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Examining the significance and scope of form generation in digital design through boolean operations: A Case study of contemporary buildings post-2000

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ABSTRACT

Contemporary architectural designers strive for diversity and originality in form creation by actively employing digital design tools in their processes. This study investigates the design methodology of Boolean operations and assesses its potential for expansion and application through a case study approach. For the case study, contemporary buildings constructed after 2000 are examined to investigate the relationship between the use of Boolean operations and the scope of their application, as well as the role of digital design tools in architecture. It reveals a range of form and spatial generation across scales, achieved by selecting the results of basic Boolean operations such as union, difference, and intersection. The digital design process using Boolean operations differs from conventional coordinate-based methods. It relies on computational thinking, which enables alterations to entire forms via instruction from computer programs. In particular, the Boolean operations resonate with topological operations such as penetration, inclusion, and void. It can be extended to reinvent topological spaces and form creation. Although Boolean operations originated as a form of logical mathematics, these now contribute to intensifying the generation of architectural forms and spaces with the aid of digital design and construction tools by functioning as a generative diagram that expands into topological space.

Keywords: boolean operations; digital design; form generation; case study; topology

Introduction

In contemporary architecture, buildings feature an unprecedented level of varied and plentiful forms and spaces. This has resulted in the examination of diverse methods for implementing creative forms that embody the essence of the present era as designers continue to experiment with form generation to achieve optimal results. Moreover, given that a building is ultimately defined by its form and the space it occupies, it holds a substantial amount of power and influence, for its users and the public, who consider it as a communal asset.

In recent years, there has been an observable trend toward the active use of digital tools to create more distinctive and innovative forms that differ from those of the past [1-4]. Consequently, architects now use digital design tools to present the development process of their designs more conveniently and are leading the way in form generation

by applying various parameters in digital architecture. This process is not arbitrary and rather aims to achieve form diversity while establishing a clear design process.

This study aims to evaluate the potential of Boolean operations an established field of form generation in digital architecture by examining its methodology and investigating its applications and implications. Specifically, this study seeks to identify the scope and expandability of Boolean operations and present a systematic case study that interprets its role in form generation. While previous research on digital architecture has focused on core keywords and emerging trends, this study offers a unique perspective on the form-generation process in contemporary architecture in terms of Boolean operations.

The study proceeds in the following order. First, a literature review is conducted to trace the origin and history of Boolean operations, which were initially developed in logical mathematics, and evaluates their significance in the field of architectural design as the use of computers becomes increasingly important. Next, seven contemporary buildings are selected as case studies and analyzed in terms of the principles of Boolean operations and the role of digital design tools in the form generation process. In the discussion stage, the correlation between the application of Boolean operations and the use of digital architectural design tools is examined in detail to yield significant implications. Finally, the study concludes by presenting its observations, indicating its significance and limitations, and recommending potential directions for future research.

Literature review

Origin of Boolean operations

George Boole (1815-1864), an English mathematician from the 19th century, developed and formalized Boolean algebra. It has become the foundation for logical operations in mathematical logic and computer science. Boolean operations are applied to a set of operations for truth and falsehood. These consist of three main operations: union, intersection, and difference. The union operation merges two shapes into one, combining the resulting shape with two input shapes. In contrast, the intersection operation generates new features that represent the overlap between two input features, whereas the difference operation extracts one input shape from another to form a new shape.

Boolean operations were initially developed in mathematics and logic. Subsequently, these were integrated into computer science, where the design of digital circuits utilized two states: true (1, True) and false (0, False). The connection between Boolean operations and architectural design emerged with the increase in the use of computer-aided design (CAD) in the field of architecture.

Boolean operations as a form-generating tool

One of the methods for shape generation using computer operations introduced by William Mitchell, a professor at MIT's School of Architecture, is Boolean operations [5]. He considered design operators as a means of manipulating features in design systems and as a function for producing new states. As illustrated in Figure 1, he

described transformation as a type of unary operator that transforms one object into another, whereas combination implies that a binary operation is required to produce a third state from two objects. He proposed that the scope of application for this binary operation could be extended from a two-dimensional polygon to a three-dimensional solid, and that the outcome of the operation could be a three-dimensional solid as well as a two-dimensional plane or a line.

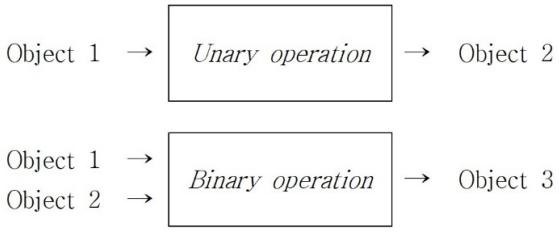

Figure 1. Arity of an operation.

Drawing on this theoretical foundation, researchers such as Portmann, Asperl, Hofer, and Kilian [6], and Melendez [7] determined that Boolean operations can be used to generate new geometric shapes that may be challenging to anticipate or time-consuming to visualize. Figure 2 depicts the outcomes obtained by performing union, intersection, and difference operations on two distinct three-dimensional figures: a cube and pyramid.

