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Representation of Non-Metric Concepts of Space in Architectural Design Theories

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Abstract The concept of space is one of the most important parts of architectural theory. There are many theories of space in architecture which can be examined from different point of views including mathematics and philosophy. In a mathematical sense, most of the architectural space theories deal with the three-dimensional Euclidean geometry. However, the development of the contemporary architecture has been marked with some other geometric concepts as well. New concepts of space, different from the three-dimensional Euclidean space, have had an impact on architecture since the beginning of the twentieth century. Moreover, in the past two decades growing interest toward a non-metric conception of spaces, where a notion of distance is not relevant, emerged in the theory and design of some contemporary architects. In this paper the relationship between non-metric conception of spaces and architectural design theories are analyzed and evaluated in order to show and the extent to which they are related.

Keywords Design theory · Design analysis · CAD · Modeling · Non-metric space · Projective geometry · Topology · Transformations

Introduction

There are various approaches to the concept of space in architecture which most often rely on sensory and existential characteristics. For centuries space sensory perception and imagination have been linked to the concept of three-dimensional

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geometry of Euclidean space, this thus being the dominant thinking process. In the nineteenth century, the development of other mathematical concepts of space also had a big impact on the wider cultural frameworks, including architecture.

The doctoral thesis of mathematician Bernhard Riemann titled *On the Hypotheses which Lie at the Bases of Geometry* in 1868, created the basis for a global vision of the geometry and the variation of different types of space, Euclidean or non-Euclidean, with different numbers of dimensions ≥ 3. Riemann's thesis has opened the door for the study of different types of metric spaces, in which the three-dimensional Euclidean is only a special case. Felix Klein in his famous manifesto of 1872 known as the Erlangen program defines geometry as the science of figure properties that are invariant in character in relation to a particular group of transformations. Geometrical frames defined in such a way paved the way to the new non-metric definition of space.

The impact of new ideas of space that certain architects implemented in their theoretical discourse influenced the relativization of the concept of space in art and architecture. The foundation for a new, modern geometry in which the three-dimensional Euclidean space is only one special case, moved the boundaries of space perception, which initiated a different approach to the problems of form in architecture. Some members of the architectural avant-garde, such as Theo van Doesburg, Cornelis van Eesteren and El Lissicky, associated with mathematicians and were very familiar with new ideas about space and geometry. They tried to implement new mathematical discoveries about Non-Euclidean and four-dimensional spaces in their design theories and artistic statements[1] (Emmer 2004; Evans 2000). At the same time, a way to introduce new ideas about space influenced the use of different types of representations, especially axonometric projections, for which El Lissicky's Abstract Cabinet drawings made a great contribution (Tepavčević and Stojaković 2012). During the 1920s and 1930s, new geometric theories contributed to relativization of the space concept, initiating a different view of geometric form in architecture. In the last decade of the twentieth century more abstract conceptions of space, based on non-metrical forms of geometry emerged in the theory and design and representation of architecture.

Since the design and construction process of building is impossible without the notion of distance, the aim of this research is to show to what extent non-metric spaces are truly applied in the architectural design theory and representation. Here, it is important to stress that it is impossible to create the architectural working drawings in any other kind of space different from Euclidean, but it is possible to trace the form-generating processes in architectural design through the diversity of shapes that represent continuous transformations in some other kind of geometry. In that respect, various form-finding techniques based on geometric transformation as a part of instrumental approaches in contemporary architectural design are examined

[1] Architects associated with the Dutch artistic movement De Stijl, used an image of a visualized tesseract published in H.P. Manning's *Geometry of Four Dimensions* (1914) both as a formal analogy and as an artistic concept. The relationship between the image of tesseract designers' intentions are clearly evident in the project of the private house by Theo van Doesburg and Cornelis van Eesteren's illustrated and published in L'Architecture Vivante in 1925.

in order to find to what extent they are justified within the space-related design theories.

