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Architecture
Integration of Art and Engineering

Edited by
Oleg Kapliński, Agata Bonenberg,
Wojciech Bonenberg and Marco Lucchini

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Architecture: Integration of Art and Engineering

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Editors

Oleg Kapliński
Agata Bonenberg
Wojciech Bonenberg
Marco Lucchini

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Editors
Oleg Kapliński
Poznań University of Technology
Poland

Agata Bonenberg
Poznan University of Technology
Poland

Wojciech Bonenberg
Poznań University of Technology
Poland

Marco Lucchini
Department of Architecture and Urban Studies
Italy

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

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About the Editors

Oleg Kapliński

Oleg Kapliński is currently a professor at the Faculty of Architecture, Poznan University of Technology in Poznan, Poland. He received his Ph.D. and DSc. in civil engineering and has authored or co-authored 280 publications (articles, reports), including 12 books (academic scripts and monographs) on related topics. His academic achievements cover the theory of decision making, including multicriteria decision aiding; construction processes organization and modeling, including analysis of the phenomena of waiting, the phenomena of equilibrium, the balancing of the construction processes in conditions of uncertainty, risk in management, network planning, and reliability of production systems; research on resentment and predilection to risk in the light of utility theory; work ethos; integrated design and management; and sustainable development. Currently, his research at the Faculty of Architecture includes interactions between architects and engineers. Kapliński is a member of the Civil Engineering Committee of the Polish Academy of Sciences and Doctor honoris causa of VGTU, Lithuania. Honorary member of EURO Working Group: Operations Research in Sustainable Development and Civil Engineering (EWG-ORSDCE).

Agata Bonenberg

Agata Bonenberg is a professor and head of the Institute of Interior Design and Industry Design at Faculty of Architecture, Poznan University of Technology, Poland. Interests: flexible interior design; design of inclusive and universal environments; color in architecture.

Wojciech Bonenberg

Wojciech Bonenberg is a professor at the Faculty of Architecture of the Poznan University of Technology, Poland. He is the promoter of 26 doctoral dissertations and 150 diploma theses. He is the author or co-author of over 100 scientific publications, including nine books. His research interests are related to sustainable design, architectural revitalization, and requirements engineering in architecture. He has been invited for seminars and a series of lectures by universities in Germany, Netherlands, Italy, Belarus, Ukraine, and China. He is the author of more than 200 architectural projects, many of them awarded. These include the projects of the largest trans-European road terminals: Terminal Swiecko–Frankfurt/O, Terminal Koroszczyn–Brest (route Moscow–Paris), Terminal Olszyna–Forst (route Kiev–Strasbourg). Bonenberg is a member of the Architecture and Urban Planning Committee of the Polish Academy of Sciences and of the Council of Scientific Excellence in Poland.

Marco Lucchini

Marco Lucchini is an architect and an Associate Professor at the School of Architecture Urban Planning and Building Construction and at the Department of Architecture and Urban Studies, Politecnico di Milano. He is a visiting professor at Faculty of Architecture of Poznań University of Technology and is a member (as external collaborator) of the 'Grupo de Investigación en Arquitectura: Experiencias del Entorno (GIA_EDE), Universidad de Alicant, Departamento Project y Expresion Grafica'. His research activity focuses on housing design at different scales, the relationship among tectonics, building construction and expression, the narrativity in architectural design and the identity of architecture. In recent years, he has focused on the relationship between Barcelona and Milano modernist architecture. As his interests are modern literature and philosophy, he frequently explores the associations between architecture and philosophy itself.

Preface to ”Architecture: Integration of Art and Engineering”

The book is addressed to architects, as well as those involved in art, interior design, and construction engineering. There is always something interesting going on at the interface of disciplines. It is also the case here, i.e., at the interface of architecture, art, and engineering. The border is multidimensional, but it is clear that research plays an important role. The range of subjects of the presented articles is diverse, there are also indications of new research techniques, resulting in new approaches, and being the keystone that brings together designers involved in these disciplines. The reader is welcomed to learn about all the novel findings.

Oleg Kapliński, Agata Bonenberg, Wojciech Bonenberg, and Marco Lucchini
Editors

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Editorial

Architecture: Integration of Art and Engineering

Oleg Kapliński

Faculty of Architecture, Poznań University of Technology, ul. Jacka Rychlewskiego 2, 60-965 Poznań, Poland; oleg.kaplinski@put.poznan.pl

Abstract: The current Special Issue is a synthetic overview of 21 published articles. The contact point of architecture–art–engineering is multidimensional, and therefore, this synthesis of works takes into account three criteria: (a) research subject indication, (b) research problem identification, and (c) sublimation of the research techniques and instrumentality used. Research problems, scientific values, and utility values have been highlighted. This synthetic tripartite is intended to make it easier for the reader to find an interesting subject and instrumentality. As the topics of the articles overlap, guided by the dominant values of each article, five subject groups have been sublimated. These are: structural aspects and design, digitization, architectural heritage, aesthetics and emotions vs. engineering, and interior architecture. The characteristic values of each subject group are presented. The indicated new design and research tools do not separate but combine the subject industries; they connect the entities of the investment process.

Keywords: architecture; art; building engineering; research methods; synthesis

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1. Introduction

Art and engineering integration is a process taking place before our eyes, in a dynamically changing reality. Architectural IQ is not only a theory, whereas modelling and digitization have become commonplace in everyday activities and, above all, in design and implementation, i.e., in architecture, art, and engineering. The importance of knowledge-based design is systematically growing. Once modest and restrained, research in various areas of life is now permanently interwoven into our reality as the basis of creativity, resourcefulness, and efficiency of human existence. It is favoured and even forced by new design requirements (e.g., integrated design) or simply by the paradigms of sustainable development. Contemporary challenges grow in importance: they make architects react to climate change or they demand a reaction (now generally accepted) to energy consumption limitations.

Concepts such as researcher and AECO (architect–engineer–contractor–owner) have become inseparable. The set of publications in the current issue confirms the observation that spectacular achievements are the result of the cooperation of all entities in the investment process and all industries, and the concept of research should be present at all stages of this process in advanced design. This current Special Issue is about the interlacing of research and the importance of its presence in architecture.

This edition follows on from an earlier Special Issue [1], which shows a tendency to make connections rather than disconnect architecture and engineering. A comprehensive summary is provided in [2].

2. Contributions

The current Special Issue includes 18 research articles, one review, one project report, and one communication. A total of 60 authors or co-authors took part.

The distribution of authors (and co-authors) by country is presented in Figure 1. Participants originate from 11 countries, with participants from Poland, the United Arab Emirates, and China dominating.

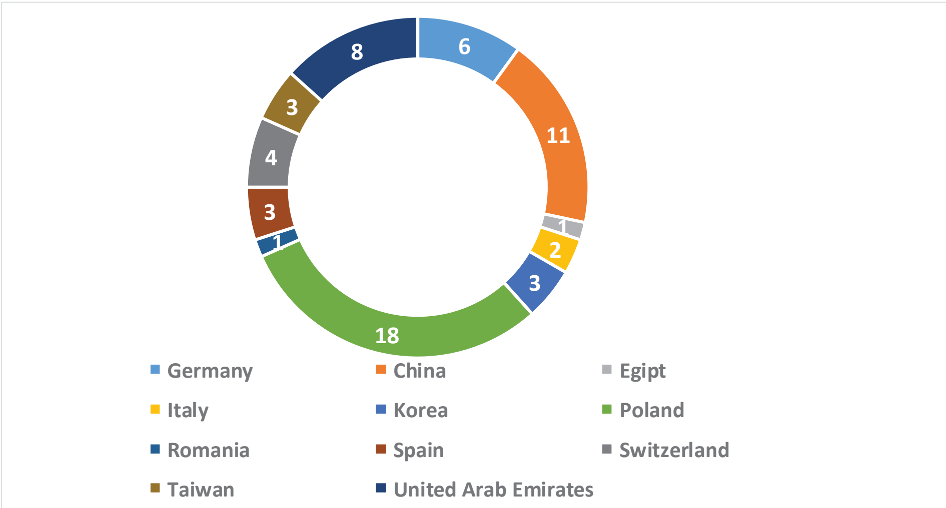

Figure 1. Distribution of authors by countries.

Each of the presented works contains interesting values. A synthetic summary of the values of all 21 works is presented in Table 1. The synthesis of works takes into account three criteria: (a) indication of the research subject, (b) identification of the research problem, and (c) sublimation of the research techniques and instrumentality used. As part of the subject of research, not only parts of buildings, types of structures, and city districts were indicated but also the researched phenomena. As part of exposing the research problem, not only the aim of the research and the relationships sought but also scientific values have been indicated.

The characteristic research tools are presented in the third column of Table 1. They are extremely diverse: from bibliometric analysis, through the online questionnaire, to elements of artificial intelligence. This synthetic tripartite is intended to help the reader find answers to questions of interest, also in terms of topics and instruments.

The last column (on the right side of Table 1) shows the subject group to which the article has been classified. Obviously, the topics of the articles overlap. Guided by the dominant values of each article, five subject groups have been sublimated. They are: structural aspects and design, digitization, architectural heritage, aesthetics and emotions vs. engineering, and interior architecture. Characteristic values of individual subject groups are presented below.

Four papers have been qualified for the *structural aspects and design* group. Article [3] is a good example of seamless integration between the disciplines of architecture and structural design. The geometry of a light spatial installation called Canop is discussed. Scientific support for new architectural forms is included in [4]. The side surfaces of various *Conoid*-type structures used in architectural engineering are considered. A proprietary calculation procedure, based on differential geometry, is proposed. This paper should be of particular interest to lovers of Antonio Gaudi's architecture. Architectural and construction forming of all-glass objects is the content of the next article [5]. The reader will find relations between functional–spatial aspects, form, and structure. Identifying the carbon neutrality effect is the domain of work [6], presenting the results of post-competition projects of a 15-building housing estate in China. A case study of a cable-driven facade installation robot is presented in [7].

Table 1. The content of the Special Issue "Architecture: Integration of Art and Engineering". Synthetic collation.

Author	Subject of the Research	Research Problem	Research Techniques Instrumentality	Subject Group
Wang et al.	The Canopy—a lightweight spatial installation The design and fabrication process of the temporary installation	The geometry of the perforated hanging membrane	Graphic statics Relationship between form diagram and force diagram.	Structural aspects and design
Cabeza-Lainez, J.	The Conoid The Antisphera A revolution of forms	The evolution of new architectural forms Calculus of surface areas	A differential geometry procedure. Parametric design	
Jóźwik, A.	Glass structures All-glass pavilions, extensions, and links	Indication of the relationship between functional and spatial aspects, form and structure. Shaping all-glass structures in buildings	EN 1990:2002 + A1 Eurocode-Basis of structural design—Section 5.2 Design assisted by testing.	
Li et al.	The Third Solar Decathlon China (SDC)	Architecture vs. carbon dioxide emissions. Defining active and passive technologies	Scoring of 15 competition solutions	
Hu et al.	Facade installation. Curtain wall modules;	A case study of a cable-driven facade installation robot, cost–benefit analysis (CBA)	Single-task construction robots (STCRs)	
Zhang & Liu	Thermal comfort. The Universal Thermal Climate Index (UTCI) Two districts in Beijing	The study of buildings' outdoor thermal comfort in urban areas	Longer-term, digital techniques Grasshopper 3D and Rhinoceros 3D. Three-dimensional models	Digitization
Maksoud et al.	The University of Sharjah's (UoS) campus	Improving the visual and environmental conditions of the interior Optimize daylighting and solar radiation exposure	Parametric design. The Ladybug tool for Grasshopper. Rhinoceros 3D. Solar radiation analysis	
Kołata & Zierke	Designer position in architecture The replacement of humans by machines	Will computers eliminate the human factor in the design?	Literature review Artificial General Intelligence (AGI)/Strong Artificial Intelligence (SAI) Active Augmented Reality	

Table 1. *Cont.*

Author	Subject of the Research	Research Problem	Research Techniques Instrumentality	Subject Group
Butelski, K.L.	Odeons: form, function. The Odeon in Biała Podlaska, Amphitheater in the Royal Baths Park in Warsaw	Mobile forms of roofing	Typology of open cultural spaces	Architectural Heritage
Taraszkiewicz et al.	Medieval Bourgeois Tenement Houses The historical centre of Gdańsk	Archetype for contemporary architectural and construction solutions	Iconographic analysis. 3D modelling of structural systems	
Targowski & Kulowski	The European Solidarity Center. Corten plates usage	Influence of material homogeneity on room acoustics	Reverberation time Flutter echo	
Niebrzydowski, W.	Brutalist architecture	Identification and characterization the most important ideas and principles common to avant-garde art	Historical interpretative studies. Studies of buildings in situ	
Anghel et al.	Historical origins modern architecture in East Asia. Space syntax	Preserving the architects' legacy Historical research	Syntactic approach to architectural composition	
Liu et al.	The Tainan bus station construction project Artistic symbol of urban architectural	Modern urban renewal Balancing the cultural value of historic buildings	The Delphic Hierarchy Process (DHP). The AHP expert questionnaire. The MATLAB, a compiling software.	
Malewczyk et al.	Multi-family housing Aesthetics-expectations of recipients	The degree of the composition regularity of the facade elements	Online questionnaire Social network (Facebook) Psychology and neurosciences elements	Aesthetics and emotions vs. engineering
Lee, K.	An emotional connection between space and the body. A phenomenological understanding of interior space	How people experience interior space Which aspects improve the quality of spatial and emotional experience	Multi-sensory experience and emotional connection: A review	
Celadyn & Celadyn	The sustainability of building skins. The building's enclosure as an active boundary Aesthetical longevity	Technical durability and aesthetical longevity of building skins	The proposed Apparent Destruction Architectural Design (ADAD)	
Park & Lee	Design studio Creative design pedagogy	Increasing the creativity of students in the design studio.	Bibliometric analysis	

Table 1. *Cont.*

Author	Subject of the Research	Research Problem	Research Techniques Instrumentality	Subject Group
Celadyn & Celadyn,	Aesthetic functionalism; Sensorial experiences	Improving the Environmental Performance of Interiors	creative introduction of advanced construction techniques	Interior architecture
Jung et al.	The Seniors' Happiness Centre in Ajman UAE. Architectural design for elderly with depression	Colour therapy The physiological and psychological responses Colour preferences	A survey using the Geriatric Depression Scale (GDS) Electroencephalogram (EEG	
Chen et al.	Informal learning space (ILS)	The relation between users' perceptions and the spatial environments	Visual perception analysis. Eye tracking technique	

Several articles are candidates for the *digitization* subject group (some of them have been allocated in the remaining groups). The use of parametric modelling and digital simulation techniques to ensure continuous and effective assessment of the buildings' outdoor thermal comfort is presented by Zhang and Liu [8]. Here, digital tools such as Grasshopper 3D and Rhinoceros 3D are used to create three-dimensional models. The article by Maksoud et al. [9] is discussed in the Interior Architecture group, but instrumental richness should be indicated here. Two sets of codes are designed: for environmental simulations (sun path, solar radiation, wind rose diagrams), and for generating Islamic geometric patterns. Parametric design techniques include The Ladybug tool for Grasshopper and Rhinoceros 3D.

This subject group includes the above-mentioned article on the construction of all-glass objects (see [5])—the use of Eurocodes and, above all, the article [4] for parametric design and the new differential geometry procedure for creating conoidal surfaces.

In the *architectural heritage* group, cultural heritage is intertwined with historical heritage. Under the provocative title 'Can a Computer Design Fine Architecture without Human Input', the authors of Kołata and Zierke [10] prophesy the decline of architects. Fortunately, they withdraw from the ruthless statement about the decline of the designer's position in architecture, leaving the reader with concepts such as Active Augmented Reality, Artificial Super Intelligence, Artificial General Intelligence (AGI), and Strong Artificial Intelligence (SAI). Nonetheless, it does not preclude further polemics.

Butelski [11] introduces us to open cultural spaces, from amphitheatres to odeons (roofed theatres, membranes, and canopies). It is an example of cultural heritage with a tendency to support form and function. A striking example of cultural heritage is the paper [12] about the historic centre of Gdańsk, including burgher residential buildings in the context of archetypes of contemporary architectural and construction solutions. Targowski and Kulowski [13] present the European Solidarity Centre Building in Gdańsk. The relationship between a strong architectural vision and expectations regarding acoustics is described here. The importance of the finishing material is emphasized, which underlines the importance of cultural heritage. However, the European Solidarity Centre itself is already a historical legacy today.

Brutalist architecture is also culture and history. These are the 60s and 70s of the last century. The greatest impact on brutalism was exerted by such avant-garde trends as *art autre*, *art brut*, and *musique concrète*. Details can be found in [14]. Historical heritage dominates the next two articles. Anghel et al. [15] examine and recall two European architects (acting independently) who influenced the form of modern architecture in East Asia. Liu et al. [16] combine historical and cultural layers with architectural engineering, thus balancing the cultural value of historic buildings with the concept of a bus station (in aiwan).

Aesthetics and Emotions vs. Engineering is the fourth subject group. Malewczyk et al. [17] introduce us to the world of facade composition, aesthetics, and neurosciences. They indicate the importance of adapting the visual dimension of architecture to the expectations of its recipients. Multi-family housing in Poland is an example here. The title of the article [18] is significant: 'An Emotional Connection between Space and the Body'. Therefore, it is about the way people perceive inner space. This issue is clearly related to the interior architecture subject group. Technical durability and aesthetical longevity of building skins are the subjects of Communication [19]. The apparent destruction of the building material is the basis for further consideration. Park and Lee [20] glorify creative thinking. The slogan of creativity covers the pedagogy of creative design in a design studio. The topic may be useful in planning college syllabuses.

Interior architecture is the fifth subject group. The above-mentioned problems of emotions and ethics have their consequences, visible in interior design. An example is an aforementioned article [18] which presents quite sensitive research: how the problems of interior architecture are influenced by multi-sensory space and how this space is connected with the emotional experience of the user. The influence of advanced construction techniques and the physical properties of materials on the aesthetics and increasing the functionality of designed interiors is the domain of research presented in the article by Celadyn and Celadyn [21]. The article by Maksoud et al. [9] is also mentioned in the ***digitization*** subject group because of its instrumental richness. In this article, the issues of interior design are strongly highlighted. The research concerns daylighting and exposure to solar radiation in desert climates. The results are used to improve the visual and environmental conditions of corridors in one of the universities in UEA.

Colour therapy is closely related to interior design. Colour therapy is a widely accepted treatment for depressive symptoms in the elderly. Jung et al., a team of researchers, presents the results of the analysis of physiological and psychological reactions of patients to the proposed colour preference in [22]. The research was carried out using electroencephalograms. This research serves to improve the quality of life of the elderly. Relationships between the users' perception and the spatial environment are the subject of research by Chen et al. [23]. In this case, interior architecture is supported by visual perception analysis and instrumentally armed with eye tracking. This technique should be used more often in architectural studies. In Chinese universities, learning spaces constitute the subject matter of research.

3. Discussion and Comments

The division into subjects presented in Table 1 is a working version, but to a large extent, it shows the state of knowledge covered by this Special Issue. At the same time, it indicates that the issues are multi-threaded and multi-layered. In all subject groups, there are technical (construction) problems, there is a clear attitude fostering sustainable development, and economic issues are present. What is important is that all the works (articles, reviews, project reports, and communications) are research-based or discuss research.

The presented research emphasizes the fact that new design and research tools do not separate but combine subject sectors. They constitute a strong trend that binds together and inspires various disciplines of science and technology. The review of works presented in the current SI has shown and confirmed that looking for divisions between engineering and art is unnecessary: it is important that the structures are both beautiful and functional while meeting human needs.

The digital techniques presented (especially in the *digitization* subject group) greatly enrich the view of architecture, engineering, and art. Parametric engineering is the best example of this, five works can be mentioned here [4,5,7–10]. The human–computer interactions type thread appeared against this background (see [10]). It concerns not only digitization but, above all, artificial intelligence. It is worth engaging in polemics on this subject (not only with the authors). This is what inevitably awaits us.

Clearly, shared research areas have emerged, but it is less about design paradigms as such, especially Integrated Project Delivery (IPD) and Building Life Cycle Modelling (BLCM). The current Special Issue does not give the problem closure, but in the near future, it will also be worth paying attention to VR/AR (virtual and augmented reality), design paradigms based on the neurosophic approach, and taking into account biometric systems. On the other hand, in the current SI, there is the quality of the built environment (including the quality of life and the quality of spatial experiences): [8,15,17,22,23].

In the articles in the Aesthetics and Emotions vs. Engineering subject group, the role of the senses in architecture came up (e.g., [18]). Obviously, intuition helps to make choices but the observation–evaluation–feeling relationship is important. We enter a delicate and sensitive field of sensuality, i.e., perceiving stimuli using senses. This is where unsolved problems arise at the interface between engineering and art. Not denying the importance of sensuality, it must be said that, in architecture, nonetheless, sight is decisive. We receive about 80 percent of information about the environment through sight. [24]. Architects call it the "sixth sense of architecture", which means that, e.g., a construction drawing has a lower rank than the context of a location. There is a slight analogy to the human–computer interaction issue mentioned above. Nevertheless, it is necessary to take into account empathy [25]. This is a step towards empathic design, which not only stresses the attitude of sensitizing users, these are also procedures and methods.

There are two interesting and important aspects of this issue worth mentioning here. Architecture responds to climate change; in this case, clear examples are [6,9]. The reaction presented there is in line with the mission of 'ARCHITECTURE 2030' [26]. It is worth using these experiences in the light of climate change around the globe and the international movement: architecture in the age of climate change. Another aspect, interior design, is an increasingly attractive topic among architects because architect-researchers use sophisticated instrumental measures more and more often, and they also use brainwaves [22]. New, interesting instruments dramatically increase the usefulness of their designs—see [9,18,21–23].

4. Conclusions

The issues emerging at the interface of architecture–art–engineering are very broad and open-ended. This review of 21 articles shows that these problems are multi-threaded and multi-layered. The research techniques presented here are of great importance, as they significantly enrich the core of the matter and the view on architecture, engineering of a building, and art. All the studies presented here are aimed at improving the quality of life.

It is clear that the methods known in other disciplines, such as psychology or artificial intelligence, are now successfully transferred to the field of architecture. Hence, the scope of the research presented in this book is quite wide: from parametric engineering to the role of the senses in architecture.

Taking over the instrumentality as well as the presented research emphasizes the fact that new design and research tools do not separate but combine individual industries and connect the entities of the investment process. The very process of the research in question, research techniques, technological progress in construction, and integrated design combined with life-cycle modelling means that not only research is collaborative but design itself has become a team game.

All this is meant to improve the quality of the built environment, fostered by empathic design. All this creates new challenges.

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Project Report

The Canopy: A Lightweight Spatial Installation Informed by Graphic Statics

Shuaizhong Wang *, Federico Bertagna, Patrick Ole Ohlbrock and Davide Tanadini

Department of Architecture, ETH Zurich, 8093 Zurich, Switzerland; bertagna@arch.ethz.ch (F.B.); ohlbrock@arch.ethz.ch (P.O.O.); tanadini@arch.ethz.ch (D.T.)
* Correspondence: shuaizhong.wang@arch.ethz.ch; Tel.: +41-77-977-6840

Abstract: This paper illustrates the design and fabrication process of the temporary installation *The Canopy*, developed as part of the fib Symposium on Conceptual Design of Structures 2021. The geometry of the perforated hanging membrane that forms *The Canopy* is the result of seamless integration between the disciplines of architecture and structural design, which was one of the driving inputs for the entire process. Particularly, the use of geometry-based models and graphic statics allowed activating the interplay between these disciplines. This was the key to balancing the relationship between architectural spaces and structural requirements, and to informing the multifaceted design exploration of *The Canopy* from conceptual design to construction.

Keywords: temporary installation; architecture and structure; structural design; graphic statics; lightweight structure

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1. Introduction

The Canopy (Figure 1) is a temporary lightweight installation made of wide perforated fabric strips hanging from steel cables inside the *Kiesofenhalle*, a former cellulose factory in Attisholz, Switzerland. The project aimed at creating a venue for the 3-day event of the International fib Symposium on "Conceptual Design of Structures" [1], which was held in September 2021 and hosted over 150 participants. In conjunction with the conference, an exhibition explored the Swiss contribution to structural design looking at design methods and exemplary projects. Particular emphasis was given to the use of physical models for form-finding and graphic statics, represented by the work of renowned Swiss engineers such as Heinz Isler (1926–2009) and Robert Maillart (1872–1940).

Figure 1. The front elevation of *The Canopy* as seen from the reception desk. Photo by Shuaizhong Wang.

The objective of this paper is to illustrate the design, fabrication, and erection processes of *The Canopy*. Drawing inspiration from the work of Sekler [2], this paper elaborates on the strategy to integrate and balance the relationship between structure, construction, and tectonics. These three aspects are addressed from three perspectives throughout *The Canopy*'s design process: conceptual design, fabrication and assembly, and final spatial expression. The paper shows the instrumental role of graphic statics in unfolding the relationship between form and forces and thus in reconciling spatial artistic needs and structural requirements from the conceptual design phase. Graphic statics provides an ideal medium for integrating the design of structure, construction, and tectonics, with the aim of fostering a collaborative and creative interaction between architecture and engineering. *The Canopy*'s design process exemplifies the significance of this collaboration.

2. Background

The *Kiesofenhalle* is a former industrial hall located inside the industrial estate of Cellulose Attisholz AG, a company that operated for over 100 years in the paper production industry. The company was founded in 1881, merged with the Balsthal paper mill in 1914, and finally was acquired the German company Hakle in 1983 [3]. Since the end of 2016, in collaboration with the municipality of Riedholz and the Canton of Solothurn, the area has gone through radical transformation that aimed to turn it into a mixed-use artistic and cultural district while preserving the original cultural values of the industrial buildings [4] (Figure 2a).

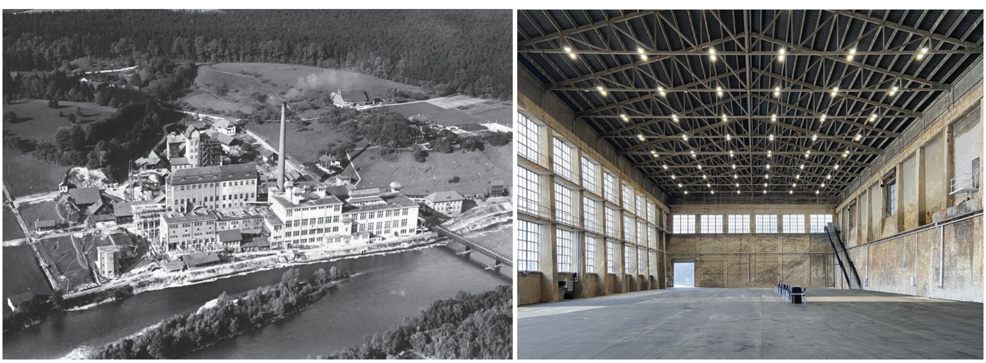

Figure 2. (**a**) Aerial view of the industrial complex Cellulose Attisholz AG in 1924, © Walter Mittelholzer/ETH Library (http://doi.org/10.3932/ethz-a-000492184 (accessed on 30 May 2022)); (**b**) The interior of the *Kiesofenhalle* today. Photo by Shuaizhong Wang.

The overall size of *Kiesofenhalle* (Figure 2b) exceeds 3000 m^2 and reaches a maximum height of 17.5 m. The hall served as a storage for raw material whose chemical properties greatly enhanced the risk of corrosion of metal elements. For this reason, even the roof slender trusses are in fact made of concrete, thus remarking the strong industrial expression of the hall. Furthermore, the building's exceptionally tall scale and large, continuous south-facing windows contribute to the creation of an almost sacred spatial experience similar to a modern concrete church.

The enormous size of the hall called for a series of interventions that would frame the space and create a human-scale venue to accommodate the different functions required by the organizer of the conference. In particular, it was necessary to separate the hall into a conference space, an exhibition area, and a registration and catering area.

Apart from a limited amount of time for on-site assembly—only three days—another requirement was to intervene on the existing structure as little as possible. This excluded the possibility of using the existing roof trusses as supports, or anchoring elements to the ground. Moreover, the possibility to introduce high external forces in the walls was also limited. Because of these constraints, the design was defined as a lightweight structure made of parallel steel cables and perforated fabric strips hanging from above. The undulating geometry of the fabric allowed for a continuous generation of vertical partitions and of horizontal surfaces with different heights above ground. Thanks to this simple logic, the elements could be pre-fabricated off-site and easily transported and assembled in the given time frame. In this sense, the combination of cables and textile elements represented a suitable way to generate the desired spaces, while complying with the given requirements, as demonstrated by several reference projects [5–8].

In response to the conference's functional requirements, the hall was divided into three main areas based on different privacy levels: a public area with registration desks and a catering area; a semi-public exhibition area; and a relatively intimate auditorium for lectures and discussions (Figure 3). In the auditorium, the height of the fabric had to be higher than 4.8 m to avoid obstructing the projector but less than 7 m in order to create the feeling of an enclosed space. Conversely, the more public character of the exhibition and reception areas called for more open spaces, with fabric heights reaching up to 11 m above ground. The division between these three functional areas was achieved solely through the geometry of *The Canopy*. As better explained in Section 4.1.1, by manipulating the lower boundary line of the fabric sags, it was possible to create a subtle spatial division between the different areas, thus suggesting a new spatial order to the enormous hall. Aspects related to the acoustics of the diverse spaces were not considered as integral part of the design process since the Symposium program did not include parallel sessions, and the catering and exhibition areas were not used during the presentations.

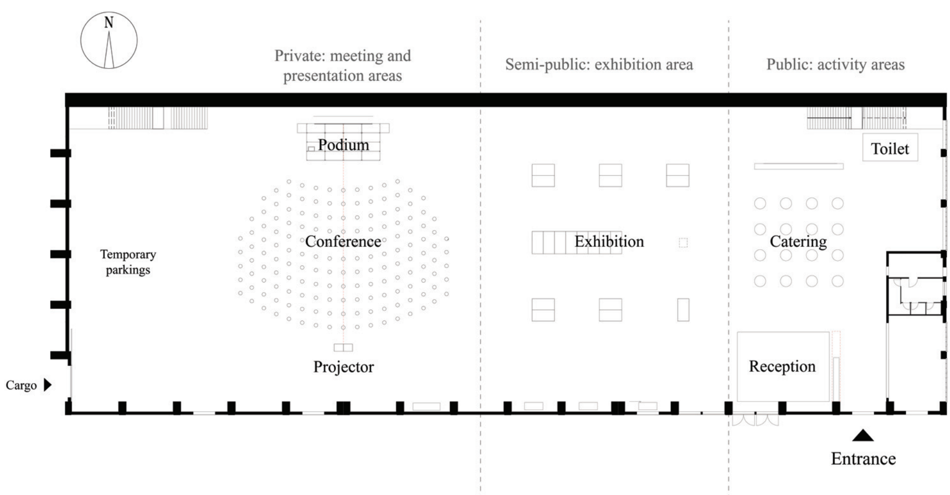

Figure 3. Floor plan and functional planning. The hall was divided through the sole use of hanging fabric strips into three areas characterized by different levels of privacy.

Based on the design concept, to achieve the sensation of lightness and a floating effect, *The Canopy*'s supporting structure had to be designed to be as invisible as possible. Therefore, when conceiving the structural system, we sought to minimize both the size and number of components. The slender and clear supporting structure for *The Canopy* was made of simple steel cables. The catenary line that they draw as they span over the hall recalls the historical methods of form-finding using hanging models, also relating to the content of the exhibition. The use of hanging models as a design tool to determine the optimal form for structures is a technique used by many architects and engineers, especially before the introduction of analytical methods. Antoni Gaudí (1852–1926) already used the hanging model as a three-dimensional design tool to determine the optimal form for structures subjected to purely compressive loads at the turn of the 20th century, and ultimately obtained the structural form of the *Sagrada Familia* [9]. Later on, the Swiss engineer Heinz Isler has been a key protagonist in the use of this technique to determine the optimal shape for shell structures [10]. For them, the physical model entails not only a method for determining the ideal shape, but also a method of thought and operation [11]. Similarly, graphic statics was used as a key method in the design of *The Canopy.*

3. Methodology

In the design process of *The Canopy*, the simultaneous requirements related to form and forces were reconciled using graphic statics. Graphic statics is a set of geometric rules that allow unfolding in a diagrammatic way the relationship between the form of a structure in static equilibrium and the forces within it [12–14]. Several scientists contributed to the development and formalization of graphic statics starting from the 16th century. Interestingly, many of the early works related to graphic statics make use of the hanging models under given loads to illustrate the basics of the method [15–17] (Figure 4a). Graphic statics was eventually formalized and expanded by the German engineer and ETH Professor Karl Culmann in his two volumes of *Die Graphische Statik* [18] (Figure 4b). His work on graphic statics significantly influenced renowned Swiss engineers such as Robert Maillart (1872–1940) [19], and this legacy remains an integral part of the teaching of structures at ETH Zurich to these days [20]. The use of graphic statics as the structural design tool for the canopy is a tribute to this legacy.

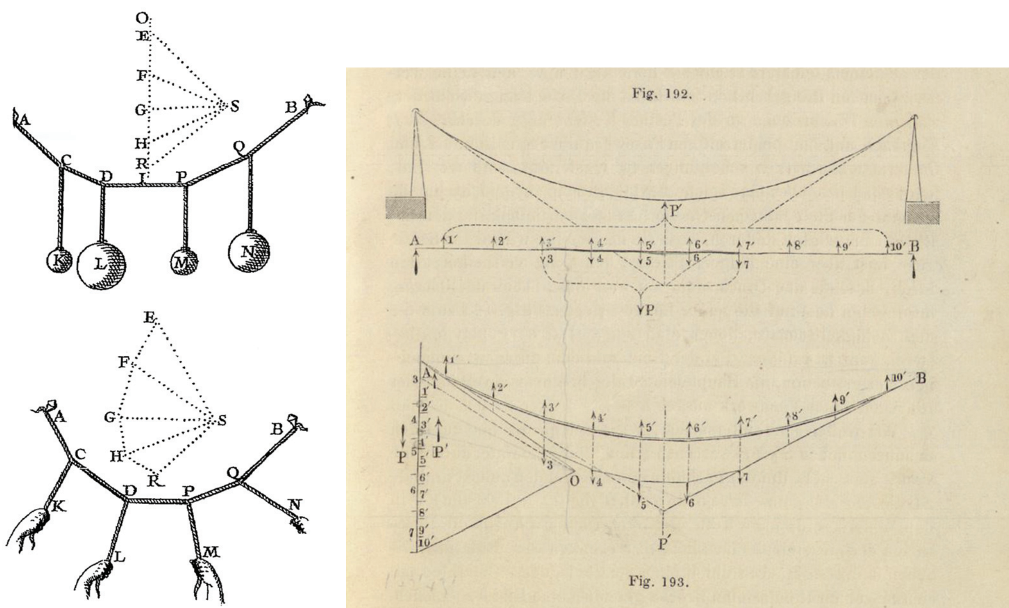

Figure 4. (**a**) Stevin's diagrams illustrating equilibrium states for a cable under different loads, and the corresponding internal forces using graphic statics [16]; (**b**) Culmann's introduction of the polygon of forces and funicular polygon [18] (p. 513).

It is worth mentioning that this approach is radically different compared to conventional Finite Element Analysis (FEA) software for structural engineering. In fact, unlike graphic statics, FEA software is based on analytical models that are solved through numerical techniques [21]. When used for design purposes, FEA shows several shortcomings as it generally tends to conceal the relationship between form and forces. This often hinders the possibility to operate on a conceptual level and to create an effective dialogue between architects and engineers [20]. Conversely, the diagrammatic nature of graphic statics offers a common ground between disciplines and an effective design tool for the conceptual design phase of a structure [22]. Additionally, it also facilitates the early integration of the art and technology of structures as part of the architectural design process by reducing the design of load-bearing structures to basic equilibrium concepts and by translating calculations into simple geometric operations [23,24].

In addition to its visual nature, the constructive and generative nature of the vector-based operations of graphic statics enables easy integration with digital design methods that began to emerge in architecture in the early 2000s [25–28]. Digital implementations of the method allowed for overcoming the inherent limitations of manual applications and proved effective for the creation of architectural spaces informed by form and forces simultaneously [29–31]. A simple digital implementation of graphic statics has also been used in the design of *The Canopy* for rapid form-finding and calculation of forces using Grasshopper3D.

4. Case Presentation: Structure, Construction, and Tectonics

To elaborate *The Canopy's* design and fabrication methods, this paper utilises Eduard F. Sekler's critical aspects of structural design to dissect its embedded structural thinking: structure, construction, and tectonics [2]. In his article, Structure, Construction, and Tectonics, Sekler defines structure as an "intangible concept" that is "realized through construction and visualized through tectonics" [2]. Thus, structures are bonded to the construction technique and the perceptual representation of the tectonic form (Figure 5). Based on this understanding, the following section of the paper describes how graphic statics was used to inform the design in order to facilitate early collaboration between the architects and engineers.