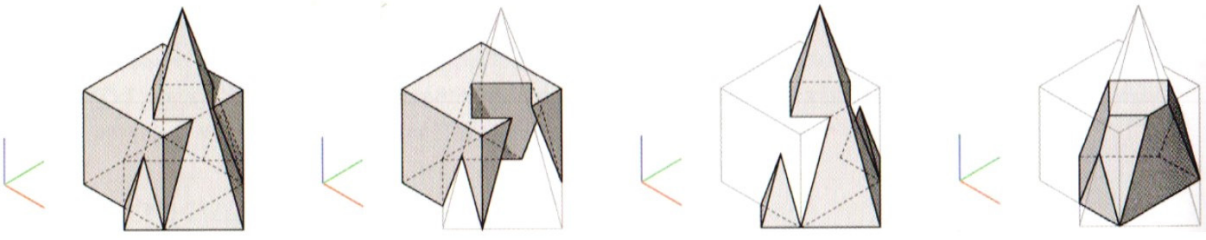

Figure 2. Boolean operations applied to a cube and a pyramid.

Boolean operations were originally developed for computer logic operations. However, these have also been examined in the context of form generation using CAD and other digital design applications. Kim investigated this approach and observed that primary modeling, a conventional modeling concept, has been transformed from manual work to computer work for the final expression of the completed design [8]. Primary modeling is categorized into wireframe, surface, and solid modeling. In solid modeling, designers can apply solid objects through a series of Boolean operations, displacement, and rotation to examine new shaping languages in an arbitrary manner.

Lee and Park conducted an analysis of architects' use of computers and divided digital processing of architectural design into two categories: 1) digitizer data and code methods and 2) architects' intuitive work methods [9]. They identified Boolean as one of the methods of digitizing data and code alongside techniques such as animation, mix,

morph, and layering. One of the characteristics of digital architectural design is that it deviates from the proportional system or classical style that can be explained in a reasonable and rational manner. It is established, created, and transformed automatically by the system rather than being planned or defined by the rational will of the architect.

Lee and Lee observed that in the digital architecture design process, digital data is used as a variable and that logical and scientific methods are applied to derive the form [10]. Computers have become essential tools in architectural design with the increasing acceptance of digital processes. These provide computational and visualization capabilities that were previously infeasible. Digital architecture is characterized by its active and comprehensive use of computer-generated forms that rely on objective and scientific processes. In this context, architects assume the role of coordinators, whereas computers generate the entire form.

Kim and Ahn sought to examine the link between hybridization thinking in contemporary architecture and digital modeling [11]. With this objective, they examined several hybrid digital modeling techniques such as blob, particle, morphing, loft, and Boolean. Furthermore, they analyzed the concept of hybrid modeling by relating representative examples with the notions of time, fluidity, complexity, and connectivity. Specifically, with regard to Boolean techniques, they posited that "the combination of positive and virtual negative spaces can produce a new hybrid form." After analyzing various cases, they concluded that the movement and passage of time, in conjunction with the overlapping of objects with each other, can generate diverse forms through convergence, intersection, and difference. Moreover, and the resulting spaces can offer a new identity in a closely linked manner.

To summarize, the use of Boolean operations is expanding their scope as a field of digital architectural design process, starting from existing computer operations. Most importantly, the use of digital tools empowers designers to expand their design process. This allows for the generation of complex forms by combining or altering basic three-dimensional shapes.

Form generation similar to Boolean operations before utilizing digital design tools

In addition to the terms union, intersection, and difference used in Boolean operations, prior publications and studies examined and elucidated the principles of form generation in architecture in a similar fashion. First, Ching indicated that 1) two geometries can collide and 2) the new form and space derivation differ from the previous one according to whether the overlapping part is selected with the two positions [12]. In addition, he explained the various precedents that can be found in architectural history from a reduction point of view of the design. A form can be generated through a deduction or subtraction process to produce an entrance, courtyard, or window from a basic three-dimensional volume. as illustrated in Figure 3. Charles Gwathmey's "Gwathmey Residence" is an example. In contrast, the expansion-based approach proposes that lines, faces, and volumes are generated based on the physical interactions and relationships among one or more shapes. The "Redentore Church" designed by Palladio is suggested to illustrate this aspect. The church's form can be explained by breaking it down into a combination of fundamental stereoscopic shapes, such as domes, rectangular parallelepipeds, semicircles, and cones.