In this paper, the term non-metric space is used to refer to those concepts of space where a notion of distance is not relevant. In mathematical terms, all kinds of non-metric spaces are topological spaces. Apart from the *topological space*, there are also notions of *projective space* and *heterogeneous space*, founded in the texts written by contemporary architects, which could be considered as non-metric (topological) in mathematical terms. In this research, they are examined independently because concepts of space in architecture should not be considered as exclusively reducible to mathematical models in its disciplinary sense. Moreover, systematical research about the influence of geometric (non-metric) concepts of space is yet to be done. This research explains to what extent each of these non-metric approaches to space concepts in architecture redefines the theoretical framework of contemporary architecture and affects the process of architectural design.

Projective Space in Architecture

Projective geometry is a branch of geometry dealing with the properties that are invariant under projective transformations. An example of a projective transformation of space is the perspective transformation that preserves geometric properties such as incidence relationships and cross-ratio, but does not preserve sizes or angles. Therefore, projective geometry may be defined as an elementary non-metrical form of geometry that describes objects "as they appear". The sequence of projective transformations of a basic solid block as a form finding technique is given in Fig. 1.

Projective Geometry originated in the works of Girard Désargues[2] and it was further developed in the nineteenth century by Jean-Victor Poncelet[3] and Charles Julien Brianchon,[4] but its fundamental ideas stem from the work of artists and their perspective drawings during the Renaissance (Field 1997).

The projective thinking approach emerged in architectural discourse in the second half of the twentieth century. The notion of projectivity in architecture was

[2] French mathematician, engineer and architect Girard Désargues wrote several papers during the period 1636–1640 that may be considered the "first works" about projective geometry. In his work *Manière universelle* (1636), Désargues was the first person to offer the perspectival theory in which the abstract viewer's eye is positioned in infinity. For such observers, parallel lines do not converge in a vanishing point, but stay parallel. In that way, he anticipated the theoretical framework for the development of axonometric representation (Gomez and Pelletier 2000).

[3] Jean-Victor Poncelet's *Traité des propriétés projectives des figures* (1822) was the next significant work about projective geometry after Désargues. Poncelet's work contains fundamental ideas of projective geometry such as the cross-ratio, perspective, involution and the circular points at infinity (O'Connor and Robertson 2008).

[4] Charles Julien Brianchon as well as Jean-Victor Poncelet were disciples of Gaspard Monge, the founder of Descriptive geometry. As a student, Brianchon wrote a *Mémoire sur les surfaces courbes du second degré* (1806) in which he recognized the projective nature of Pascal's Theorem. Brianchon's Theorem, which is a dual of Pascal's Theorem, is the result for which Charles Julien Brianchon is best known (Tabak 2009).

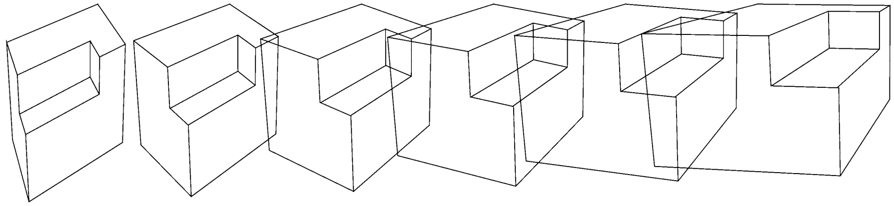

Fig. 1 The sequence of projective transformations of a basic solid block as a form finding technique