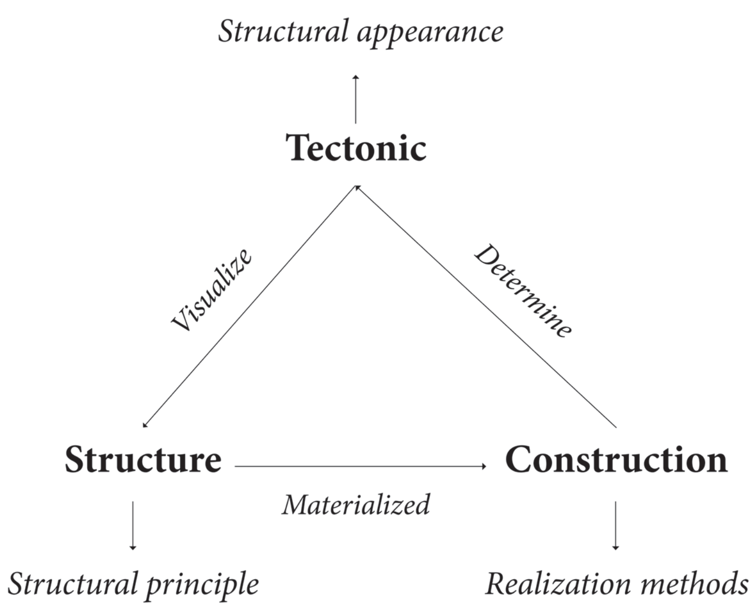

Figure 5. The graphical representation of the relationship between Structure, Construction, and Tectonic from the concept of Eduard Franz Sekler.

4.1. Structure: A Lightweight and Minimal Intervention

The most challenging aspect of intervening in the building was transforming the over-scale floor height into a human-scale exhibition and lecture space with the least amount of means. This led to the main design concept: designing a small, nested space within the building with a limited height above ground that separates three functional areas with varying dynamic and static partitioning. Due to the spatial qualities of the original structure, it was decided early on to create this enclosure out of a translucent or perforated material. As such, the installation would limit the space while preserving the context of the surrounding scene. The three main functional areas were identified based on the main entrance's location, located in the south-east corner of the building (Figure 3).

The project was conceived as a lightweight spatial installation, a translucent, abstract, white fabric canopy that floats within the hall in a gradual wave pattern. Each fabric fold corresponds to the axis of the building's original concrete trusses, achieving geometric and visual continuity. While defining the space beneath it, the fabric separates the different functions of the private density through the fluctuating height changes of the fabric in the vertical direction, linking the entire space in a holistic and continuous form while meeting the requirements for the conference activities. The free-falling, hanging form of the fabric seeks to recall the image of paper rolls that were once produced at Attisholz and the logic of the catenary curve as a pure structurally-informed shape. This interplay between form and force was also addressed repeatedly in the exhibition that was organized in conjunction with the conference.

From the beginning of the design process, the diagrammatic nature of graphic statics allowed for the intuitive expression, rapid communication, and visual definition of these structural forms during the design brainstorming phases (Figure 6).

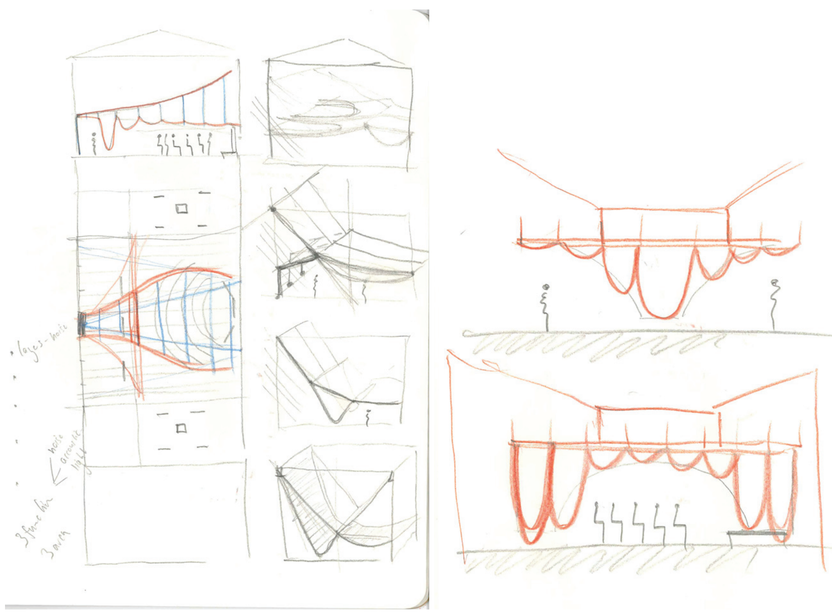

Figure 6. (**a**) The early canopy design concept based on graphic statics describing how to use compression element in the center and tension elements on both sides to create a covering surface; (**b**) Sketches of the canopy's different hanging methods according to different functional use.

Due to the enormous size of the canopy, with the fabric sagging up to 6.5 m, the choice of fabric properties such as porosity, weight, and elasticity had a significant impact on the final result. To simulate the material as realistically as possible, several 1:1 mock-ups were built and tested (Figure 7). In particular, these tests showed that fabrics that were too light could not easily result in a precise catenary geometry for the lack of sufficient self-weight. Heavier fabrics, despite generating cleaner catenary lines, proved to be excessively opaque, thus considerably weakening the desired architectural image and the relationship with the context. Additionally, fire safety represented an additional requirement that excluded the possibility to use several types of materials. The final choice was a polyethylene 2-m wide white mesh of 5 mm and a weight of 0.1 kg/m^2.

Figure 7. Physical suspension mock-up of different fabric materials. The analysis of diverse physical models allowed finding the desired balance between weight and translucency of the fabric. Photo by Shuaizhong Wang.

Before the detailed design of the hanging structure, a crucial design step was to decide whether to suspend the fabric using longitudinal or transversal rows of cables in the *Kiesofenhalle*. Even though the building footprint is symmetrical in its short section, the north side of the façade is almost entirely closed with a solid retaining wall, whereas the south side of the building has stunning continuous windows that give the building a sense of breathing. Due to the shorter transversal distance, the first test comprised an array of parallel cables along this direction (Figure 8a). However, the presence of windows heavily limited the freedom in choosing locations for the hanging structure's anchor points. Moreover, because of the inevitable sagging of the cable when spanning, it was difficult to maintain the same height for fabric strips that belong to the same row. This would have called for the need to add a second array of cables in addition to the main one, which would have significantly affected the simplicity and abstraction of the overall form. Therefore, we ultimately decided to suspend the fabrics along the building's longitudinal axis (Figures 8b, 9 and 10). This decision results in four direct benefits:

1. It provides more freedom in the placement of anchor points on the walls;
2. The anchor points of each cable are placed further away one from each other, thus evoking a sense of ambiguity due to *The Canopy*'s incomprehensible structural logic as users cannot see both arrays of anchor points simultaneously;
3. The cables span the entire 94.5-m-long hall, elongating *The Canopy* longitudinally, expanding the covered area, and enhancing the dialogue with the building;

4. The longitudinal anchorage allows the lower portion of the fabric to remain horizontal in the vertical direction while slightly lifting the sides due to its own sagging, giving the sides of the building a geometry that follows the interior circulation more closely.

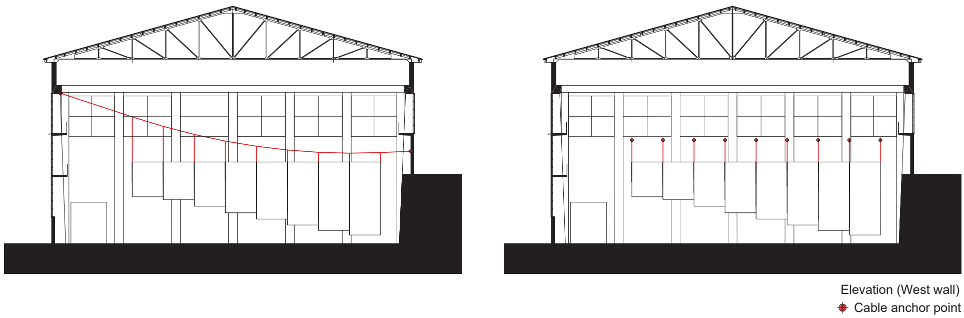

Figure 8. (**a**) Spanning the cables along the short side of the building would have called for a secondary structure to keep the top part of the fabric strips on the same height; (**b**) Conversely, when the cables span the longitudinal direction, it is possible to avoid the need for this secondary structure.

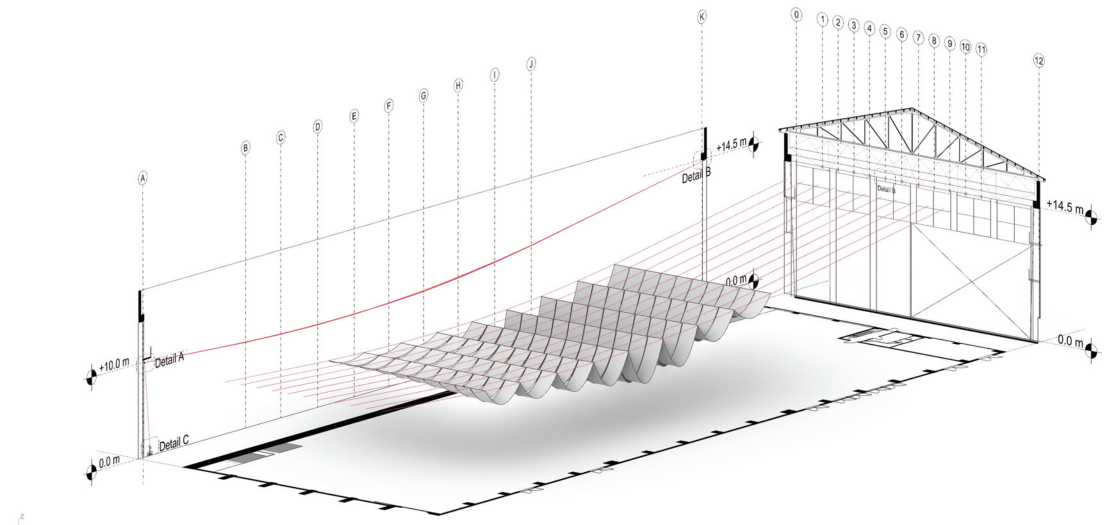

Figure 9. Axonometric diagram of the relationship between the structural model and the order of the existing building. In its final configuration, the cables were suspended along the building's longitudinal axis, thus eliminating the secondary structure and giving more freedom for the placement of anchor points on the walls.

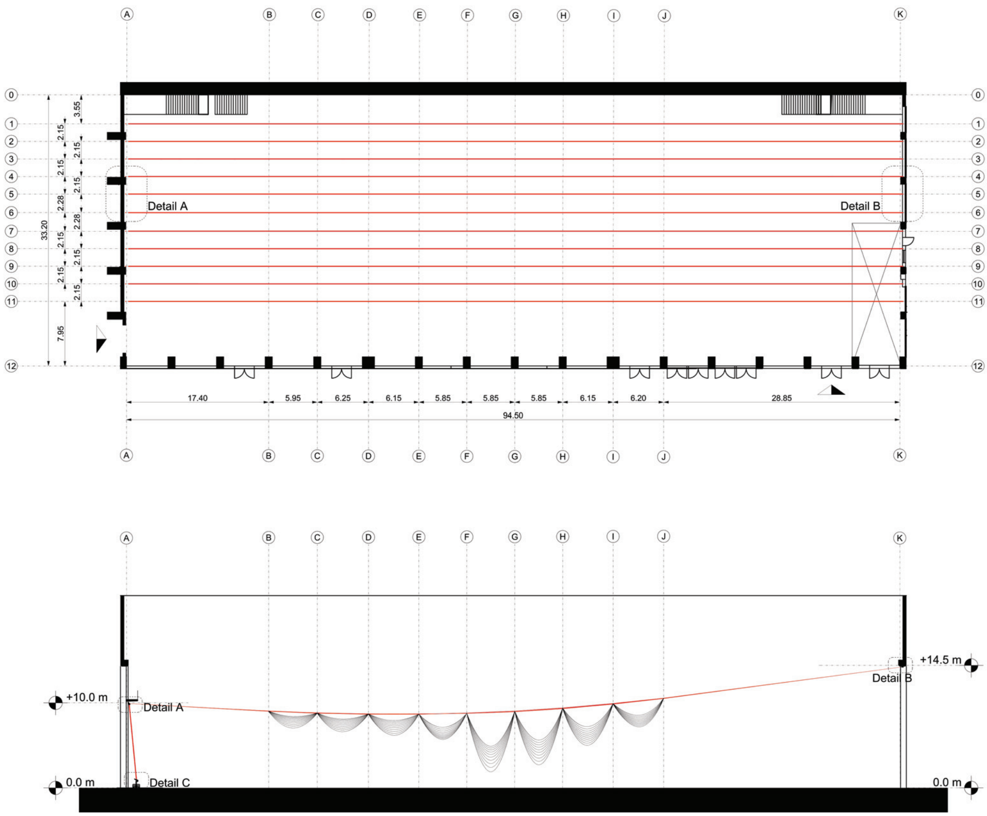

Figure 10. The plan and section drawings of *The Canopy*.

4.1.1. Form-Finding through Graphic Statics

After the definition of the hanging direction, graphic statics was used to investigate the geometry of the cables that would support the fabric strips, as well as to control the forces in the supports. *The Canopy*'s catenary line is not just a formal translation of the form diagram of graphic statics. Instead, it is an attempt to retrace the design logic of graphic statics as a method and integrate it with the site and functional needs of the conference. Therefore, the interaction and synergy between the force diagram and the form diagram were used in many ways as the leading logic in designing the structures of *The Canopy*. The use of graphic statics allows for a clear illustration of the relationship between form and forces to control the relationship between the height of each fabric strip, as well as their length. Figure 11 shows the final geometry, as well as two variants with a slightly lower (Variante 1) and higher (Variante 2) cable. The corresponding force diagrams show the change of the force F in the cable connected to the counterweight according to the three different geometries. It is worth mentioning how the force in the cable is extremely sensitive to changes in cable height and vice-versa. Thanks to the use of graphic statics, this dependency between design parameters (i.e., depth of the cable sag, force in the cable, and reaction forces) is represented in an explicit manner. The manipulation of form and force diagrams represented an extremely important design tool that allowed controlling the form of the cable and the resulting forces in the walls jointly. The geometric lower boundary of the installation is determined by the separation function that the fabric needs to provide. The final design is, therefore, a tradeoff that enhances the expressiveness of the canopy and its functional aspects, while keeping the forces under control.

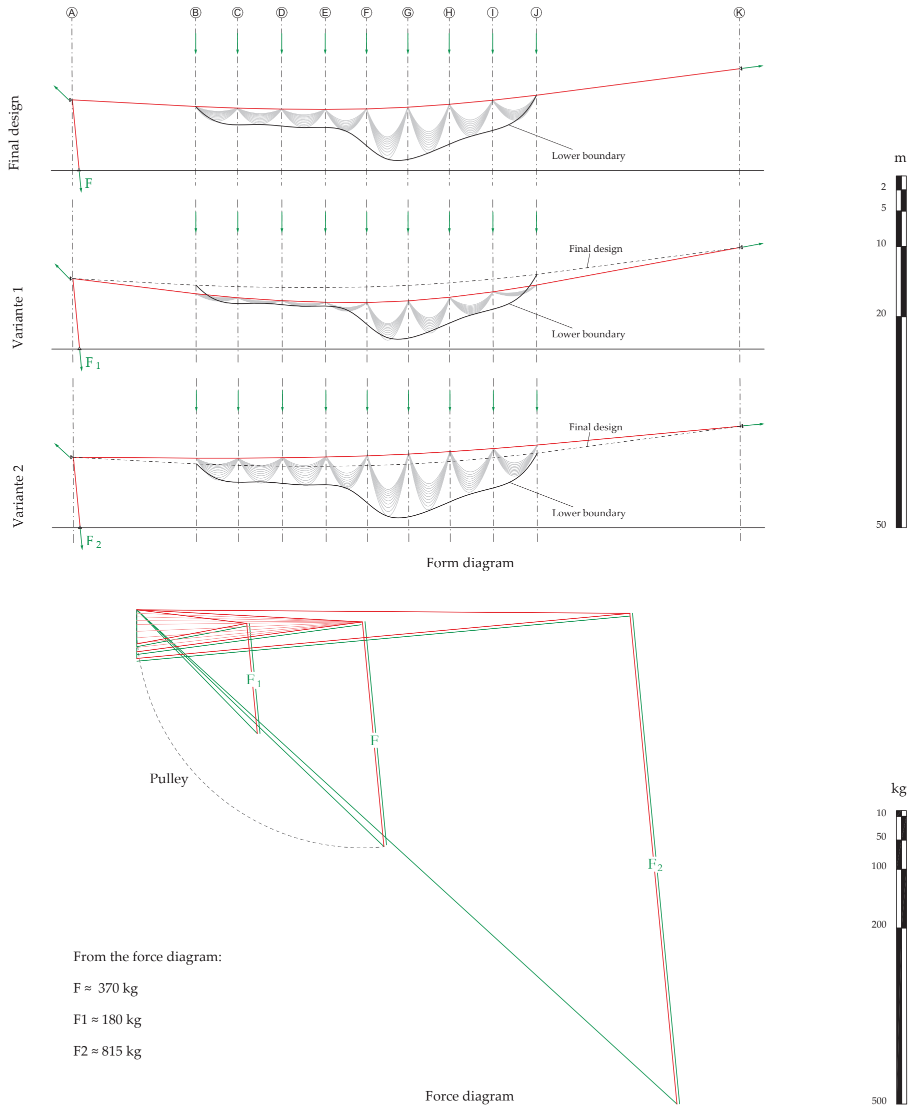

Figure 11. Graphic statics unfolds the relationship between the shape of *The Canopy* (Form diagram) and the forces acting in the cable and supports (Force diagram). For each element in the Form diagram, there is a corresponding segment in the Force diagram, whose length is proportional to its internal force. The figure shows a superposition of form and force diagrams for three different options. The mutual relationship between Form and Force diagrams shows in an explicit way that even small changes in the form of the cable greatly affect the internal forces in it and vice-versa. For instance, a reduction in the sag of the cable (Variante 2) would result in deeper sags for the fabric—which enhances the spatial effect of the strips—but it would also result in extremely high reaction forces that might create problems when anchoring the cable to the walls.

Because of the undulating form, the weight distribution at each point where the fabric and the cable are connected were different. The magnitude of the force at each connection point informed the geometry of the cable and, consequently, the relative height between each strip and the adjacent strip of the fabric. This necessarily results in an iterative form-finding process in which the shape of the fabric and the cable are interdependent. Thanks to the use of parametric tools (i.e., Grasshopper3D), it was possible to instantly update the relative relationship between the form of the fabric and the force on the cable, as well as provide immediate feedback on the magnitude of the force and the corresponding form. As a result, the folding positions of the ten fabrics waves corresponded to the positions of the concrete trusses on the roof, and the precise control of the forces enabled the structural elements to be as thin as possible, thus enhancing the dialogue between *The Canopy* and the existing structure.

Due to production and transportation constraints, the longest dimension of a fabric roll was limited to 75 m. Therefore, we implemented a simple optimization algorithm to approximate as closely as possible the relationship between the desired undulating form and the total length of the fabric, in the attempt to minimize the need for cuts and overall material waste. This optimization problem was solved using Galapagos [32], a native Grasshopper3D component.

4.1.2. Structural Detailing

Once the overall force distribution pattern was determined, it was necessary to develop a connection system between extremely thin steel cables (⌀ 5 mm) and aluminum pipes (⌀ 17 mm) on which the fabric is folded. The system had to be easy to produce and it had to allow for simple adjustments on site also considering that neighboring pipes might result in misalignments along the vertical direction. For this reason, the joint between the cable and the pipes was designed as a hook that is pin-jointed to the pipes in order to guarantee the necessary tolerances with respect to vertical movements. The connection between fabric strips and pipes was solved using 3D printed holders to be screwed directly onto the pipe (Figures 12 and 13). To meet the constraints of a three-day construction period and a one-day dismantling period, *The Canopy* was designed in such a way that all the components could be pre-fabricated and partially pre-assembled in the workshop. The following section illustrates the pre-fabrication process and how the assembly was then carried out on site.

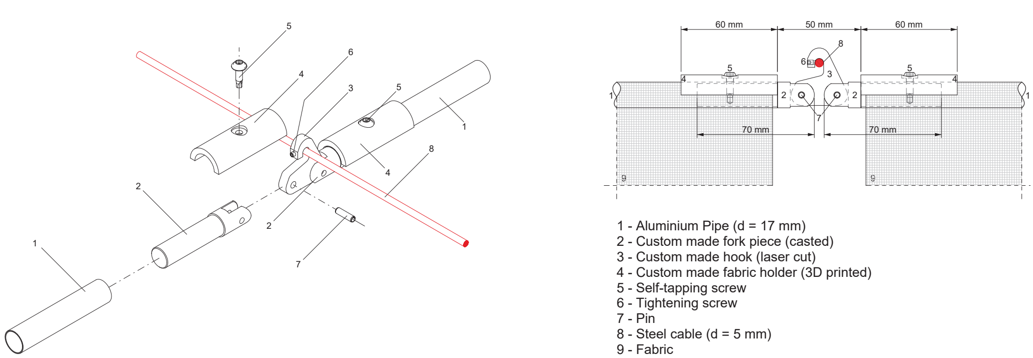

Figure 12. The structural detail drawings of the fabric, pipe, and cable connections.

Figure 13. (**a**) The detail of the joints' final expression; (**b**) The joints become invisible from a distance. Photos by Shuaizhong Wang.

4.2. Construction: A Convenient and Flexible System

The Canopy's entire structure was pre-fabricated at ETH Zurich and partially assembled before transporting it to the site. The components of the nodes were custom made-using 3D printing and laser cutting, and pre-assembled onto the pipes (Figure 14a). This made it possible to quickly hang and adjust them on-site during construction. To ensure that the fabric folding position could be precisely measured and that the aluminum pipes could be fastened without creating creases or discoloration of the fabric from repeated fabrication processes, a customized rolling machine was developed at the Raplab at ETH (Figure 14b). This allowed for precise measurements of the fabric strips and for an easy installation of the pipes at the right location along the strips.

Figure 14. (**a**) The 3D-printed and laser-cut elements for the joints (Photo by Alessandro Tellini); (**b**) The rolling machine for measuring the fabric strips and for the installation of the pipes developed at the Raplab (ETH Zurich) (Photo by Giulia Boller).

Eventually, the 10 fabric rolls—with pipes already installed on them—were transported on site. At that point, 11 pairs of anchor points were installed on both walls. Due to the structure's extreme lightness, the anchor points for the cable consisted of 22 mm threaded bars and stainless steel rings. The 22 anchor points represent the sole direct intervention on the existing structure.

The stainless steel cables were connected on one end directly to the anchor points on the wall, whereas the other end is redirected to a set of counterweights placed on the ground using a pulley. The counterweights were created on site using sandbags. To facilitate the assembly process, the counterweights were equipped with a hand-operable winch to control the length of the cables, and thus their height above ground. Once the cables were arranged, the 10 fabric strips were unrolled on the ground and connected to the cables using the hooks (Figure 15a). The erection process consisted of a simultaneous rise of the 11 cables until they reached their final position (Figure 15b). The overall erection process was carried out in less than two days, whereas the final disassembly required only three hours, including the process of rerolling the fabric for future reuse.

Figure 15. The 10 fabric strips were first unrolled on the ground and connected to the cables (**a**). The entire system was later lifted into the final position through a set of hand-operable winches located at the ground level (**b**). Photos by Shuaizhong Wang.

4.3. Tectonic: An Abstract Floating Cloud

Due to the in-depth consideration of the structure, the final expression of *The Canopy* appears as a temporary cloud floating in the *Kiesofenhalle* in a pure and ethereal way, showing ever-changing levels of transparency as the user moves in the space. The user's perception is challenged, as the structural logic is not evident at first glance. This was achieved thanks to the extremely thin cables that almost disappeared in the height of the hall. This ambiguous structural expression also invites users to discover and explore the entire installation from all sides, inadvertently echoing the conference's intention to refine and stimulate conceptual thinking about structures through a multidisciplinary exchange. Furthermore, the long side of *The Canopy*, with its gaps between the fabrics, exposes as much as possible of the original walls, thus defining the scale of the space primarily in terms of height. This enhanced the existing architectural quality of the space and gave it new life subtly and reverently, swiftly transforming it into a new functional space (Figure 16). Interestingly, the *Kiesofenhalle* is also used for cultural events and exhibitions, and it featured an indoor immersive light show that was displayed at the end of the conference (Figure 17). Although it was not considered in the design process, such a unique lighting condition greatly enhanced the floating image of *The Canopy*.

Figure 16. (**a**) *The Canopy* as seen from the entrance of the *Kiesofenhalle*; (**b**) A side view showing the partitioning elements between the lecture hall and the exhibition area; (**c**) The relatively small height of *The Canopy* above the lecture hall allowed creating an intimate space at human-scale; (**d**) The exhibition area under *The Canopy*; (**e**) A view of the entire installation from above; (**f**) The superposition of several layers of fabric in space created very diverse levels of transparency that stimulated user curiosity and interaction with *The Canopy*. Photos by Shuaizhong Wang.

Figure 17. (**a**) Some of the lighting situations greatly enhanced the ethereal character of *The Canopy*; (**b**) *The Canopy* reacting to the immersive light show present in the venue. Photos by Shuaizhong Wang.

5. Discussion

The final materialization of *The Canopy* demonstrated that all the design intentions, functional requirements, and site constraints were met. The thinking process behind this project reflects the interaction between form and force, creating a space of "Strong Structures" [33] through a synergy of structure, construction, and tectonic aspects with an extremely lightweight and minimal intervention. *The Canopy* ultimately succeeded in providing an attractively proportioned and functionally partitioned temporary space for the conference, always respecting the existing space in which it was immersed. By considering the structure from multiple scales and perspectives, the design concept and the intended function of the space are achieved.

The use graphic statics enabled simultaneous control of form and forces during each design phase, and helped to reconcile structural constraints, functionality, and spatial expression of the factory building. The development of the form and force diagrams in 2D, as in the case of *The Canopy*, is in fact very simple to the point that it can also be conducted by hand. However, the development of a 3D structure soon results in more demanding graphical constructions as the geometric complexity significantly increases. This might represent the sole limitation of the method proposed in this paper, meaning that three-dimensional applications are often possible only with the help of 3D modelling software or specific digital implementations.

Finally, the workflow of *The Canopy* shows that the pursuit of structural art is not about letting the structure's sound overshadow the building itself [34]. We can instead find an interdependent and solid balance between the two by utilizing the proper design medium and process [35,36]. Obviously, achieving this equilibrium requires multiple iterations of the design process instead of allowing the structure to realize the building's form in a "post-rationalization" manner.

6. Conclusions

This paper described the design, fabrication, and erection process of *The Canopy*, a temporary spatial installation created as part of the International fib Symposium on "Conceptual Design of Structures". *The Canopy* is the result of a multidisciplinary design process in which spatial, structural, and functional needs were reconciled using graphic statics. The diagrammatic and intuitive nature of graphic statics enabled the rapid communication and definition of structural concepts using both qualitative hand-sketches in the conceptual design phase and digital implementations of the method in the form-finding stage. The diagrammatic and cross-scale nature of graphic statics also clarifies the subsequent detail processing and construction process, enabling the structural concept to be systematically linked to the construction, thereby harmonizing the relationship between structure, construction, and tectonic in the design and reinforcing their relevance. The design process of *The Canopy* demonstrates the significance of collaboration and the use of common and practical design methods in structural design such as graphic statics. In fact, without the establishment of an effective common ground between architects and structural engineers *The Canopy*'s final spatial expression would not have been possible.

At the end of the conference, the company currently managing the *Kiesofenhalle* expressed the desire to preserve *The Canopy* and reuse it for future events. *The Canopy* is currently stored in the warehouse adjacent to the hall and will be re-erected in the hall to recreate, with extremely simple means, that space-within-a-space that allowed a radical, yet respectful transformation of the *Kiesofenhalle*.

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buildings

Article

Architectural Characteristics of Different Configurations Based on New Geometric Determinations for the Conoid

Joseph Cabeza-Lainez

Department of Architectural Composition, University of Seville, Av. Reina Mercedes 2, 41002 Sevilla, Spain; crowley@us.es

Abstract: The aim of this article is to orient the evolution of new architectural forms offering up-to-date scientific support. Unlike the volume, the expression for the lateral area of a regular conoid has not yet been obtained by means of direct integration or a differential geometry procedure. In this type of ruled surface, the fundamental expressions I and II, for other curved figures have proved not solvable thus far. As this form is frequently used in architectural engineering, the inability to determine its surface area represents a serious hindrance to solving several problems that arise in radiative transfer, lighting and construction, to cite just a few. To address such drawback, we conceived a new approach that, in principle, consists in dividing the surface into infinitesimal elliptic strips of which the area can be obtained in an approximate fashion. The length of the ellipse is expressed with certain accuracy by means of Ramanujan's second formula. By integrating the so-found perimeter of the differential strips for the whole span of the conoid, an unexpected solution emerges through a newly found number that we call psi (ψ). In this complex process, projected shapes have been derived from an original closed form composed of two conoids and called Antisphera for its significant parallels with the sphere. The authors try to demonstrate that the properties of the new surfaces have relevant implications for technology, especially in building science and sustainability, under domains such as structures, radiation and acoustics. Fragments of the conoid have occasionally appeared in modern and contemporary architecture but this article discusses how its use had been discontinued, mainly due to the uncertainties that its construction posed. The new knowledge provided by the authors, including their own proposals, may help to revitalize and expand such interesting configurations in the search for a revolution of forms.

Keywords: conoid; ellipse; calculus of surface areas; number psi; number Pi; parametric design; cubature architecture; design paradigms

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1. Introduction

Outline of the Problem

Since antiquity the meaning of the number Pi has been associated with the length of a circumference, that is, such length, if the diameter of the said circumference is the unit, equates Pi, and correspondingly for different measures of the diameter. Even in the Bible, when an injunction is transferred to building an offering's laver (the Sea Bronze) of circular design in Solomon's Temple, it is mentioned that the perimeter ought to be three times the diameter [1]—a revealing estimate.

Given this, it is reasonable to speculate, from a scientific point of view, about the meaning of different powers of Pi, for example, Pi^N?

The answer is positive, and in this article, we would discuss the particular case of the second power of π, that is, Pi squared or Pi^2. Such a situation arises when we try to calculate the surface area of a Conoid, a ruled surface generated by parallel straight lines that project from a circumference directrix onto a linear edge (Figure 1).

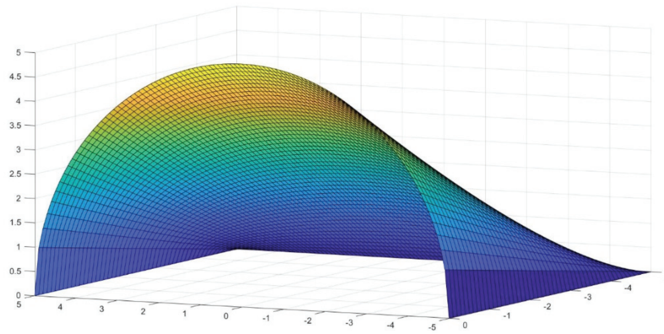

Figure 1. A typical straight conoid with circular directrix, where $R = L = 5$.

The equation that regulates such a warped figure for x and y positive is:

$$\frac{L^2 z^2}{(L-x)^2} + y^2 = R^2 \tag{1}$$

where R is the radius of the directrix in the case of a circumference and L is the length in the X-direction as shown in Figure 2. If we make $L = R$, it turns out that,

$$\frac{R^2 z^2}{(R-x)^2} + y^2 = R^2 \tag{2}$$

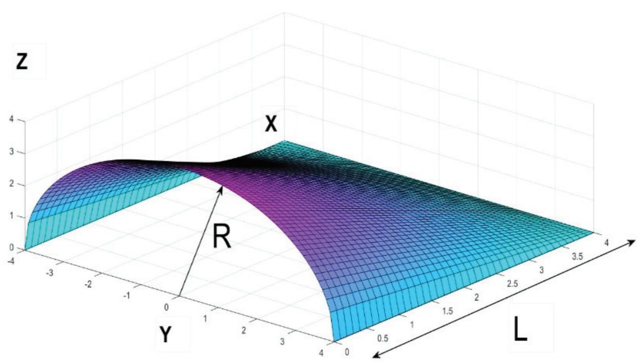

Figure 2. Explanation of the parts of a straight conoid with circular directrix, in this case $R = L = 4$.

To solve the problem of the lateral area of such surface, after failed attempts for a solution with other methods, we employ Ramanujan's second approximation for ellipses [2].

2. Methods and Materials

2.1. Resolution of the Proposed Approximation

In his well-known proposal to calculate the perimeter of an ellipse, Ramanujan stated that the perimeter (P) of the curve equates:

$$\mathrm{P} = \pi\left(3(a+b) - \sqrt{(3a+b)(3b+a)}\right) \tag{3}$$

where a is the major and b is the minor semi-axis. Such an approximation is fairly easy to handle and it works well for the extreme case of $b = 0$, a straight line, which tends to appear in the limit edge of the conoid and its boundaries.

The error committed by using this formula is not constant since it depends on the diverse conoidal sections. On the other hand, as we do not possess an exact expression for the length of an ellipse, there is no proper way to compute such error in a mathematical fashion. In Table 1 we have attempted to do so by numeric methods.

Table 1. Results of computing the area of several conoids by the method proposed by the author and with graphic interpolation procedures allowed by the software *Grasshopper* and the command *Alphashape* of Matlab.

Radius = L Unit	Alpha-Shape	Cabeza Approx.	Grass-Hopper	Delta Δ Alphas	Delta Δ Grassh
0.25	0.1958	0.1862	0.1842	0.0096	−0.002
0.50	0.7712	0.7446	0.7369	0.0266	−0.0077
1	3.0726	2.9784	2.9476	0.942	−0.308
2	12.155	11.913	11.790	0.242	−0.123
3	27.734	26.805	26.528	0.929	−0.277
4	48.886	47.654	47.161	1.232	−0.493
5	76.019	74.460	73.690	1.559	−0.77
6	109.27	107.22	106.11	2.05	−1.11
7	148.83	145.94	144.43	2.89	−1.51
8	194.54	190.61	188.64	3.93	−1.97
9	246.41	241.25	238.75	5.16	−2.5
10	304.254	297.841	294.76	6.413	−3.081

For the said directrix, we can substitute a for R, the radius of the circumference.

Thus, $a = R$ and it is easy to prove that being R/L, the tangent of the angle formed by the middle section of the figure, the minor semi-axis is nothing but $b = x \times R/L$. It should be noted that in the following calculations, the positive direction of the x-axis is reversed for simplicity from that in Figure 2 and the origin of coordinates is at the linear end of the figure and not at the extreme of the circumference.

Then, as previously stated, R is the radius of the end semicircle and L is the total length and for any x value between 0 and L, we would obtain,

$$\mathrm{P} = \pi\left(3(R + xRL) - \sqrt{\left(3R + \frac{xR}{L}\right)\left(\frac{3xR}{L} + R\right)}\right) \tag{4}$$

And grouping similar terms,

$$\mathrm{P} = \pi\left(3R(1 + x/L) - \sqrt{R(3 + x/L)R(3x/L + 1)}\right) \tag{5}$$

$$\mathrm{P} = \pi\left(3R(1 + x/L) - \sqrt{R^2(3 + x/L)(3x/L + 1)}\right) \tag{6}$$

The half perimeter is,

$$\mathrm{P}_1 = (\pi/2)\left(3R(1 + x/L) - \sqrt{R^2(3 + x/L)(3x/L + 1)}\right) \tag{7}$$

We can take R out of the whole expression,

$$\mathrm{P}_1 = (\pi R/2)\left(3(1 + x/L) - \sqrt{(3 + x/L)(3x/L + 1)}\right) \tag{8}$$

And L as well,

$$\mathrm{P}_1 = (\pi R/(2L))\left(3(L + x) - \sqrt{3x^2 + 10Lx + 3L^2}\right) \tag{9}$$

To obtain the lateral area of the conoid composed by diminishing strips along the central section, we need to perform the integration of,

$$A_c = \frac{\pi R}{2L} \int_0^L \left[3L + 3x - \sqrt{3x^2 + 10Lx + 3L^2)}\right] dx \tag{10}$$

The first two terms are immediate and give the solution;

$$I_1 + I_2 = \left[3Lx + \frac{3x^2}{2}\right]_0^L \tag{11}$$

And the final result for these two terms, applying the limits of integration is,

$$I_1 + I_2 = 3 \times L^2 + \frac{3L^2}{2} = \frac{9L^2}{2} \tag{12}$$

This, multiplied by the constants out of the integral gives, $\frac{9\pi RL}{4}$;

The third term is slightly more complicated following the square root type and it involves a logarithmic primitive.

$$I_3 = \int_0^L \left[\sqrt{3x^2 + 10Lx + 3L^2}\right] dx \tag{13}$$

This integral presents the root of an expression of the type $a + bx + cx^2$.