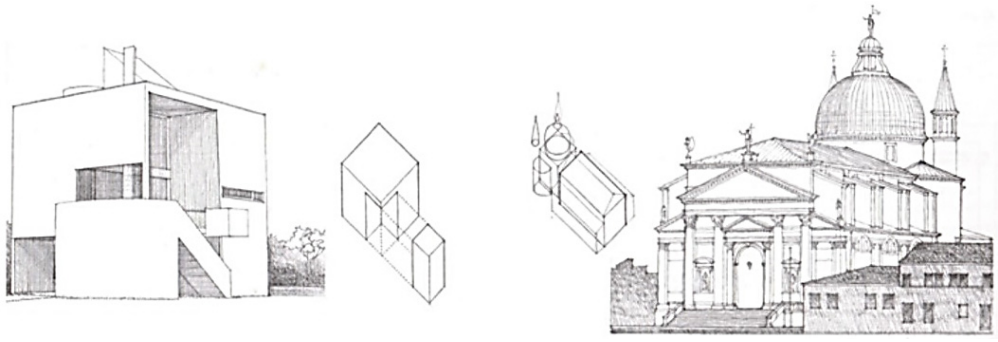

Figure 3. Gwathmey Residence and Redentore Church.

Unwin's book [13] indicates that modern architects aim to extend the boundaries of architecture by shifting away from the strict geometry based on Euclidean principles. as shown in Figure 4. An example of this is observed in Daniel Libeskind's Imperial War Museum North. It incorporates fragments of a sphere destroyed by an explosion. Another example is Jorn Utzon's Sydney Opera House. Here, three-dimensional sections of a sphere are cut into varying sizes to generate a symbolic structure.

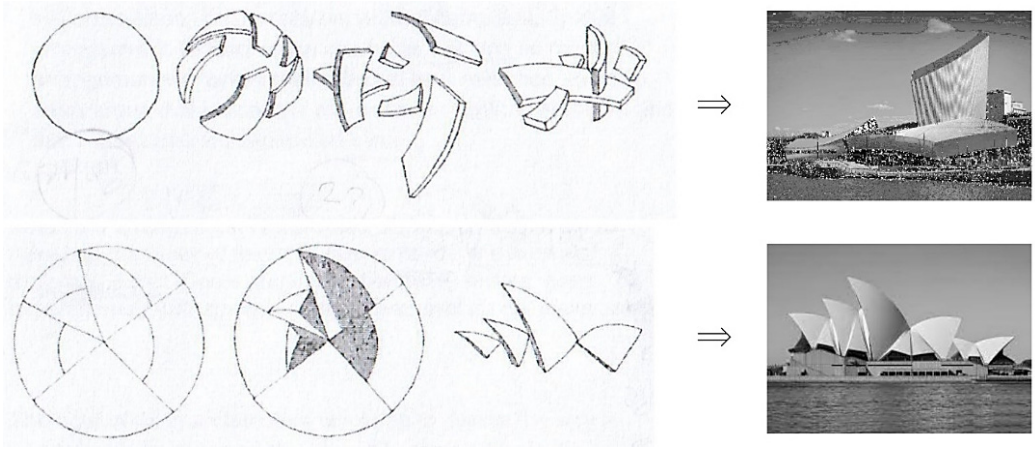

Figure 4. Imperial War Museum North and Sydney Opera House.

Lim proposed a method for obtaining irregular and amorphous forms through geometric collisions, rather than relying on basic geometric shapes to maintain the order and structure [14]. This approach was characterized as a departure from Renaissance architectural principles toward a highly expressive Baroque sculptural view. Additionally, the incorporation of productivity concepts into this morphological trend has resulted in the development of modern Baroque thinking. Lim used the Pilar and Juan Miro Foundation designed by Raphael Moneo as an example to illustrate how the building's overall composition could be achieved by combining acute radial masses along the central axis of the rectangular parallelepiped (see Figure 5). This generates formal order and geometric collisions.

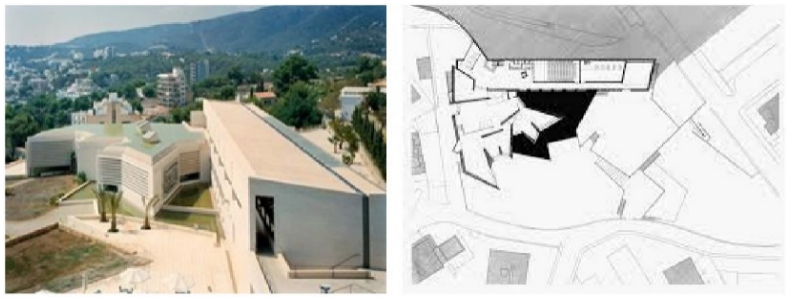

Figure 5. Pilar and Juan Miro Foundation.

Kim examined the architectural approach of Aires Mateus during their second period, particularly the use of a subtraction design technique that involves excavating a void space from a solid structure [15]. This technique is also evident in other studies. It is a defining feature of the architect's integrated design approach. For example, in the House in Leiria, a central courtyard linked to the basement is surrounded by various programs. Meanwhile, the underground bedrooms expand radially, thereby creating a plane with an individual courtyard (see Figure 6). This verifies that Aires Mateus commonly employs the subtraction technique in their works to achieve an organic arrangement of space.