addressed by formal experiments through design drawings in order to achieve reversibility of the axonometric view. In some cases, these drawings were not only formal experiments in the design process but also a reflection of the ideological positions of certain architects, who were trying to achieve "autonomy of architecture", through a "new way of seeing" (Diaz 1977). As Diaz noted, in the work of the *New York Five*[5] during the end of the 1960s and early 1970s the projective element is self-consciously eliminated in order to ally themselves with the dominant ideology. For John Hejduk, a member of the New York Five, implementation of frontal axonometry is crucial for his drawing experiments: reversibility of the axonometric view in the Diamond and Bernstein house projects is a key step in the design process. "The two-dimensionality of a plan projected into the three-dimensional isometric, still appears two-dimensional, closer to the two-dimensional abstraction of the plan and perhaps closer to the actual two-dimensionality of the architectural space" (Hejduk 1985). Hejduk believed that these transactions between two-dimensional and three-dimensional space exemplified the difficulty involved in producing and representing architectural space (Healy 2009). Tendencies were directed toward "collaging" three-dimensional views and were further developed in the drawings of Daniel Libeskind's *Collage Rebus II* and Katsuhiko Muramoto's *Detached House, Separated Even* projects, but the projective thinking approach in the theory of architecture of the twentieth century is rather metaphoric and narrative than mathematical in its disciplinary sense. Sample approaches of the collaging three-dimensional view is given in Fig. 2.

A unique approach to projective geometry as a compositional device is used in the series of Preston Scott Cohen's projects entitled *Stereotomic Permutations*. Cohen used various projection techniques in order to overcome formal limitations. At the same time he combines orthogonal and perspective projection as a tool for projective transformation of geometric forms. The distortion of starting compositional geometric form is derived by mapping three-dimensional shapes to a two-dimensional plane, that are further used as models for projective transformations. In the competition proposal for a Head Start Facility, an initial perspective of a six-sided object is taken to be an elevation view, from which other orthographic

[5] The New York Five refers to a group of five New York City architects (Peter Eisenman, Michael Graves, Charles Gwathmey, John Hejduk and Richard Meier) represented in the CASE meeting in the Museum of Modern Art in 1969 and the book *Five Architects*, New York, Wittenborn (1972). The New York Five architects were among the most influential architects in the second half of the twentieth century.

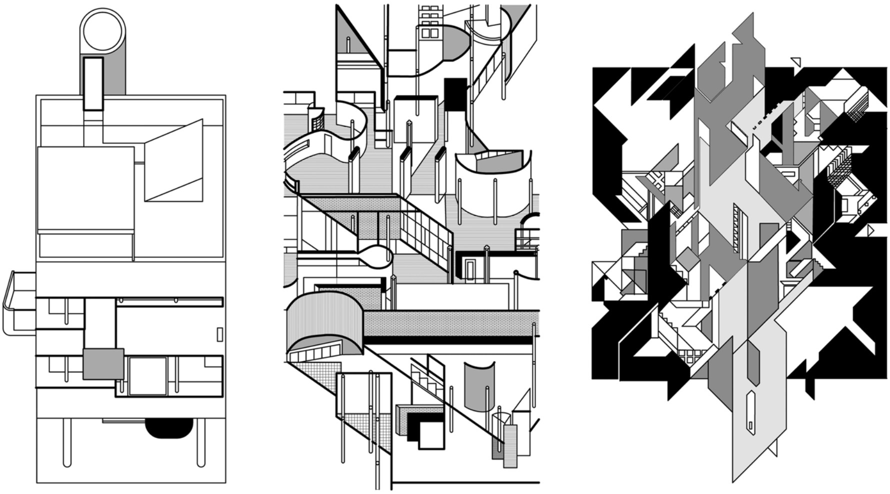

Fig. 2 The reversibility of the axonometric view in the projects of Hejduk (*left*), Libeskind (*middle*) and Muramoto (*right*). Redrawn by the author

projections are further derived. The working schema for deformation and shape generation is derived through successive permutations of a single volumetric object. In his competition proposal for a Head Start Facility, a perspectival drawing of a six-sided object is assumed to be an orthographic projection (an elevation), from which other views are further derived. Preliminary variations of the secondary perspective determine patterns/diagrams for deformation of the symmetry along a near vertical axis. Such a projective method of form finding suggests a model in which permutation of shapes is a derivation of particular circumstances, viewpoints, use and context (Cohen 2001). The architectural scale models he created in later project phases have one specific viewpoint where they look like the perspective drawing. However, the visual appearance of the model seems completely different and distorted when viewed from every other angle. Cohen's instrumental approach is based on projective geometry in which certain geometric properties of shape remain unchanged after projective transformations. Introducing homology between perspective and axonometric representations, Cohen laid the groundwork for the instrumental approach to the projective space in architecture. As Moneo (2001) noted, Cohen's work shows that projective geometry can be a valuable tool for architects in the development of new design methods.