As such, it is recommended to find the value of $\Delta = 4ac - b^2$, for this case, $36L^2 - 100\,L^2 = -64L^2$

The solution yields, [3]

$$I_3 = \left[\frac{6x + 10L}{12}\sqrt{3x^2 + 10Lx + 3L^2} - \frac{64L^2}{24}\left(\frac{1}{\sqrt{3}}\right)\log\left(2\sqrt{3(3x^2 + 10Lx + 3L^2)} + 6x + 10L\right)\right]_0^L \tag{14}$$

And substituting,

$$I_3 = \left[\frac{4L}{3}(4L) - \frac{64L^2}{24}\left(\frac{1}{\sqrt{3}}\right)\log\left(2\sqrt{3(16L^2)} + 16L\right)\right] - \left[\frac{10L}{12}\sqrt{3L^2} - \frac{64L^2}{24}\left(\frac{1}{\sqrt{3}}\right)\log\left(2\sqrt{3(3L^2)} + 10L\right)\right] \tag{15}$$

$$I_3 = \left[\frac{16L^2}{3} - \frac{5\sqrt{3}L^2}{6} + \left(\frac{8L^2}{3\sqrt{3}}\right)\log(16L) - \left(\frac{8L^2}{3\sqrt{3}}\right)\log\left(8L\sqrt{(3)} + 16L\right)\right] \tag{16}$$

By virtue of the properties of division of the logarithm,

$$I_3 = L^2\left[\frac{16}{3} - \frac{5\sqrt{3}}{6} - \left(\frac{8}{3\sqrt{3}}\right)\log\left(\frac{\sqrt{3}+2}{2}\right)\right] \tag{17}$$

And from Equation (12), the sum of the two previous immediate integrals was,

$$I_1 + I_2 = \frac{9L^2}{2}$$

The total result for the so-conceived area, subtracting I_3 from Equation (17) is,

$$\frac{\pi R}{2L}L^2\left[\frac{9}{2} - \frac{16}{3} + \frac{5\sqrt{3}}{6} + \left(\frac{8}{3\sqrt{3}}\right)\log\left(\frac{\sqrt{3}+2}{2}\right)\right] \tag{18}$$

After careful simplification, the Area of the conoid based in R and L gives:

$$I = \frac{\pi RL}{2}\left[\frac{27-32}{6} + \frac{5\sqrt{3}}{6} + \left(\frac{8\sqrt{3}}{9}\right)\log\left(\frac{\sqrt{3}+2}{2}\right)\right] \tag{19}$$

which can be reduced to,

$$I = A = \frac{\pi RL}{2}\left[\frac{5\sqrt{3}}{6} - \frac{5}{6} + \left(\frac{8\sqrt{3}}{9}\right)\log\left(\frac{\sqrt{3}+2}{2}\right)\right] \tag{20}$$

And consequently,

$$A = \frac{\pi RL}{4}\left(\frac{1}{9}\left[15\left(\sqrt{3}-1\right) + 16\sqrt{3}\,\log\left(\frac{\sqrt{3}+2}{2}\right)\right]\right) \tag{21}$$

2.2. Discussion of the Findings

For several reasons we have decided to name this new number ψ,

$$\psi = \frac{1}{3^2}\left[15\left(\sqrt{3}-1\right) + \left(4^2\right)\sqrt{3}\,\log\left(1+\frac{\sqrt{3}}{2}\right)\right] = 3.140923532703498 \tag{22}$$

$$\psi \cong \pi \tag{23}$$

For computational purposes both numbers can be equated, and it will considerably simplify Equation (21) as,

$$A = \frac{\pi RL}{4}[\psi \cong \pi] = \frac{\pi^2 RL}{4} \tag{24}$$

We find such a result remarkable in sundry senses. Firstly, because, ψ is a transcendental number [4], akin to Pi but original in concept. Secondly, if substituted for Pi in the discussion it could perhaps improve the accuracy of Ramanujan's approach, and this remains a question open for discussion in future developments.

Thirdly, it involves the fact that the area of the figure studied, the conoid, if $R = L = 1$ would be a fourth of Pi squared or Pi multiplied by itself.

2.3. Definition of the Antisphera

A volume composed of four symmetrical opposed conoids, as previously defined (radius = 1), would have a lateral surface of π^2, that is Pi squared.

When conceiving such a form, obvious similarities with the sphere come to mind and that it is why we have named this curious figure in Grecian "*Antisphera*". The plan of the figure resembles a square of two by two, but the front view is a circle of diameter one. It constitutes a three-dimensional example of the circle's quadrature, sought since antiquity [5].

Its equation responds to,

$$\frac{R^2 z^2}{(\pm(R-x))^2} + y^2 = R^2 \tag{25}$$

We consider just the former to be a noticeable finding. However, the problem is not completely solved since the parallel infinitesimal strips may not fit perfectly with the curved surface and they would act as a kind of envelope. For engineering purposes this is deemed sufficient when the angle of inclination of the figure, θ, is not too steep (less than $\pi/2.5$), but in order to improve accuracy, we have calculated a coefficient to take into account the differences of width of the said strips.

Since we certainly know that at the middle section of the surface, the width of an actual unit section of the conoid is not dx but instead $dx/\cos\theta$, we need to take into account this feature and effect an interpolation between both values.

It can be discussed whether the variation of the strip is curvilinear or not, but several experimental calculations (See Section 2.4), estimate that for the time being, this is the preferred approximation for angles under Pi/2.5 (other approaches are also being considered for higher values of θ, see Section 2.5).

Such a coefficient of Cabeza-Lainez, κ, would accordingly be,

$$\kappa = \frac{1+\sec\,\theta}{2} = \frac{1+\cos\,\theta}{2\cos\,\theta} \tag{26}$$

where tan (θ) = R/L as θ is the arctangent of the central section of the figure.

Therefore, the final expression to compute the lateral area of this particular surface, with the caveats referred above, produces,

$$A = \frac{\pi^2 RL}{4}\frac{(1+\cos\,\theta)}{2\cos\,\theta} \tag{27}$$

But if R and L coincide, Equation (27) is reduced to,

$$A = \frac{\pi^2 R^2}{4}\frac{\left(1+\sqrt{2}\right)}{2} \tag{28}$$

In the case of a new volume that we have defined as *Antisphera* ©, if R is the unit and if we adjoin the four quarters of which it is composed (Figure 3),

$$A = \pi^2 R^2\frac{\left(1+\sqrt{2}\right)}{2} = \pi^2\frac{\left(1+\sqrt{2}\right)}{2} \tag{29}$$

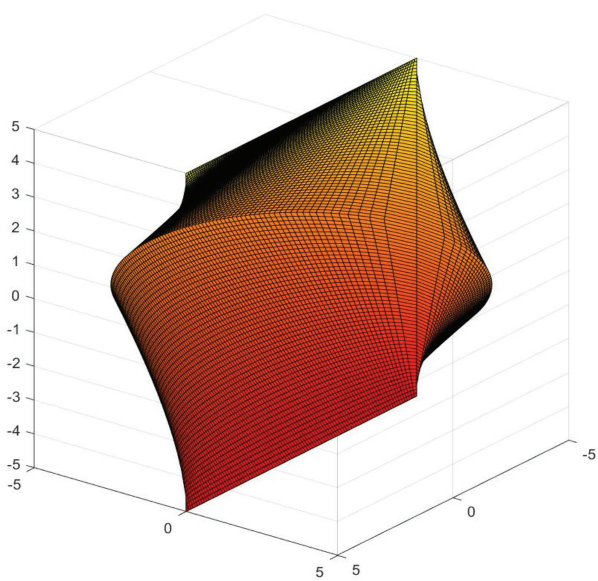

Figure 3. Depiction of the *Antisphera* for R = 5. View from below.

Nevertheless, if we should make,

$$R^2 = \frac{2}{\left(1+\sqrt{2}\right)} \tag{30}$$

It would mean that for an *Antisphera* of precise Radius = 0.9102,

$$A = \pi^2 \tag{31}$$

In this fashion, a new and distinct meaning, has been attributed to the second power of π, by virtue of such elaborate demonstration.

2.4. Comparison with Other Approximate Computing Methods

Subsequently, we have proceeded to compare the aftermath with other numerical simulations available, for instance the command *Alphashape* for computation of areas in Matlab and the graphic interface *Grasshopper.* The results show a considerable agreement, and our findings stay in the middle of the output for both approximate tools (Table 1).

More thorough data are being prepared, but the procedure for the graphic interfaces is clumsy and haphazard as a bespoke volume is required every time in order to compute the areas, and the mesh of interpolation has to be decided beforehand with frequent hollow regions. This is a clear advantage of our method.

2.5. Discussion for Higher Values of the Conoid Angle

The κ coefficient previously defined must, for coherence, remain over,

$$\kappa > \frac{2\ \tan\ \theta}{\pi} \tag{32}$$

It is however clear that, for values of $\theta > 1.25$ the former relation may cease to verify (Figure 4).

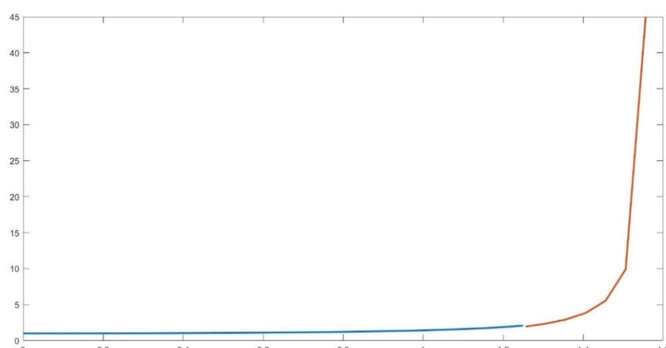

Figure 4. Depiction of Cabeza-Lainez coefficient κ (blue) and limit case (red).

For lower quantities, the coefficient performs smoothly, since cos θ tends to be one and the same as κ does, so our prediction becomes even more accurate.

But for values over Pi/2.5, it is convenient to define a new coefficient. We are currently estimating different adjustments to present them in a further development of our theory. In the meantime, a tentative assumption for the value of the area, would be the following,

$$A = \frac{\pi^2 RL}{4} + \frac{\pi R^2}{2} = \frac{\pi R}{4}(\pi L + 2R) = \frac{\pi^2 RL}{4}\left(1 + \frac{2R}{\pi L}\right) \tag{33}$$

Thus, the new coefficient κ_1 would be,

$$\kappa_1 = 1 + \frac{2\,\text{tg}\ \theta}{\pi} \tag{34}$$

A suggested experimental refinement of this factor from $\theta = \pi/2.5$ and onwards is,

$$\kappa_2 = \sin\left(\frac{\pi}{2} - \theta\right) + \frac{2\,\text{tg}\,\theta\ \sin\ \theta}{\pi} \tag{35}$$

In most problems of engineering, high values of the said angle are rare because they imply that the conoid is very close to the circle or in other words, there is little or no space left inside the surface, which may become contradictory to the nature of spatial design [6].

2.6. Calculations of the Area for an Elliptic Conoid

In Section 2.1 we had delayed the discussion after attaining the area values for the conoid ending in a circumference, but in a similar manner we can continue to use Ramanujan's prediction for an ordinate fragment of the same conoid whose extreme is logically an ellipse. For any real number n, the area yields,

$$A_{ec} = \frac{\pi R}{2L}\frac{(1+\cos\ \theta)}{2\cos\ \theta}\int_0^{nL}\left[3L + 3x - \sqrt{3x^2 + 10Lx + 3L^2)}\right]dx \tag{36}$$

$$A_{ec} = \frac{\pi RL}{216}\frac{(1+\cos\ \theta)}{2\cos\ \theta}\left[\begin{array}{c} 9\left(18n(2+n) - (6n+10)\sqrt{n(3n+10)+3} + 10\sqrt{3}\right) + \\ 96\sqrt{3}\ \log\left(\frac{\sqrt{3n(3n+10)+9} + 3n + 5}{8}\right) \end{array}\right] \tag{37}$$

For $n = 1$ the solution is Equation (21).

As before, we have employed the coefficient κ, but we need to be aware that for values of θ nearing $\pi/2.5$ the expressions proposed in the previous section, that is, κ_1 or κ_2 should be introduced in its stead.

2.7. Calculations of the Volume of the Conoid

As a complement for the theories exposed, the computation of the volume of the conoidal figure by means of the previous integral method is relatively simple and exact. Since the value of the area of an ellipse is πab, and as before, $a = R$ and $b = xR/L$

$$V = \pi R\int_0^{nL}[xR/L\,]dx = \frac{\pi R^2 n^2 L}{2} \tag{38}$$

This equates the volume of the equivalent cylinder multiplied by s = $n/2$.

If $n = 1$ and the limit is L,

$$V = \frac{\pi R^2 L}{2} \tag{39}$$

that is half the volume of the equivalent cylinder (as s = ½).

Finally, if $L = R$, the volume gives

$$V = \frac{\pi R^3}{2} \tag{40}$$

Making $R = 1$ as in the *Antisphera*, we receive $V = \pi/2$.

With $R = 0.9102$ as in Equation (30), the volume reaches, 0.3770 π.

The volume and area properties in the conoid are smaller than in the cylinder but still larger than the equivalent cone. This will prove advantageous for the sustainability of structures and buildings (Sections 5 and 6) as the envelope and consequently the energy exchange and materials are less costly.

The finding of the volume of a conoid is sometimes attributed to Johannes Kepler but to our knowledge the first polymath to deduct it by comparison with the volume of a cone of the same basis, was Guarini in *Euclides Adauctus* [5].

3. Repercussions for Radiative Heat Transfer

3.1. Introduction to the Problem of Surface Factors

In previous studies [6], some of which were published in this journal [7], Cabeza-Lainez highlighted that the radiative exchange factor for any manifold surface is dependent on the equation:

$$F_{12} = \frac{1}{A_1}\left[\int_{A_2}\int_{A_1} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dA_1 dA_2\right] \tag{41}$$

In a volume composed of only two surfaces, the same author established its second principle of radiation [8], which states that in the said situation, the rate of exchange is proportional to the areas of the intervening surfaces. For example, in a hemisphere (see Figure 5), the respective areas are $A_1 = 2\pi R^2$ and $A_2 = \pi R^2$.

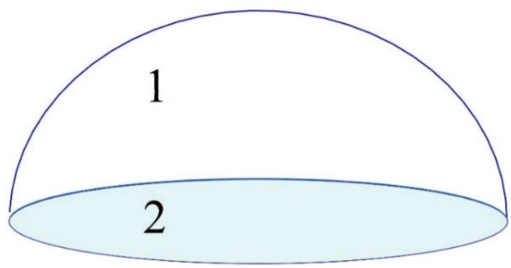

Figure 5. The second radiation principle of Cabeza-Lainez form-factors applied to a hemisphere.

As such, the corresponding form-factor from the half sphere to its base disc is [8],

$F_{12} = \frac{A_2}{A_1} = \frac{1}{2}$, and the amount of energy from the hemisphere to itself, F_{11} is also ½ [8].

By the principle of conservation of energy, all interchanges must add up to 100% or unity [6].

However, if the disc were topped by a double symmetric conoid (Figure 6), since previous to our finding we ignored the value of its lateral area, the question remained unknown.

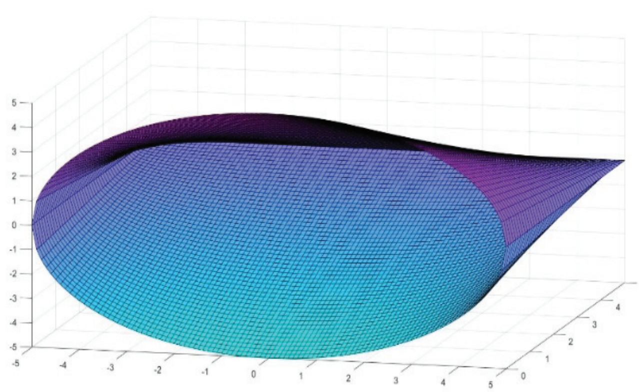

Figure 6. The second radiation principle of Cabeza-Lainez applied to the form-factor of a double conoid.

We are finally in the position to respond to this issue with perfect ease. It is opportune to outline that the above integral equation, Equation (41), is deemed unsolvable for the conoidal geometry [7].

The area of this double conoid is,

$$A = \frac{\pi^2 R^2}{2} \frac{\left(1+\sqrt{2}\right)}{2} \tag{42}$$

3.2. Example 1

In all the cases where $\theta = \pi/4$, the relationship between the area of the base circle πR^2 and the double conoid is precisely,

$$F_{12} = \frac{A_2}{A_1} = \frac{4}{\pi\left(1+\sqrt{2}\right)} = 0.527393 \tag{43}$$

This is the factor from the conoidal top to the circular base and since $F_{11} + F_{12} = 1$, the self-factor F_{11} is then,

$$F_{11} = 1 - F_{12} = 1 - 0.527393 = 0.4726 \tag{44}$$

For this particular disposition, the values are not dissimilar from those of the hemisphere, 0.5, but they will need to be included in a standard comparison among radiative shapes described in reference [8].

Let us now discuss a new and more difficult situation for a conoid with radius 2 and length 4 (Figure 7).

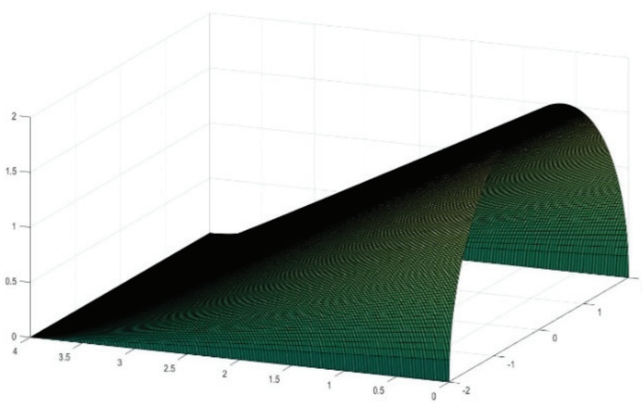

Figure 7. The single conoid limited by a rectangular plane and semicircle.

3.3. Example 2

In reference [9], Cabeza-Lainez has partly solved Equation (31) for some circular fragments.

For any vertical circular sector with a center situated in the middle of the edge x of a horizontal rectangle of dimensions, x and y; by virtue of the Cabeza-Lainez seventh principle, [10] the configuration factor from the sector of radius r to a point in the perpendicular rectangle, will be:

For $t = r^2 + y^2 + x^2$, $m = \sqrt{x^2 \sin^2\theta_1 + y^2}$ and $n = \sqrt{x^2 \sin^2\theta_2 + y^2}$

$$f_{12} = \frac{y}{2\pi} \times \left(\frac{\cos\,\theta_1}{m} \arctan \frac{r}{m + \frac{\cos\,\theta_1 x}{m}(\cos\,\theta_1 x - r)} - \frac{\cos\,\theta_2}{n} \arctan \frac{r}{n + \frac{\cos\,\theta_2 x}{n}(\cos\,\theta_2 x - r)} \right) + \frac{y}{4\pi x} \ln\left[\frac{(t - 2\,\cos\,\theta_1 r x)}{(t - 2\,\cos\,\theta_2 r x)}\right] \tag{45}$$

Bearing in mind that the sector is comprised between the angles θ_2 and θ_1 and being its radius r as mentioned.

In the usual situation of a semicircle the above expression is reduced to,

$$f_{12} = \frac{1}{2\pi}\left(\arctan\frac{r+x}{y} + \arctan\frac{r-x}{y}\right) + \frac{y}{4\pi x}[\ln\left(r^2+y^2+x^2-2rx\right) - \ln(r^2+y^2+x^2+2rx)] \quad (46)$$

By numerical procedures detailed in [7], we extend the above expression to the whole rectangle to find the form-factor, whose value is of F_{12} = 0.1272. It represents fraction of exchange of radiative energy from the horizontal rectangle under the conoid (A_1) to the semi-circular side of the figure (A_2).

The previously unknown area of the conoid A_3, following the above stated formulas (Equation (27)) is 20.9042

From the reciprocity principle [6], A_1 F_{12} = A_2 F_{21}, whence,

$$F_{21} = (16/2\pi)0.1272 = 0.3239 \quad (47)$$

Being A_1 and A_2 planar, it is mandatory that [6],

$$F_{12} + F_{13} = 1 \quad (48)$$

$$F_{21} + F_{23} = 1 \quad (49)$$

And this implies,

$$F_{13} = 1 - 0.1272 = 0.8728 \quad (50)$$

$$F_{23} = 1 - 0.3239 = 0.6761 \quad (51)$$

Applying reciprocity again [6], A_3 F_{31} = A_1 F_{13} and A_3 F_{32} = A_2 F_{23}, which yields,

$$F_{31} = (A_1/A_3)\ F_{13} = (16/20.9042)\ 0.8728 = 0.6680 \quad (52)$$

$$F_{32} = (A_2/A_3)\ F_{23} = (2\pi/20.9042)\ 0.6761 = 0.2032 \quad (53)$$

By virtue of the principle of conservation of energy [6],

$$F_{31} + F_{32} + F_{33} = 1 \quad (54)$$

$$F_{33} = 1 - F_{31} - F_{32} \quad (55)$$

Being non-planar, the fraction of energy that the radiating conoid exchanges with itself is,

$$F_{33} = 1 - 0.6680 - 0.2032 = 0.1288 \quad (56)$$

Not merely radiative heat transfer in the figure under study has been solved by this procedure, but also light transmission when it originates at conoidal skylights such as those constructed by Ilja Doganoff [11] in 1957 in Bulgaria (See Section 5.1).

3.4. Example 3

If we, as in a sort of check, would double the conoid presented in example 2 and compare in it the factor between a circle (A_2) and (A_1) the enclosing figure, (Figure 8) we obtain that, since the relation of areas is now 0.3006, the factor from the conoid to the circle is precisely this value, following Cabeza-Lainez' second principle [8].

Accordingly, the complex self-factor of the conoid to itself yields nothing but,

$$F_{11} = 1 - 0.3006 = 0.6994 \quad (57)$$

In the original half *Antisphera*, if we remember Section 3.2, and example 1, the same quantity amounted to,

$$F_{11} = 1 - 0.527393 = 0.4726 \quad (58)$$

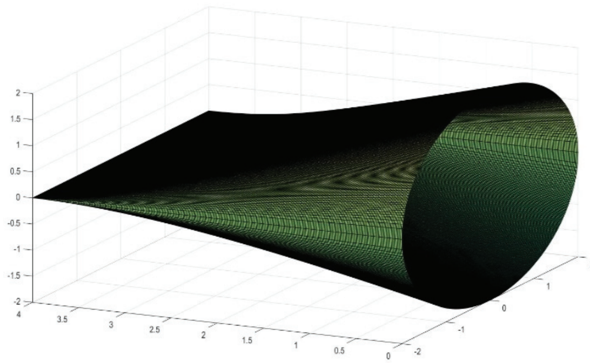

Figure 8. The same conoid of Figure 7 but closed to obtain the form-factor.

Such a difference can be explained because the area of this new conoid is larger than the previous one since the angle θ is less pronounced (in this case, the length doubles the radius), or in other words more energy is retained under the new configuration.

In the second example discussed, of a half-conoid (Section 3.3) involving three surfaces (rectangle, semicircle and conoid), the self-factor (Figure 9) was smaller, 0.1288, but a noticeable fact is that even so, it does not reach a fraction of one half of the self-factor for the whole conoid (0.6994/2 = 0.3497) of the same dimensions (Example 3), as logic would perhaps induce us to think. This exemplifies the complexity of the solutions because they often appear to rule out common sense [12].

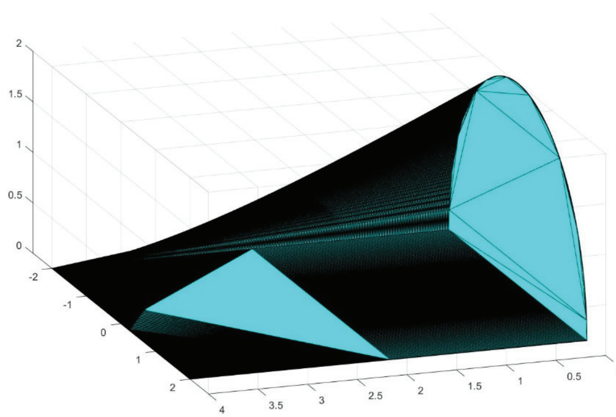

Figure 9. The three surfaces intervening in Example 2 whose area is calculated by computer graphic interpolation.

It is important to stress the utmost difficulty of obtaining these entities by any other method, including quadruple integration [7].

4. Generation of New Figures Based on the Previous Findings

In Section 2, we defined the symmetrical figure composed of four conoids, namely the *Antisphera* (Figure 10).

Nevertheless, we have conceived that by altering the symmetry and parts of the previous figure, a series of other interesting bodies is derived, maintaining initially the ratio $R = L$.

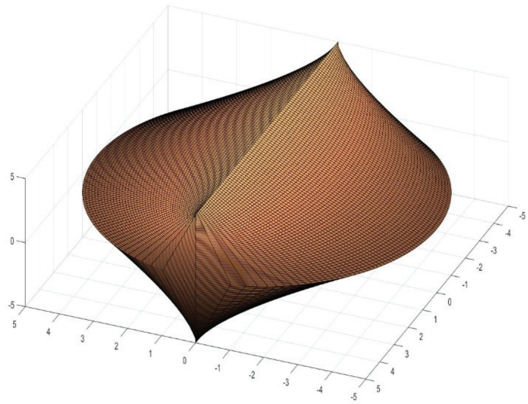

Figure 10. Three-dimensional rendering of the *Antisphera*. View from above.

The first one is opposed geometrically to the *Antisphera* because the edge straight lines intersect at its center plane, which is void. Due to this elusive, and somewhat dual, nature we have coined the name *Dyosphera* © for this shape (Figure 11).

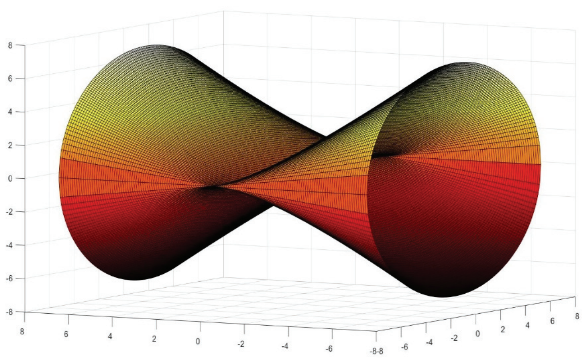

Figure 11. The horizontal part of the body known as *Dyosphera*.

In total, the *Dyosphera* features eight conoidal sections, organized in groups of four, rotated $\pi/2$ degrees (Figure 12)

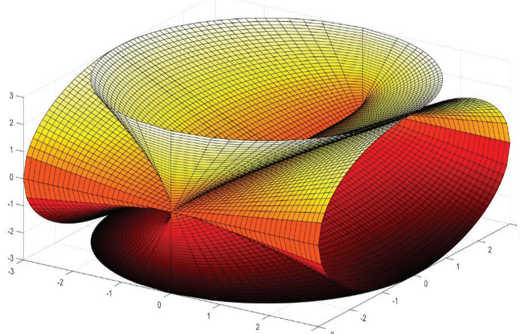

Figure 12. Distorted depiction of the complete *Dyosphera*.

The corresponding Equations are,

$$\frac{R^2 z^2}{x^2} + y^2 = R^2 \tag{59}$$

Combined with,

$$\frac{R^2 x^2}{z^2} + y^2 = R^2 \tag{60}$$

The open cavities and sinuous receptacles of this figure make it particularly suitable for aeronautical and machinery parts. It is also a very stable form because it has four circular bases.

The horizontal parts of the *Dyosphera* can be adroitly combined with the upper part of the *Antisphera* (Figure 13), to obtain a different figure, which we have called *Alosphera* ©.

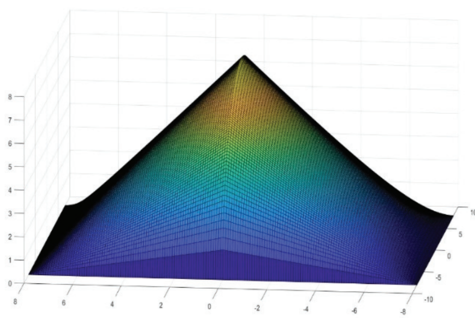

Figure 13. Detail of the upper part of the *Antisphera*.

In Figure 14, we see the Alosphera represented; its main feature is that two of the bases are square and two are circular, making it suitable for different uses, with straightforward storage of various units; we have come to guess that some cellular growths of different organisms may respond to this evolutive pattern.

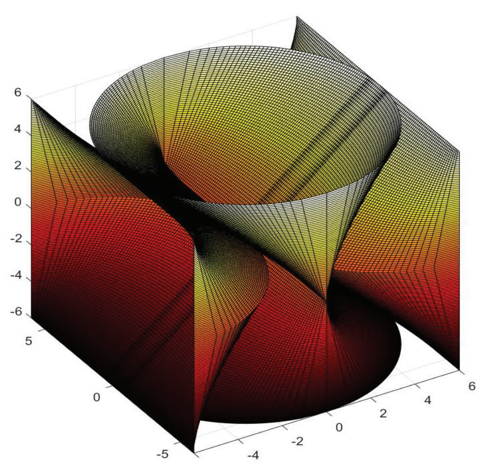

Figure 14. The Alopshera.

The *Alosphera* is the first Antisymmetric figure that we have identified but, similar to the *Dyosphera*, it also presents eight conoids.

Finally, a very important antisymmetric finding is the *Pterasphera* (Figure 15).

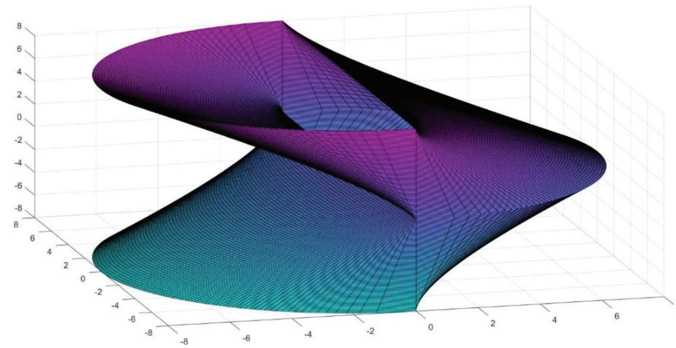

Figure 15. Initial Section of the *Pterasphera*.

This body as we shall discuss in Section 6 is tubular in nature. Being internally connected in its entirety, it is apt for conducting all kinds of fluids in an advantageous manner since, for instance, it can reduce the velocity and, at the same time, the noise of transporting the required fluids. Unlike *Antisphera*, it is self-standing and well balanced, which renders it suitable for elongation in the manner of a tower.

5. Architectural and Engineering Significance of the Geometric Findings

5.1. Historical Evolution

To our knowledge the first mathematician to introduce the conoidal figure was C. Guarino Guarini [5] in his famous treatise *Euclides Adauctus et Methodicus*. (Figure 16)

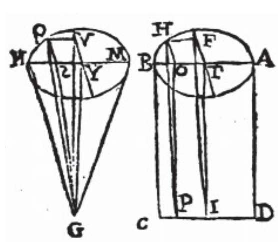

Figure 16. The point-cone and the cone that ends in a line according to Guarini.

He claims that only he has discovered the form (Figure 17) and says that it is a cone that ends in a straight line. (Later he uses the word hyperbolic conoid but for an entirely different body [5]).

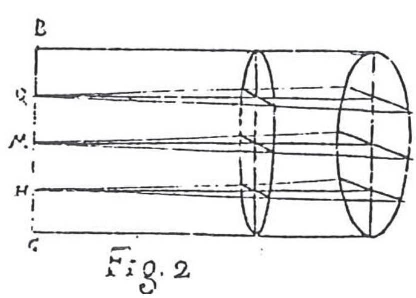

Figure 17. *Architettura Civile*. Camillo G. Guarini. Lastra IX. Trat. IV. Depiction of a cone ending in a line.

In another monumental work entitled *Architettura Civile*, published posthumously in 1737, he again refers to this unusual cone, stating that it has limited applicability in the corners of chamber vaults; we surmise that as a kind of squinch. He goes so far as to calculate the volume of the figure accurately, in the sense that we have explained in Section 2.7.

After this, the form remains all but forgotten in Architecture until, at the beginning of the 20th century, it receives a definitive impulse by the hand of revival architects such as Antonio Gaudi, who designed a roof with serially alternated conoids for a school building in front of his Sagrada Familia Cathedral in Barcelona (Figure 18).

Figure 18. The Sagrada Familia Schools re-built. A. Gaudi.

Around the 1930s, the advent of concrete shell construction favored a revolution of engineering forms and the conoid surface was the recipient of much interest, especially for building hangars, factories and warehouses [13].

One of the best extant examples is the work of the Bulgarian Engineer Ilja Doganoff who, in 1956–1957, erected a repair workshop for Bulgarian Railways featuring a hundred conoid skylights (Figures 19–21) .

Figure 19. Ilja Doganoff. Current state of the Railway Depot. Source: Author.

Figure 20. Recent aerial view of the Railway Depot by I. Doganoff.

Figure 21. Close-up of the array of the conoids still standing after 64 years without maintenance.

The shapes were prefabricated in situ and then put on the roof with the help of a crane. They are an example of the extreme feasibility of the surfaces. We have calculated the daylighting transmission of similar shapes in Section 3, an undertaking neither Doganoff nor Ramaswamy [13] were able to perform.

Ramasamy [13] and Doganoff [11,14] report that owing to the want of knowledge about the surface, structural calculations turn out to be cumbersome, yet engineers still cherish the form because of its many advantageous properties and elegance, citing lighting and economy of construction [15,16] as potential reasons to explain their predilection.

5.2. Recent Projects of Conoids Realized by J. M. Cabeza-Lainez

The present author has been working in such conoid shapes for more than twenty-five years and his experience has ignited in part the present article. Modeling of the characteristic structural, acoustic and lighting properties of conoids has encompassed a significant amount of my career as researcher. Based on that, I can attest to its sustainability and endurance [17].

From the structural point of view, as a ruled surface, it can be built directly through straight lines (beams or poles); this fact greatly facilitates the construction and scaffolding, as more natural materials such as bricks or bamboo rods can be used without difficulty, even for reinforcement or repair.

Carbon-fiber coating has become a recent alternative for reinforcement, although moderately expensive.

The arched section of the conoid, whether circular or elliptic, presents a vertical tangent, shown in the previous sections [18]. Therefore, if adequately constructed, it is free from horizontal thrusts that might compromise the supporting frame. In other words, it transmits all the loads of the structure vertically and avoids the use of buttresses (Figure 22).

Figure 22. School of Engineering of the University of Sevilla. Aerial view of conoidal skylights.

These consistent and diminishing arches function as girths for most parts of the surface [19] and provide increased resistance to a significant degree. It is true that calculation of hyper-static arches is not widely treated in the literature, but we suggest the column analogy method proposed by H. Cross [20] as a helpful and programming-friendly procedure.

Due to its curvature, the aerodynamics of the roof is excellent for bearing wind loads and other meteorological phenomena such as rain, drizzle or snow. At the same time, because of the former, it enhances air flow from the outside or from the internal stack effect with appropriate vents.

Regarding lighting properties if, as usual, the glazed apertures lie in the curvilinear extremes of the forms, they bring uniform illuminance, as we calculated in Section 3 (Figure 23) and can be easily shaded by eaves protruding from the same brim of the surface (Figure 24).

Figure 23. Interior view showing light diffusion at the central conoid. School of engineering of Seville.

Figure 24. Semicircular opening and projecting overhang at the extreme of the central conoid of the School of Engineering of Seville.

Acoustic properties stem from the circumstance that the inside surface of the conoid is mostly convex as we have checked mathematically [6]. Sound waves are diffused in this kind of ceiling and consequently, noise and reverberation become dampened. If, through appropriate design, the conoid covers a trapeze or fan-shaped plan (Figures 25 and 26) the effect of an even sound pressure is manifest [21]. (In this last case the surface is not a proper conoid as the forming lines are not all parallel to a common plane).

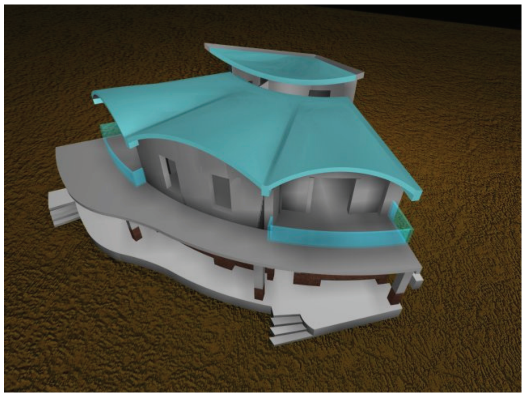

Figure 25. Three rotated conoidal roofs designed for a musicians' family. Sanlucar (Seville).

Figure 26. View of the house of the musicians. The vaults are entirely constructed in brick with occasional steel reinforcement.

The aforementioned acoustic benefits are extensive to interior illumination for the same reason of convexity of forms.

The cover in Figure 25, strictly-speaking is not a conoid, because its equation differs from what we have explained above. The forming straight lines are not parallel to a plane but they all coincide along a central vertical axis; such is a new form named Cabeza-Abajo surface (after the author). However, topping of a fan-shaped plan with this kind of surface offers a very interesting structural property: the larger spans between pillars are covered by arches, while the tapered end of the trapeze features a common slab or planar beam, which seems very logical from the constructive aspect [21].

In this way, the shells' materials can be lighter and smoother, in Figure 27 we present three vaults consisting of thin layers of hollow brick with steel mesh as a reinforcement. The result has proven to provide increased insulation and adds variety of light effects (Figure 28).

Figure 27. Vault pieces are constructed in hollow thin brick with steel mesh for reinforcement and attached to a concrete frame.

Figure 28. Detail of pseudo-conoid roofs in which the sun-path produces intriguing variations through the day.

5.3. Future Proposals

As a corollary to the theories elucidated, we will discuss two project-forms that we have created with conoids, taking into account evolving technologies. The first one is a system of skylights similar to the one depicted in Figures 21 and 24, but in this case, the glazed parts instead of being planar are also conoids (Figure 29). Bearing in mind the discussion on heat and light transfer of Section 3, this feature presents undoubted advantages [22]. Firstly, the glazing is better shaded and protected by the opaque upper conoid. Secondly, sunlight and heat transmission are modulated by the smooth curves conjoined to the innovative glass properties. In this way the glass surface becomes load-bearing and collaborates with the general structure. The form can be easily adapted to arrays of skylights (Figure 30).