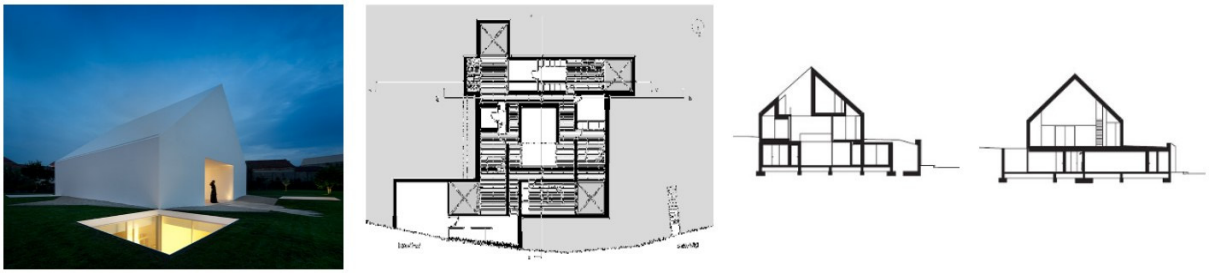

Figure 6. House in Leiria by Aires Mateus.

To summarize, the form generation methods described above (including subtractive and additive forms, geometric breakdown, geometric collision, and subtraction design) share similarities with the form generation process that results from union, intersection, and difference operations using Boolean operations. This can be summarized as shown in Table 1.

Table 1. Literature review of form generation similar to Boolean operations before utilizing detail design tools

Keywords	Examples	Sources
Subtractive form	Gwathmey Residence	Ching (2007) [12]
Additive form	Redentore Church	
Breaking geometry	Imperial War Museum North, Sydney Opera House	Unwin (2016) [13]
Geometric collision	Pilar and Juan Miro Foundation	Lim (1999) [14]
Subtraction	Aires Mateus Architecture	Kim (2016) [15]

The objective of this study is to provide an in-depth analysis of the scope of the applications and uses of shape generation through Boolean operations, which is an area of digital architecture. The study aims to contribute to the understanding of this topic and provide significant insights. Moreover, it seeks to distinguish itself from previous studies on digital form generation by offering a new perspective on the use of Boolean operations and scalability in the process of generating advanced architectural forms.

Methodology: Case Study Analysis

Case Study Methodology and Data Collection

The objective of this research is to comprehend the process of form generation through a case study. Yin indicated that the case study method examines phenomena using diverse data sources. This results in more comprehensive and significant information [16]. This research approach aids various objectives including exploratory, descriptive, technical, and evaluative research. Although it is challenging to generalize research results using this method, it is widely accepted in the social sciences. This is because it facilitates the understanding of specific phenomena and contexts in a comprehensive and detailed manner. The case selection was limited to projects after the 2000s that used common computer applications to implement Boolean operations and digital architecture, as featured in Architectural Records, Architects, and the web magazine ArchDaily. The case analysis primarily examines the context and program requirements and analyzes the form derivation process based on the Boolean operation. Table 2 presents the selected cases, and Chapter 4 discusses the results of the case analysis in higher detail.

Table 2. Case Study list

No.	Project Name (Year)	Designer
Case 1	MIT Sean Collier Memorial (2015)	Howeler+Yoon
Case 2	Poly Grand Theater (2015)	Tadao Ando
Case 3	Exploration Place (2000)	Moshe Safdie
Case 4	United States Institute of Peace (2011)	Moshe Safdie
Case 5	Cathedral of the Light (2009)	SOM
Case 6	Zeitz MOCAA (2017)	Heatherwick Studio
Case 7	Tianjin EcoCity Ecology and Planning Museum (2013)	Steven Holl

Case 1. MIT Sean Collier Memorial

The Sean Collier Memorial is situated at MIT. It commemorates police officer Sean Collier. He was one of the victims of the tragic bombing of the 2013 Boston Marathon. The architect who designed the memorial was inspired by MIT's motto, "Mens et Manus (=mind and hand)," and aimed to represent the victim's dedication with open hands and an empty space at the center using the difference Boolean operation technique (see Figure 7). To make

the monument accessible to the public rather than being only a monumental object, he created a void space beneath the structure so that passersby could view and move around it from any angle. This was achieved to make it a public artwork that could be appreciated by all [17].

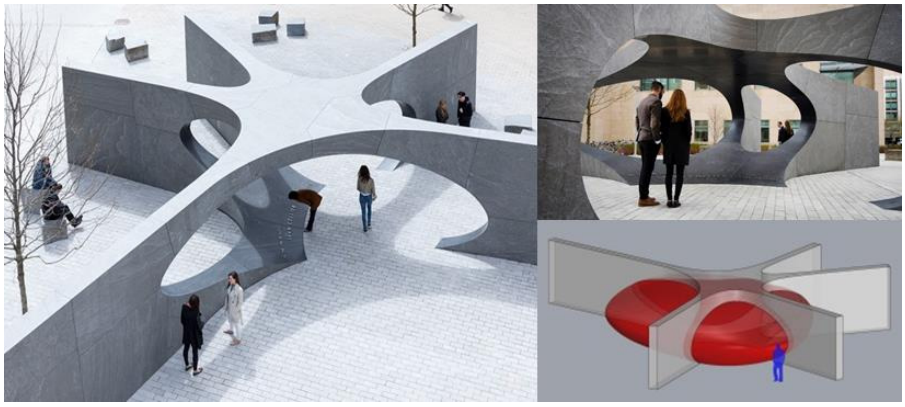

Figure 7. MIT Sean Collier Memorial and diagram.

