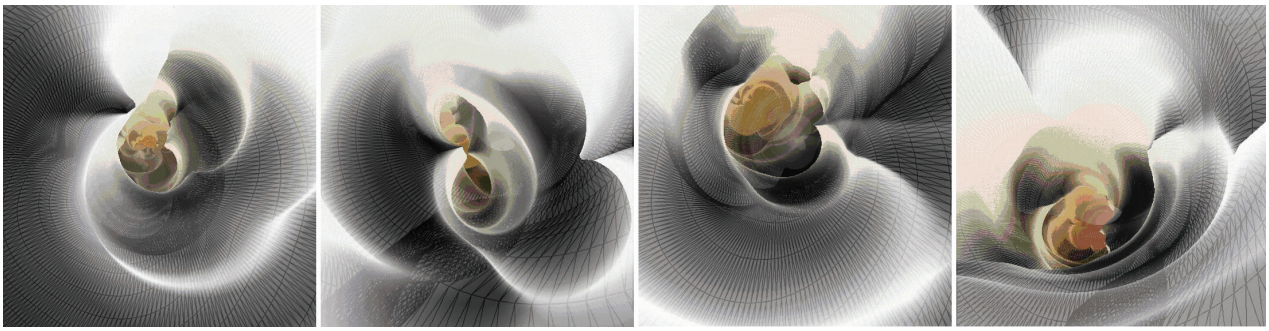

Fig. 5. Kinetics: simulation of the mutability of shapes of an interactive and transformable spatial structure in time – a sequence of selected frames in the space-time continuum (drawings by A. Kwiatkowska)

Il. 5. Kinetyka: symulacja zmienności kształtów interaktywnej i transformowalnej struktury przestrzennej w czasie – sekwencja wybranych klatek w kontinuum czasoprzestrzennym (rys. A. Kwiatkowska)

that are most often considered refer to the principles of growth, mutation, deformation or transformation of spatial structures [28]. This means that designers try to define living forces similar to the genetic codes of living organisms, generating and stimulating their structural transformations. For example, the Fab Tree Hab: Living Graft project by TerreformONE [25] expresses the idea of sustainable development and growth of the habitat modelled on living plant organisms. Another example is the project He Shot Me Down, created by R&SIE(N) [25], showing architectural structures as hybrid landscapes that change under the influence of programmed biomechanical forces that define the movement of their components and affect the mutability of their volumes. Computer simulations of possible transformations of architectural objects under the influence of acting forces simultaneously allow for full control of the work of their structural systems.

Steering kinetic form means control of the flow of information and energy in the spatial structure by means of a command interface and sensors that force the movement of their components (e.g. rotational vs. progressive, rectilinear vs. curvilinear, uniform vs. variable, periodic vs. non-periodic motion etc.). Examples of such interactive, command-responsive objects are Muscle ReConfigured and Interactive Wall, created by Hyperbody Research Group [29]. These structures change shapes in response to user commands or contextual stimuli received by sensors. Computer simulations allow to create and verify control systems for kinetic forms and show how spatial structures respond to user commands and varying sensor parameters (Fig. 5). Other interesting implementations of kinetic architecture, as examples of interactive control of selected elements of the spatial structure for functional reasons, include movable façades (e.g. One Ocean Pavilion in Yeosu, South Korea – arch. SOMA, Kiefer Technic Showroom in Styria, Austria – arch. Ernst Giselbrecht + Partner, Bund Finance Center in Shanghai, China – arch. Foster & Partners), movable roofs (e.g. National Stadium in Warsaw, Poland – arch. JSK Architects, Mercedes-Benz Stadium in Atlanta, USA – arch. HOK) or movable cubature elements of buildings (e.g. Sharifi-ha House in Tehran, Iran – arch. Alireza Taghaboni). Interactions with kinetic forms require users' access to spatial structure control systems [17]. Users have control over the transformation of spatial structures through command interfaces. A more complex level of interaction with kinetic forms is associated with users' access to the source codes of spatial structures not only in the creation phase but also in the exploitation phase, allowing them to be redesigned and changed according to the needs of users.