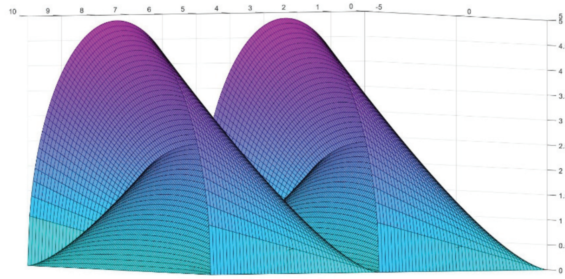

Figure 29. Outline of proposed skylights with internal conoid glazing.

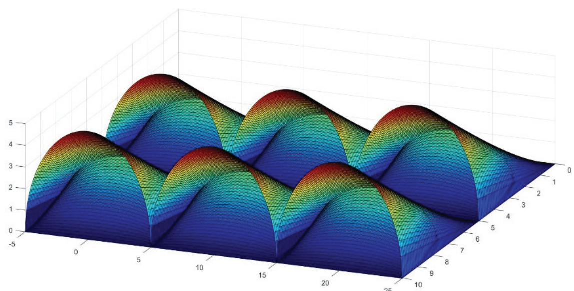

Figure 30. A suggested array of six conoidal skylights.

The new skylights are more impervious, break-proof, safer and cleaner in the absence of maintenance, as dust collection is diminished with the curvature.

The second form consists of an innovative proposal for an amphitheater, music or sports venue (Figure 31).

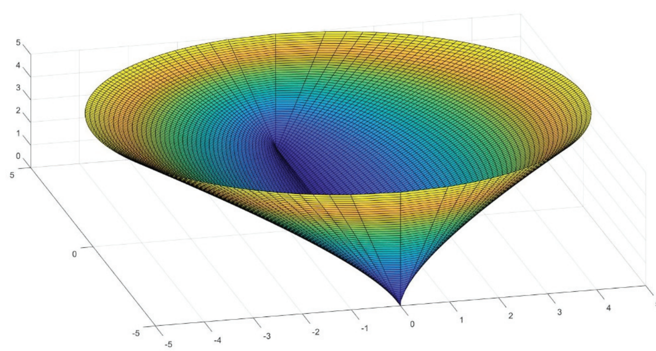

Figure 31. 3D drawing of the new Amphitheater.

In this case, being a double conoid, the advantages previously elucidated are even increased. The sections are closed curves, such as the ellipse and the circumference in the brim. Thus, they work as tension rings or girdles to hold the structure together without severe deformations. The bearing capacity of the shape is extreme. The tiers of the amphitheater are the obverse of the external façade; there is no need to superimpose a conical structure inside a cylinder such as in the Colosseum or in Spanish bull-rings. Among other problems, the ancient structures were forced to build giant discharge vaults and galleries, which transferred severe thrusts to the outer façade. As a result, we have calculated that savings in building materials of this proposed facility could be massive.

Still, the structure can be easily constructed with straight beam elements and reinforcements. The foundations are pointing to the soil as in a kind of arrow, which means that it will be very stable, safe and simple to develop.

The outer surface of the conoid is not vertical but inclined, and so the surroundings of the amphitheater would be self-shaded—an interesting feature in warm climates.

As for the grandstands, it is not difficult to adapt awnings or other shading systems to the inside area in order to protect the tiers from the rain or the sun (Figure 32).

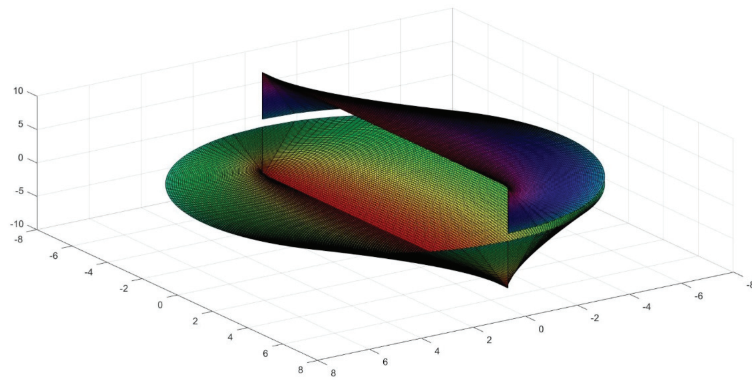

Figure 32. The Amphiteater with proposed retractable shade.

As mentioned above, the effect of concentration of sound, rather annoying in conventional stadiums will be almost completely avoided due to the convexity of the surface. In Reference [6], we have demonstrated such effect by acoustic ray-tracing procedures. These rely on the finding of the normal to the conoid surface at each point.

The procedure to extract the normal is first-order differentiation of the equation of the surface defined as $F(x,y,z)$. The normal vector is obtained as $N = (F_x, F_y, F_z)$ and in this case, has the value of:

$$N = \left(\frac{R^2 z^2}{(R-x)^3}, \; y, \; \frac{R^2 z}{(R-x)^2} \right) \tag{61}$$

We can trace a vector field with the reflected sound-rays from an emission point to check that they are effectively dispersed in the air and not concentrated [6].

The only remaining questions would be those of selecting the relative heights of the stages and platforms and other design issues such as circulation in the venue. Nonetheless, we believe that our proposal could be another good example of how the conoid-based bodies are able to create a significant volumetric space with a comparatively small enveloping surface; the key is that they offer a high spatial compactness, which is usually an added value in terms of heat exchange, costs reduction and sustainability, in general.

6. Repercussions for Technology

So far, we have presented scientific design developments that we hope will find a myriad of applications in technological areas such as Nautical, Aerospace, Building, Heritage, Retrofit and associated industries or machinery. Such facts attest to the versatility and feasibility of the solutions presented, which derive from our mathematical investigation. In the last part of the research, due to their complexity, the surfaces have been materialized with the help of 3D fabrication procedures to help decide about some difficult points of the equations or to reflect on future realizations of the proposals. It is undeniable for us that the results attain to the domains of Art and Design (Figures 33–36). They have been included in the study, as they constitute a veritable revolution of forms.

Figure 33. Antisphera in bronze by the artist Sergio Portela and in plastic 3D print (green).

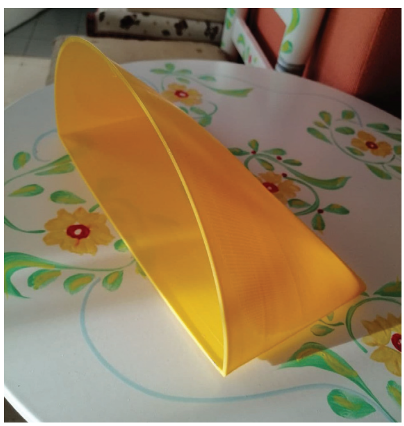

Figure 34. 3D print of a conoid similar to Doganoff's skylight.

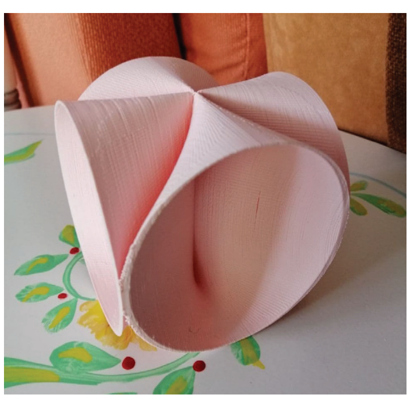

Figure 35. The Dyosphera in 3D print, detail of interlocks.

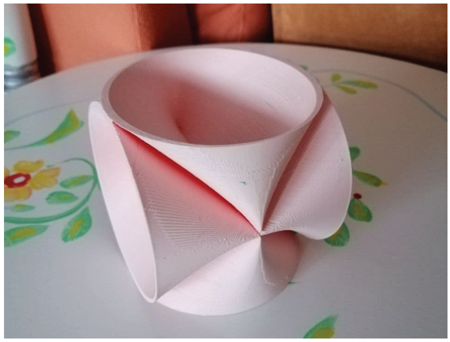

Figure 36. The Dyosphera standing on one of its four bases.

We believe that the implications of this geometrical advance are far-reaching. Due to its internal logic, it would be suitable for biotechnology. Especially the last development, the *Pterasphera*, being of a tubular nature, would be prone to fluid transportation. As a spring-like configuration it conjoins flexibility and balance. In Figures 37 and 38, we present examples of possible association and growth in parallel or opposed patterns.

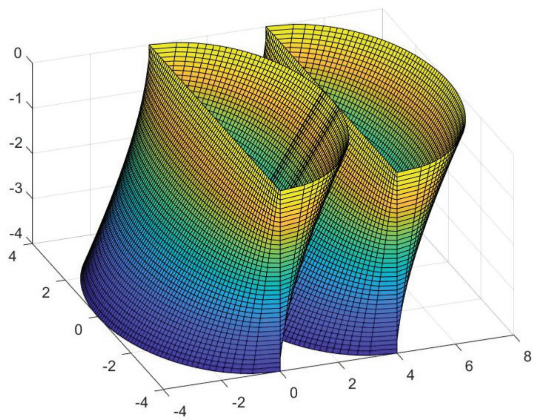

Figure 37. Two parallel *Pterasphera* tubules.

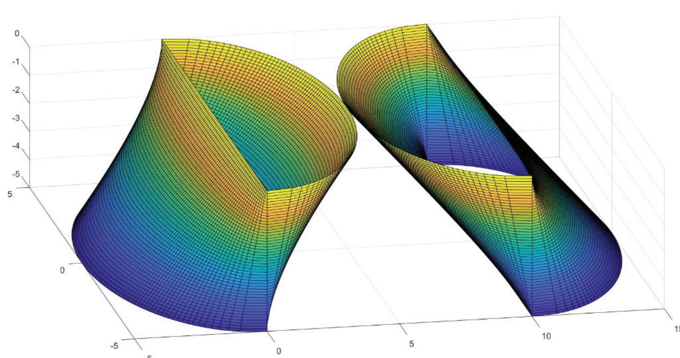

Figure 38. The same tubules opposed.

If we analyze the internal section of the tubules (Figure 39), it is composed of two semi-ellipses of varying sizes, but the span is constant at R; the extreme one is a semi-circumference of radius R and the middle horizontal section is a complete ellipse of minor axis R and major axis $2R$.

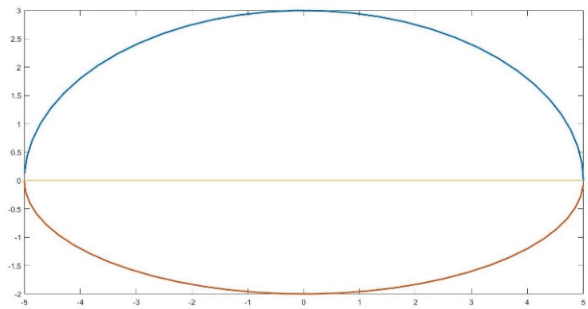

Figure 39. Horizontal section of a *Pterasphera* of major axis 10 and minor 5.

The dimensions of the section are constant, but its shape is not; thus, the velocity of the fluid inside the tubule can be deftly regulated from the same form. This would offer a clear alternative to reduce the noise level in the ducts or to decant particles in suspension.

The longitudinal central section of the *Pterasphera* gives a lozenge of horizontal dimensions R and the sides are inclined to the angle $(\pi/2 - \theta)$, with $\theta = \arctan(L/R)$. The perpendicular distance between inclined sides is of $d = R\cos\theta$.

This characteristic will facilitate insertion in existing rectangular ducts. for example, in retrofits. Mass fabrication is also simple since the form allows cuboid molds of the middle section over $2R \times R\cos\theta$.

In Figures 40 and 41, we present examples of vertical growth of the tubules, resembling vegetal pillars. Such form connects with the art tradition of coloana infinutului by Constantin Brâncuşi and with the architectural orders of classical architecture.

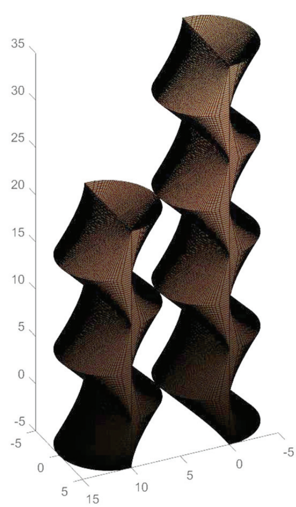

Figure 40. A pair of tubules of different height.

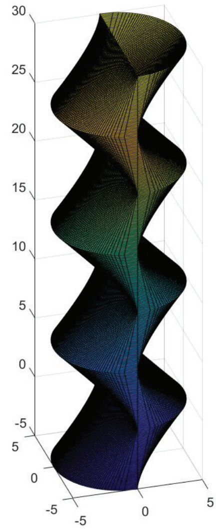

Figure 41. Different perspectives of the tubule.

We decided to explicate this finding because of the possibilities that it showcases, for instance, in tower buildings. Vertical connections are always feasible at the middle plane of the column, but the external envelop will benefit from the sun-tracking or shading properties already elucidated, combined with new photic materials of variable transparency (Figure 41). In consequence, lighting, thermal and acoustic features will considerably improve the existing conditions.

The structure of the so-conceived tower can be as lightweight as desired due to its inner balance and counterweight. As we have explained previously, alone or better in groups (Figure 42), it should perform adequately under earthquakes, extreme wind conditions or other unpredictable circumstances.

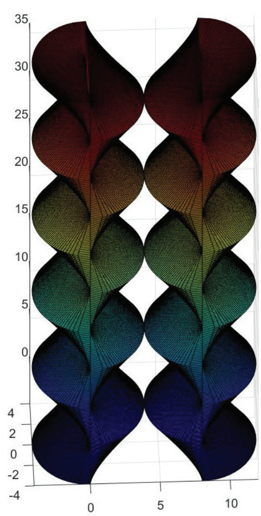

Figure 42. A symmetric array of twin tubules.

Conversely, the authors, by designing operations have achieved the form of a straight tubule of reversed sections.

Diverse technological fields could have a keen interest in the new forms that we have found, both for the macro- and micro-scales. It is indeed a leap into a sustainable future, which we hope go beyond.

7. Conclusions and Future Aims

In the first part of the article, we have identified adroit mathematic procedures, which greatly enhance our understanding of conoidal shapes. In the process, a new transcendental number has been obtained. We would call this cipher ψ. Being of a very precise nature, it provides a surprisingly accurate approximation of π. Thanks to Ramanujan's conjecture, we have been able to find the lateral area of the conoid, a recurrent form in organic structures whose scientific and technical knowledge was insufficient, although much desired for the benefit of art and architecture.

With such a procedure, we have created no less than four new types of figures that present high potential in many realms, such as aerospace, naval industries, transport, communication, biotechnology and fluid, light and sound-conducting devices.

Consequently, we have developed a vast array of revolutionary forms that showcases their utility for the design of sundry aeronautical parts and vessels. Due to their particular geometric properties, they can work, both for heat storage or dissipation, as the case may be. They perform aptly in thermal, luminous and acoustic radiation domains.

As a concession to the architectural discourse and paradigm, we have discussed how the notions that led to this form have evolved since early modern times; former examples of structures demonstrate integration of tradition with sustainability.

Further advantages to be outlined include that they enhance the employment of engineering and architectural forms, which can save considerable amounts of materials and building time, not only when used as cover or roofing in the sense of vaults or domes, but also vertically for cantilevered stadiums and amphitheaters, based on the cylinder since the Roman colosseum. Additionally, towers and high-rise buildings can be designed after the last form presented, *Pterasphera*, owing to its tubular nature, which opens the way for its use in transport infrastructures.

From the building perspective, easy reinforcement for pre-stressed construction and enhanced structural behavior could be other reasons for their use. Self-shading of the structure and built-in protection from weather phenomena are added values and contribute to its durability. An ample field of research in new materials is inaugurated with the properties revealed by the said forms.

The repertoire of possibilities derived from such geometric findings and explorations seem to be never ending.

Finally, from the mathematical point of view, a precise and non-trivial meaning has been attributed to the number π^2; this is an unexpected achievement that leaves us room to speculate on the notions of π^3, π^N and π elevated to infinite power ∞ and their applications in future art and architecture.

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Application of Glass Structures in Architectural Shaping of All-Glass Pavilions, Extensions, and Links

Anna Jóźwik

Department of Structural Design, Construction and Technical Infrastructure, Faculty of Architecture, Warsaw University of Technology, 55 Koszykowa Street, 00-659 Warsaw, Poland; anna.jozwik@pw.edu.pl

Abstract: This article covers the issues of applying structural glass in shaping all-glass architectural objects. Glass, as a transparent material, is a source of inspiration for new architectural solutions. With the development of technology and the increasing knowledge of glass's mechanical and strength properties, the possibility of using the material for construction purposes has also been acknowledged. Structural elements and building envelope elements can create a uniform material structure of all-glass objects. This observation contributed to the analysis presented in the article. The research was mainly aimed at investigating the architectural and structural-related conditions in shaping all-glass structures in buildings. In this paper, we specify criteria and typology in terms of the applied design solutions. The criteria investigated in the study included functional-spatial aspects, the form, and the structure. All-glass objects were divided into pavilions, extensions, and links in terms of functional and spatial aspects. Architectural forms were specified and characterised as cubic, cuboid, cylindrical, and free-forms. Regarding structural solutions, frames, grillages, beam-wall, and plate-wall systems were indicated as the main load-bearing structures implemented in the buildings under study. The results have been obtained to describe the architectural and structural shaping of all-glass objects. One of the main results of the work is the indication between functional-spatial aspects, the form, and the structure. This correlation confirms the close relationship in architecture between art and engineering.

Keywords: glass; glass structures; structural glass; glass pavilions; glass extensions; glass links

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1. Introduction

Glass is a significant material in contemporary architecture. Transparency is its main advantage, as the material allows daylight into the interior. The rich history of glass dates back to 5000 BC, but it was not until its use in coloured stained-glass windows of Gothic churches and cathedrals that the material was applied in architecture. It allowed the light into the interior and was closely related to the aesthetic perception, as the colour was seen as a source of beauty [1] (p. 125).

Several centuries had passed from the Middle Ages before the widespread use of glass in construction was established. Significant changes occurred during the industrial revolution in the 19th century when new technologies for the production of glass panes were first introduced [2]. The erection of the Crystal Palace in London in 1851 may be seen as a turning point for architectural development. The building, erected for the Great World Exhibition, was made of glass used on an unprecedented scale. A building, with transparent walls and a roof, was created among the brick buildings of Victorian London. Transparency allowed for the dematerialisation of the border between the inside and the outside. In the first decades of the 20th century, the era of glass in architecture began, and projects that influenced the development of contemporary architecture were initiated [3] (pp. 10–13). Significant buildings of that time include the glass pavilion designed by Bruno Taut [4] for the Werkbund exhibition in Cologne in 1914 (Figure 1). The building implemented the vision of a world filled with buildings of coloured glass, with glass ceilings and stairs. Bruno Taut was inspired by the literary works of Paul Scheerbart and his words, "Glass heralds a new age/The culture of brick brings only sorrow" [5].

Figure 1. The Glass Pavilion, designed by Bruno Taut, Cologne Werkbund Exhibition, 1914 (public domain).

Glass is equated with modernity. The development in glass technology exerts a significant influence in this respect. However, its transparency is of significance as well [6,7], as it provides a source of inspiration for various architectural works. Hence, art and engineering merge, thus providing a constant challenge to artists involved in forming contemporary architecture. This is especially visible since glass no longer serves only as an enclosure material but is increasingly used as a construction material. Hence, as a result of the intensive development of glass technology, the concept of engineered transparency [8,9] (p. 57), ref. [10] has emerged in recent years. The meaning of this term is rightly defined by Peter Rice, who described "the role of the engineer working with glass as someone who transformed the simple architectural statement into an essay on the nature of transparency and how to use the physical properties of glass to convey fully the concept of transparency" [8] (p. 58).

Therefore, introducing the engineering transparency concept confirms the interpenetration of art and engineering. Reflection of this approach in design may be found while designing all-glass structures, such as pavilions, extensions, or links. Glasbau-Hahn exhibition hall in Frankfurt by the Main, erected in the 1950s, was among the first objects designed exclusively of glass [11,12]. It was constructed by a company that produced glass display cases. The use of glass as a structural material was an innovative solution at that time. Currently, the use of glass structures offers new design possibilities, not only for engineering but also for integrating the whole construction. Thus, glass solutions provide a source of creative inspiration in architecture. This change results from developing knowledge and research on its mechanical and strength properties. The potential for using glass as a structural material was well ahead of regulations in the form of adequate harmonised guidelines and standards [13,14]. Over time, national normative documents began to be introduced, and the experience gained in the design of structural glass contributed to the development of a European standard for the design of glass structures, Eurocode 10, which is due to be published at the end of 2024 [14–16].

The lack of applicable design guidelines has given rise to a number of design problem-solving research [17]. An issue that emerges from the possible use of structural glass is related to the design of all-glass structures. The issue is not a new one and has been undertaken by researchers: Herman [18], Teixidor [19], and Weiler [20]. As the topic is valid, suggestions and analyses of experimental projects are being made [21–23]. However, despite ongoing research, this subject is not fully recognised. There is a lack of broad recognition of what lies behind the term all-glass structure, and importantly, how such a structure can be applied to architecture. These studies focus on single solutions or case studies. There is no generalised recognition and characterisation of these solutions and no indication of their possibilities and limitations. Therefore, the topic of an all-glass structure is addressed in this work.

2. Materials and Methods

The main research goal was to investigate the architectural and construction conditions in shaping all-glass objects provided. These objects have been defined as buildings or parts thereof, with glass used as the enclosure and structural element material. This approach is related to the development of contemporary technologies and the increase in knowledge concerning the mechanical and strength properties of glass, as well as the development of rules for structural glass design. The research scope covers the last twenty-five years, in which a significant increase has occurred in the implementation of buildings using glass structural elements.

The research consisted of several stages:

1. State-of-the-art literature review

The initial stage involved the source literature review concerning the conducted research, i.e., scientific articles, books, reports, guidelines and standards, and internet sources on the topic. In this regard, publications on the following issues can be indicated:

- current glass technologies in terms of their application in architecture;
- physical properties of glass used in glass envelopes;
- structural glass in terms of mechanical and strength properties;
- structural glass in the view of recent design guidelines and standards, as well as issues relating to its structural design principles;
- the possibility to apply structural glass in architecture, including case studies;
- theoretical considerations related to the issue of transparency and the use of glass in architecture.

Based on the conducted source literature analysis, the main research problem was defined concerning the use of structural glass in terms of integrating architectural and construction issues. Hence, attention was paid to the issues concerning the design of all-glass objects.

2. Selection of examples for the research to be conducted and the preparation of materials

The second research stage selected a group of objects that met the adopted research assumptions. Over 40 buildings were selected (Table 1) in which all-glass structures were implemented, with the use of glass in an exterior enclosure and the load-bearing elements. The scope of literature-based research was narrowed down at this stage, while the studies on the examined buildings were expanded. Both published and unpublished materials obtained from the designers of these buildings were used, as well as the on-site observations by the author.

3. Analysis of the main research task

The systematics of all-glass objects was conducted as part of the main research task. According to the classic tripartite division into function, form, and structure, basic divisions and characteristics have been developed. However, due to the research subject, the concept of function refers to functional and spatial conditions. By introducing the systematics, it was possible to determine the architectural and structural conditions that affect the design of all-glass structures. The following research methods were used in this part: the source literature analysis, comparative analysis, case study, logical interpretation, descriptive analysis, and in situ studies [24].

4. Results and conclusions

The final stage involved developing the results and conclusions. Particular attention was paid to the interrelationships between the functional-spatial aspects, the form, and the structure. The results were presented regarding architectural concepts in which a load-bearing structure with structural glass can be implemented instead of typical solutions with steel, aluminium, or wooden structures. The conclusion section presents the possibilities and limitations related to the use of glass structures.

Table 1. Chronological list of analysed all-glass objects.

Name of Building	City	Construction Year	Architect/Glass Engineer	The Function of Glass Object	Type of Structural System
Glass Museum	Kingswinford (GB)	1994	Design Antenna/Dewhurst Macfarlane and Partners	Extension—entrance to the museum	frames
Footbridge	Rotterdam (NL)	1994	Kraaijvanger-Urbis/Rob Nijsee	link between two buildings	glass beams, plate–wall system
Kubus Export	Wien (AT)	2001	Architects Tillner & Willinger	exhibition pavilion	frames
Norwich Castle Lift	Norwich (GB)	2001	Purcell	lift	frames
Glass Cube Memorial	Mannheim (DE)	2003	sculptor Jochen Kitzbihler	sculpture/installation	plate–wall system
House at King Henry's Road	London (GB)	2003	Paul Archer Design/Fluid Structures	extension—dining room	beam–wall system
Roel Farm Glass Cube	Gloucestershire (GB)	2004	Jamieson Associates/Marl Lovell Design Engineers	link between two buildings	grillage system
Apple Store Fifth Avenue	New York (USA)	2006/2011	Bohlin Cywinski Jackson/Eckersley O'Callaghan	pavilion—entrance to the store	grillage system
Rietberg Museum	Zurich (CH)	2006	ARE Grazioli, Krischnzitz/Ernst Basler + Partner AG, Ludwig + Weller	pavilion—entrance to museum	frames
Apple Store 367 George Street	Sydney (AU)	2007	Bohlin Cywinski Jackson/Eckersley O'Callaghan	extension—facade	frames
John Lewis Department Store	Leicester (GB)	2008	Foreign Office Architects FOA/AKT-II	link—footbridge between two buildings	beam–wall system
American Academy of Arts and Letters	New York (USA)	2009	JVC Architect/Robert Silman Associates	glass link between two buildings	glass beams, steel frames in walls
House at Mapledene Road	London (GB)	2009	Platform 5 Architects	extension—kitchen/dining room	plate–wall system

Table 1. *Cont.*

Name of Building	City	Construction Year	Architect/Glass Engineer	The Function of Glass Object	Type of Structural System
Leibniz Institute for Solid State and Material Research pavilion	Dresden (DE)	2009	Blum und Schultze Architekten/GSK—Glas Statik Konstruktionen GmbH	exhibition pavilion	frames
Apple Store Pudong	Shanghai (CN)	2010	Bohlin Cywinski Jackson/Eckersley O'Callaghan	pavilion—entrance to the store	grillage system, glass frames
President's House	Philadelphia (USA)	2010	Kelly Maiello Architects/Rydal Engineering	exhibition pavilion	grillage system
The Park Hotel	Hyderabad (IN)	2010	SOM/SOM	link between buildings	frames
Costa Coffee Tower Vaults	London (GB)	2011	Dyer/IQ Project	extension—tearoom	frames
House at Souldern Road	London (GB)	2011	DOS Architects/Firman Glass	extension—living room	frames
New Headquarters Bank of Georgia	Tbilisi (GE)	2011	Architectural Group and partners (AG&P)/Verroplan GmbH	pavilion—entrance to the office	grillage system
60 Victoria Embankment	London (GB)	2012	TP Bennett/OAG	extension—entrance to office	frames
Coach Restaurant	Hatfield (GB)	2012	Brooks/Murray Architects/	extension—dining room	frames
Glass Cube	Haarlem (NL)	2012	Kraaijvanger Architects/ABT–Rob Nijsse	pavilion—entrance to underground car parking	glass fins and steel cables
Glass House Milnthorpe Corner	Winchester (GB)	2012	AR Design Studio	extension—kitchen/dining room	frames
House at Castelnau	London (GB)	2012	RRA Architects/Culmax	extension—living room	beam–wall system
Westfield Shopping Center	Sydney (AU)	2012	John Wardle Architects	link—footbridge between two buildings	frames
Castle Grimma	Grimma (DE)	2013	Bauconzept/GSK—Glas Statik Konstruktionen GmbH	link between buildings	frames
Daman Building	Dubai (UAE)	2013	Perkins & Will/Malishev Engineers	Pavilion—entrance	grillage system
Dilworth Park	Philadelphia (USA)	2014	Kieran Timber-lake/Eckersley O'Callaghan	pavilions—entrance to underground station	plate–wall system

Table 1. *Cont.*

Name of Building	City	Construction Year	Architect/Glass Engineer	The Function of Glass Object	Type of Structural System
Salvation Army Conference Center	Sunbury Court (GB)	2014	Dyer	extension—dining room	frames
Bestseller Building	Aarhus (DK)	2015	C. F. Møller/Skandinaviska Glasssystem	Pavilion—entrance	grillage system
Bodelwyddan Castle	Bodelwyddan near Rhyl (GB)	2015	PWP Architects/O J Taffinder Ltd.	hotel/restaurant entrance	frames
Spencer Park House	London (GB)	2015	Borgos Pieper/Eckersley O'Callaghan	extension—living/dining room	beam–wall system
Centraal Museum	Utrecht (NL)	2016	SODA/ABT	link—footbridge between two buildings	plate–wall system
Pier Visitor Center	Clevedon (GB)	2016	O'LearyGoss Architects/Glass Solution	extension—tea room	frames
The Liberty Square/The National Forum of Music	Wroclaw (PL)	2016	ASPA Pracownia Projektowa	pavilions—entrance to underground parking	grillage system
House of European History	Brussels (BE)	2017	Chaix & Morel et Associés; JSWD Architects/Werner Sobek	upper extension	frames, grillage system
House Christchurch	London (GB)	2009/2017	Mc2design/Markam Associates	extension—living room	beam–wall system
Tottenham Court Road Underground Station	London (GB)	2017	Stanton Williams/Seele	pavilions—entrance to underground station	glass frames with steel inserts
Apple Piazza Liberty	Milan (IT)	2018	Foster + Partners/Eckersley O'Callaghan	pavilion—entrance to the store	plate–wall system
Burford Lane Farm	Burford (GB)	2018	James Bell Architecture	link between two buildings	frames
Lahti Travel Center	Lahti (FI)	2018	JKMM	pavilion—entrance to underground station	grillage system
Restaurant pavilion Wienerwirt	Graz (AT)	2018	Claire Braun/Karner Consulting	pavilion—dining pavilion	grillage system
Office in Chiswick	London (GB)	2019	Paul Vick/Malishev Engineers	link between two buildings	glass frames, plate–wall system

Table 1. *Cont.*

Name of Building	City	Construction Year	Architect/Glass Engineer	The Function of Glass Object	Type of Structural System
Residential at Woodsford Square	London (GB)	2020	Shape Architecture	extension—living/dining room	plate–wall system
Tourist information point	Glurns (IT)	2020	Jürgen Wallnöfer/GBD Group	pavilion—inside building	frames
The old vicarage, Ambrose Place	Worthing (GB)	2021	Saville Jones Architects/Glass Structures Limited	extension—dining room	frames
The Craiova Art Museum	Craiova (RO)	2022	Dorin Stefan/GSK	exhibition pavilion	glass wall systems with glass fins

3. Results

The investigated all-glass objects were characterised by a different spectrum of architectural and construction solutions resulting from their location, including orientation, climatic conditions, function, and scale. A common feature of these structures is the use of glass in both the envelope and the structural elements. However, a distinction can be made between the characteristics of glass for use in façades and roofs and the mechanical and strength characteristics relevant to load-bearing elements (Figure 2).

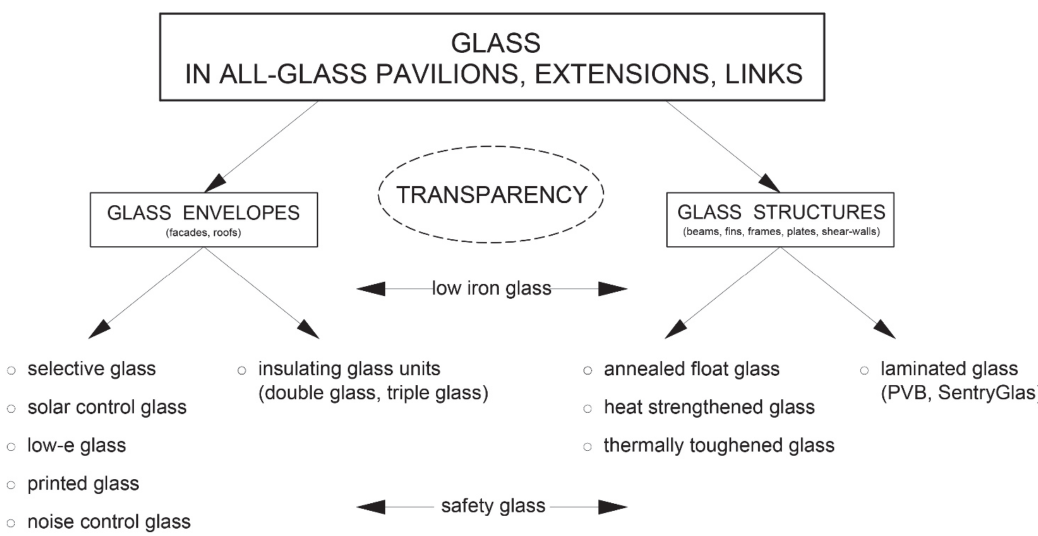


Figure 2. General characteristics of glass used in all-glass pavilions, extensions, and links (figure by the author).

The performance of partitions is quite important due to the occupancy of people in the interiors. Various test methods are being developed to assess the comfort of the built environment. One of them was developed by ABSIC (Advanced Building Systems Integration Consortium at Carnegie Mellon University in the USA) and indicates building quality criteria: space quality, thermal comfort, air quality, acoustic quality, and optical quality [25]. It can be noted that indirectly, these criteria can be related to façade parameters. In the studied objects, the properties of glass elements in the enclosure create the comfort of the internal environment by providing light to their interiors, protection against heat loss, protection against overheating of glazed spaces, and protection against noise when glass with acoustic parameters is used.

The glass parameters used in transparent building envelopes are related, among other things, to spectrophotometric properties [26], which quantify the contribution of light transmission, reflection, and absorption by the glass pane (Figure 3). The aim is to obtain as much daylight as possible to be transmitted into the building. The LT factor determines the direct visible light transmission. Along with daylight, solar energy is transmitted into the interior, characterised by the total solar energy transmittance factor g. Solar energy causes thermal discomfort for building users. A favourable solution to reconcile these two spectrophotometric aspects is to use highly selective glass, i.e., glass with a high selectivity coefficient. The selectivity coefficient is defined as the ratio of the direct visible light transmittance LT to the total solar energy transmittance g. A selectivity coefficient can characterise modern generations of glass within the range of 2.0, e.g., LT = 70% and g = 35%. For cases where greater solar protection is desirable, products dedicated to this purpose can be used, i.e., glass with a reduced total solar energy transmittance g, for example, with parameters LT/g = 50/25. The highest direct daylight transmittance LT occurs with extra-clear (low iron) glass, i.e., with reduced iron dioxide content, and such glass, in addition to its aesthetic value, can also be utilized for passive solutions [26].

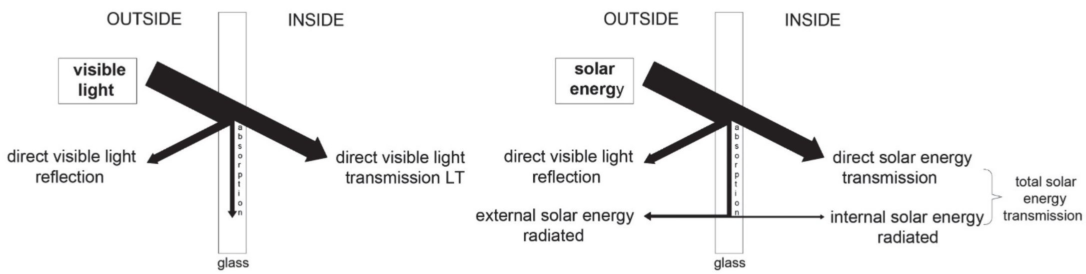


Figure 3. Schematic of the transmission of visible light and solar energy through glass panes (figure by the author).

In terms of thermal protection, using low-emissivity glass, i.e., coatings that effectively reduce radiant heat loss, significantly improves performance. Another solution concerns the arrangement of the panes themselves. Double or triple-glazed units are filled with air, argon, xenon, or aerogel [27]. This gas filling reduces heat loss through a convention. The so-called warm frames connecting individual glass panes are additionally applied. Currently, the most advanced solutions are characterised by the heat transfer coefficient U significantly below 1.0 W/m^{2}K. Triple-glazed panes with low-emission coatings and filled with xenon have particularly favourable parameters. In the buildings surveyed, the thermal protection requirements of the glazed spaces can be seen to vary. Some spaces are not heated and do not require the design of partitions to protect against heat loss.

Due to the use of glass as a structural material, its mechanical and strength properties are important. Glass is a brittle material compared to other construction materials such as steel or wood. The general physical and mechanical properties of basic lime silicate glass are shown in Table 2. The strength of annealed float glass is 45 MPa. This value is determined according to standard EN-572 [28] for bending tension. In order to increase the strength of the glass, thermal modification is used to obtain thermally strengthened glass with a strength of 70 MPa [29] and toughened thermally glass with a strength of 120 MPa [30]. These are the characteristic bending strength values of prestressed basic soda lime silicate glass. The design value of glass is also determined for the design of structural components [14].

Table 2. General physical and mechanical properties of basic soda lime silicate glass [28].

Type of Properties	Value
Modulus of elasticity	E = 70,000 MPa
Poisson's ratio	v = 0.23
Coefficient of linear thermal expansion	$\alpha_t = 9 \times 10^{-6}$ L/K
Glass density	$\rho = 2500$ kg/m^3

The thermal modification of the glass also has an impact on the crack pattern/type of grid. When cracked, annealed float glass is characterised by large fragments with sharp edges, whereas thermally toughened glass has a fine crack grid with small fragments, which reduces the risk of injury. An intermediate condition in terms of the size of the fragments in the fracture grid is found in heat-strengthened glass [14,31].