Case 2. Poly Grand Theater

The Poly Grand Theater is located in the Jiading District northwest of Shanghai and was designed by Tadao Ando. It is a large theater capable of performing at various scales. The theater features an overall configuration achieved through Boolean operations. It utilizes the difference between five tunnels that penetrate the interior of a rectangular box made of concrete with a glazing envelope. These tunnels are of various sizes and are located at various positions, thereby providing a striking contrast to the static appearance of the rectangular parallelepiped. As shown in Figure 8, the intersection of these tunnels generates a strong, atypical acute-angle shape that draws attention to both interior and exterior spaces as well as vertical and horizontal spaces of the theater [18].

Figure 8. Poly Grand Theater and diagram.

Case 3. Exploration Place

Exploration Place is a science museum aimed at stimulating scientific curiosity and imagination in local children, and offers various exhibitions and educational programs. The torus shape of a doughnut generated by rotating a circle in a three-dimensional space is utilized as a difference operation in this project. Specifically, the first torus is positioned above the building, thereby removing the upper portion of the mass. The other torus is located beneath the other building, thereby removing the roof section to form a convex roof as shown in Figure 9. Consequently, the plane is composed of a collection of various basic shapes such as circles, squares, and triangles, whereas the roof outline with an identical curvature provides a cohesive overall appearance [19].

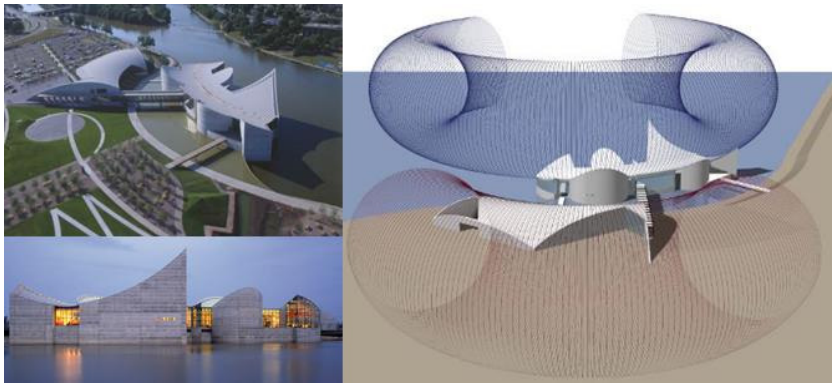

Figure 9. Exploration Place and diagram.

Case 4. United States Institute of Peace

The northwest corner of the National Mall in Washington, D.C., houses the United States Institute of Peace. The building's unique roof covers the five-story atrium space and differs from typical roofing styles. To achieve this distinctive design, Moshe Safdie Architects utilized the torus form and rotating circle technique used in the Exploration Place. They selected a portion of the surface generated by the interlocking of the torus and two spheres as shown in Figure 10. This design creates an impressive skyline at the National Mall and draws the attention of both interior and exterior viewers. Thereby, it effectively serves as a symbolic representation of the building's purpose [19].

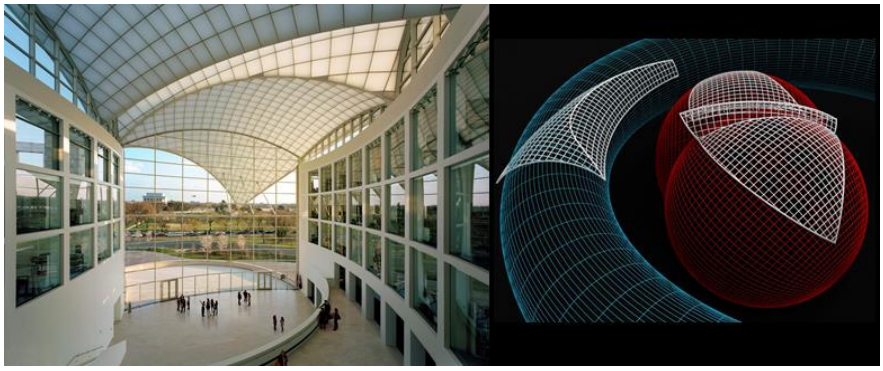

Figure 10. United States Institute of Peace and diagram.

Case 5. Cathedral of Christ the Light

The formation of the Cathedral of Christ the Light begins with the interlocking of two spheres, which is also the basis of its shape. The intersection of the spheres generates a common area that corresponds to the *vesica piscis*. This is a sacred geometric form commonly used in Christian art to symbolize resurrection and new beginnings in life and death. As illustrated in Figure 11, a remarkable aspect of this project is that the *vesica piscis* was transformed from a two-dimensional shape into a three-dimensional form and interior space using Boolean operations that involve intersections [20].