Unlike the narrative projective thinking approach in architectural discourse in the second half of the twentieth century, Cohen's formal experiments with projective transformation offer a new way of design thinking based on a constant change of volume shapes preserving some projective characteristics.

In that way, a drawing is a trace of the process of continuous perspectival mutations, rather than a representation of a single object. Cohen's drawings for the competition proposal for a Head Start Facility are prime examples of such an approach as shown in Fig. 3.

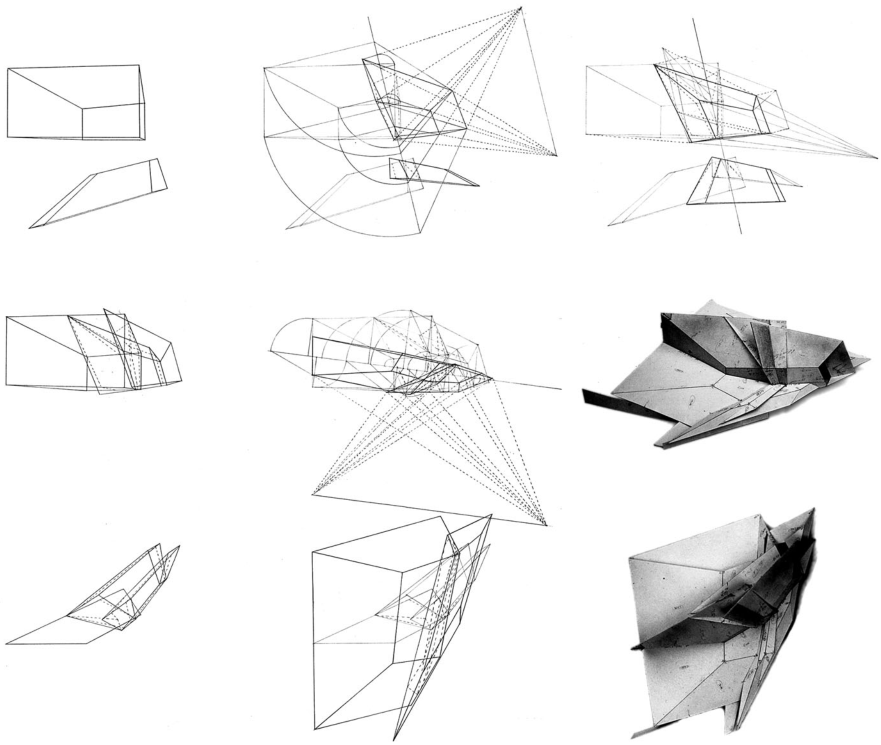

Fig. 3 Projective design exploration for a competition proposal for Head Start Facilities. © Preston Scott Cohen

Topological Space in Architecture

Topology is the branch of mathematics that can be defined as a study of qualitative properties of certain objects that remains unchanged after undergoing a certain kind of transformation. Topological spaces are objects that can preserve qualitative properties such as convergence, connectedness and continuity upon transformation. Topology deals with those problems that don't depend on the exact shape of the objects. Topological geometry deals with problems as well as geometric properties such as the orientability of surfaces, handle decompositions and local flatness. An example of a form-finding process based on topological transformation is given in Fig. 4.