Laminated glass is used to increase the safety level of glass structures. This type of glass consists of two or more glass panes connected by adhesive layers susceptible to rheological phenomena. The strength of laminated glass is, therefore, the same as that of the glass layers used in laminated glass (annealed float glass, semi-tempered glass, toughened glass). Polyvinyl butyral (PVB), ethylene-vinyl acetate (EVA), and thermoplastic polyurethane (TPU) [32], formerly resin, are used to bond the glass layers. Their mechanical properties significantly depend on the temperature and duration of loads [14,33]. PVB film with a thickness of 0.38, 0.76, or 1.52 mm is most commonly used to bond glass sheets. There are numerous PVB interlayers used for different solutions (acoustic, structural, solar) [33]. In the case of structural elements, special-purpose materials such as extra stiff PVB or the SentryGlas ionomer [34] are increasingly being introduced. Especially the SentryGlas ionomer is characterised by better strength parameters, including high tensile strength and five-times-greater tear strength than the conventional PVB. Apart from being used for glass–glass connections, SentryGlas ionomer also enables the use of glass–steel connections in glass structures [35].

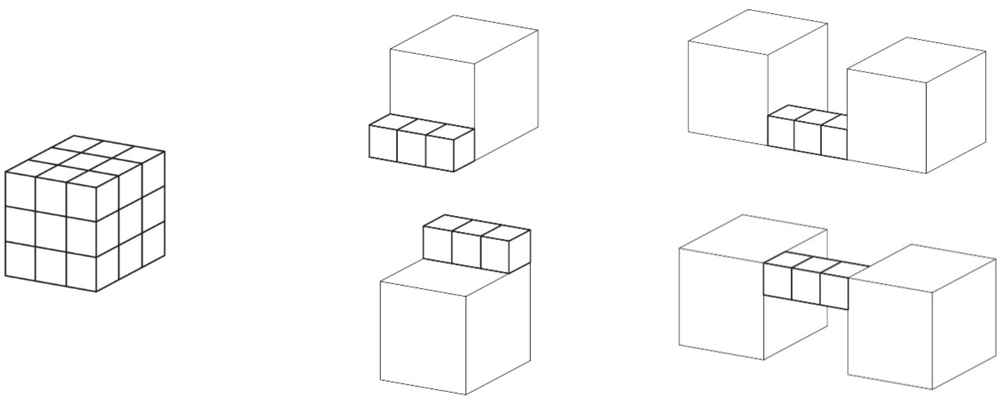
The basic method for verifying structural glass in the European standards currently being developed is the limit state method [Jóźwik]. This design concept is also included in EN 16612 [36] for lateral load resistances of linearly supported glaze used as infill panels and consists of checking two main conditions. According to the ultimate limit state (ULS), the maximum normal stress σ_{max} is calculated for the most unfavourable combinations of loads. This stress σ_{max} must not exceed the design value of the bending strength $f_{g,d}$. However, for serviceability limit state (SLS) requirements, the maximum design value of deflection w_{max} is determined for the most unfavourable load combinations in relation to the design value of deflection w_d. The European standard Eurocode 10 for the design of glass structures under development assumes that glass structures shall be designed in accordance with the general rules given in EN 1990, such as resistance, serviceability, durability, and robustness [37]. Due to the brittle nature of glass, a glass component should be designed for the following limit states: the serviceability limit state (SLS), the ultimate limit state (ULS), the fracture limit state (FLS), and the post-fracture limit state (PFLS) [14,16].

The use of glass as a brittle material introduces significant limitations to the use of all-glass solutions in seismically active areas. However, most of the facilities studied (Table 1) are located in areas where earthquakes do not occur. Authors of publications in this area, Stepinac [13], Bedon [38], Santarsieroa [39], and Stepinac [13], point to the insufficient investigation of glass solutions in earthquakes and the lack of relevant standard regulations. Eurocode 8 [40] does not consider glass elements as structural elements. However, current research indicates that properly modelled glass elements can exhibit some dissipation capacity and show signs of ductility in the case of in-plane lateral loads. Santarsieroa studied glass frames [39], and Stepanic and his team studied timber–structural glass composites [13].

3.1. Typology and Functional-Spatial Analysis of All-Glass Objects

The function provides a key term in architecture. It is most commonly understood as a synonym for a purpose [41] (p. 3). Such a definition of the function concept allows for an unequivocal determination of the building's purpose related to its use. It should also be noted that function and purpose can be used unequivocally or distinguished, mainly depending on the context [41] (p. 23). The function of all-glass objects may vary partly due to their location context and partly due to their arrangement and organisation. For the analyses regarding the use of structural glass in all-glass objects, it seems more advisable to focus on the functional-spatial layout and how functions are organised [42,43]; therefore, the following were distinguished in this context (Figure 4):

- pavilions,
- extensions,
- links.



(**a**) (**b**) (**c**)

Figure 4. Typology of the all-glass structure by functional-spatial aspects: (**a**) pavilions; (**b**) extensions; and (**c**) links (figures by the author).

3.1.1. Glass Pavilions

The first group includes pavilions, including the free-standing ones. Due to the material and structural solutions, these objects are not large-sized. Therefore, they are characterised by limited usable areas. All-glass pavilions have an exhibition function, such as the Leibniz Institute for Solid State and Material Research in Dresden or the Kubus Export in Wien. Another common function performed by the glazed pavilions is the building entrances. This space is deliberately designed as transparent, which emphasises its openness.

Additionally, the entrance can be accentuated with a contrasting architectural form [26] (p. 37). The Apple Cube, located on Fifth Avenue in New York, may be an example of this design approach. The pavilion is an entrance to the underground retail space under the square in front of the General Motors building. This object was situated symmetrically on the square axis, becoming its main compositional element (Figure 5). A glass cube with a visible grillage serves as a skylight above the trade display from the inside. Spiral glass stairs arranged around a cylinder placed in the centre of the cube's floor plan lead from the square to the underground salesroom. Therefore, it seems that in the case of this design, the external and internal worlds are mutually exclusive, both in perceptual and practical terms, as stated by Arnheim [44] (p. 102). A visually attractive form is noticed from the outside, encouraging the recipient to enter the interior; the inside has an entirely different utility function.

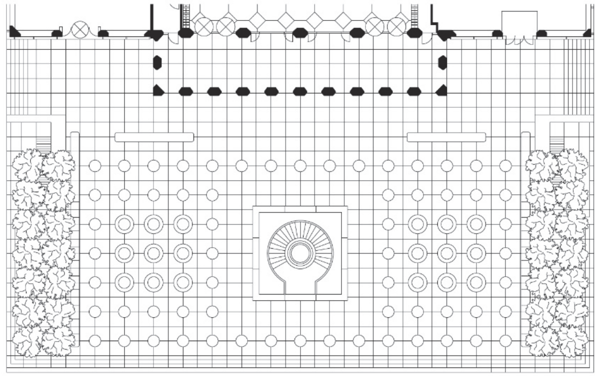


Figure 5. Glass entrance pavilion to the Apple Retail Store, Fifth Avenue in New York (© Foster + Partners).

3.1.2. Glass Extensions

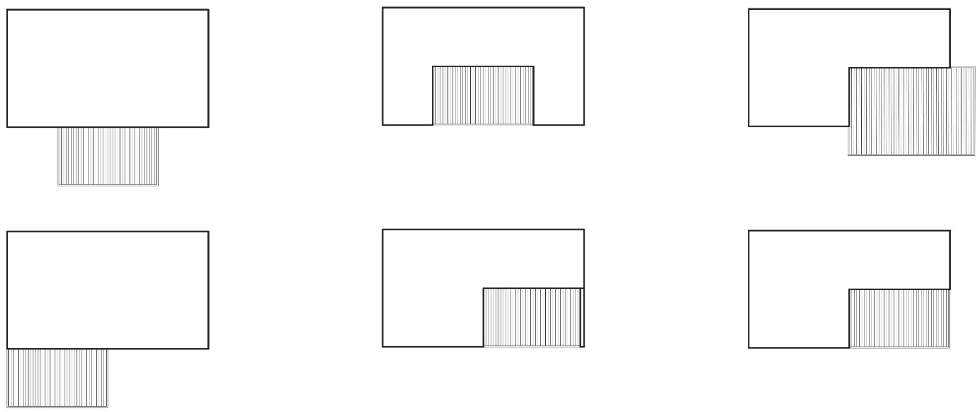
In the examined buildings, all-glass structures were often designed as extensions. This building development form tends to be integrated into the existing building. This form of development is most often incorporated into an existing building, which is usually in connection with its modernisation or the addition of a new function. The use of all-glass structures seems significant in this respect, as it may be associated with the quality improvement of the existing functional solutions. The addition of glass building development creates a new space. However, the material solutions used also affect the functional features, such as better interior lighting with daylight. Due to its transparency, the glazed construction allows the external and internal spaces [45] to interpenetrate, which predisposes to specific material solutions. This visual connection between the building's interior and external surroundings is often crucial in design decisions. Moreover, it can be assumed that large transparent openings to the outside space from the inside of the building act as screens behind which the external landscape is exposed, e.g., a garden, greenery enclaves, a specific fragment of a neighbouring building development, etc. [46] (pp. 14–15) [47]. Moreover, the intertwining of the cognition of the natural environment and spatial, experiential perceptions can create phenomenological architectural experiences [48]. These advantages result from the interpenetration of internal and external space. They can often be applied in residential buildings with the use of glass extensions.

The extension form in residential development is particularly popular in the UK. The terraced houses with a front close to the street and a garden at the back of the plot have become widespread since the industrial revolution [49]. This development is still in use, while older houses are undergoing upgrades to make them more comfortable to live in. One of the elements added to existing housing is the glazed extension, often inspired by greenhouses [50]. This is, therefore, not a new design solution, except that the contemporary use function of these glass structures has changed. The glass extension is now no longer used for growing plants, but is rather a part of a building with a specific utility function tailored to the needs of the building, such as a living room, kitchen, or dining room.

With the development of glass technology, material solutions are changing. Increasingly, glass extensions are being realised that are homogeneous in terms of material, i.e., with glass facades and roofs, but also structural elements made of glass. For the design of an all-glass extension, its layout on the plan of the existing building is important. Therefore, the all-glass objects in Table 1 were analysed concerning the arrangement of extensions in the building plan, and three main arrangements were distinguished (Figure 6):

- extension placed outside the building floorplan contour, e.g., Spencer Park House in London, Castelnau House in London, and House Salvation Army Conference Center in Sunbury Court;

- extension placed inside the building floorplan, enclosing the building floorplan contour, e.g., Milnthorpe Corner House in Winchester and Mapledene Road House in London;
- extension placed in the corner, e.g., Souldern Road House in London and Ambrose Place House in Worthing.



(**a**) (**b**) (**c**)

Figure 6. Extension in houses: (**a**) placed outside the building floorplan contour; (**b**) placed inside the building floorplan; and (**c**) placed in the corner (figure by the author).

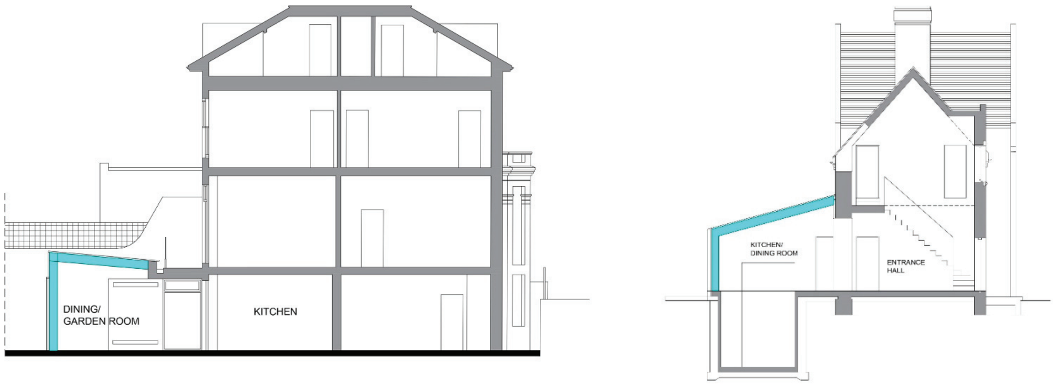
Depending on the floor area, aspect ratio, and height of extensions, different design and material solutions are used, including those using glass exclusively.

Another important aspect of glass extension is the possibility of using this glass structure as a sunspace, i.e., an element of passive architecture [51,52]. On a sunny day, thanks to the large transparent surfaces on the side, spaces located on the south (south-west or south-east) collect sunlight and collect it in a thermal mass on the walls or floor [36]. There are several types of sunspaces, depending on how solar energy is collected in the building structure and transferred to neighbouring rooms. One of their distinguishing features is the type of partition separating the sunspace from the rest of the rooms [53,54].

With large glazed areas, overheating can occur during the summer. It is, therefore, advisable to use other solutions in facades with appropriately selected glass, such as a shading element, effective ventilation, and sufficient thermal insulation to make the internal environment comfortable [55].

Among the buildings analysed, the glazed extension solution was used in a residential house at Castelnau in Barnes, in the Richmond upon Thames area of south-west London. The central section of Castelnau contains numbers 85–125, which are listed as Grade 2 [56]. The building development in this street area is characterised by the semi-detached villas erected by Major Boileau in 1842. The two-story houses come with a basement. The building is located away from the street line, and gardens are behind it. The houses are of restrained classical style, with each house framed by two full-height decorative lonick plasters in stucco. Many pairs of houses were connected by garages (formerly coach houses) adjacent to the sidewalls and adjusted to the scale of the main building.

In one of the houses at Castelnau, an internal renovation was conducted, and an all-glass garden room was implemented. With respect to the historic building development, a simple form with a uniform material structure was deliberately selected, with glass frames as the load-bearing structure (Figure 7a). Glass proved to be a neutral material for historical building development. This solution identifies contemporary architecture and distinguishes it from a 19th-century building. The transparent enclosure of the garden room also has a great utilitarian advantage, as it lets daylight into the building and improves its daylight illumination. Moreover, the adopted solution creates a visual and functional link between the building's interior and the garden by introducing the garden room.



(**a**) (**b**)

Figure 7. Extension in houses: (**a**) house at Castelnau in London (developed by the author based on the architect's drawings); (**b**) house at Milnthorpe Corner in Winchester (developed by the author based on the architect's drawings).

In the Manor House at Milnthorpe Corner, Winchester, a similar solution to the one in the villa on Castelnau was used (Figure 7b). The building, erected in 1852, underwent refurbishment and extension. A glazed extension that opens onto the garden at the back of the property was implemented. It contains an open-plan kitchen, lounge, and dining area. Therefore, an element of modern architecture was introduced into the historic house building. The load-bearing structure of the glass extension is a system of frames with a pronounced roof slope. This way, a space connecting the interior with the garden was created. However, this space also integrates the function layout inside the house itself, both horizontally and vertically.

Due to its location on the southeast side, the glass extension can be a passive element in energy extraction. The newly created space is separated from the rest of the building mainly by a masonry wall with glazed doors. This wall can act as an element to accumulate heat from the sunlight penetrating through the glazed partitions of the extension.

3.1.3. Glass Links

Among the examined buildings with glass enclosures and glass structural elements, design solutions can be indicated in the links between the buildings. This group creates glass structures to obtain communication connections between two identical or different utility functions. Such a design solution is often aimed at improving the existing functional solution. The links can be located on the ground floor or higher stories. These elements are most commonly characterised by a linear form and an organisation [42,43] whose function is related to communication.

The linear layout is visible in the 13th-century Grimma Castle. The historic castle complex was renovated, reconstructed, and commissioned in 2013. The Grimma Castle became the seat of the court and the prosecutor's office. Three new glass structures were added as part of the utility function transformation. These included a glass corridor along the wall to connect the castle to the tower ruins and the entrance rooms. The link was almost 25 m long (Figure 8), and its structure was made of glass frames with a span of 2.5 m, spaced every 1.5 m. The link, perceived as neutral, was led along the northern wall of the castle [57,58].

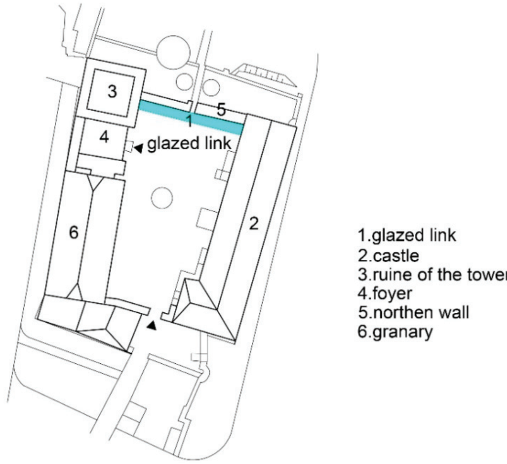
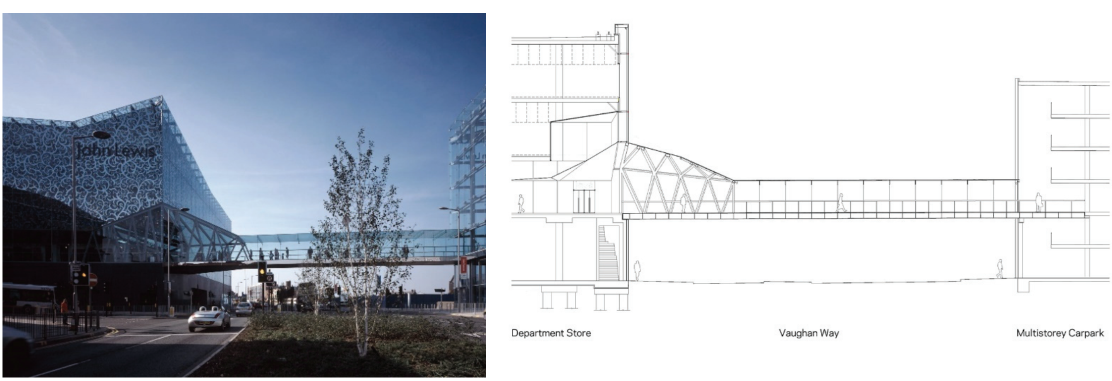


Figure 8. Glass link in the Grimma Castle plan (figure by the author).

Footbridges with a glass enclosure constitute a special example of glass link group solutions. Depending on the distance between the connected buildings, various load-bearing structures are applied, usually designed as steel structures. However, certain examples of searching for steel and glass structural solutions can be indicated [59]. At short spans, glass structures can be used in the housing and platform structures [60]. However, with larger spans of such footbridges, glass structures are used only as enclosure elements. One such example is the footbridge at the John Lewis Department Store, Leicester (Figure 9a). The structure was designed as an integral part of the entire complex. It connects the shopping mall building with the multi-story car park above the six-lane Vaughan Way bypass. The distance between the connected buildings equals 36 m; the footbridge width in the middle of its span is about 4 m [61].



(**a**) (**b**)

Figure 9. The footbridge at the John Lewis Department Store in Leicester: (**a**) view of the footbridge from the Vaughan Way, (© Satoru Mishima); (**b**) section through building John Lewis Department Store and Parking, (© AZMPL).

Another issue concerned the integrity of the entire complex in terms of aesthetic solutions. Hence, it was decided that the connection between the parking lot and the shopping centre building, whose characteristic glass facade was decorated with an ornamental print, would be implemented with a glass housing. Due to the significant distance between the connected buildings, it was necessary to shape the footbridge structure to avoid intermediate support. To eliminate the need to introduce additional support in the Vaughan Way bypass and simultaneously reduce the footbridge span, a cantilever truss was designed to be anchored in the reinforced concrete frame of the shopping centre building (Figure 9b). The funnel-shaped truss was introduced into the building body. This solution allowed for a smooth connection between the footbridge and the shopping mall in terms of functionality. The effect of the applied solution is also visible on the facade of the John Lewis Department Store.

On the other hand, the footbridge was designed with an extended pier whose interior extends from the side of the car park. From the outside, its end corresponds with the glass facades of the car park. The self-supporting glass structure of the footbridge housing consists of glass beams that transfer loads to the walls of its housing; the structure cooperates with a steel railing mounted in the footbridge structure.

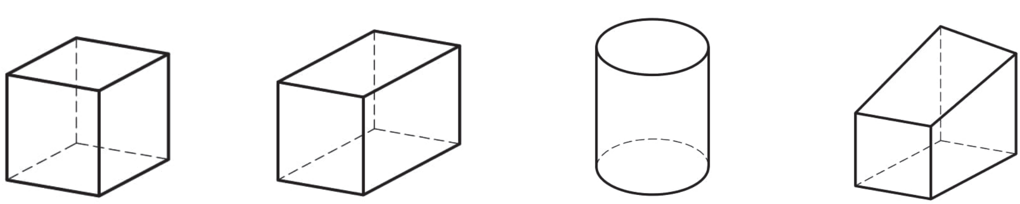
3.2. Typology and Form Analyses of All-Glass Structures

Glass pavilions, extensions, and links can be shaped in various geometrical forms. When designing them, archetypal architectural forms are often used. One example is the Louvre museum's entrance pavilion, designed by Ieoh Ming Pei. The form of a glass pyramid directly references the Egyptian pyramids. The solid is one of the five platonic solids, described by Plato as "beautiful forms", as they are based on the principles of logic and mathematics [62] (pp. 55–60). The shape of the sphere can be seen as another archetypal form. The sphere belongs to the basic solids, but its geometrical specificity is not commonly implemented in architecture [63]. However, it is difficult not to refer to the domes envisioned in Buckminster Fuller's designs that still offer inspiration for subsequent glass structure designs.

However, in the case of all-glass objects, the scope of the applied forms is significantly narrowed. The cube or cuboid form is dominant, which results from the architectural specificity of these objects, including the context of the building development or its functions. However, the way glass structures are shaped regarding their construction exerts the most significant influence in this respect.

Based on the conducted analysis, with the account of the geometric form criterion applied in pavilions, extensions, and links, the following were distinguished (Figure 10):

- cubes,
- cuboids,
- cylinders, and
- free-forms.



(**a**) (**b**) (**c**) (**d**)

Figure 10. Typology of glass form: (**a**) cubes; (**b**) cuboids; (**c**) cylinders; and (**d**) free-forms (figures by the author).

3.2.1. Cubes

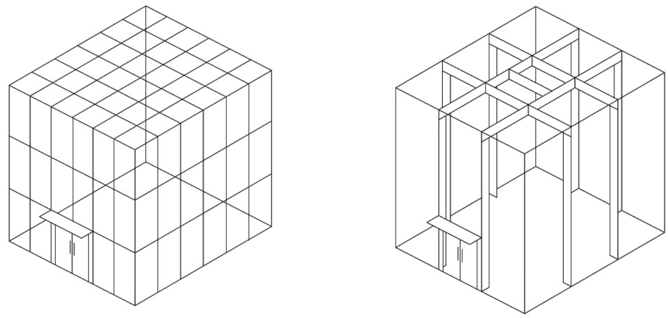
It is worth emphasising that Le Corbusier considered the cube, the cone, the sphere, and the pyramid to be the most beautiful solids with which to shape architecture [64] (p. 80).

When combined with a transparent material, one of the abovementioned forms, the cube, allows the design of objects characterised by form purity and distinguishable in space. The cube's dimensions are of great importance to obtain a transparent form. Depending on the solid's dimensions, the planes of the sides are divided, with the account for the current technological possibilities of the glass material. The cube's dimensions also determine the design solutions applied to these objects. Grillage systems are mostly implemented in the case of cubes.

The construction possibilities of glass limit the scale of these objects. Nevertheless, they prove quite significant for creating meaningful place-making [65,66]. The Glass Cube Memorial in Mannheim may be seen as an example of this approach. The object was erected in the public space as a monumental sculpture to commemorate the inhabitants of Jewish origin murdered during World War II. The tilted cube, 3 × 3 × 3 m in dimension, was designed by Jochen Kitzbihler. The object's scale meant it could be constructed with no additional divisions of the glass walls. It is necessary to take the plane divisions on the sides of the cube into account for larger dimensions.

The Fifth Avenue Apple in New York is the most representative example of a glass cube (Figure 11). The adopted spatial solution was inspired by the glass pyramid being the entrance to the Louvre museum [67], as well as the fact that Steve Jobs [68] (p. 117) indicated the cube as the "purest form". The first variant of the glass cube was erected in 2006. At that time, the technological possibilities allowed for the production and lamination of glass panes with dimensions of 3.0 × 6.2 m. This fact had a decisive impact on the pavilion's form [69]. Its walls were divided into eighteen parts, whereas the roof was made up of thirty-six parts (Figure 12a). However, intensive development of glass technology followed, which contributed to the rapid progress and offered the possibility of producing much larger glass panes. Hence, the decision was made to redesign the pavilion, which led to its current visual perception. In the second form erected in 2011, glass panels with a width of 2.295 m reaching up to the cube's height (10.3 m) were used, which reduced the number of wall divisions to twelve only, whereas the roof was made up of three panes in total (Figure 12b) [70]. The material solutions were also modified. The laminated glass walls in the new pavilion were designed of three layers of toughened float glass, 12 mm thick, glued with the SentryGlas ionomer. In the original version of the cube, the glass panels were laminated of three layers of heat-strength glass, 10 mm thick.

Figure 11. The Fifth Avenue Glass Apple Cube in New York (© Aaron Hargreaves/Foster + Partners).



(**a**) (**b**)

Figure 12. Glass Apple Fifth Avenue Cube: (**a**) 2006 version; (**b**) 2011 version (figures by the author).

The redesign of the cube also involved significant modifications to the main structural element solutions. Reducing the number of glass elements impacted the reduction in the number of joints and enhanced the structure's uniformity [71] (p. 132). Therefore, greater transparency of the pavilion was also achieved, whereas the form became more uniform. It should be noted, however, that glass sheets with dimensions larger than the standard, i.e., 3.0 × 6.2 m, are not a typical solution due to their cost [72].

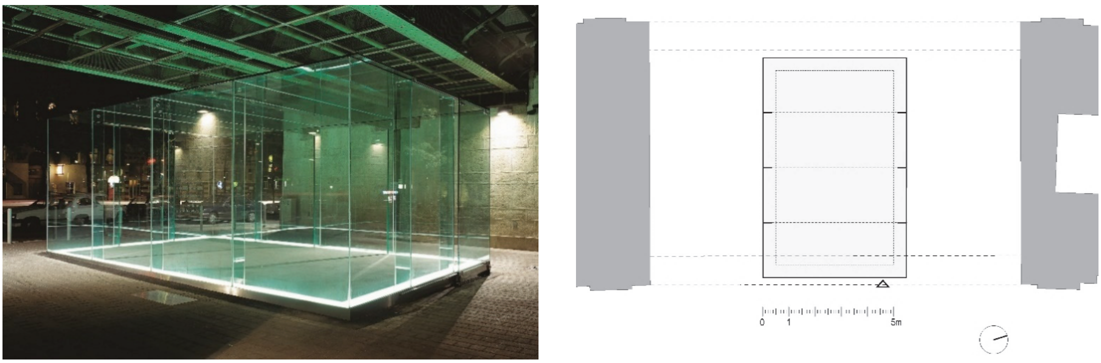
A similar solution, where the pavilion serves as the entrance to the underground parts, was applied in other projects, such as Glas Kubus in Haarlem. In this project, a glass cube with a side of almost 7 m serves as the underground car park entrance [73]. In Lahti, on the other hand, the glass cube was designed as an entrance to the underground floor at the Travel Centre. The facility is a new transport junction erected in the city centre, next to the historic railway station. A similar functional solution with a glass cube was applied at the headquarters of the National Bank in Tbilisi. The object is located in a former building of the Ministry of Highway Construction of the Georgian SSR. It was completed in 1975 in a brutalist style. A glass cube, whose side measures 12 m, serves as an entrance and consists of a simple solid that differs from the existing buildings in terms of material and form solutions. Depending on the cube's dimensions and the design solution adopted, it is necessary to introduce the divisions of the cube sides.

3.2.2. Cuboids

Apart from the cube, the cuboid is the most commonly implemented form of all-glass objects. Its floor plan is a rectangle. The geometric harmony of the form can be achieved if appropriate proportions are maintained as indicated by, e.g., Palladio [74]. This fact is significant for outside–inside objects, in which the interior intertwines with the external environment. The dimensions of the glass solid affect its visual perception, both inside and outside the object. The cuboid proportions are important in this sort of object. Palladio and Alberti recommend that the lengths of rooms should be either the harmonic, geometric, or arithmetic means of the heights, lengths, and breadths. Alberti provided the shapes of the floor plan based on a shape close to a square, a rectangle, and an elongated rectangle in addition to defining the proportions for cuboidal rooms as 2:3:4, 3:4:6, 2:3:6, and 2:4:6 [75] (pp. 224–226). Similarly, Palladio recommended the plan shapes for rooms [75] (p. 244), as well as indicated the cuboid proportions to obtain geometric harmony as 1:1:1, 1:1:2, 1:2:3, 2:2:3, 2:3:4, and 3:4:6 [75] (p. 226).

A few examples of glass pavilions, extensions, and links can be analysed when considering geometric canons. The Export Pavilion in Vienna (Figure 13a) is a cuboid object. It was designed as a pavilion for the presentation of art and performances. A fairly simple and transparent form characterises it. The frame-structure pavilion was placed under the railway viaduct. Its floorplan measures 5.5 × 8.2 m (Figure 13b); thus, its proportion is 2:3.

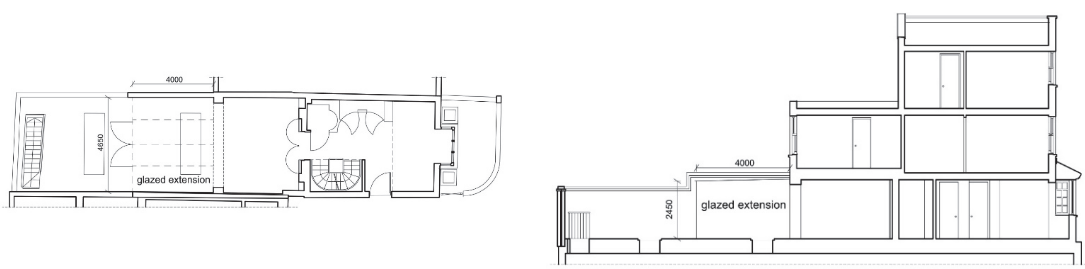
Palladio indicated this proportion as one of the seven ideal plan shapes for the room. The pavilion's height is 3.2 m. The proportions are close to 2:1:3 considering the entire block.



(**a**) (**b**)

Figure 13. Export Pavilion in Wien: (**a**) view of the pavilion (© Rupert Steiner); (**b**) floor plan of the pavilion (© Architects Tillner & Willinger).

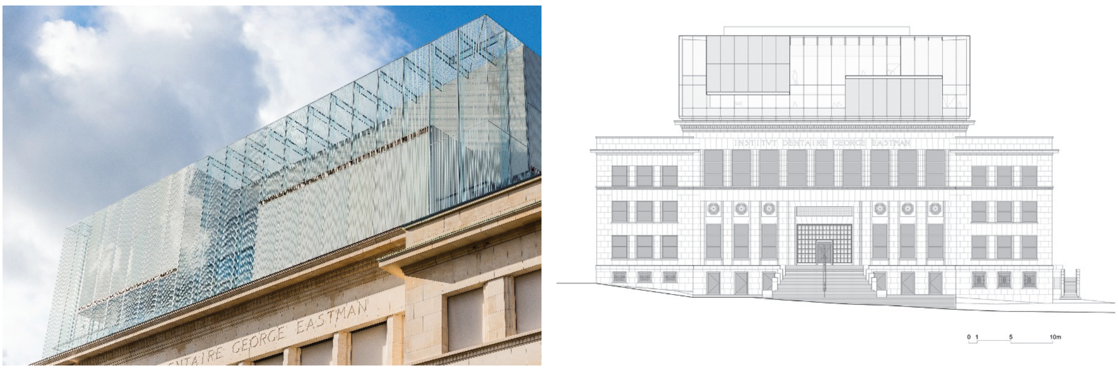
The building's geometry, including its proportions, can provide a source of canonical beauty in architecture. When designing free-standing pavilions, the projection dimensions and heights can be selected in such a way as to obtain any selected proportions, in addition to the canonic ones. However, it is not always achievable in the case of all-glass objects located in closed spaces. This situation is evidenced by the extension (Figure 14a) in a five-story house on Christchurch Street in Chelsea, London. During the recent refurbishment, fundamental changes were introduced to its three-story spatial arrangement. The extension at the back of the house was also enlarged. It was intended for the living room space. Compact development and its geometry significantly limited the design freedom in room plans. Its floorplan measures 4 × 4.65 m, and its height is 2.45 m (Figure 14b), meaning the entire solid proportion is close to 2:1:2.



(**a**) (**b**)

Figure 14. House at Christchurch in London: (**a**) ground plan; (**b**) longitudinal section (figures developed by the author based on the architect's drawings).

As mentioned above, the cuboid form is most commonly used in all-glass objects. The form itself can shape the architecture of pavilions, extensions, and links. It can also be implemented as an element that creates a form of larger buildings. At the House of European History headquarters in Brussels (Figure 15a), glass cubes were applied to obtain a new building form during its modernisation. The most remarkable modification was made visible by adding the superstructure of two stories. The glazed superstructure contrasts with the stone facade of the George Eastman building from 1935 (Figure 15b). The fairly simple, cuboid-shaped form provides a characteristic feature of the new part of the building. Extra-clear glass with a low iron oxide content with vertical print was used to dematerialise the form. The structural elements were also designed as glass frames, grillages, and fins to obtain a uniform structure in the facades of the upper extension and the roof part [76].



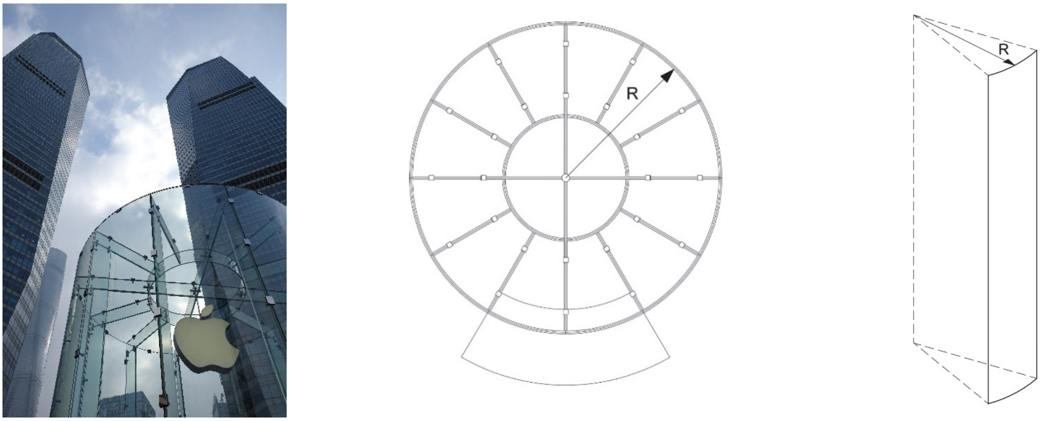
(**a**) (**b**)

Figure 15. House of European History in Brussels: (**a**) glass upper extension (© Christian Fabris); (**b**) eastern façade (© Chaix & Morel et Associés/JSWD).

3.2.3. Cylinders

Cylindrical solids are characterised by a circle-shaped floor plan, the geometry of which is described by a radius. These forms are rarely implemented in all-glass buildings. A small number of solutions of this type may be observed in the non-orthogonal geometry and curved glass shapes. However, technological progress and the increasing possibilities of obtaining and modifying bent glass geometry will reduce the limitations of designing curved-shaped objects. Solutions in which curved glass is applied are increasingly common in the exterior enclosure of free-form buildings using steel or wooden structures [77]. Curved glass can be made using hot and cold bending [78]. However, the geometric determinants of the glass pane are of crucial significance [79]. The glass may be bent along one plane, i.e., single curved, or in two planes, i.e., double curved [80]. The range of shapes used in bent glass is also on the increase, and so are their dimensions [81].

Among the analysed objects, the entrance pavilion to the Apple Store in Shanghai Pudong (Figure 16a) may be analysed as an exemplary use of a cylinder solid. The design concept resembles that of the Apple Cube in New York, in which an attractive glass form is implemented as an entrance pavilion placed on the square. A similar solution was introduced in Shanghai, where the glazed cylindrical pavilion provides an entrance to the underground part. A spiral glass staircase leads to the underground commercial space. The pavilion is 13 m high, whereas a 5-m radius defines its floor plan. The object was implemented with innovative solutions, one of which is the use of curved glass panes with dimensions that had not been produced before [82]. The pavilion is covered with 12 panels whose dimensions equal 12.5 × 2.6 m; its radius equals 5 m (Figure 16b,c). It is made of laminated glass composed of three layers of panes.