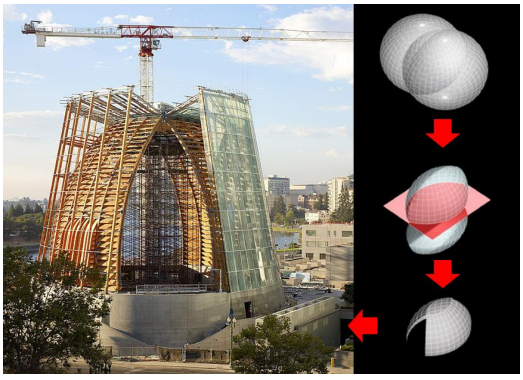

Figure 11. Cathedral of Christ the Light and diagram.

Case 6. Zeitz MOCAA (Museum of Contemporary Art Africa)

Zeitz MOCAA is a project that converted a silo constructed in 1924 into an African Museum of Contemporary Art. The most unique feature of this project is the atrium space created by excavating the center of 42 silos, each standing 27 meters tall. Unlike the anonymous exterior, the interior of the silos opens up to a space that overwhelms the human scale, and permits natural light to flow in as shown in Figure 12. This is reminiscent of medieval Gothic architecture. To achieve this, an indoor atrium space was created through a Boolean calculation process that involved the transformation of three-dimensional shapes known as cylinders (silos) into three-dimensional surfaces. The boundary of the newly formed empty space was determined by expanding the original grain of corn that the silo was designed to store. To ensure accuracy, a three-dimensional scan was performed accurately to determine the location of each existing concrete silo, and marked accordingly on its surface [21].

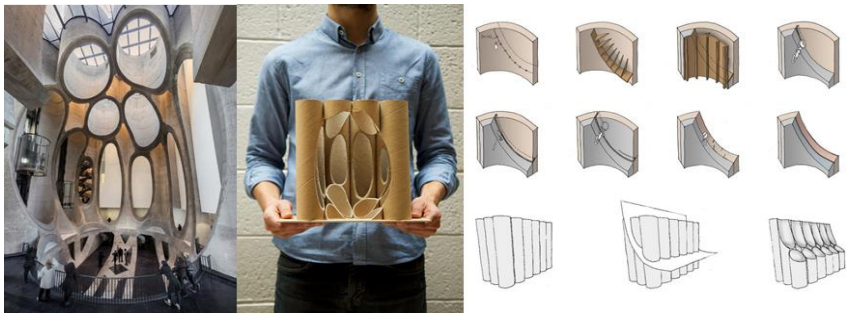

Figure 12. Zeitz MOCAA and diagram.

Case 7. Tianjin EcoCity Ecology and Planning Museums

The upcoming construction project in Tianjin Cultural District, China, encompasses two buildings that cover an area of 60,000 square meters each. The design was led by Steven Holl. It initially began with a rectangular parallelepiped, which represents the concept of yin and yang in Chinese tradition. The ecology museum occupies a portion of it, and the planning museum occupies the remaining. Essentially, the planning museum has a simple rectangular parallelepiped form. However, the void space was solidified to construct an ecology museum. Consequently, the two structures were shaped into a fluid curved exterior. As shown in Figure 13, this translated into dynamic and interconnected interior spaces with a plaza in between [22].

Figure 13. Tianjin EcoCity Ecology and Planning Museums and diagram.

Discussion

Generation of various forms and spaces according to the application of Boolean operations

It was verified through a case analysis that a combination of basic Boolean operations including union, difference, and intersection can generate various forms and spaces. Architects can apply these operations depending on the size, part, and type of three-dimensional shapes to achieve the desired results. To summarize, the following are the manners in which Boolean operations can be utilized by architectural designers.

The first observation from the case analysis is that the difference operation can generate empty void spaces internally or externally within primitive forms (Cases 1, 2, and 6). Meanwhile, the results of the union and intersection operations can produce dynamic and three-dimensional roof surfaces that deviate from conventional roof types (Cases 3 and 4). Second, the scale at which Boolean operations are applied can vary from pavilions (Case 1) to single detached buildings (Cases 2, 4, 5, and 6) and even multiple buildings (Case 3). In addition, the difference operation can be used to renovate existing structures to generate remarkable interior spaces (Case 6). Third, the case studies identified the primitive forms of cube, sphere, torus, and cylinder as the starting points for Boolean operations. However, irregular shapes were also used in Cases 1 and 6. Finally, the meaning conveyed by a form can be enhanced through the use of Boolean operations. This could be observed in Cases 1 and 5. Herein, meaningful forms were transformed into dramatic three-dimensional structures.

According to Jang's recommendation [23], "meta" refers to the high-dimensional meaning and form of the upper level, whereas "morphic" refers to the metamorphosis architecture of the meaning, which is an architecture generated with the concept of embryological morphological transformation and expression intention. This architecture is constructed through traces of morphological transformation, vitality and movement, dynamic interaction, and symbolic meaning. It conveys the vitality, sensation, and power implied by form. Given these characteristics, the generation of form using the Boolean operation can be considered one of the specific methods for implementing metamorphic architecture.