A great contribution to the development of topology as a branch of mathematics was given in the nineteenth century,[6] but the instrumental thinking approach in

[6] Leonard Euler's academic paper *Solutio problematis ad geometriam situs pertinentis* (Euler 1741) with the solution of the Königsberg bridge problem is considered to be the first in the field of topology. As is obvious from the paper's title, Euler was aware that he was dealing with different kinds of geometric problems where the notion of distance is irrelevant. The term *topologie* (topology) was first introduced in the work of Johann Benedict Listing in *Vorstudien zur Topologie* (Listing 1848) and many mathematicians of the nineteenth century gave a great contribution to the development of this branch

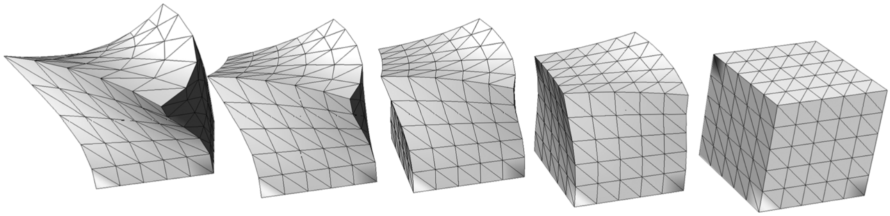

Fig. 4 The application of motion based modeling technique (morphing tool) in topological transformation of a solid as a form finding technique

science and art based on topology was developed at the beginning of the twentieth century. Schematic diagrams which represent the elements of a system using abstract rather than realistic graphic elements and their connection were used extensively at the turn of the twentieth century.

During the 1930s a topological approach appeared in visual arts and graphic design. Harry Beck's revolutionary design of the London Tube Map from 1933, shown in Fig. 5, is an important example of a topological design approach that has been widely adopted to other transport maps across the world. His map, with straight vertical and horizontal lines and 45° diagonal lines, wasn't based on the geographic but rather the relative positions of stations and their connections. Two decades later, such a topological approach in thinking appeared in the theory and design of architecture.

The concept of topology appeared for the first time in the context of the theory of architecture in 1955 in the essay *New Brutalism* by Reyner Banham (1955), where he set up a distinction between architectural composition based on "rule-and-compass geometry" and topological design. Describing the informal approach of spatial organization, Banham noted: "in the Smithsons' Sheffield project the roles are reversed, topology becomes the dominant and geometry becomes the subordinate discipline" (1955: 361). For Banham, what concerns topology in architecture is not the shape of the object but the way architecture relates to its surroundings and its own structure.

In this context, the use of diagrams gains a new emphasis in the architectural representation of design ideas. This shift can be seen in the diagrams by Alison and Peter Smithson, who generated ideas during the design process. Some of these diagrams were completely stripped of any figurative expression, demonstrating just the links between the individual elements. This approach can be seen in the diagram-drawing by Alison Smithson made for the project Snowball Appliance house from 1957 in which the spatial and functional units and directions are

Footnote 6 continued
of mathematics. Listing and Möbius discovered independently the "one-sided surface" and published a description of a Möbius band (Herges 2005). Henri Poincaré published *Analysis Situs* (1895) introducing the concepts of homotopy and homology and Maurice Fréchet introduced the metric space in 1906 in his PhD dissertation, unifying the work on function spaces of Georg Cantor, Vito Volterra and others (Fréchet 1906). In 1914, Felix Hausdorff developed a systematic theory of topological spaces in his *Grundzüge der Mengenlehre* (Hausdorff 1914).

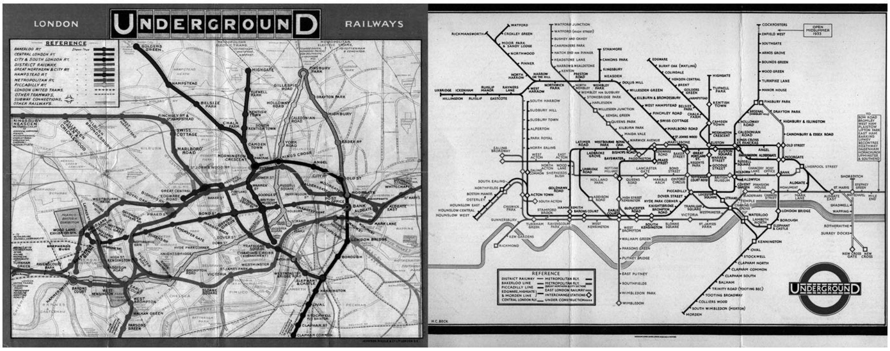

Fig. 5 *Left* London tube map from 1908 based on geographic positions. *Right* Harry Beck's revolutionary design. © TfL from the London Transport Museum collection

represented by circles and arrows. During the second half of the twentieth century diagrams became accepted as having a creative potential for exploring the complex problems of abstract structures.