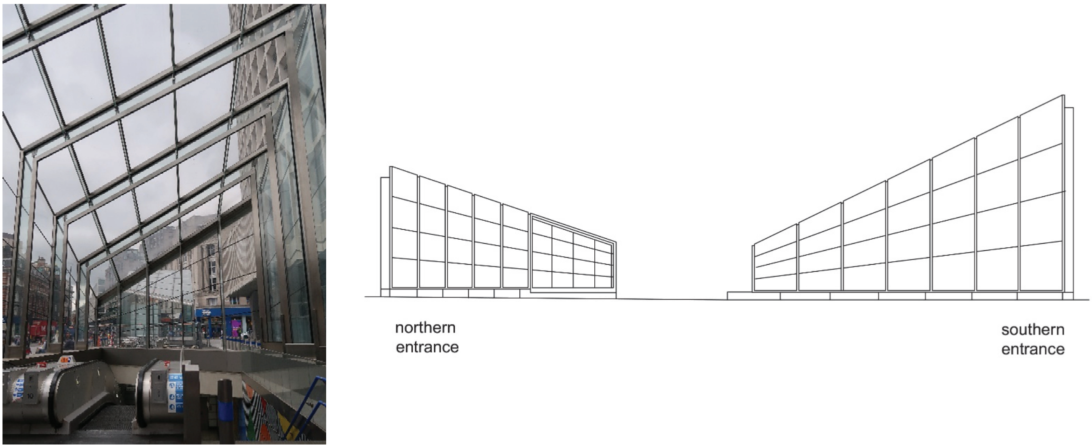
(a) (b) (c)

Figure 16. The Apple Retail Store in Shanghai Pudong: (**a**) view of the transparent pavilion (WikimediaCommons/Kallera/CC-BY-S-4.0); (**b**) roof plan (figure by the author); (**c**) shape of the glass pane (figure by the author).

3.2.4. Free-Forms

The last group of solutions includes free-form solids characterised by irregular shapes. Due to the specificity of the examined objects, the term "free-form" does not refer to parametric forms, such as buildings with steel structures and glass enclosures [83]. This term rather results from modifying the form concerning the shapes of solids classified as cubic, rectangular, and cylindrical. These geometric modifications aim to adjust to the existing building development or arrive at an original building form. It should be emphasised that free-form solids are often perceived as dynamic forms [44].

Two entrance pavilions to Tottenham Court Road Station, placed in the square in front of Center Point in London, provide examples of a free-form facility (Figure 17a). The two crystal-like entrance structures above the ground attract attention. Both pavilions are geometrically diverse. The larger of the two has a floorplan shaped like an irregular tetrahedron, i.e., its sides are not parallel. The floor plan's dimensions are 11 × 22 m, with a height of 14 m of the pavilion considering its longest sides. The irregularity of the form results in the spacing of the main structural elements, i.e., glass frames. In the southern pavilion, the structural span equals 11 m. The frames are not placed parallel to each other due to the floor plan's irregularity. A significant slope in the longitudinal and transverse directions [84,85] provides the architectural form with a dynamic perception. The geometric irregularity of the form and the resulting structural element spacing also contribute to the irregular grid by which the façade divisions and the roof are delineated. Each glass pane has a different shape and dimensions (Figure 17b).



(**a**) (**b**)

Figure 17. The Tottenham Court Road Station in London: (**a**) view from inside (photo by the author); (**b**) western facades of pavilions from Charing Cross Road (figure by the author).

The classification adopted for the typology of all-glass structures is based on simple forms. These forms, as consolidated forms, are also more favourable in terms of the energy efficiency of the building. One of the main parameters in this respect is the form factor, i.e., A/V [86], which describes the ratio of the external surface area A to the internal volume V [87]. The building should be as compact as possible, i.e., as close as possible to a cube, cuboid or sphere. Then the building has a smaller A/V ratio value and consequently less heat loss. More fragmented/extended forms may increase heat energy consumption [88].

When considering the influence of the A/V ratio on the shape of the all-glass objects analysed, it should be taken into account that not all objects are heated, which results from their function. However, considering the geometry of these objects, it is easy to show how the building shape index is subject to a strong scale effect. Increasing the dimensions of the building leads to a significant reduction in the A/V ratio. Proof of this statement can be seen, for example, in the comparison of the cubic forms analysed in this article, although with the same assumption on the partition parameters and heating conditions. For a 3-m cube factor, A/V is 2.0; for a 7-m cube factor, A/V is 0.86; for a 10-m cube factor, AV is 0.6; and for a 12-m cube factor, A/V is 0.5.

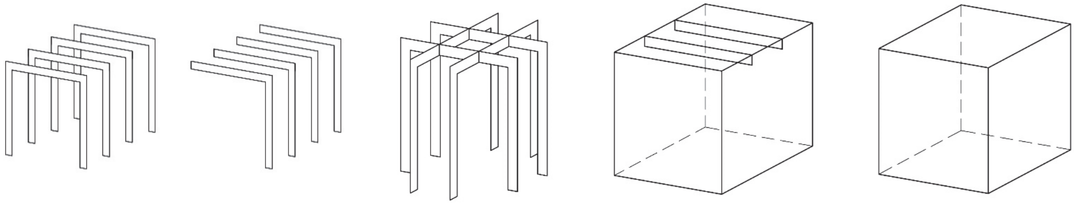
It can therefore be seen that the manipulation of the shape of a building can change its energy consumption value, even though the physical properties of the envelope remain unchanged. This conclusion applies not only to the scale of the building but also to its shape [89,90].

3.3. Topology and Structural Analysis of All-Glass Objects

While considering the possibilities for all-glass object design, both material conditions and structural-spatial solutions should be accounted for. Such features influence the choice of the load-bearing structure as the object's geometry.

Based on the analyses, the following load-bearing structures used in pavilions, extensions, and links were distinguished (Figure 18):

- frames,
- grillages,
- beam-wall systems,
- plate-wall systems.



(**a**) (**b**) (**c**) (**d**)

Figure 18. Typology of glass structural systems used in all-glass objects: (**a**) frames; (**b**) grillages; (**c**) beam-wall systems; and (**d**) plate-wall systems (figures by the author).

3.3.1. Frames

Glass frames are the most frequently used load-bearing structures in shaping all-glass objects. These bar-shaped structural elements consist of horizontal rafters and vertical glass columns. Portal frames and half-frames (frames with one column) can be distinguished. The frames are spaced at a distance of 1 to 3 m (Table 3). Most often, the frame spacing is not wide for safety reasons. When designing glass load-bearing structures, the possible damage to one of the structural elements is often considered. In such a case, the loads are borne by the adjacent frames. The frame spacing is also correlated with the dimensions of the glass panes used in the external enclosure, both walls and roof.

Table 3. Analysis of the geometrical condition of the glass frames.

Name of Building, City	Types of Glass Frames	Distance between Frames S	Span of the Frame/Rafter L	Height of Column H	Cross-Section of the Rafter $h_{rafter} \times b$	Ratio $\frac{h_{rafter}}{L}$	Cross-Section of the Column $h_{column} \times b$	Ratio $\frac{h_{column}}{H}$
		[m]	[m]	[m]	[mm]		[mm]	
Glass Museum, Kingswinford (GB)	half frame	1.10	5.70	3.50	300 × 33.00	$\frac{300}{5700} \approx \frac{1}{20}$	200 × 33.00	$\frac{200}{3500} \approx \frac{1}{18}$
Rietberg Museum, Zürich (CH)	portal frame	1.80	4.40	6.48	350 × 26.28	$\frac{350}{4400} \approx \frac{1}{13}$	350 × 42.00	$\frac{350}{6480} \approx \frac{1}{19}$
Leibniz Institute for Solid State and Material Research, Dresden (DE)	portal frame	1.90	4.40	2.77	250 × 36.00	$\frac{250}{4400} \approx \frac{1}{17}$	250 × 36.00	$\frac{250}{2770} \approx \frac{1}{11}$
Costa Coffee Tower Vaults, ondon (GB)	half frame	1.50	4.50	2.70	300 × 44.50	$\frac{300}{4500} \approx \frac{1}{15}$	200 × 44.50	$\frac{200}{2700} \approx \frac{1}{14}$
Souldern Road House, London (GB)	half frame	1.00	3.10	2.40	270 × 39.00	$\frac{270}{3100} \approx \frac{1}{12}$	250 × 39.00	$\frac{250}{2400} \approx \frac{1}{10}$
Bank JP Morgan, London (GB)	half frame	2.90	7.90	7.20	700 × 57.10	$\frac{700}{7900} \approx \frac{1}{12}$	600 × 57.10	$\frac{600}{7200} \approx \frac{1}{12}$
Castle Grimma, Grimma (DE)	half frame	1.50	2.50	2.20	300 × 45.30	$\frac{300}{2500} \approx \frac{1}{8}$	300 × 45.30	$\frac{300}{2200} \approx \frac{1}{7}$
Pier Visitor Center, Clevedon (GB)	portal frame	1.50	3.94	2.19	250 × 39.00	$\frac{250}{3940} \approx \frac{1}{16}$	250 × 39.00	$\frac{250}{2193} \approx \frac{1}{8}$
House of European History, Brussels (B)	half frame	1.65	1.60 ÷ 5.60	3.00 ÷ 14.00	350 × 80.00	$\frac{350}{5600} \approx \frac{1}{16}$	350 × 80.00	$\frac{350}{14000} \approx \frac{1}{40}$

The structural span of glass frames usually equals 3 to 6 m, sometimes slightly more (Table 3). As it stems from the conducted analysis, it is even possible to shape elements at a span of over 10 m. In comparison, steel portal frames are used with spans of 10 to

60 m [91] (p. 79). The glass element spans are significantly smaller than similar steel structure solutions. However, these values allow eliminating other structural materials and obtaining uniform structures, which constitutes a significant advantage over such solutions. Steel inserts can be introduced to obtain larger spans between the frames, especially in the tension zones of the cross-sections. This solution was used at Tottenham Court Road Station (Figure 17a). The cross-section is a four-ply laminated safety glass element with stainless steel sections on the top and bottom [84,85].

The frame cross-sections are shaped using laminated glass. As with other structural elements, a minimum of three layers of glass bonded with PVB film or SentryGlas is used. The dimensions of the cross-section depend on many factors, including geometrical conditions. Table 3 presents this analysis. One of them is the dependence of the height of the frame rafter cross-section h_{rafter} on its span L. In the investigated buildings, this dependence was determined as 1/8 to 1/20, which gives a rather large discrepancy. However, taking into account the frame spacing of about 1.5 m, it can be determined that the height of the frame rafter cross-section h_{rafter} in relation to its span L is 1/15. In a steel portal frame, by comparison, this relationship is 1/33; for a 10 m span frame, the rafter height is 300 mm [91] (p. 79). However, in steel frames, much larger cross-sections occur at the nodes connecting the rafter to the column (haunch).

It should also be emphasised that in the glass frame rafter cross-section, the width dimension is much smaller than its height h_{rafter}. Due to the proportions of the cross-section in bending elements such as rafters, lateral-torsional buckling must be considered [92,93].

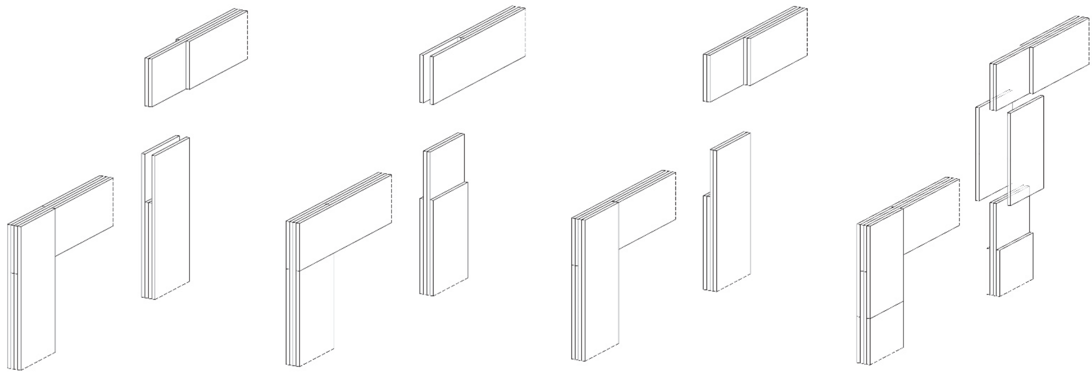
The rafter's cross-section is determined by its span; likewise, its height is of key importance in the columns. The frame height and the column heights often result from the object's utility function or the building development context. Columns are elements designed to sustain compressive and buckling forces. In Table 3, an analysis of the relationship between the cross-section height of the h_{column} and the H_{column} common height is presented. The obtained relationships are similar to those determined in the rafter case.

While shaping the glass frames, the connections between the rafter and the column are crucial. According to the assumptions, the frame connection should be rigid, which is the case in steel structures as well. However, a semi-rigid [94] combination is required in the case of glass structures. The rafter and the column are most commonly connected by [95,96]:

- UV-curable adhesives or
- bolted connection.

Due to the transparency effect, combinations with a limited number of steel elements seem more advantageous. In this respect, connecting the elements with UV-curable adhesives is a good solution. However, it should be remembered that these connections suffer from limitations related to their load-bearing capacity, hence the requirement that such a connection should be tested in laboratory conditions [97]. Such laboratory tests confirm the operation of the transparent connection. This design solution is evidenced by using such elements in the pavilion in Dresden [98] or the Castle in Grimma [99].

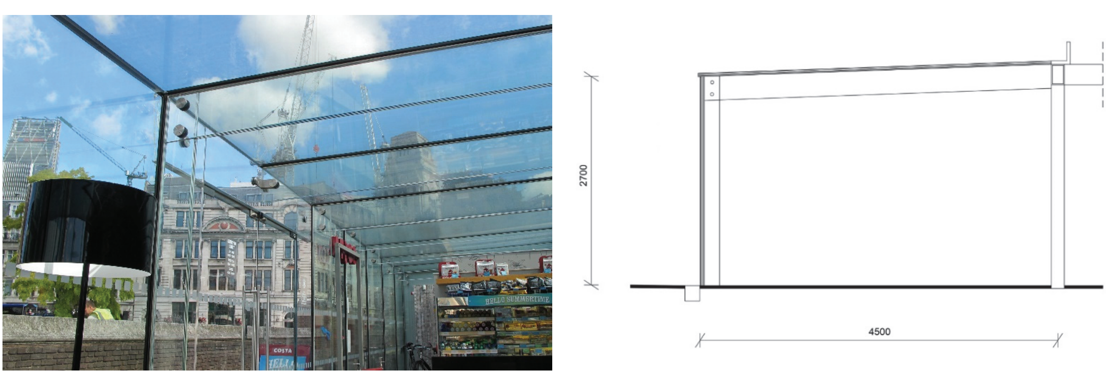
Different layer arrangement is applied in the connections between the rafter and the column [100]. Figure 19 shows the four layering options for four-layered laminated structural glass elements. The first option consists of a tongue-and-groove joint, with a tongue in the rafter part and a groove in the column (Figure 19a). In the second type of tongue-and-groove joint, the groove is in the rafter part, whereas the tongue is in the column (Figure 19b). In the connections between the rafter and the column, it is possible to use a lap connection (Figure 19c) and a connection with cover layers (Figure 19d). The tongue-and-groove connections joined with UV-curable adhesives are the most commonly used system of layers.



(**a**) (**b**) (**c**) (**d**)

Figure 19. The types of connection glass layers in frames nodes: (**a**) tongue and groove; (**b**) tongue and groove; (**c**) single lap; and (**d**) cover layers (developed by the author based on the [99]).

The examined pavilions using glass frames include the Costa Coffee pavilion (Figure 20a), located adjacent to the historic Tower Hill in London. The main argument in favour of the use of glass was to improve the views of the neighbouring historic buildings. The pavilion was integrated into the existing Tower Vaults building. The facility is open on three sides through glass walls and a partially glazed roof. The construction was also designed with glass as a construction material to unify this part of the pavilion's structure. The main load-bearing elements come in the form of frames with a span of 4.50 m and a spacing of 1.5 m. The frames are supported by a column on one side and a rafter on a steel beam on the other side (Figure 20b); hence, they are known as half-frames in contrast to a typical portal frame. The cross-sections in the structural elements were shaped using laminated glass made of four layers of heat-strengthened float glass, 10 mm thick, glued with SentryGlas Plus ionomer, 1.52 mm thick; the total cross-sectional width of the element equals 44.50 mm (4 × 10 mm heat-strengthened low-iron glass + 3 × 1.52 mm SGP). The height of the rafter cross-section equals 300 mm, and the column is 200 mm. The connection between the rafter and the column has been designed using bolted connections.



(**a**) (**b**)

Figure 20. The Costa Coffee London: (**a**) view inside the glass pavilion (photo by the author); (**b**) glass frame geometry (figure by the author).

The glass frames were also applied while designing to form the tea room pavilion at the New Visitor Center in Clevedon (Figure 21a,b). The design assumptions comprised creating a building, almost invisible from the road, that would not obstruct the view along the pier. The existing ramp along the road to the pier descends over its entire length by over three meters. A new visitors' building is integrated into this three-meter slope, minimising access from the road to the pier.

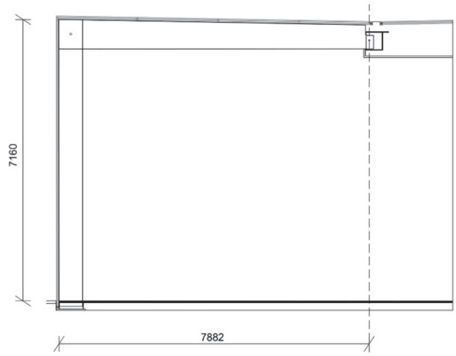
(**a**) (**b**) (**c**)

Figure 21. The Clevedon Pier Visitor Center: (**a**) view of the tearoom pavilion (© Fotohaus); (**b**) view inside the pavilion (© Fotohaus); and (**c**) glass frame geometry (figure by the author).

The tearoom pavilion constitutes a transparent part of the New Visitor Center complex with terraced building development. It was designed using glass frames (Figure 21c), glass walls, and a glass roof. The portal frames span almost 4.0 m and are spaced at a 1.5 m distance. The column heights vary due to the ramp slope. The cross-sections of the structural elements equal 250 mm high and 39 mm wide (3 × 12 mm thermally toughened safety glass + 2 × 1.52 mm PVB). A bolt connection was applied between the rafter and the column.

The analysed objects include the entrance pavilion to the bank headquarters at 60 Victoria Embankment, London (Figure 22a). In the indicated location, two objects compose the building development, i.e., the historical building of the former day school for boys, City of London School, from 1880 on Victoria Embankment, and a 1980 office building, the main entrance to which is located at John Carpenter Street. Recently, the complex has been thoroughly modernised, aiming to adapt the object to the current requirements for an office building. Another reason was to increase the representative function of the bank's headquarters. The design and construction work comprised the main entrance located at John Carpenter Street. The previous entrance pavilion had been erected in the early 1990s in the postmodern style. The reconstruction project included the demolition of the existing pavilion, whose stone, partially glazed façade was demanding in reception. In its place, a completely glazed building was designed. The resulting pavilion links the historic City of London School and office buildings. The new entrance structure consists of a system of two-story half-frames with a span of 7.90 m (Figure 22b). The cross-sections of the structural elements were formed with laminated glass composed of five layers of heat-strengthened float glass, 10 mm thick, glued with a double layer of SentryGlas ionomer, 2 × 0.89 mm thick, the total section width of which equalled 57.10 mm. The height of the rafter cross-section varies from 650–700 mm, and the column's height is 600 mm.

(**a**)

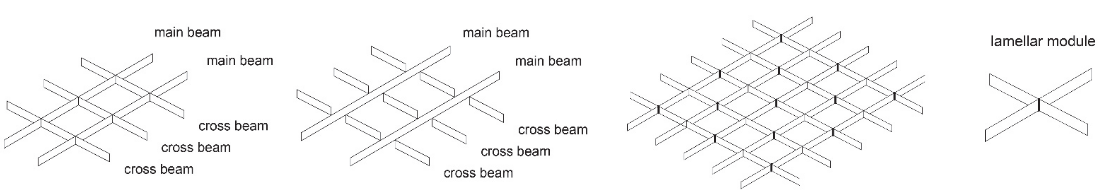


(**b**)

Figure 22. The 60 Victoria Embankment in London: (**a**) view from John Carpenter Street (photo by the author); (**b**) geometry of glass frame (figure by the author).

3.3.2. Grillage Structures

The choice of a frame or grillage largely depends on the geometrical conditions. In this case, the analogy to the static work of the panels [101] (p. 56) may be applied. Namely, with the floor plan ratio defined as b/a ≥ 2.0 (b should be taken as the long dimension and a should be taken as the short dimension), the structures work in one direction, in which case the use of frames is a more practical solution. However, when the ratio equals b/a < 2.0, i.e., when the floor plan assumes a square shape or is close to it, grillages are applied in all-glass objects. The hierarchy of beams in the entire system is important if the grillages are used (Figure 23a). Main beams work in one of the directions, while the cross beam is used in the opposite direction [102]. In such a case, the system of intersecting beams creates a netting with meshes in the glass grillages, whose range equals from 1.5 to 4 m. The cross-section is shaped according to the single-span beam principles. However, the method used for joining the beams in the grate nodes is crucial. Such a connection can be formed through steel elements using metal sheets, covers, clamps, and screws. Due to the different thermal expansion values of materials, the connecting steel elements in glass structures are distanced from the direct point of contact with the glass element through purpose-built spacers. The connection solution itself is custom designed.



(**a**) (**b**)

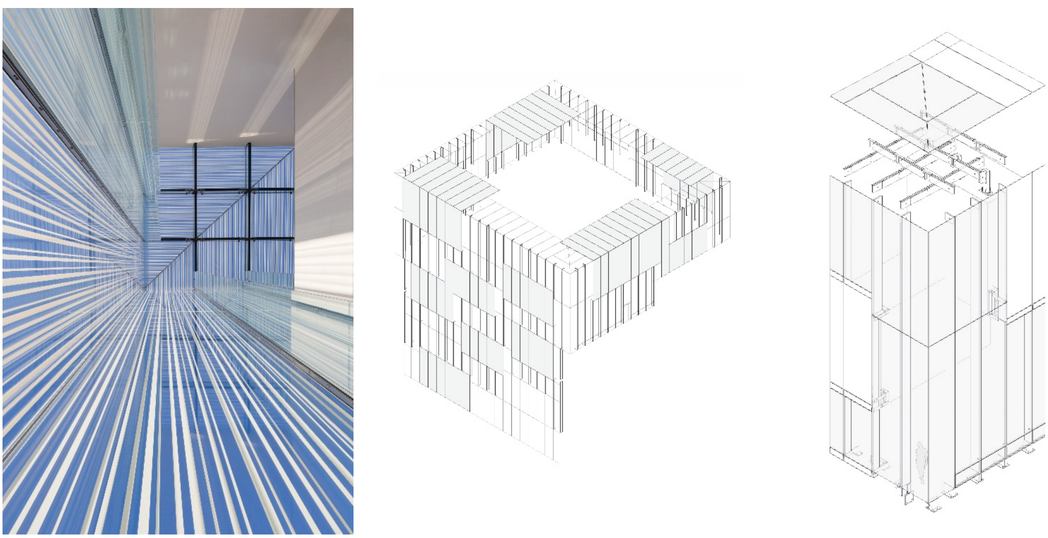
Figure 23. Arrangement of beams in the grillage: (**a**) hierarchy of beams; (**b**) lamellar system (figures by the author).

Due to the cross-section shape, the grillage systems are used in objects such as pavilions with cube-shaped forms. Such a solution was implemented in the original variant of the

Apple Cube in New York. At the time of its construction, the grid was divided into thirty-six meshes. Then, a beam system called the lamellar structure was applied, which the Chinese previously used in the ancient roof (Figure 23b) [103]. This solution eliminated the necessity of point connections through the glass element to achieve longer spans with shorter beams. The roof beams measure 35 cm high in cross-section and are composed of five layers of heat strengthened float glass, 12 mm thick.

Along with redesigning the pavilion, the geometry of the grillage was modified. The grid is now divided into nine meshes. In the current version, a simple 10-m spanning beam is braced laterally at the third point with a cross glass beam [70].

The grillage structural system was also implemented in Brussels's House of European History. A grid determines its geometry with a mesh size of 1.65 m (Figure 24a,b). The grillage was designed with a hierarchy of beams. Continuous beams are used in the main direction, and cross beams connect them perpendicularly (Figure 24c).



(**a**) (**b**) (**c**)

Figure 24. The House of European History in Brussels: (**a**) view of the grillage in the corner of the upper extension (© Christian Richters); (**b**) elements of the glass enclosure (© Chaix & Morel et Associés/JSWD); (**c**) arrangement of glass structural elements in the corner (© Chaix & Morel et Associés/JSWD).

The beam connections in the grid are designed using inside stainless steel clamps inserted into the multi-layer cross-section of the beams and fixed by the bolted connection. The cross-section height of the $h_{grillage}$ beams equals 350 mm, which is 1/16 of the span L. The beam cross-section consists of six layers of thermally toughened float glass, 12 mm thick, connected with a 1.52 mm SentryGlas ionomer; the total value equals 80 mm. The static calculations assumed that the total load would be transferred even in the case of damage to one of the toughened glass layers in the cross-section [104].

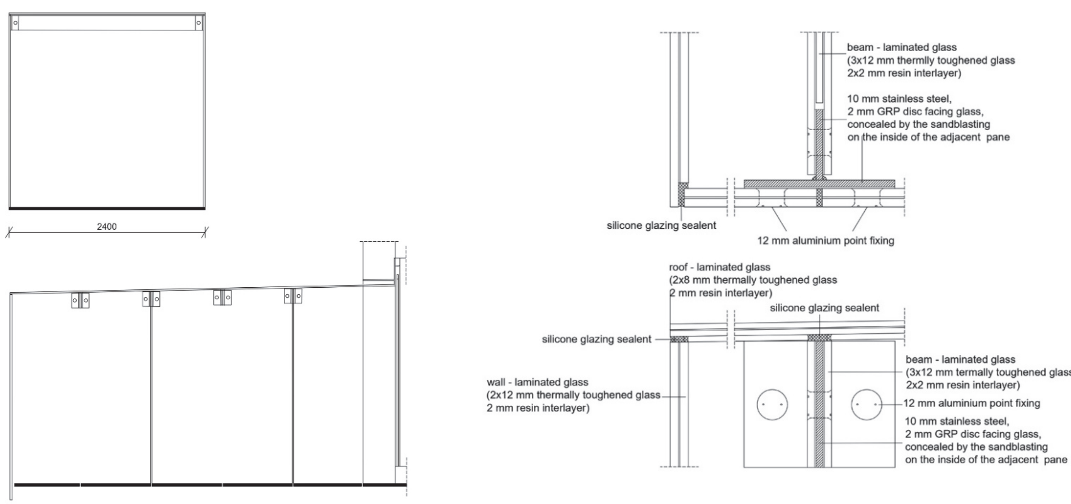
3.3.3. Beam-Walls Structural Structures

In shaping all-glass objects with small spans, the system of glass beams transferring loads to shear walls may be applied. In shaping glass structures, the basic principles characteristic of designing glass structures are applied. The glass behaviour upon breakage is fundamental [105,106]. The issue is essential for the safety of the structure. Therefore, the beam cross-sections are shaped as multi-layer glued structures made of several glass panes.

The cross-section itself has the dimension b × h_{beam}, with b being much smaller than h_{beam}. The height of the cross-section of a simply supported glass beam can be determined from the proportion as approximately 1/17 of the span L, whereas the height of the beam should measure at least 200 mm [67]. The beam spacing is 1 to 2 m and, most often, results from the geometry of the glass panels used in the roof.

An important issue remains the support of the beams on the shear walls, which work as a pin. Loads from the roof panels are transferred to the beams and then to the walls. Beam supports are most commonly used with stainless steel connectors. The aim is to reduce the steel elements' size, as seen in the footbridge project at the John Lewis Department Store in Leicester or the Spencer Park House in London.

Of all the analysed buildings, the solution of beams based on load-bearing glass walls was implemented in the glass extension at House at King Henry's Road in London [107] (Figure 25a). A room was added to the existing house. The aim was to achieve the effect of being outside as much as possible while still being inside. This explains the reasons for applying glass both as the material in the enclosure of the new structure and the structural elements. The roof's structure consists of laminated beams composed of three layers of thermally toughened float glass, 12 mm thick, glued with resin, 2 mm thick. A single pane, 4700 × 2440 mm, made of laminated glass with two layers of thermally toughened float glass, 8 mm thick, glued with 2-mm-thick resin, was implemented on the roof. The beams are supported against the glass walls with 10-mm stainless steel connections (Figure 25b). The connections are attached with a 12-mm diameter point fixing. The extension walls were made of laminated panes, which were made of two layers of thermally toughened float glass, 12 mm thick, glued with 2-mm-thick resin.



(**a**) (**b**)

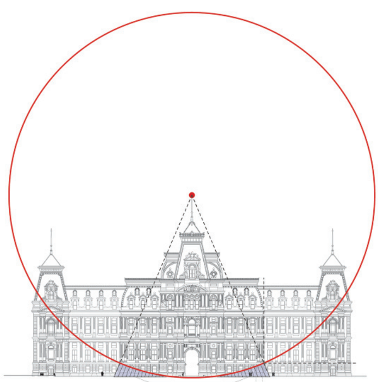
Figure 25. House at King Henry's Road in London: (**a**) cross-section and longitudinal section through extension; (**b**) detail of supported glass beam in the shear wall (figures by the author).

3.3.4. Plate-Wall Structural Systems

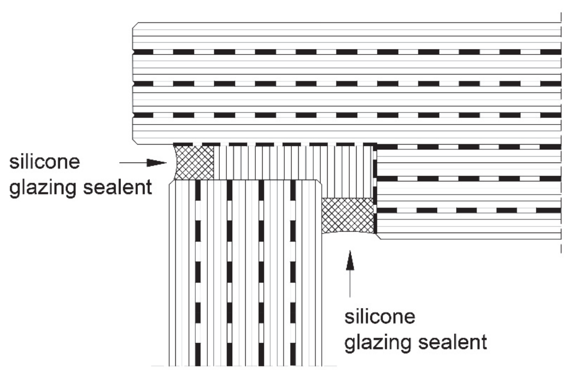
The development of silicone-bonding technology and the technology for manufacturing glass panes has contributed to the possibility of forming all-glass buildings using only panels in the roof and shear walls and without additional structural elements such as beams, fins, or frames. Technological possibilities allow obtaining larger glass pane dimensions and reducing the number of divisions and connections, which is extremely beneficial to obtaining a uniform architectural form. Both slabs and shear walls constitute surface elements. However, loads are borne in various ways. In the case of panes, loads are applied to their surface, while in shear walls, loads are transferred to edges. The panes serve as structural elements in bending, while shear walls are used as compressive elements, with buckling and shearing, which impacts their design [108,109]. The support method of these elements is another important issue. Shear walls can be supported pointwise or linearly. In the case of wall–pane systems, linear support is most common [110]. The basic assumption is that the roof should connect all glass panels and act as a stiff diaphragm. The next assumption concerns global stability, which bonding glass panels can provide with structural silicone at the vertical joint [108].

In terms of shaping the cross-section, multi-layer laminated panes were the basic principle. As a rule, the thickness of the plates or shear walls is achieved by laminating a minimum of four glass sheets. Each additional glass pane increases the section thickness of the structural element, including the effective thickness considered while designing the laminated structural elements [111].

The plate–wall system was applied in the entrance pavilions at the Dilworth Park underground station, Philadelphia, of all the analysed all-glass structures. These structures were integrated into the square in front of Philadelphia City Hall, which provided the determinant for obtaining the form of the glass structure. The tip of the mast at the top of the western façade of the building serves as a starting point to the arch shaping the pavilion's form (Figure 26a). The design assumption was to emphasize the monumental complex as a whole, despite the minimal presence of the pavilions themselves.



(a)



(b)

Figure 26. The underground station Dilworth Park in Philadelphia: (**a**) form of pavilions (© Kieran-Timberlake), (**b**) detail of roof plate–wall connection (developed by the author based on [112]).

The construction is based solely on glass panes, which, in static terms, work as a plate on the roof and shear walls in the vertical elements. Its geometry is significant, as the pavilion is approximately 6 m high at its highest point and over 5 m wide. Due to the pavilion's dimensions and the lack of stiffeners, the board and the disc were shaped so as to ensure adequate stiffness of the entire structure. A laminated glass pane was used in the roof, 5130 × 1390 mm, consisting of seven layers of 10-mm-thick heat-strengthened float glass connected with the SentryGlas ionomer. In the case of the plate, laminated glass with five layers of heat-strengthened float glass, 10 mm thick, was used. The glass walls are fixed within a stainless-steel shoe and cantilever up from ground level. Connections between wall and roof panels have silicone joints with backer rods [112]. The connection detail is shown in Figure 26b.

The plate–wall system was also used in the pavilion located at Liberty Square in Milan (Figure 27a). The glass cuboid is the main composition element of the square; it towers over the underground Apple Retail Store. The wholly glazed pavilion was designed as the coping of the amphitheatre that descends to 3.2 m below the street level. Inside, stairs leading to the store were built. In plan, the pavilion is 2.5 × 12 m and 8 m high. All elements that form the cuboid's planes are structural elements and were designed as four-layer laminated panels made of 12-mm-thick glass glued with 1.52 mm SentryGlas ionomer (Figure 27b). The connections of the roof panel and shear walls were made with the use of structural silicone. In the corners, diagonal joints were introduced, which required appropriate cutting of the glass sheets [113]. Shear walls, 12 m long, are sealed in steel shoes with the use of silicone connections. Narrower walls, including the entrance wall, are mechanically fixed at their base.

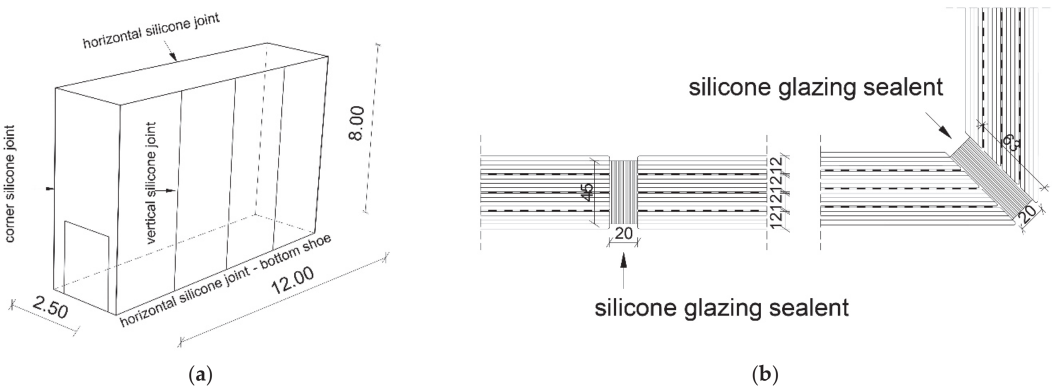


Figure 27. The Apple Retail Store in Milan: (**a**) axonometry with marked silicone joints; (**b**) detail of the connection of glass panes in the wall and the pavilion's corner (developed by the author based on the [113]).

4. Discussion

The all-glass building concept was born at the beginning of the 20th century. However, the implementation became possible only towards the end of the 20th century. The advancements in glass technology and the increasing knowledge of its mechanical and strength properties made the use of glass structures feasible. As shown by the results presented above, the scope of structural glass application is significantly extended in architecture.

The work presented here addresses the use of structural glass in all-glass buildings. A typology was made as an element of recognition and to answer the question of where such solutions can be used. One criterion was the functional and spatial aspects. Hence, it was determined that these were pavilions, extensions, and connectors. Another typology had to do with spatial form, and here the following were distinguished: cubes, cuboids, cylinders, and free forms. A typology of load-bearing structures was also introduced. It was pointed out that all-glass buildings use load-bearing elements in the form of frames, grates, beam-wall, and plate-wall systems.

The results presented in the above article showed the mutual dependencies between the functional-spatial aspects, the form, and the structure in all-glass object design. Geometric conditions significantly impact the use of glass structures, which is strongly related to the object's form; the form may be determined by functional and spatial aspects (Figure 28).

The indicated dependencies are present in many of the examined buildings. The Apple Cube on Fifth Avenue, New York, is one of the most representative examples. All three determinants were closely interconnected in the design process of this glass pavilion. However, it should be emphasized that the glass engineering issues proved the most significant. This aspect applies to the technology and the possibility of obtaining larger glass panes to design all-glass enclosures, including glass structures. The redesign of the glass building shortly after its erection resulted from the dynamic changes in glass engineering.

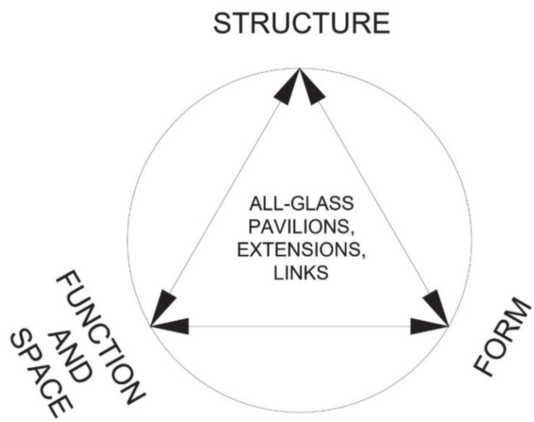


Figure 28. A diagram of the relationship between function and space, form, and structure (figure by the author).

The results presented in this article also concern the determination of structural systems implemented in all-glass objects. Earlier studies on the issue lacked a comprehensive approach to identifying feasible structures in pavilions, extensions, and links. As established above, the selection and shaping of the structural system in all-glass buildings is conditioned by the functional-spatial aspects and the architectural form. Table 4 defines the relationship between the choice of a given structural system and the form implemented in pavilions, extensions, and links and the function of these objects. These relationships were defined as: strong (●●●), medium (●●), weak (●), possible but not present at the studied objects (○), and unlikely to occur (-). The results in Table 4 indicate that in the case of pavilions, cubic all-glass objects are most commonly designed, whereas their structural systems are shaped as grillages and as cuboid forms in which frames are used. The table below clearly shows the significant role of glass frames as load-bearing systems in the design of all-glass buildings. At the same time, it should be emphasised that further development of solutions based on glass panels and shear walls is to be expected. This situation is supported by developments in glass technology, connections, and research to determine the load-bearing capacity of glass shear walls [109,114].