Architects such as Howeler+Yoon, Moshe Safdie, and Steven Holl have consistently employed Boolean computational techniques in their other projects. Specifically, Moshe Safdie and Steven Holl attest to a significant transition in their formal vocabulary after adopting Boolean operations and digital building tools. This serves as evidence that designers including architects have established Boolean operations as a viable method for generating innovative forms and spaces because digital design tools allow for more experimentation and more convenient generation of forms until satisfactory results are achieved. Table 3 lists the projects discussed in this study.

Table 3. Designers project list utilizing the Boolean operations

Project Name (Year)	Designer
DDP Kiosk (2016) Litho Wellness Center (2023)	Howeler+Yoon
Peabody Essex Museum (2003) Khalsa Heritage Centre (2011)	Moshe Safdie
Taiwan Chinpaosan Necropolis (2013) Winter Visual Arts Center (2020)	Steven Holl

Utility of Digital Tools

The development of digital design tools has expanded the field of form generation in recent years. This has enabled designers to generate architectural forms based on three-dimensional curved and irregular non-Euclidean geometry, rather than relying only on existing Euclidean geometry and order systems. Therefore, Lee attributed the use of computer forms as a fundamental tool for examining folding and curves since the mid-1990s [3]. The use of computers in digital architecture has given architects more autonomy and expanded their vocabulary in multidimensional ways.

Binary-based interaction shapes the design process through Boolean computation. This yields dynamic spaces that convey forces and various senses through curved shapes and spaces (as observed in Cases 1, 2, 5, and 6). Digital design tools offer an advantage over previously used Euclidean geometry-based forms by facilitating the location of curved points.

Various commands used in computer programs are now transformed by computational thinking rather than conventionally performed by inputting coordinates [24]. This implies that rather than specifying a particular

method of composition, complex and irregular forms are derived from several computational results and are connected to computational thinking that alters the entire form through these operations. However, in this study, the resulting forms are generated directly by designers' experimental trial through the movement of external surfaces, lines, and objects, rather than through indirect design based on the computer's algorithm that generates results according to clear and logical procedures to respond to design requirements.

Digital design tools and technologies focus primarily on new construction projects. Case 6 illustrates how these tools can also be utilized for renovation projects in existing buildings. In this particular case, it was necessary to determine precise three-dimensional coordinates through digital scanning because certain parts of the silo structures needed to be removed. Thus, the role of digital tools has expanded from shape generation to construction facilitation as shown in Figure 14. This involves considering production and construction technologies for actual construction in the virtual realm, which is also relevant to the design process utilizing Boolean operations [25]. A stereotactic method is employed to generate space by partially carving and cutting out the original form [26].

Figure 14. Zeitz MOCAA: Marking for cutting existing silo surfaces.

Scalability to Topological Space through Boolean Operations

It is evident from the analysis of the case in Chapter 3 using Boolean operations that the resulting shapes and spaces are organic, flexible, and integrated. This differs from those based on previous Euclidean geometry [27]. These shapes and spaces cater to the complexity of modern society's uncertain connectivity structures and are interested in topological relationships [28]. Moreover, according to Chang (2022), topology studies the position of points, lines, and surfaces in space and modifies the topological relationship through computational thinking, such as penetration, plissement, inclusion, and imbrication [24]. This is a deviation from form-oriented structural thinking and enables the creation of a new type of architecture through computational thinking via topological structures and relationships. To summarize, the compositional and computational thoughts of the present are characterized and resonate with modern society (See Table 4).

Table 4. Compositional and Computational Thinking (Source: Chang, 2022 [24])

Compositional Thinking	Computational Thinking
Form	Structure
Entity	Relation
Composition	Operation
Geometry	Topology

The discussion regarding topological operations presented by Chang can be explored further. It is apparent that the Boolean subtraction operation allows for an operation where one set penetrates another set [24]. This operation is evident in Cases 1, 2, and 6, where the architectural space relates to the space utilized by human activities. Penetration operation refers to the passage, movement, or part of the building program where human action occurs. In Case 2 (Poly Grand Theater), the penetration operation was executed through five tubes representing various architectural programs: the entrance lobby, ground and roof theater, foyer, ground amphitheater, and connecting internal and external networks. As a result, the circulation or space considered the exterior combines with the interior, and the natural site setting expands continuously into the building's interior, walls, and ceilings.

The second aspect to consider is the preservation of topology after the application of the transformation operation. This is demonstrated in Cases 3 and 4. As mentioned earlier, this corresponds to maintaining the same homotopy group by selecting only a portion of the surface through the intersection of Boolean operations without modifying the topology. It is noteworthy that the combination operation is performed through a binary operation to generate a third new form from two objects without modifying the topology.