In the late 1950s and early 1960s, the complex issue associated with the development of future cities was abstracted in diagrams in which the problems of traffic flow are reduced to the problems of one-dimensional topological spaces—graphs. Being involved in the development of cities, Christopher Alexander wrote an influential essay titled "A City is Not a Tree" in 1965, in which the structure of the city is reduced to the problem of graphs (Baba 2009). At the same time, projects by Kenzo Tange for Tokyo Bay (1960) Candilis-Josic-Woods for Free University Building (1963) and Toulouse le Mirail project (1961), provided various solutions for structuring city layouts, relying on topological variations of street networks.

In the last decade of the twentieth century the concept of topology re-emerged into the design theories of some contemporary architects. The development of digital design tools as well as Gilles Deleuze's notion of the "Fold" in contemporary architectural theory played the major role on setting up the groundwork for the concept of topology in architecture. A series of essays published in *Folding in Architecture*, an issue of Architectural Design in 1993 edited by Greg Lynn, created a favourable environment for spreading new ideas about topology in architecture. In his famous essay "Architectural Curvilinearity: The Folded, The Pliant and the Supple" published in 1993 in *Architectural Design*, Greg Lynn (1993) noted that "Topology considers superficial structures susceptible to continuous transformations which easily change their form… Deformation is made possible by the flexibility of topological geometry in response to external events, as smooth space is intensive and continuous".

Recognizing the impact that digital morphing techniques applied in the film industry have had on art and culture at the beginning of the last decade of the twentieth century, Lynn identified motion-based modeling techniques as topological models of representation in architecture in which the time is a measure of changes in the form of the object. In his very influential book *Animate Form*, Lynn (1997) stresses that the fundamental characteristics of digital media of representation are

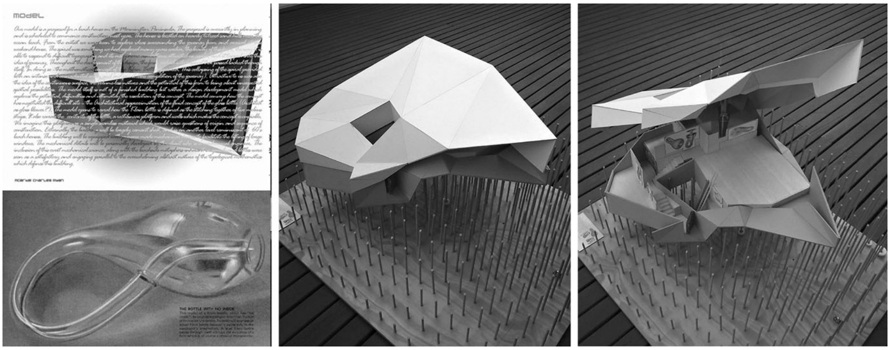

Fig. 6 McBride Charles Ryan: the Klein bottle as a conceptual model for a house project. © McBride Charles Ryan and John Gollings

topology, time and parameters. Bending, stretching, twisting and folding of architectural forms is one of two evolutionary lines of a topological thinking approach in architecture that is influenced by the development of digital design technologies.