It is worth emphasizing that the spans in the range of 10–12 m are currently the largest dimensions in glass cubes and cuboid design, in which glass load-bearing structures can be implemented. More extensive facilities require steel structures integrated with the glass facades and the roof. The Glass Cube in Madrid, designed by Alfonso Millanes, may be provided as an example of such a building [115]. The pavilion has a square projection of 30 × 30 m, and its height is 21.4 m. This building implemented stainless steel tensile rods of 30 mm diameter to obtain the greatest transparency. The structural elements are arranged with panes of 2.5 × 2.5 m.

The structural system's geometry (structural element spacing, structural element grid, etc.) of all-glass pavilions, extensions, and links remains closely related to the divisions of their cladding elements in the roof and walls. If the glass is used both in the enclosure and structural elements, a uniform structure emerges that strongly influences the visual perception of the building. The research shows that transparency and striving to obtain the most transparent form remain the key values. High transparency is ensured by neutral glass, i.e., glass with a reduced iron oxide content. While using glass structures, larger glass panes may be implemented in order to obtain greater transparency, while fewer structural elements and connections may be applied. Moreover, SentryGlas as an intermediate layer may be applied to connect individual glass panes [116].

Table 4. Relationship between the structural systems and the functional-spatial, the forms, and the function aspects.

Functional-Spatial Types of All-Glass Object	Forms	Structures			
		Frames System	Grillage System	Beam-Wall System	Plate-Wall System
Pavilions	Cubic	○	●●●	○	●
	Cuboid	●●●	●●	●●	●
	Cylinder	○	●●	○	○
	Free-form	●●●	○	○	●
Extensions	Cubic	○	○	○	○
	Cuboid	●●●	○	●●	●●
	Cylinder	-	-	-	-
	Free-form	●	○	●	○
Links	Cubic	○	○	○	○
	Cuboid	●●●	○	●●	●●
	Cylinder	-	-	-	-
	Free-form	○	○	○	○

Glass structures in all-glass buildings offer a spectrum of new possibilities in architectural design. The use of glass as a structural material also presents certain limitations. One of them is the small span of structural elements compared to other construction materials. Glass is a brittle material that can spontaneously break. It should also be noted that solutions using glass as a brittle material are not suitable for implementation in seismically active areas or other situations where dynamic loads may occur.

5. Conclusions

The research determined the possibilities and limitations of using structural glass in all-glass object design. The use of glass as a building envelope material in the walls, roof, and load-bearing structures may be seen as advantageous. In this case, a homogeneous structure in terms of material emerges, which impacts the aesthetic value of the designed solution. The share of transparent elements increases, whereas their neutral visual perception is greatly advantageous.

Several limitations result from the use of glass structures in all-glass objects. These undoubtedly include a smaller construction span than other construction material solutions. Therefore, all-glass objects are characterized by smaller dimensions, including usable areas, or must be combined with other structures, such as in the case of extensions added to the existing structures.

Due to the need to maintain the structure's safety, laminated glass is used both in structural and cladding elements. As a rule, cladding elements stiffen the entire structure spatially. Cross-sections in structural elements are multi-layered with at least three thermally strengthened or toughened float glass layers. In construction solutions, stiff PVB films or SentryGlas ionomers are used to connect glass panes.

The method of joining and fixing glass elements is crucial in the design of all-glass structures. In this matter, technological progress is important, as it makes it possible to reduce the proportion of metal connections significantly. This aspect is also significant from the point of view of aesthetics and striving for the highest possible transparency of the entire facility.

As indicated by the analysis of the examined objects, their design is largely influenced by the progress in glass technology and glass connection methods. Notably, the existing solutions are constantly being improved and modified; new advanced solutions are also being introduced. This phenomenon is known as "engineered transparency".

The use of glass as a structural material in all-glass facilities offers new design possibilities characterised by substantial aesthetic values resulting from glass transparency. The glass as a material, on the boundary between existence and non-existence, provides a separation of spaces. At the same time, it allows the interpenetration of the inside and the outside. This feature of glass remains its main advantage and inspires creative and engineering searches in architecture.

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buildings

Article

The Third Solar Decathlon China Buildings for Achieving Carbon Neutrality

Bin Li [1,2,†], Weihong Guo [1,3,4], Xiao Liu [1,3,4,5,*,†], Yuqing Zhang [1,2,3] and Luca Caneparo [2]

1 School of Architecture, South China University of Technology, Guangzhou 510641, China; 201810100800@mail.scut.edu.cn (B.L.); whguo@scut.edu.cn (W.G.); 202010100982@mail.scut.edu.cn (Y.Z.)
2 Department of Architecture and Design, Politecnico di Torino, 10125 Torino, Italy; luca.caneparo@polito.it
3 State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510641, China
4 Architectural Design & Research Institute Co., Ltd., South China University of Technology, Guangzhou 510641, China
5 Department of Urban Planning and Design, Faculty of Architecture, The University of Hong Kong, Hong Kong 999077, China
* Correspondence: xiaoliu@scut.edu.cn
† These authors contributed equally to this study and shared the first authorship.

Abstract: This research explored buildings for carbon neutrality to solve the global warming problem in the Third Solar Decathlon China (SDC). The methods were derived from subjective and objective evaluation aspects based on the competition rules. Then, the results of the concepts, technologies, and prospects of 15 buildings were output. The conclusion was summarized after a discussion as follows: (1) Solving global warming through carbon neutrality is widely required and research into this issue is required now. (2) Research methods were determined via five subjective and five objective contests with multiple sub-contests. (3) Fifteen buildings' concepts, technologies, and prospects were determined regarding the carbon neutrality aspect. (4) A good architectural design concept was needed before building for carbon neutrality. (5) This research summarized the current development of architecture concepts and technologies in academia and industry. (6) Thirty-five kinds of active and passive technologies were determined, where PV as an active method and modular assembly as a passive method were the most used in this competition. (7) The technologies used with a low frequency, such as wind turbine, Stirling engine, hydrogen fuel cell, UHPC, PCM, and SST walls technologies, also need further attention. (8) The prospect of carbon neutrality, especially for energy production in residential buildings, may shift people's passive acceptance of carbon neutrality to active energy production. (9) Using ANP to produce the SDC ranking may be considered for more scientific investigations to demonstrate the carbon neutrality effect. (10) The limitations will continue to be researched in the future. Finally, this research aimed to make a contribution to solving the global warming for sustainable development.

Keywords: global warming; carbon neutrality; architectural design; energy use; sustainable development; Solar Decathlon China

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1. Introduction

1.1. Background

Global warming has been a global problem for a long time. At least from the 19th century, scientists began to recognize the involvement of carbon dioxide in global warming [1]. From 1950 to 1971, more and more researchers solidified the hypothesis of anthropogenic global warming [2,3]. Although there also exist some queries about man-made global warming, the conclusion that global warming is man-made is generally considered to be common sense given the abundance of research evidence [4]. In 1972, a series of international policies on global warming began to develop. The United Nations Conference on the

Human Environment (UNCHE) in Stockholm roused international concern about global warming [5]. In 1987, Our Common Future was published by the World Commission on Environment and Development (WCED) to define a consensus-based concept of sustainability for global development. The book explained that the amount of carbon dioxide should be reduced, as it leads to global warming [6]. In 1992, the United Nations Conference on Environment and Development (UNCED), also called an Earth Summit, held in Rio de Janeiro, resulted in the Rio Declaration on Environment and Development, as well as Agenda 21, and introduced the Framework Convention on Climate Change (UNFCCC) for achieving sustainable development through specific actions, including carbon reduction [7]. In 1997, the Kyoto Protocol was issued, which was the first quantified legal document under the UNFCCC to promote global energy conservation and emissions reduction for sustainable development [8]. In 2009, the 15th United Nations Climate Change Conference was held in Copenhagen, Denmark, to discuss the global emissions reduction agreement from 2012 to 2020 after the first commitment period under the Kyoto Protocol expired. Unfortunately, at that time, no agreement on a new legal document was reached. A second commitment period was agreed to in 2012 to extend the agreement to 2020 [9]. In 2015, the 21st United Nations Climate Change Conference was held in Paris, France. Negotiations resulted in the adoption of the Paris Agreement, which has governed climate change reduction measures since 2020. The first evaluation based on this quantified legal document will be in 2023. One of the aims is to keep the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels [10]. Therefore, carbon neutrality is more and more important for attenuating global warming to achieve sustainable development.

1.2. Literature Review

Carbon neutrality refers to offsetting the generated carbon dioxide (CO_2) through carbon capture, storage, and conversion within a certain period to achieve "zero emission" of greenhouse gases [11]. This concept was accepted worldwide after the Danish government initiated a competition to find a model for a carbon-neutral community. In the 1990s, Denmark's Minister for the Environment, Svend Auken, returned from the Kyoto Climate talks enthusiastic about his country reducing its carbon emissions. In 1997, he announced this competition, and the winner was Samsø, which became the world's first 100% renewable-energy-powered island in 2005 [12–14]. In the same year, Future Forests used the term "carbon neutral" in their business plan and founded a company in London, which was later rebranded as The Carbon Neutral Company [15,16]. In 2006, the New Oxford American Dictionary's Word of the Year was "Carbon Neutral" [17]. Although such terms alternate between "neutrality" and "neutral", more and more academic and research institutions use "carbon neutrality" nowadays. In 2018, the glossary in the Intergovernmental Panel on Climate Change (IPCC)'s Working Group Report used "carbon neutrality", defining it as "net zero CO_2 emissions", which means that anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period [18].

Regarding carbon neutrality development in China, in 2014, the country proposed its intention to achieve its carbon peak around 2030 [19,20]. In 2020, Chinese President Xi Jinping pledged to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060 at the 75th session of the United Nations General Assembly. This is China's first long-term climate goal, which requires China to rein in CO_2 and probably other greenhouse gas emissions to net zero [21]. Recently, at the 2021 World Economic Forum, President Xi Jinping advocated for international cooperation on climate change in the context of carbon neutrality to achieve the United Nations 2030 Agenda for Sustainable Development [22]. Based on China's current national conditions, the goal of carbon neutrality for sustainable development will be achieved mainly from the research and design application of green buildings, smart technologies, healthy living spaces, renewable energy, building materials and structures, urban renewal, rural revitalization, and other aspects. In this research, the Third SDC buildings are researched for carbon neutrality.

1.3. Research Significance

To solve the global warming problem, carbon neutrality needs to be achieved from the international to country levels. This research focused on carbon neutrality through a Third SDC buildings analysis with the aim to contribute to solving the global warming problem. Based on the architecture concepts, technologies, and prospects, this research produced a significant contribution toward achieving carbon neutrality for sustainable development.

2. Research Objects

2.1. The Third SDC Buildings

The Third SDC buildings were constructed in Desheng village, Zhangbei county, Zhangjiakou city, China, in 2021 for an international collegiate science and technology competition for solar-powered buildings. This competition was introduced by the Solar Decathlon (SD) of the United States Department of Energy with the aim to create a fully functional, comfortable, livable, and sustainable living space by freshly integrating clean energy, energy conservation, and environmental protection into the architectural design [23]; this was hailed as the Solar Olympics and the Green Building Expo.

In the Third SDC competition, 15 demonstration buildings were built by 15 teams from 29 universities globally. Information on the 15 buildings and the teams is shown in Table 1. The site construction progress from July to September 2021 is shown in Figure 1, and photos of the building sites are shown in Figure 2.

Table 1. Information regarding the 15 competition buildings and teams.

No.	Teams	Projects	Universities	Countries
1	Y-Team	Y-Project	Xi'an Jiaotong-Liverpool University Zhejiang University/University of Illinois at Urbana-Champaign Institute Thomas Jefferson University	China China USA
2	DUT and Associates	24 × 35 Housing Home	Dalian University of Technology	China
3	HIT+	Modular Sustainable Cube	Harbin Institute of Technology	China
4	DTU-SUDA	Aurora	Technical University of Denmark Soochow University	Denmark China
5	THU	The Steppe Ark	Tsinghua University	China
6	HUI	HUI House	Hefei University of Technology University of Lille	China France
7	SRF	Pixel House	Shenzhen University RMIT University	China Australia
8	CUMT&AGH&HSP	T&A House	China University of Mining and Technology AGH University of Science and Technology	China Poland
9	Tianjin U+	R-CELLS	Tianjin University The Oslo School of Architecture and Design Tianjin Chengjian University	China Norway China
10	XJTU+	SMART	Xi'an Jiaotong University	China
11	CCMH	Pitched House	Chongqing University	China
12	BJTU+	BBBC	Beijing Jiaotong University Loughborough University	China UK
13	Solar Ark	Solar Ark 3.0	Southeast University Swiss Federal Institute of Technology Zurich Sanming University	China Switzerland China

Table 1. *Cont.*

No.	Teams	Projects	Universities	Countries
14	Hope Land	Hope Land-Natural Courtyard	Zhejiang Normal University Shenyang Jianzhu University Chemnitz University of Technology	China China Germany
15	Qiju 3.0	Qiju 3.0	Xi'an University of Architecture and Technology Southwest Minzu University	China China


Foundation construction


Building assembly


Building completion

Figure 1. The Third SDC construction progress.


No. 1: Y-Project


No. 2: 24 × 35 Housing Home


No. 3: Modular Sustainable Cube


No. 4: Aurora


No. 5: The Steppe Ark


No. 6: HUI House


No. 7: Pixel House


No. 8: T&A House


No. 9: R-CELLS

Figure 2. *Cont.*

No. 10: SMART | No. 11: Pitched House | No. 12: BBBC

No. 13: Solar Ark 3.0 | No. 14: Hope Land-Natural Courtyard | No. 15: Qiju 3.0

Figure 2. Buildings site photos.

2.2. Research Framework

The theme of the Third SDC was sustainable development, smart connection, and human health. Even though the theme of each session changes with the times, the Third SDC presented a significant contribution to the attainment of carbon neutrality, both in practice and academia. Thus, this research on carbon neutrality based on the Third SDC buildings aimed to investigate useful ways to avoid global warming to some extent.

Following the introduction of this paper, based on the background of global warming and a literature review of carbon neutrality, the SDC buildings are discussed as research objects.

The research framework discussed in the next section focuses on the analysis methods based on the competition rules, including subjective and objective evaluations. Then, the research results were determined from the Third SDC buildings. The discussion section discusses carbon neutrality in building concepts, technologies, and prospects. Finally, the conclusions are presented.

3. Methods

3.1. Competition Rules

The methods were based on the competition rules. The SD competition had 10 separately scored contest rules (hence the term decathlon), and some contests contained one or more sub-contests [24]. The competition rules of the Third SDC mainly focused on architecture, engineering and construction, energy, communications, market potential, indoor environment, renewable heating and cooling, home life, interactive experience, and energy self-sufficiency aspects. Each contest had a maximum value of 100 points. The final ranking of the SDC was based on 1000 total points. These 10 contests were divided into subjective and objective evaluation methods. The SDC buildings aimed to satisfy the requirements with different methods, especially for carbon neutrality. The Third SDC contests are shown in Table 2.

Table 2. The Third SDC contests.

Contest Name	Available Points	Sub-Contest Name	Available Points	Contest or Sub-Contest Type
Architecture	100	n/a	n/a	Juried
Engineering and construction	100	n/a	n/a	Juried
Energy	100	n/a	n/a	Juried
Communications	100	n/a	n/a	Juried
Market potential	100	n/a	n/a	Juried
Indoor environment	100	Humidity	25	Measured/monitored
		CO_2 level	25	Measured/monitored
		PM2.5 level	25	Measured/monitored
		Lighting	25	Measured/task
Renewable heating and cooling	100	Space	60	Measured/monitored
		Hot water	40	Measured/task
Home life	100	Refrigerator	15	Measured/monitored
		Freezer	15	Measured/monitored
		Clothes washer	20	Measured/task
		Clothes drying	20	Measured/task
		Dinner party	20	Juried/task
		Movie night	10	Juried/task
Interactive experience	100	Media	25	Measured/task
		Theme day	25	Measured/task
		In the SDC house	25	Measured/task
		In the SDC community	25	Measured/task
Energy self-sufficiency	100	Net-zero	50	Measured/monitored
		Off-grid	50	Measured/monitored

3.2. Subjective Evaluation

The subjective evaluation included architecture, engineering and construction, energy, communications, and market potentials aspect. For the architecture aspect, the evaluation mainly focused on the architectural design in terms of the concept, aesthetics, and function. For the engineering and construction aspect, the main focus was on engineering systems that were energy efficient and energy producing, and the construction aspect concerned resource recycling. The energy aspect was primarily judged in terms of energy production, efficiency, management, and safety. For the communications aspect, aside from communication efficiency during teamwork, the new technologies for better communication, such as a VR display and online activities, were also considered. As for the market potential, this contest mainly evaluated the project's potential contribution to the local and regional market with target clients. Subjective evaluation from the human sensation side was based on the quality of the building, construction process, future development, etc.

3.3. Objective Evaluation

The objective evaluation was based on quantitative indicators regarding the indoor environment, renewable heating and cooling, home life, interactive experience, and energy self-sufficiency.

For the indoor environment evaluation, the humidity, CO_2 level, PM2.5 level, and lighting were used for the review. The time-averaged interior humidity was suitable when it was between 40% and 60%. As for the CO_2 level, it was considered better when below 1000 ppm indoors. Moreover, the PM2.5 level needed to be below 35 $\mu g/m^3$. For the lighting, the required illuminations in different function zones are shown in Table 3.

Table 3. Lighting environment evaluation.

Function Zone	Specific Space	Strength of Illumination
Living room	Normal activity	100 lx (0.75 m upper floor)
	Reading and writing	300 lx (0.75 m upper floor)
Bedroom	Normal activity	75 lx (0.75 m upper floor)
	Reading and writing	150 lx (0.75 m upper floor)
Dining room	Normal activity	150 lx (table surface level)
Kitchen	Normal activity	100 lx (0.75 m upper floor)
	Cooking	150 lx (working surface level)
Bathroom	Normal activity	100 lx (0.75 m upper floor)
Walkway	Normal activity	75 lx (0.75 m upper floor)

For the renewable heating and cooling evaluation, each space's dry-bulb temperature needed to be between 22 °C and 25 °C. Furthermore, this also required providing water of at least 40 °C before an average of 500 mL of water had passed through each sink faucet under normal operation.

For the home life evaluation, six aspects were evaluated: refrigerator, freezer, washing clothes, drying clothes, dinner party, and movie night. For the refrigerator evaluation, the time-averaged interior temperature of a minimum 170 L volume between 1 °C and 4 °C was favorable. For the freezer evaluation, a time-averaged interior temperature between −30 °C and −15 °C was required. The freezer volume needed to be a minimum of 57 L. For the washing clothes and drying clothes evaluations, the normal washing machine functions were required to be completed. As for the dinner party and movie night sub-contests, they were quantitative assessments of social activities in the building. Here, we do not go into detail on these two aspects—only building studies related to carbon neutrality were focused on in this research.

For the interactive experience evaluation, the media, theme day, in the SDC house, and in the SDC community aspects comprised the evaluation content. Although all of these used data as quantitative indicators, the aim was to display and publicize buildings in the form of voting. Here, no further concern was given in the main body of the research.

For the energy self-sufficiency evaluation, the net-zero and off-grid were the review contents. For net-zero, all available points were earned at the evaluation period for a net electrical energy balance of at least 0 kWh. For off-grid, each building was required to maintain normal functioning for at least two days (48 h). Normal functioning included a comfortable indoor environment, a fire protection system, living activities, and others.

The Third SDC competition rules included 10 contests with several sub-contests, which were evaluated using five subjective and five objective evaluation methods. Even though the final review of the competition has not yet finished, the designers of each building tried their best to meet the requirements of the competition. In this study, the results based on the aspects of the buildings related to carbon neutrality were researched.

4. Results

4.1. Y-Project

The first project, namely, the Y-Project, used a Y-shaped roof, hence the name "Y". The "Y" also references the Chinese character for "people (人)". The design concept was based on the human living environment and incorporated solar heating, daylight, and agricultural production to achieve carbon neutrality [25]. The structural system used bio-based materials to provide long-term carbon storage, wherein bamboo and straw were joined together to develop a new structural system (Figure 3a). The building envelope used adaptive outer films of ETFE and perovskite photovoltaic (PV) cells, which supplied almost 100% of the building energy. The ETFE membrane mixed the thermal response, natural ventilation, and daylight functions. It could also protect the plant walls during the cold period for carbon neutrality (Figure 3b). The plant walls and natural materials guaranteed better air quality (CO_2 absorption, oxygen release, no VOC emission) (Figure 3c). A greywater reclamation system was selected to recycle and reuse greywater in the household for non-potable purposes. Water from bathtubs, showers, kitchens, and washing machines were treated and reused for toilet-flushing purposes (dual supply) and landscape irrigation, significantly reducing the reliance on water (Figure 3d) [26,27].

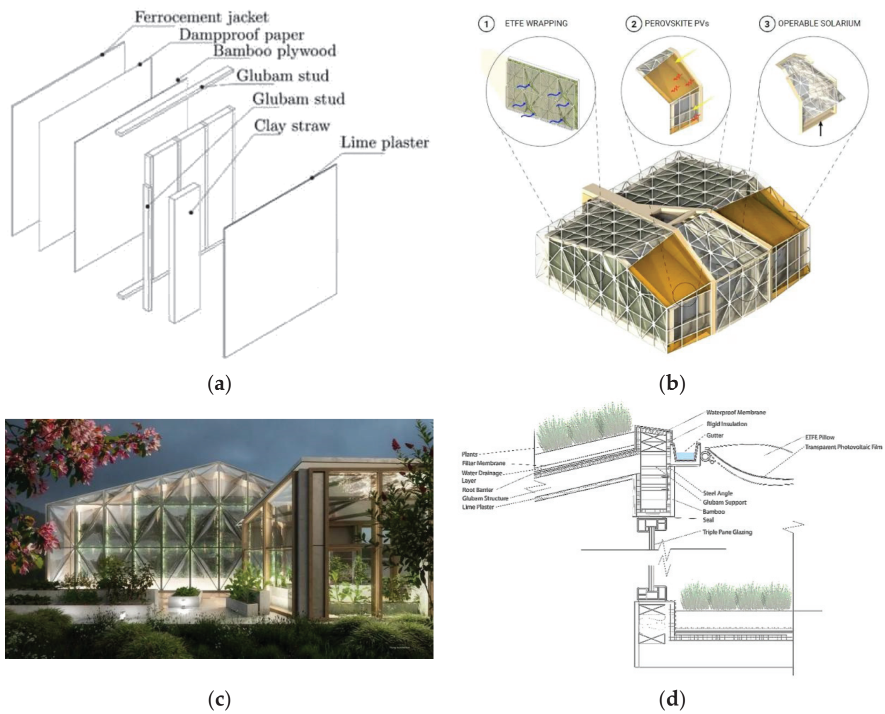
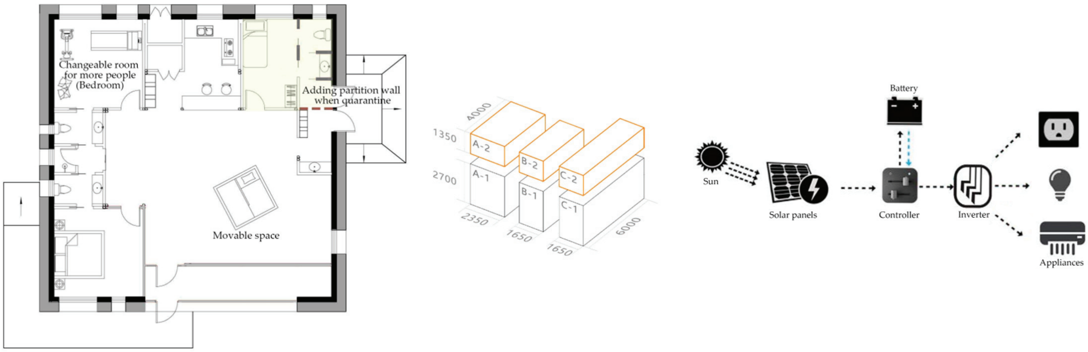


Figure 3. Main results of the Y-Project. (**a**) Bio-based structural system. (**b**) ETFE envelope. (**c**) Plant walls. (**d**) Greywater reclamation system.

4.2. 24 × 35 Housing Home

The 24 × 35 Housing Home refers to 24 h-a-day living and 35-year residential life through the changeable design of the space to meet the users' varying functional needs in the full life span of the house to achieve sustainable development, especially carbon neutrality [28]. The architectural design concept combined changeable space for different needs, especially for epidemic patients who do not need to quarantine in a hospital, making the design suitable for low-carbon living to some extent (Figure 4a). The structure adopted a three-stage component assembly strategy, which included the framework, structural insulated panel systems (SIPS), and related decoration. The module size was designed to meet the capacity of a 1AAA 40-foot-high container to facilitate transportation for low-carbon development (Figure 4b). The renewable energy system used the PV effect of solar cell semiconductor material to convert solar radiation into electric energy. Then, the electric energy through the controller charged the battery or supplied the load using the accumulator when the sunlight was insufficient (Figure 4c) [29].



(**a**) (**b**) (**c**)

Figure 4. Main results of the 24 × 35 Housing Home. (**a**) Flexible space. (**b**) Transportation module. (**c**) Renewable energy system.

4.3. Modular Sustainable Cube

The Modular Sustainable Cube used straw bale modules to build a house to achieve carbon neutrality (Figure 5a). The modular straw bale wall enclosure structure was simplified into five modules and was prefabricated in the factory to avoid unnecessary carbon emissions at the construction site using the Engineering Procurement Construction (EPC) model [30] (Figure 5b). The combination of each module ensured the diversity of architectural space and architectural form. It also focused on energy production through the roof's colorful light-transmitting PV panels to maximize the utilization of natural resources [31] (Figure 5c).

(**a**) (**b**) (**c**)

Figure 5. Main results of the Modular Sustainable Cube. (**a**) Straw bale modules. (**b**) Prefabricated materials. (**c**) PV panels.

4.4. Aurora

Aurora means dawn, and dawn is a part of the natural cycle of light. This courtyard building focused on human health, with the aim to combine natural resources to achieve low-carbon living. The Aurora's solar roof was an important part of the design. It not only provided energy but also created a feature of the overall environment and architecture. It provided a place for solar panels and supported a zero-energy house (Figure 6a). The building also adopted underfloor heating/cooling to provide more efficient and well-distributed space conditioning. The system consisted of two water tanks and one heat pump, which alternated according to the water condition in the tank and the season (Figure 6b) [32]. The building material comprised bamboo for the structures, external cladding, and interior design. Bamboo is a sustainable and local material that contributes to a low carbon footprint. In this building, cross-laminated bamboo and bamboo sticks were used (Figure 6c). In the construction, mixed reality (MR) technology was used for guiding the roof truss and bamboo brick installation. It was easier to install by direct sight without drawings, which not only decreased the construction difficulty but also saved paper in pursuit of the low carbon demand (Figure 6d).

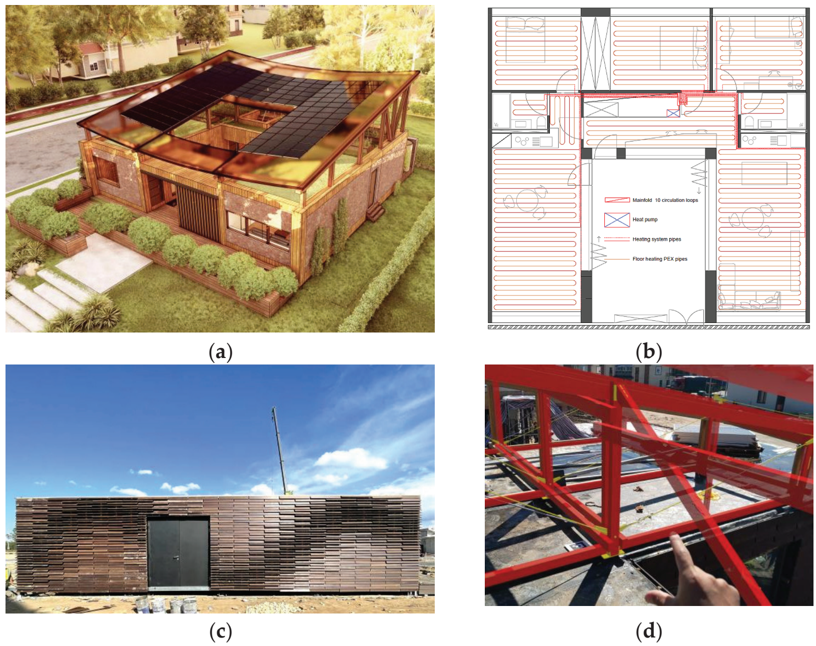


Figure 6. Main results of the Aurora. (**a**) Solar roof. (**b**) Underfloor heating/cooling. (**c**) Bamboo brick wall. (**d**) MR for construction.

4.5. The Steppe Ark

The Steppe Ark focused on the nomadic living characteristics in the competition site of Zhangjiakou city. Zhangjiakou is the connection between agricultural societies in the south and nomadic societies in the north. It is grassland that was once used by nomadic residents to live. This building focused on prefabricated modules, where the designers tried to achieve a shared low-carbon house. It was certified as an active house [33–35]. The Steppe Ark used the modern method of trying to quickly build a new yurt using box structure assembly (Figure 7a). Ten lightweight prefabricated modules were factory-made in advance. The size of the modules was suitable for transportation, and these modules were assembled on site by crane, reducing the carbon footprint during the construction period. For the development use of The Steppe Ark, the sharing concept was also considered, especially for tourism rentals. Shared living not only makes it easy for tourists to experience the nomadic life but is also good for homeowners to earn some money and thus achieve a win-win low-carbon lifestyle (Figure 7b). This building design also fully considered the technologies for carbon neutrality. Indoor light was provided by skylights, side window lighting, and indoor lighting to achieve an energy-saving environment. The air conditioner utilized ground radiation and a convection system to form an efficient and adjustable indoor temperature. Insulated walls used a phase change material (PCM) to passively save energy (Figure 7c). The imitation aluminum PV panels on the roof formed building-integrated PV (BIPV), with a Stirling engine generating renewable energy to offset carbon emissions. The rainwater recycling system ensured the efficient use of water resources (Figure 7d) [36,37].

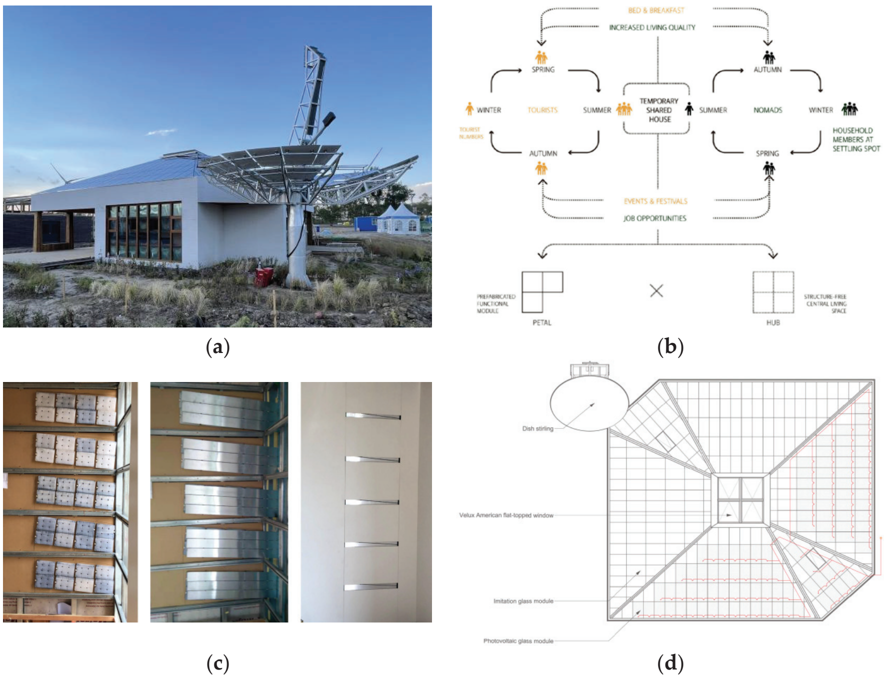


Figure 7. Main results of The Steppe Ark. (**a**) Modern yurt. (**b**) Shared low-carbon life. (**c**) PCM wall. (**d**) PV panels and Stirling engine.

4.6. HUI House

The HUI House was based on Huizhou-style architecture, which is the famous architectural style in China. The building aimed to adopt traditional Huizhou architecture and transform and utilize it in the new era, especially for rural revitalization. The HUI House focused on carbon neutrality by using green building technologies to try to solve the common problems of low quality in traditional Huizhou architecture (Figure 8a). A flexible thin-film solar chip was precisely encapsulated in the glass with highlight transmittance through the laminated packaging process of inner and outer layers. It converted solar energy into electric energy and renewed the traditional tiles with a new aesthetic. With the evaporator installation, the working temperature of the PV cell decreased, which could maintain the photoelectric conversion efficiency (Figure 8b) [38]. A multifunctional supplying system combined the solar-assisted heat pump with power heating and cooling. The heating was not only used for hot water but also for radiant floor heating. The generated electricity also drove the operation of the fresh air equipment to realize fresh air effectively. Moreover, an underground duct system was used to adjust the supply air temperature to form a passive and active carbon neutrality system (Figure 8c) [39]. As for rainwater use, an artificial wetland was planned to be built for rainwater purification using the anaerobic pool, hypoxia regulation, and aerobic pool (Figure 8d) [40].

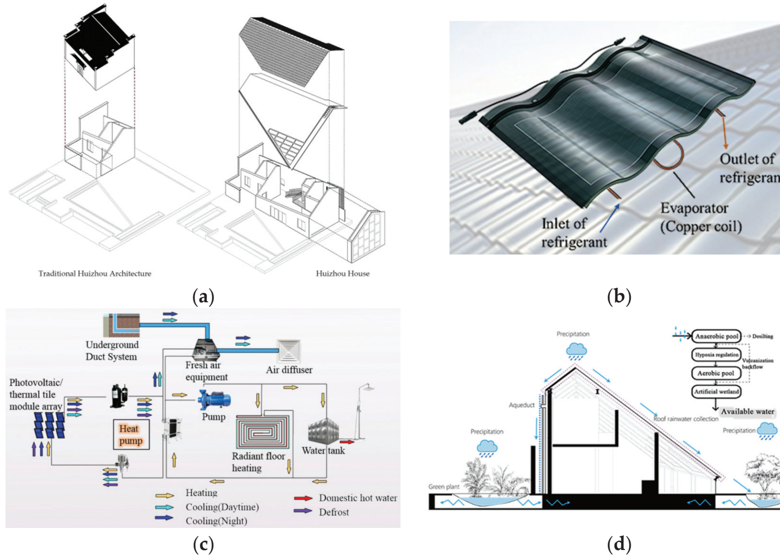


Figure 8. Main results of the HUI House. (**a**) Modern Huizhou architecture. (**b**) Solar chips. (**c**) Multi-functional supplying system. (**d**) Rainwater use system.

4.7. Pixel House

The Pixel House, which was named based on its changeable and flexible spaces, met multiple needs and achieved energy saving and carbon neutrality goals. The indoor movable modules could create multiple spaces for different uses. The functions of this building not only formed various living spaces for various family members with the changeable modules but could also change according to the needs of certain activities. This was beneficial for meeting the changing needs of occupants and reducing carbon emissions to a certain extent (Figure 9a). This building used passive priority and active combination technologies to achieve carbon neutrality. For passive technology, the Trombe wall system was used to save the energy of the thermal environment. The active technology mainly used the BIPV technology on the roof to generate electric energy. Solar bricks and lamps were used in the courtyard. The fence also used PV panels to increase the energy production area (Figure 9b) [41]. The structure of the building was based on prefabricated wooden beams and columns to facilitate quick installation, which decreased the construction carbon emissions, and the wooden material was recyclable and acted as a carbon sink (Figure 9c) [42].

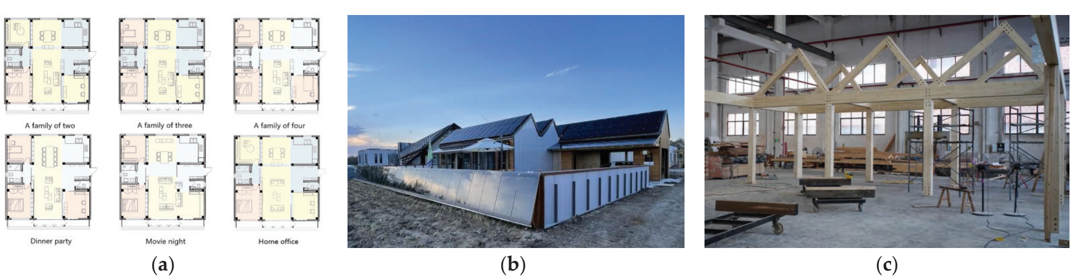
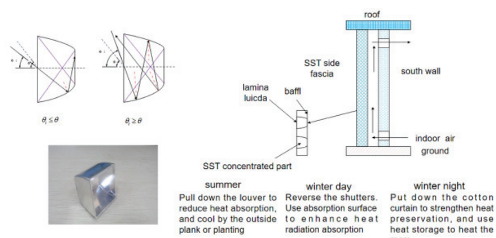


Figure 9. Main results of the Pixel House. (**a**) Changeable modules. (**b**) BIPV and PV fence. (**c**) Prefabricated wooden structure.