In the Tianjin EcoCity Ecology and Planning Museums of Case 7, the subtraction operation in three dimensions resulted in the separation of a hexahedron into two distinct buildings: an ecological museum and a planning museum. It is noteworthy that a void is transformed into a solid through void operation. This is equivalent to the reversal or inversion of the void/solid, which is a topological operation frequently used by Rem Koolhaas and can be observed in physical models developed by architects.

The system of order in Euclidean space, which is based on the vertical and horizontal axes, deviates from the perspective space developed during the Renaissance and generates a topological space that challenges notions of distortion and gravity. This applies also to curved shapes that defy the Euclidean geometry axiom, in which parallel lines never intersect. The movement and flow of unfettered points, lines, surfaces, and volumes enhance the dynamics, rhythm, contrast, depth, and diversity of space. Consequently, Boolean operations (which originated as a form of logical mathematics) shape the buildings' form and space by utilizing digital design and construction tools. Eventually, these evolve into generative diagrams that induce transformation and expansion into a topological space. The findings of the case study are presented in Figure 15.

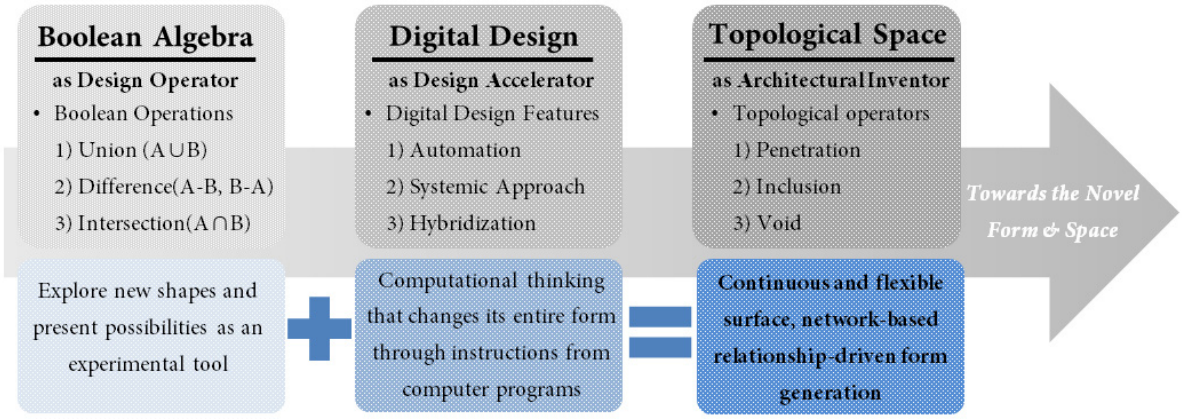

Figure 15. Research Revelation and Results.

Conclusions

March emphasized the importance of system aesthetics, which rely on objective and mathematical procedures through computer-based processes [29]. He considered that science explores existing forms, whereas design creates new ones. In line with this, the current study aimed to offer various shape creation techniques based on Boolean computation, a logical mathematical concept, and prior research on digital architecture to architectural designers involved in the creation of building shapes. The outcomes of this study are summarized below:

First, the application of Boolean operations allowed for the scalability of different shapes and spaces. This was achieved through the use of union, difference, and intersection operators and shape vocabulary. This, in turn, resulted in the generation of dynamic forms and surfaces depending on the computational outcome. The approach was reminiscent of metamorphosis architecture, which embodies embryological and morphological concepts, with dynamic interactions between operations and the establishment of symbolic meaning conveying the vitality of form.

Second, the design process involving Boolean operations generated three-dimensional shapes through binary interactions. The resulting curved shapes and spaces conveyed various sensations and transmit forces through dynamic spaces. Unlike the conventional method of inputting individual coordinates, this process relies on computational thinking to alter the entire form by using computer program instructions. However, the case study discussed in this research did not rely on self-organizing algorithms. Rather, designers directly controlled the movement of points, lines, surfaces, and objects on the external side using commands. Additionally, in the context of existing building renovations, digital design tools can extend their role beyond shape generation to facilitate actual construction using a stereotactic approach.

Third, Boolean operations transcended the Euclidean order system to embrace curved geometry that challenges the axioms of Euclidean geometry. The movement and flow of unfettered points, lines, surfaces, and volumes enhanced the dynamics, rhythm, contrast, depth, and heterogeneity of space. Boolean operations enabled

topological operations such as penetration, inclusion, and void. This expanded their scope by creating new building types through various topological space and shape generation. Therefore, Boolean operations, which originated from logical mathematics, played a vital role in shaping buildings and spaces using digital design and construction tools. These served as a generative diagram that induces transformation and expansion into topological spaces.

This study is significant because it provides a systematic and in-depth review of the form creation process and scope of use of Boolean operations, which have recently been identified as a field for digital architecture form creation. However, this study has limitations in objectifying intentions and design processes of architects or designers because it is based on an analysis of existing cases. To overcome this limitation, it would be effective to perform actual designs using the results of this study and systematically organize and present the progress achieved.

Conflicts of interest

The author declares no conflict of interest.

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