Another line of the development of the idea of topological space in architecture can be seen in relation to the research and implementation of the qualitative characteristics of topological forms in architecture. Topological surfaces have been recognized as a way to implement new ideas about space. In this sense, the Möbius strip, Klein bottle or torus offer important topological properties that can change the traditional approach to the structure, organization and perception of space in architecture. The intriguing properties of non-orientable surfaces,[7] especially the Möbius strip, were already a controversial topic in the art of the twentieth century in a variety of artistic interpretations, symbolizing the cyclical and continuous forms. It is a symbol of infinite but limited surface, where movement in one direction reaches the starting point. The architectural interpretation of a non-orientable surface symbolizes spatial relativity between the exterior and interior. The Möbius strip in architecture was first introduced by Peter Eisenman as a type of a mathematical diagram, which is an idea that explores some of the characteristics of architectural space. At the turn of the twenty-first century, non-orientable surfaces such as the Möbius strip and Klein bottle, were soon accepted as conceptual models with other architects of our time such as Ben van Berkel, Steven Perella, Zaha Hadid, McBride Charles Ryan, Aquilialberg studio and BIG Architects studio. Such an approach is illustrated in Fig. 6.

Despite the fact that intriguing geometric properties of the Möbius strip and Klein bottle are used as a basis for metaphoric and narrative models for some architects in the twenty-first century, the concept of topology is still important for

[7] In mathematics, the surface is considered as orientable if it is possible to make a consistent choice of a surface normal vector at every point. Consequently, orientable surfaces have two sides. Most surfaces we encounter in the physical world are orientable such as planes, spheres, boxes or tori. As opposed to orientable surfaces, non-orientable surfaces do not have two sides. Such examples are: Möbius strips, real projective planes and Klein bottles.

further development in the design thinking and form-finding process in architecture because it provides a framework for a more abstract way of perceiving space problems in architecture.

Heterogeneous Space in Architecture

Unlike the previously described space concepts in architecture, the notion of heterogeneous space in architecture is not derived from the particular mathematical space concept. Moreover the concept of heterogeneous space in architecture emerged from an array of models and theories in mathematics and other scientific disciplines that can be used to explain the phenomenon of complexity. There are numerous approaches to the notion of complexity in science, and it can be defined as the study of the phenomena which emerge from a collection of interacting objects (Johnson 2009). Definitions of complexity often depend on the concept of a "system", a set of related objects or forces. The behaviour of a complex system is highly sensitive to initial conditions, and relations between the system and its environment are non-trivial. An example of the form-finding process through continuous transformations in heterogeneous space is given in Fig. 7.

Relying on some of the basic characteristics of complex adaptive systems such as self-organization, emergence, adaptability, and self-similarity, one of the directions of development of twenty-first century architecture is oriented towards the application of new mathematical models of information and discoveries in geometry which complex adaptive systems can be described with. The notion of complexity is a relatively young scientific term and refers to the set of elements that are correlated and whose joint behaviour is non-trivial and unexpected. The application of new design strategies based on scientific models and theories that are used for simulation of complex systems has given rise to the question of space in architecture and the answer is given in the formulation of heterogeneous space by Hensel et al. in their book *Space Reader*. In the aforementioned book, a compilation of seminal essays and previously published texts by architects, philosophers and biologists leaning on complexity theory in science and philosophy, Hensel et al. (2009) give a theoretical framework which will determine further directions of development of the space concept in architecture. For authors, Stan Allen's theoretical shift "from object to field" and Deleuze and Guattari's opposition of smooth and striated spaces are one of the key references in constructing a concept of heterogeneous space in architecture. Heterogeneous space is considered as smooth in Deleuze–Guattari terms. In that respect, the

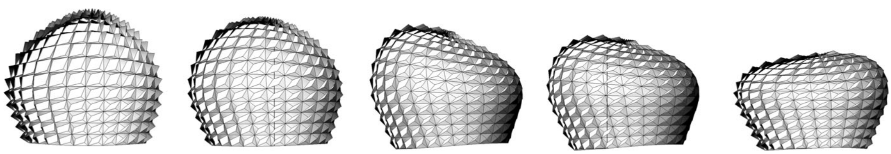

Fig. 7 An example of the form-finding process through continuous transformations in heterogeneous space

heterogeneous space of Hensel et al. can be treated in mathematical terms as a non-metric model of space. As Plotnitsky (2003) argues, the mathematical model of the smooth space in Deleuze and Guattari's sense is defined by the topology of the differential manifold, which need not entail a metric model. Moreover, for Hensel and Menges (2009) the "arbitrary boundary" may have a sense even for architects in the context of interaction between material systems and the environment.