The source codes of kinetic forms and the command interfaces of the motion management programs also allow the generation of variable shapes of spatial structures and the control of their movement under the influence of external forces. Thus, they enable control over the processes of their adaptation to changing environmental conditions, imitating the way in which living organisms adapt to changes occurring in the environment. An example of such a solution is the Variomatic house, designed by Kas Oosterhuis [30], in which, in addition to interactive control of shape variation by users according to their needs, the architect also included in the code of the spatial structure its reactivity to changes occurring in the environment and adaptation to dynamic external forces by automatically reducing or increasing its volume or transforming the shape of the roof in response to changing parameters of wind pressure, air temperature or humidity in real time. Other examples of the responsiveness of kinetic architecture to external forces include movable façades, façade panels and blinds that open and close depending on the intensity of sunlight and the temperature difference outside and inside the buildings (e.g. M9-C Housing Building in Paris – arch. BP Architectures, Kolding University, Denmark – arch. Henning Larsen, Al Bahar Tower in Abu Dhabi, United Arab Emirates – arch. Aedas) or movable cubature elements of buildings that follow the sunlight (Dynamic Tower in Dubai, United Arab Emirates Arabic – arch. David Fisher) or moving under the influence of wind pressure forces (Squall Tower – arch. Hayri Atak, Kaan Kılıçdağ, Büşra Köksal, Kübra Türk).

Discussion and conclusions

The information revolution enriches the architectural design process with new computer simulation tools that enable the creation, display and control of the entire process of generating different geometries of spatial structures

as an animation of the abstract movement of one-, two- and three-dimensional elements in the unlimited digital space-time, leading to the creation of more complex forms of kinematic architecture compared to pre-digital forms based only on the idea of the initial, intermediate and final states of their geometric transformation. These tools allow to generate an unlimited number of variations of geometry states of evolved forms and to show smooth transformations of architectural objects from simple to complex structures, from embryonic to mature forms.

In the case of the expression of kinaesthetic architectural forms, computer animation allows for a smooth simulation of the sequence of views seen by a moving observer, while also allowing for the reconstruction of the view of the forms in their spatial context at arbitrarily selected points of time. To shape the forms of kinematic architecture, the use of computer simulation means the ability to recognize hidden dimensions of space, due to insight into its internal structure. This allows a better understanding of how spatial structures work, as well as the control and management of spatial objects through access to information about the characteristics and properties of these structures, making it possible to interact with their selected parameters, adapt to changes in the environment, adjust to users' needs or verify the correctness of changes initiated by the architect or user. In the case of expressing forms of kinetic architecture, computer simulations are a sine qua non for generating and controlling the movement of the entire structure or its components in time and space. All these processes reinforce the idea of architectural form as a form that is dynamic and transformed over time.

Computer simulation seems to be the best tool to express the essence of the architecture of time. This tool can be used both in the process of creation and exploitation of spatial structures, allowing to simulate, control and manage their operation. At the same time, computer animation is closest to the way in which a human perceives the continuity of space-time, allowing for a more complete presentation of the architectural form as a fluid sequence of images and views, changing along with the moving observer. One can risk the thesis that computer simulation, like the discovery of perspective in the Renaissance, will not only illustrate the form in a dynamic approach but will also influence the way of designing, and will also contribute to the emergence of a new generation of forms of kinetic architecture, which are the expression of fluid and streaming architecture.

The development of human civilization is largely associated with the conquest of space (e.g. the creation of empires, discoveries of new continents, expeditions into space, etc.), however, at the end of the 20th century, interest in the conquest of time and information began to prevail. These two dimensions have become particularly important in many scientific disciplines of the 21st century. Issues of time and information have also become central to architecture. Real-time transformations of architectural objects will be possible thanks to the use of intelligent materials and the integration of spatial structures with computer hardware and software based on artificial intelligence and deep learning, generating changes in the shape and function of spatial structures over time [18]. Users will explore a virtual representation of the spatial setting of their lives, similar to the way that gamers can navigate a virtual video game environment in real time. Exploration of the real world will be integrated with the possibilities of discovering, controlling, managing, interacting, adapting, creating and transforming its representation in the virtual world, which will ultimately strengthen the trend of medialization and virtualization of architecture.

Due to the high complexity of smart and transformable spatial structures and their dependence on technological reliability, a number of associated risks can already be expected from the loss of human control over their initiated processes of change over time and the possibility of artificial intelligence taking control of space. Likewise, the threats associated with the introduction of autonomous cars in road traffic in the near future, partially human-controlled or self-steering spatial structures representing the architecture of time will be able to lead not only to various incidents and collisions, but will also contribute to the alienation of humans in the built-environment, due to their total dependence on smart technologies and the inability to understand the processes that control them. Further research on the architecture of time will require taking into account the role of AI in managing space-time and operating on large sets of information (Big Data), which are an immanent feature of smart and transformable space-time structures.

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Abstract

Architecture of time: from motion picture to computer animation

The architecture of the digital era, exploring the dimension of time, refers to the concept of so-called time-based art. Present computer technologies allow one to simulate the space-time transformation of architectural objects connected with observer's movement and to create dynamic movable spatial structures by applying smart materials and technologies to architecture.

The purposes of the research are to analyse the influence of the concept of time on the shaping of architectural forms and the directions of the development of architectural forms determined by technologies discovered during the industrial and information revolutions (film techniques, computer visualisations, simulations, and animations). Based on the structural analysis of dynamic mutual relations between the observer, the architectural object, and the context, connected with comparative and critical analysis of modern trends, different types of architecture of time are distinguished. These types are derivatives of the expression of time in three-dimensional space and assumptions related to the degree of changeability and dynamics of the spatial structures (kinaesthetic, kinematic, and kinetic forms), and depend on the expression tools used in the creation and simulation of the mutability of forms.

Computer animation is not only a tool, but also a way of thinking about the architectural form as an object immersed in space-time, therefore it will influence the way of designing and contribute to the emergence of a new generation of forms in the near future. Time-based architecture of the information age will explore the idea of streaming architecture.

Key words: kinematics, kinetics, architectural form, kinaesthesia, space-time simulations

Streszczenie

Architektura czasu: od ruchomego obrazu do animacji komputerowej

Architektura ery cyfrowej, eksplorująca wymiar czasu, nawiązuje do koncepcji sztuki tzw. *time-based art*. Współczesne technologie komputerowe pozwalają na symulację zmienności form architektonicznych i ich percepcji w powiązaniu z ruchem obserwatora w przestrzeni oraz tworzenie dynamicznych struktur przestrzennych dzięki zastosowaniu inteligentnych materiałów i technologii w architekturze.

Celem badań było określenie wpływu koncepcji czasu na kształtowanie form architektonicznych oraz kierunków rozwoju form architektonicznych wyznaczonych przez technologie odkryte podczas rewolucji przemysłowej i informacyjnej (techniki filmowe, wizualizacje komputerowe, symulacje, animacje). Na podstawie strukturalnej analizy dynamicznych relacji między obserwatorem, obiektem architektonicznym a kontekstem, oraz porównawczej i krytycznej analizy współczesnych trendów wyróżniono różne typy architektury czasu. Typy te są pochodnymi ekspresji czasu w trójwymiarowej przestrzeni oraz założeń związanych ze stopniem zmienności i dynamiki struktur przestrzennych (formy kinestetyczne, kinematyczne i kinetyczne) i zależą od narzędzi ekspresji użytych w tworzeniu i symulacji zmienności form.

Animacja komputerowa jest nie tylko narzędziem, ale też sposobem myślenia o formie architektonicznej jako obiekcie zanurzonym w czasoprzestrzeni, dlatego będzie wpływać na sposób projektowania, a także przyczyni się do pojawienia się nowej generacji form w najbliższej przyszłości. *Time-based architecture* oparta na wymiarze czasu architektura epoki informacji będzie eksplorowała ideę architektury streamingu.

Słowa kluczowe: kinematyka, kinetyka, forma architektoniczna, kinestezja, symulacje czasoprzestrzenne