What makes heterogeneous space different from topological space in contemporary architectural theory is the notion of porosity.[8] As Hensel and Menges argue, the tendency towards "porosity" of the material systems enables the connection of the outside and the inside in a specific manner with the desired gradient modulation. In that sense, heterogeneous space can be considered as a topological space with low negative values of *Euler-Poincaré* characteristic.

The instrumental approach to the heterogeneous space in architecture is based on application of generative multi-performative design tools. Such an approach is important for a better understanding of *performance-oriented* and *morpho-ecological* approaches to design, applied in a series of projects such as the competition proposal for the New Czech National Library in Prague by OCEAN NORTH.

As Hensel et al. claim, the concept of heterogeneity in architectural space has no clear boundaries, but it provides a theoretical framework for the development of contemporary discourse on space. Although the notion of heterogeneous space is not related to any particular mathematical space concept and is without clear boundaries, it does have a great importance in contemporary architectural discourse as it is an attempt to answer new demands in generative and performance oriented design strategies.

Conclusion

In this paper it is shown that the conceptual richness of non-metric mathematical models of space play an important role in contemporary theory and design in architecture. An instrumental approach to the non-metric concept of space in architecture has been developed in two directions.

The first direction is oriented toward utilizing non-metric mathematical models as a basis for their theoretical frameworks based on narrative and metaphors. This can been seen by the notion of projectivity, on the one side, and by the implementation of non-orientable surfaces in the design on the other side.

[8] Porosity is the measure of the void spaces in a material and this concept has recently been transferred from biology, medicine, mathematics and chemistry to architecture. The notion of porosity is crucial for the design process to several contemporary architects, urbanists and theoreticians. It is used as a theoretical and design framework for several projects of Steven Holl described in his book *Experiments in porosity* (Carter 2005). For Richard Goodwin, porosity has the scale of the city—the permeable edge between public art and private space, that deals with existing structures to create three-dimensional complex public systems (Goodwin 2011). Similarly, Nan Ellin connects the notion of porosity to urban design and theory: defining it as an urban condition that allows seepage but not free flow (Ellin 2011). Moreover, for Ellin, porosity is one of the five qualities of well being of a contemporary city.

The first way is marked by the notion of projectivity in a series of drawing experiments in order to openly achieve reversibility of the axonometric view and a new way of seeing spatial relations. Such tendencies in the design representation were common for certain architects during the 1960s and 1970s. In that respect, the notion of projectivity is rather metaphoric and not really related to those from mathematics.

The second way is directed toward creating a formal analogy between the visualization of geometric shapes that are specific for certain mathematic models of space and architectural objects. Such an approach is clearly evident in the application of non-orientable surfaces in the design process. Some types of non-orientable surfaces such as the Möbius strip or Klein bottle became very interesting as conceptual models for architects since there is no distinction between the interior and exterior for such shapes. Thus, intriguing geometric properties of such surfaces are used only as the basis for metaphoric and narrative models for architects in order to justify their own design decisions and aesthetic principles.

The other direction is oriented toward the implementation of geometric transformations (morphisms) characteristic for certain kinds of non-metric spaces as a generator for new design and representational tools in the process of form finding. In that respect, stereotomic permutations, digital design tools, motion-based modeling techniques, parametric design and generative multi-performative design are recognized as a representation framework for the open-ended trace of a design process through geometric morphisms. Digital tools have opened the way toward new strategies in the design process that lean on various mathematical space conceptions.

It is important to stress the fact that new concepts of space in architecture should not be considered as exclusively reducible to mathematical models in its disciplinary sense, but they may serve as a powerful tool in the design process.

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