4.8. T&A House

The T&A House was named for the participating universities of CUMT and AGH. The building concept, which was based on traditional Chinese quadrangle dwellings, was used with the aim to construct a carbon-neutral, zero-energy house. Considering the prefabricated construction, the building was divided into four kinds of modules and then assembled on site (Figure 10a) [43,44]. Passive technologies were used, including a selective sunlight tunnel (SST) wall, a skylight over the courtyard, a sunroom, and a self-shading corridor. The SST wall used compound parabolic concentrators in the wall to optimize the spotlight effect to adjust the indoor thermal environment, whether in summer or winter (Figure 10b) [45,46]. Active technologies were also considered. The PV components were not only used on the roof but also installed on the western wall to maximize solar energy (Figure 10c). Among all the participants, the ground source heat pump system was used by only this team. This solar system had the role of cooling the roof in the summer and heating the floor in the winter (Figure 10d) [47].

(**a**)



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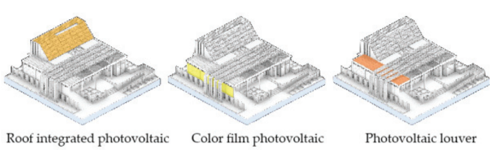

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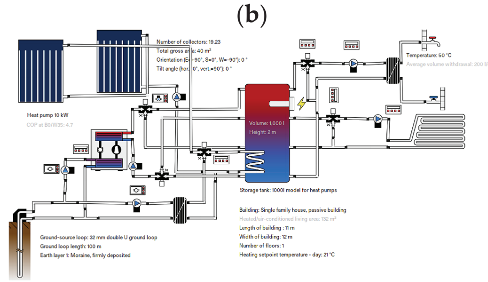


(**d**)

Figure 10. Main results of the T&A House. (**a**) Assembled T&A House. (**b**) SST wall. (**c**) PV used. (**d**) Ground source heat pump system.

4.9. R-CELLS

R-CELLS stands for renewable, recyclable, reconfigurable, resilient with customization, energy surplus, life cycle, livability, and smart. The designers intended to produce low-carbon and self-organizing cells. This building aimed to achieve a solar house prototype with positive energy, full recycling, smart use, and zero emissions by adopting a close-to-nature design, prefabricated modules, intelligent systems, and energy integration technologies. For a close-to-nature design, positive architectural design methods were considered. The building drew on traditional Chinese architecture, namely, "anti-universal to the sun", to form an asymmetric V-shaped roof for the maximum use of the south-facing natural lighting and to increase the solar gain on the north-sloping roof at the site in northern China. The main building material used was wood, which is recyclable, reconfigurable, and resilient (Figure 11a). For prefabricated modules, five customized modules divided into 15 parts for this building were used to decrease the transportation emissions and the life-cycle emissions based on the users' needs (Figure 11b). For intelligent systems, based on the building information model, the integrated and efficient design model was created in the design phase. The energy management, environmental regulation, smart home scenarios, and voice interactive and smart housekeeper systems were used in the physical building, giving users a comfortable, low-carbon life (Figure 11c). For building energy integration technologies, thin-film PV and solar photovoltaic/thermal (PV/T) modules were installed on the roof. Five vertical axis wind turbines were also used at this windy competition site. The battery stored and supplied power. Photovoltaic, energy storage, direct current, and flexibility load (PEDF) technologies were used in this building. Moreover, the rainwater collection from the roof through grey water treatment formed complementary utilization of multiple energy sources (Figure 11d) [48].

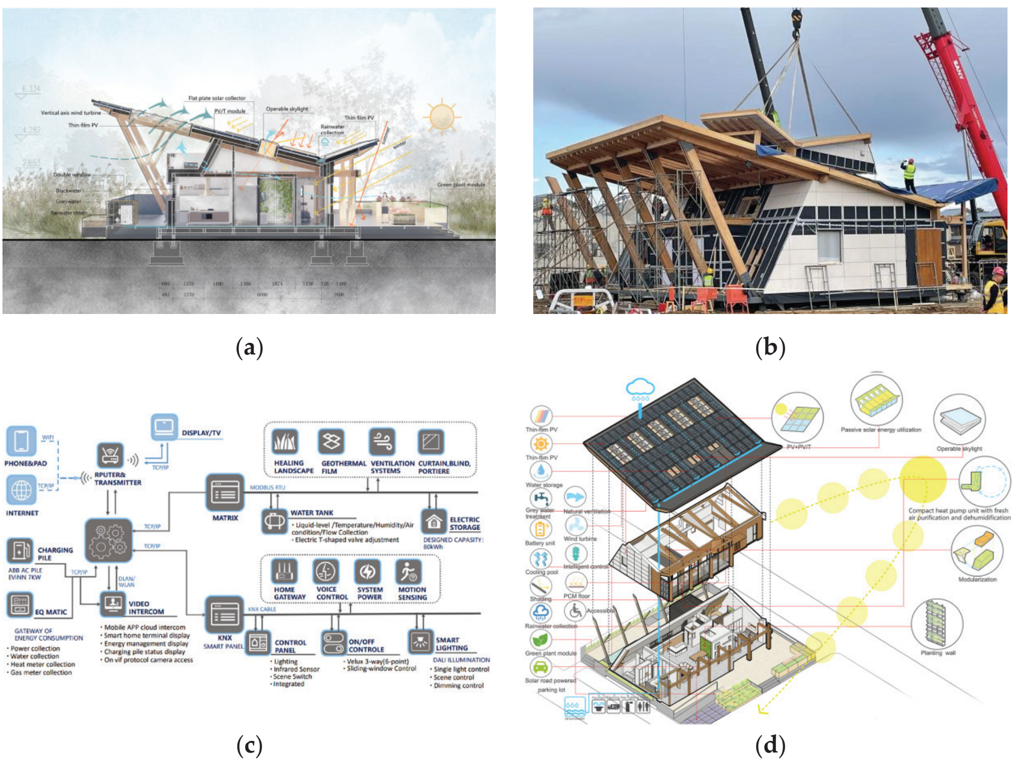
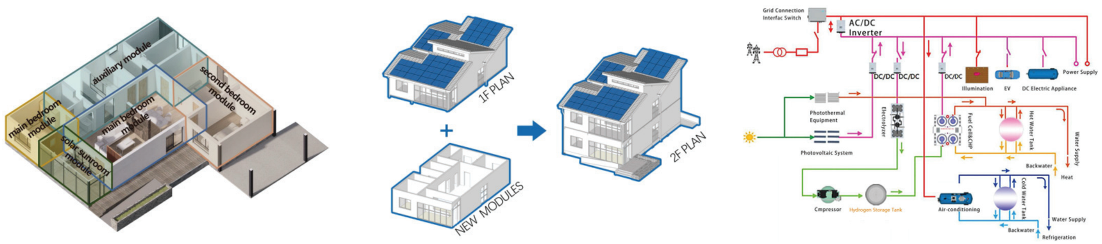


Figure 11. Main results of R-CELLS. (**a**) Close-to-nature design. (**b**) Prefabricated modules. (**c**) Intelligent systems. (**d**) Energy integration technologies.

4.10. SMART

SMART is an acronym for sustainable, modularized, alterable, residential, and technological. The concept was based on the northern China rural building with an aim toward prefabricated assembly with a changeable plan to achieve sustainable development using relevant technologies. This building was divided into five modules for prefabrication in the factory in advance so that the carbon footprint of this building was decreased compared with construction on site (Figure 12a). To make it alterable, the building's designers considered the residents' development so that new modules could be added on the second floor to construct a larger house. It was easier to achieve carbon reduction based on the prefabricated characteristic (Figure 12b). The technologies in this building focused on solar energy and hydrogen fuel cell technology. The BIPV system was used on the roof for solar energy generation. A hydrogen fuel cell was used for electricity production and hot water (Figure 12c). After a certain period, it will achieve carbon neutrality due to the renewable resources that can even be sold to the public grid [49].

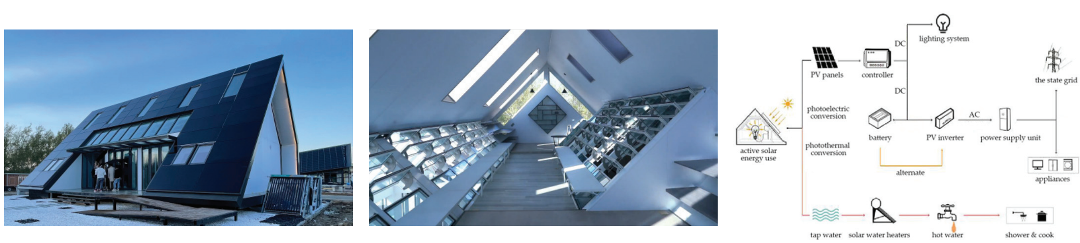


(**a**) (**b**) (**c**)

Figure 12. Main results of SMART. (**a**) Modularized modules. (**b**) Alterable model. (**c**) Energy systems.

4.11. Pitched House

The Pitched House was named for the architectural model, where the roof was inclined at 45 degrees. It aimed to be a multi-function house for living, entertainment, and work to achieve carbon neutrality. The building has two floors to use PV panels on the roof as much as possible. The panels installed on the 45-degree south-sloping roof not only maximized the use of sunlight to achieve carbon neutrality as soon as possible but also formed attractive architectural shapes (Figure 13a). The whole building incorporated a smart energy management system that used the automatic windows on the second floor to regulate indoor temperatures throughout the year (Figure 13b) [50]. Along with photoelectric conversion, photothermal conversion was also used for hot water (Figure 13c) [51].

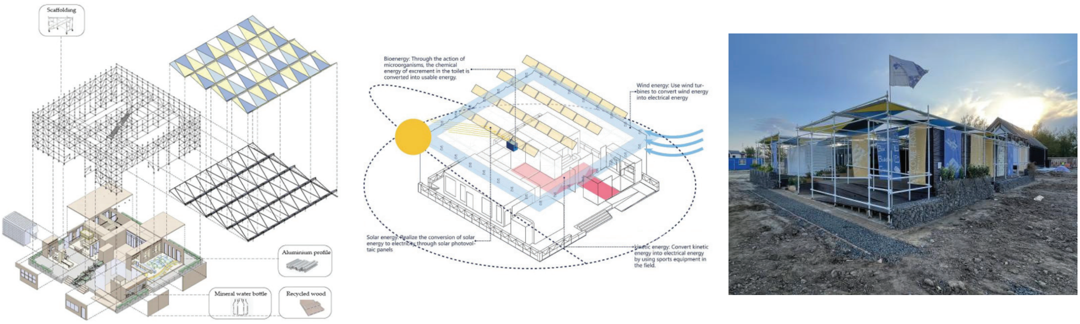


(**a**) (**b**) (**c**)

Figure 13. Main results of the Pitched House. (**a**) PV panels on the roof. (**b**) Automatic windows. (**c**) Energy systems.

4.12. BBBC

BBBC is an acronym for bag, box, building, and cloud. The architecture concept was aimed toward post-disaster reconstruction; therefore, prefabrication and energy self-sufficiency were the most important aspects. Regarding prefabrication, more than 80% of the building design utilized recyclable material, such as aluminum profiles, mineral water bottles, recycled wood, and scaffolding (Figure 14a). The materials can be reused in the future, which is good for decreasing the carbon emissions at the building material level. Concerning energy self-sufficiency, the whole building combined bioenergy, wind energy, solar energy, and kinetic energy to supply electricity for the building (Figure 14b). The building can achieve carbon neutrality and even be carbon negative with time. Overall, this building contributed to carbon neutrality by using prefabricated construction and being lightweight, recyclable, energy-efficient, and so on [52] (Figure 14c).

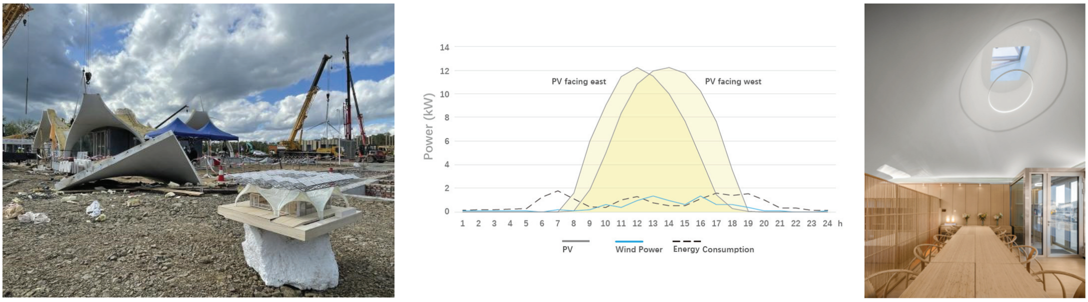


(**a**) (**b**) (**c**)

Figure 14. Main results of the BBBC. (**a**) Recyclable materials. (**b**) Energy self-sufficiency. (**c**) BBBC building.

4.13. Solar Ark 3.0

The Solar Ark 3.0 is the third generation to participate in SDC's architectural works, where it pursued the application of new technology and new energy [53]. The Solar Ark represents the continuous exploration of a better future for human life and environmental sustainability. Ultra-high performance concrete (UHPC) was used by parametric design according to graphic statics to achieve UHPC hyperboloid shells, which were prefabricated in the factory in advance. The whole building consisted of 20 shells, but all the shells were generated using only one mold. This was very helpful for carbon reduction. In addition to applying this high-strength UHPC, it saved nearly two-thirds of the concrete consumption compared with the traditional frame structure under the same building scale (Figure 15a). As for the building energy, 68 solar panels were installed on the building to maximize the use of solar energy. The special feature was that the solar panels were installed in the east–west direction, which could increase the production capacity by 10% compared with the north–south direction when using the same area, and at the same time, adapt to the law of indoor electricity consumption. In addition to solar energy utilization, wind energy was also used in the building to achieve multi-energy complementarity. A vertical wind turbine was installed in the site's northeast corner to generate electricity 24 h a day. An air source heat pump was also used in the building. The total calculated annual electricity generation was 5.2 times the electricity consumption (Figure 15b) [54]. This building could achieve carbon neutrality after 9 years of operation [55]. Passive technologies were also used for carbon reduction. Two skylights on the roof greatly improved the indoor natural lighting and ventilation situation (Figure 15c) [56]. The doors and windows had a thermal conductivity of 1.1 $W/m^2 \cdot K$ and a solar heat gain coefficient of 0.7 to achieve high efficiency and energy savings [57]. Along with the prefabrication, energy complementation, and passive technologies, a variable layout according to the user's needs, rainwater recycling, bamboo furniture, and other aspects were achieved in the building for carbon neutrality.

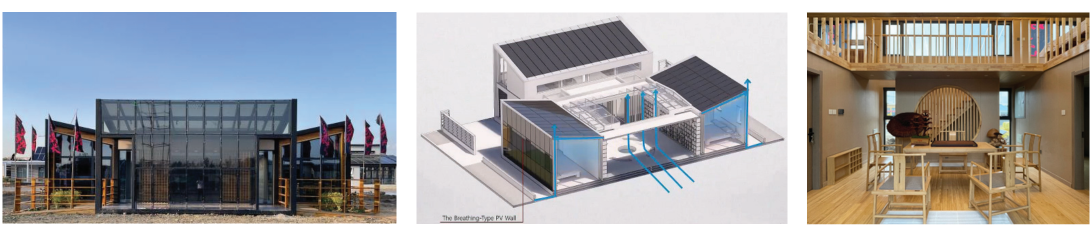


(**a**) (**b**) (**c**)

Figure 15. Main results of the Solar Ark 3.0. (**a**) UHPC prefabrication. (**b**) Energy production and consumption. (**c**) Skylight.

4.14. Hope Land-Natural Courtyard

In the design of the Hope Land-Natural Courtyard, the architecture concept came from traditional Chinese quadrangle dwellings. Four prefabricated building modules sat around the courtyard (Figure 16a). The building was dedicated to rural revitalization to solve problems such as low energy quality and environmental pollution. The PV panels on the three roofs maximized solar energy. These PV panels were combined with the courtyard to form an air conditioning mechanism. PV panels are not efficient at high temperatures, but the combination with the air layer could effectively reduce the surface temperature of the PV panels and maintain their production performance (Figure 16b) [58]. The interior of the building was mainly made of wood, supplemented by wooden furniture, which could effectively sequester carbon, save energy, and protect the environment (Figure 16c). Furthermore, the smart control system, reclaimed water purification system, indoor greening, and others were also used in this building for carbon neutrality.



(**a**) (**b**) (**c**)

Figure 16. Main results of the Hope Land-Natural Courtyard. (**a**) Hope Land-Natural Courtyard. (**b**) PV air conditioning mechanism. (**c**) Wood use.

4.15. Qiju 3.0

Qiju 3.0 was the third generation of the Qiju Decathlon building. In some sense, Qiju refers to a good living environment, which was realized through rapid assembly and independent production capacity. This building used C-shaped steel to make the framework of the lightweight and high-strength modules, which could be constructed quickly and reused in the future (Figure 17a). These modules could be freely combined according to the needs of the users, which was conducive to energy saving and environmental protection and could be set on demand without losing the required ductility (Figure 17b). Qiju 3.0 was a two-story residence. In addition to passively adjusting the indoor temperature in a circle of sunrooms on the sunny side, it also supported low-carbon living with effective ventilation, garden planting, and efficient water purification through an indoor atrium (Figure 17c) [59]. Moreover, active technologies, such as BIPV, an air source heat pump, a fresh air system, a radiant pipe, a smart management system, and a water purification system, were also considered for carbon neutrality (Figure 17d) [60].

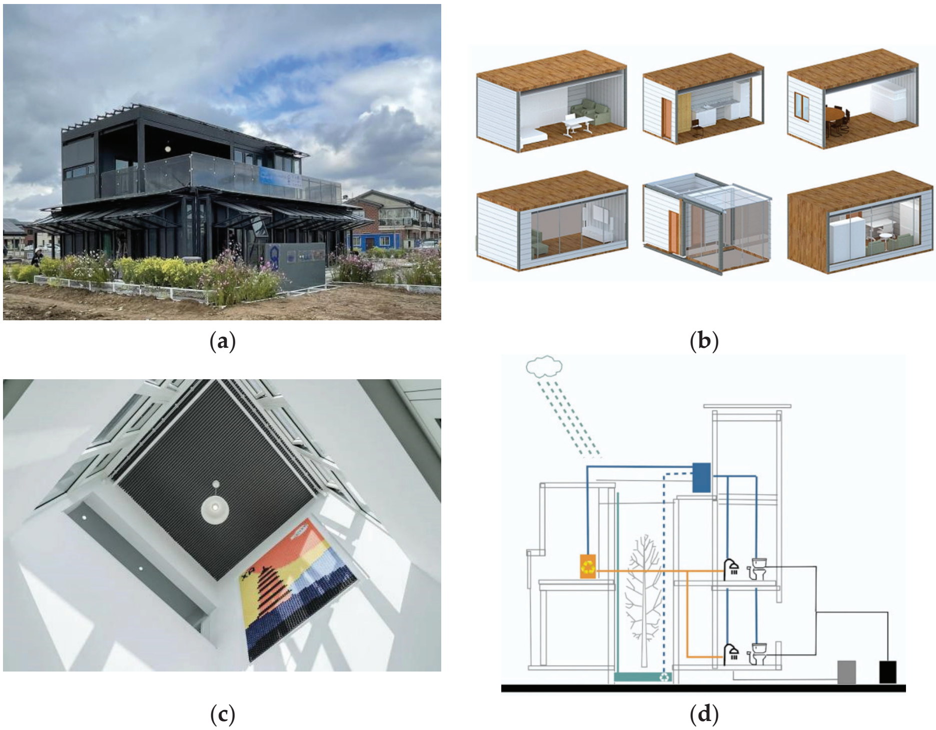


Figure 17. Main results of the Qiju 3.0. (**a**) Prefabricated building. (**b**) Changeable modules. (**c**) Indoor atrium. (**d**) Water purification system.

5. Discussion

5.1. Summary

Starting from the problem of global warming, this research focused on carbon neutrality and aimed to discover a sustainable method to solve this problem. Based on the rules of the Third SDC competition, five subjective and five objective evaluation methods were explained. After analyzing 15 competition buildings in terms of the concepts, technologies, and prospects for carbon neutrality, a summary can be discussed.

Each building had its method of pursuing carbon neutrality. For the architecture concepts, some buildings were more inclined to only focus on the competition theme of sustainable development on a technical level. Some architectural concepts started from practical issues and were committed to rural revitalization, post-disaster reconstruction, grassland features, traditional revival, future development, and more. The competition had a set mission, but each building’s solution differed. Architectural design is a complex issue that should consider a building’s meaning, technology, future utilization, and more. The concepts are generally devised prior to a building’s implementation. With a good concept, the implementation is only a matter of technology.

The technologies used in these buildings are summarized in terms of the different concepts in Table 4. Fifteen buildings started from different architectural design concepts and were then built with multiple technologies for carbon neutrality. Although the design concept may have multiple meanings and the technologies were hard to generalize, from the carbon neutrality aspect, the 15 buildings demonstrated advanced concepts and technologies at home and abroad. This showed the current state of development in architecture, not only in academia but also in the industry [61,62].

Table 4. Main concepts and technologies of the Third SDC buildings for carbon neutrality.

No.	Projects	Main Concepts	Main Technologies for Carbon Neutrality
1	Y-Team	"Y" for human	PV, bamboo material, ETFE, plant wall, greywater reclamation system
2	24 × 35 Housing Home	24 h-a-day living and 35-year residential life	PV, changeable space, assembly modular, SIPS
3	Modular Sustainable Cube	Straw modular modern house	PV, straw brick, assembly modular, EPC
4	Aurora	Solar courtyard building	PV, heating/cooling radiation system, bamboo material, MR
5	The Steppe Ark	Steppe modern yurt	PV, assembly modular, sharing living, skylight, heating/cooling radiation system, PCM, Stirling engine, rainwater recycling system
6	HUI House	Modern Huizhou building	PV, heating/cooling radiation system, rainwater recycling system
7	Pixel House	Changeable modular building	PV, changeable space, assembly modular, Trombe wall, solar bricks and lamps, wood structure
8	T&A House	Modern quadrangle dwelling	PV, assembly modular, SST wall, skylight, sun room, ground source heat pump system, self-shading
9	R-CELLS	Low-carbon and self-organizing cells	PV, assembly modular, self-shading, wood structure, smart system, wind turbine, PEDF, greywater reclamation system
10	SMART	Changeable rural residential	PV, assembly modular, changeable space, hydrogen fuel cell
11	Pitched House	Multi-function house	PV, assembly modular, changeable space, smart system, automatic windows, solar water heater
12	BBBC	Post-disaster reconstruction	PV, assembly modular, rainwater recycling system
13	Solar Ark 3.0	UHPC modular building	PV, UHPC material, wind turbine, air source heat pump, skylight, changeable space, assembly modular
14	Hope Land-Natural Courtyard	Modern quadrangle dwelling	PV, assembly modular, wood furniture, smart system, air layer
15	Qiju 3.0	Assembly modular building	PV, assembly modular, C-shaped steel, changeable space, sun room, plant wall, rainwater recycling system, air source heat pump

For further discussion, these technologies could be divided into active technology and passive technology. There were at least 35 kinds of technologies used in this competition. Based on statistical frequency analysis, a Sankey diagram was generated for the technology ratios (TRs) in Figure 18. This showed the frequency of use of the technologies in these 15 buildings. PV (100%) and modular assembly (80%) were the most used technologies for pursuing carbon neutrality. Almost every building examined here actively used solar energy to achieve carbon neutrality and combined prefabrication in a passive way to reduce carbon. Thus, to achieve carbon neutrality to solve global warming, using PV panels to generate electricity and fabricating the building modules in a factory in advance represented a consensus in this advanced competition [63].

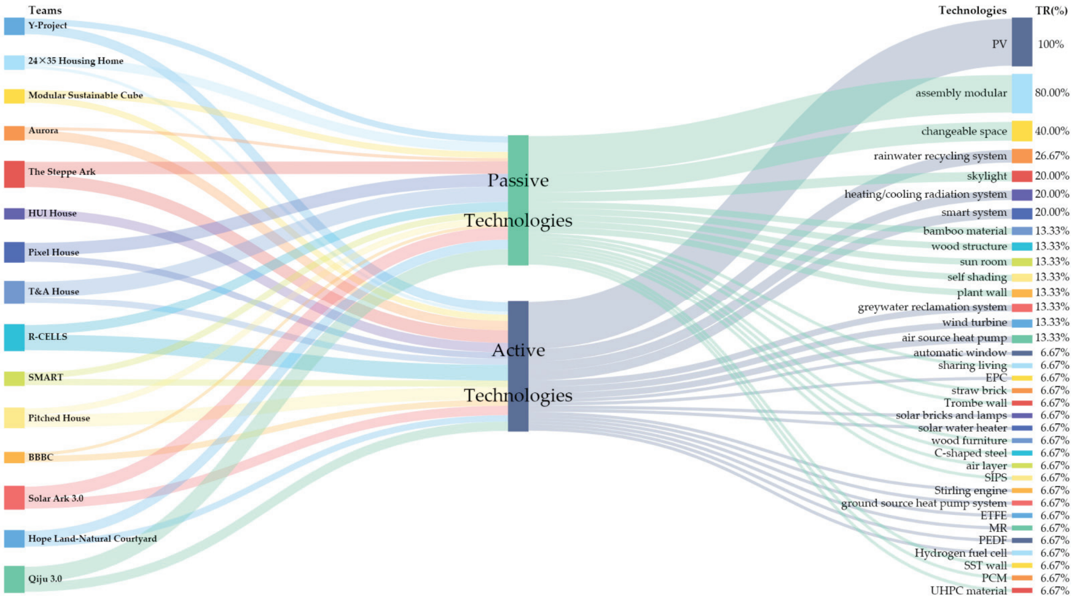


Figure 18. Summary of carbon neutrality technologies in the Third SDC.

Except for the PV technology used in these buildings, wind turbine, air source heat pump, Stirling engine, ground source heat pump system, and hydrogen fuel cell technologies were also used for clean energy generation and consumption. More attention should be paid to these active technologies. As for the passive technologies, the low frequency of use does not mean they are unimportant. In contrast, they may be innovative, cutting-edge technologies [64]. An example was the UHPC, which saved more concrete for better quality; this material may thus be produced more to reduce costs and promote applications to achieve carbon reduction for sustainable development. Additionally, PCM and SST walls were also advanced passive technologies that were used [24].

5.2. Critical Thinking

From the participating buildings of the Third SDC, in striving to meet a carbon-neutral target, some prospects were concluded. Architecture is an ancient subject that has pursued aesthetics for a long time. Nowadays, beginning with modernist architecture, architecture is more focused on technology. Given the issue of global warming, the entire industry has recently started to focus on carbon neutrality. In practice, however, this idea has not taken root in the hearts of all people, but residential buildings could generate power with the above-discussed technologies. From then on, a building can convert input into output, and can not only be energy self-sufficient but can even sell the surplus energy generated from solar, wind, water, and other sources to the public and achieve a carbon-negative status [65]. Residential buildings are the largest building type in the world. Importantly, this will effectively increase individuals' motivation to reduce carbon. Finally, the global warming problem will be proactively solved by everyone [66,67].

Moreover, due to COVID-19, the final review of SDC cannot start yet; thus, objective data are lacking. However, analytic network process (ANP) analysis could be used to simulate the ranking to compare with the present methods [68]. Here, only three projects were chosen for ranking due to the enormous calculation load. The names of these three projects have been hidden to avoid any conflicts. Based on these buildings' technology applications, 17 different technologies were counted. From the design concepts, implementation technologies, and application scenarios, three clusters were established to determine the priorities of these projects. The Super Decisions software showed that the ideals of Project C scored 1, which was better than Project B (0.85) and Project A (0.75), which meant that Project C was the best one of these three (Figure 19). This part of the research was just for showing the method of ANP that may be applied for SDC ranking based on the present ranking rules of 1000 points in total without violating the 10 contests of the SDC. In fact, different contests or sub-contests should be affected by each other with multiple weights. More scientific results lead to better carbon neutrality demonstrations.

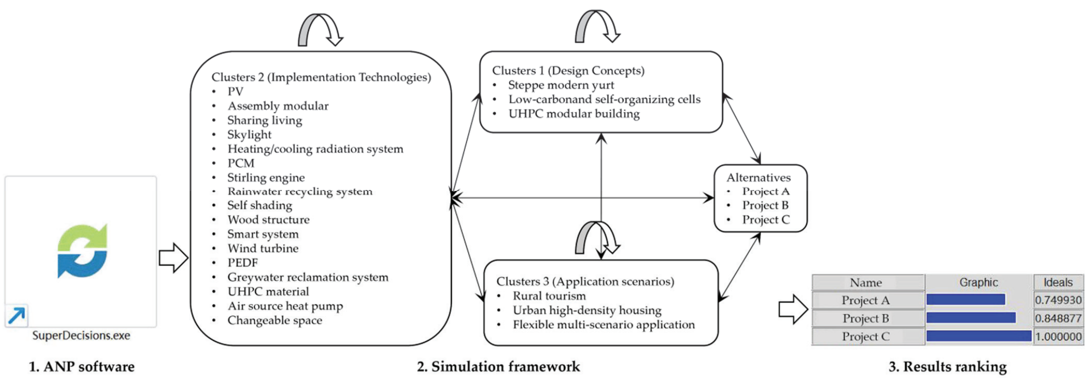


Figure 19. Critical thinking of the ANP ranking method.

5.3. Limitations

However, this research did not focus on the competition ranking but tried to analyze the individual buildings to reach universal conclusions regarding carbon neutrality for solving the problem of global warming. Moreover, with the development of the competition, this research may not be comprehensive. This research only represented the views of the authors. More research on overcoming issues and developing prospects will be done in the future.

6. Conclusions

This study researched buildings that participated in the Third SDC competition to find methods to achieve carbon neutrality to overcome global warming challenges. Some certain contributions were achieved. (1) The global warming background and literature review on carbon neutrality were analyzed. Solving global warming through carbon neutrality is widely required and research in this area needs to be done now. (2) Based on the competition rules, the methods of five subjective and five objective contests with several sub-contests were determined. (3) The results of 15 buildings in terms of the concepts, technologies, and prospects of carbon neutrality were determined. (4) Regarding the aspect of the architectural concepts, a good concept for carbon neutrality to achieve sustainable development was important and prior. (5) A summary of the Third SDC buildings' concepts and technologies was analyzed. This showed the advanced development of architecture in academia and industry worldwide. (6) Thirty-five kinds of active and passive technologies used in this competition were determined. A total of 100% of the designs used the active technology PV and 80% used the passive technology modular assembly, which provided a consensus for carbon neutrality in this competition. (7) As for the technologies used with a low frequency in the Third SDC, this does not mean that they are unimportant. The wind turbine, air source heat pump, Stirling engine, ground source heat pump system, and hydrogen fuel cell technologies used in an active way and UHPC, PCM, and SST used in a passive way should have more attention paid to them. (8) For the prospects of realizing carbon neutrality, energy-producing buildings, especially residential buildings, may shift people's passive acceptance of carbon neutrality to active energy production to achieve a carbon-negative status. (9) The ranking method of SDC could consider ANP due to the interaction of contests and sub-contests to obtain more scientific results without violating the 10 contests of the SDC and offer better carbon neutrality demonstrations. (10) The limitations of this research will be considered and overcome in future research.

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A Simple Framework for the Cost–Benefit Analysis of Single-Task Construction Robots Based on a Case Study of a Cable-Driven Facade Installation Robot

Rongbo Hu [1,*], Kepa Iturralde [1], Thomas Linner [1], Charlie Zhao [1], Wen Pan [1], Alessandro Pracucci [2] and Thomas Bock [1]

[1] Chair of Building Realization and Robotics, Department of Architecture, Technical University of Munich, 8033 Munich, Germany; kepa.iturralde@br2.ar.tum.de (K.I.); thomas.linner@br2.ar.tum.de (T.L.); charlie.zhao@br2.ar.tum.de (C.Z.); wen.pan@br2.ar.tum.de (W.P.); thomas.bock@br2.ar.tum.de (T.B.)
[2] Innovation Department, Focchi S.p.A., 47824 Poggio Torriana, Italy; a.pracucci@focchi.it
* Correspondence: rongbo.hu@br2.ar.tum.de

Abstract: Single-task construction robots (STCRs) have become a popular research topic for decades. However, there is still a gap in the ubiquitous application of STCRs for onsite construction due to various reasons, such as cost concerns. Therefore, cost–benefit analysis (CBA) can be used to measure the net economic benefit of the STCRs, compared to traditional construction methods, in order to boost the implementation of STCRs. This paper presents a simple and practical framework for the economic evaluation of STCRs and conducts a case study of a cable-driven facade installation robot to verify the method. The results show that the cable-driven robot for facade installation is worth investing in in the UK, as well as in the majority of G20 countries. Furthermore, other socioenvironmental implications of STCRs and the limitations of the study are also discussed. In conclusion, the proposed method is highly adaptable and reproducible. Therefore, researchers, engineers, investors, and policy makers can easily follow and customize this method to assess the economic advantages of any STCR systems, compared to traditional construction technologies.

Keywords: cable-driven parallel robot; construction robot; cost–benefit analysis; curtain wall modules; economic evaluation; facade installation

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1. Introduction

Ever since the first debut in the 1970s in Japan, single-task construction robots (STCRs) have become a worldwide research and development topic. They are robots or automated devices that are developed primarily for tasks on the construction sites [1]. It is a highly cross-disciplinary field which requires an integration of a variety of knowledge and expertise such as civil engineering, architecture, industrial design, construction management, robotics, mechanical engineering, electrical engineering, and informatics. Today, the application fields of STCRs continue to expand. For instance, Bock and Linner summarized 200 existing STCR systems into 24 categories based on their functions [2]. However, currently, there is still a gap in the ubiquitous application of STCRs for onsite construction due to various reasons, such as insufficient proof of net economic benefits, lack of modularity in building components, lack of skilled labor for operation, incompatibility with other construction tasks, and time-consuming onsite setup [2]. Therefore, more research evidence is needed to prove the net economic benefit of the STCRs, compared to traditional construction methods, in order to boost the speed and breadth of the implementation of STCRs. Cost–benefit analysis (CBA) is oftentimes considered as one of the most important problem-solving tools in decision-making processes, yet there is a lack of research on the quantitative evaluation of STCR systems to study their economic implications for key stakeholders. This paper aims to propose a simple methodological framework for the cost–benefit analysis of STCRs based on the case study of the onsite cable-driven facade installation robot developed in the EU research project named Hephaestus.

Cost–benefit analysis (CBA) is commonly used for economic evaluation of a project or policy. It can be dated back to the mid-19th century by French engineer and economist Jules Dupuit [3]. It is a policy assessment tool that monetizes all impacts of a project or policy to all relevant stakeholders in society [4]. According to Munger, CBA is considered as the "single most important problem-solving tool in policy work" [5]. The CBA usually can be divided into several major steps in order to make the process more manageable. The steps can usually be described as follows [4].

- Specify the set of alternatives projects.
- Decide who will be the key stakeholder for the benefits and costs.
- List impacts and determine ways to measure them.
- Predict impacts quantitatively over the life of the project.
- Monetize every impact.
- Discount benefits and costs to obtain present values.
- Calculate the net present value of each alternative.
- Perform sensitivity analysis.
- Make a recommendation.

Like every assessment tool, CBA has certain limitations, such as its imperfect process, its monetization of non-market articles, the openness of the results, the thorough examination by the public, its dependence on correctness and completeness, the difficulty of being understood, its ethics, and its neglect of long-term environmental impacts [4]. Nevertheless, considering its wide usage in the policy-making activities, it is naturally reasonable to apply CBA as a tool to evaluate the economic benefits of STCR systems.

2. Literature Review

With regard to the construction industry, there have been several instances of CBA research available to the public. In particular, Shen et al. compared the costs and benefits of prefabricated public housing projects and traditional housing projects based on survey and field research [6]. The research reported an analysis of construction costs and environmental benefits of prefabricated housing, largely based on collected questionnaires from more than 50 managers, which takes a great amount of efforts. Li and Mandanu proposed an uncertainty-based methodology for the life-cycle CBA of highway projects that handles certainty, risk, and uncertainty [7], which requires accessing a large amount of historical data. In addition, Medici and Lorenzini proposed a mathematical model for optimizing energy-saving measures on the building envelope, which reveals the relationship between energy benefit and the related cost [8]. With regard to construction automation, Jang and Skibniewski conducted a CBA of an embedded sensing system for construction material tracking, compared to manual materials tracking, method based on interviewing the experts regarding labor productivity [9]. Another interesting research by García de Soto et al. compared the productivity of robot fabrication to that of manual technique in building complex concrete walls [10], but, strictly speaking, it is a cost and time analysis rather than a comprehensive CBA. Furthermore, Kim et al. developed an assessment tool to evaluate the economic efficiency of an integrated automated onsite construction system [11], focusing on assessing an integrated automated construction system rather than a specific STCR.

These precedents provide insightful knowledge of economic evaluation for the construction sector. However, few of these methods are specifically designed for conducting the CBA of STCR systems, due to the lack of accumulated information in practical applications of construction robots, even though the research field of STCR systems is becoming more popular in recent years.

Therefore, developing a practical method of CBA for evaluating STCR systems would be beneficial to both academia and industry. The goal of this research is to explore a simple framework for the cost–benefit analysis of STCRs, compared to conventional methods, which can be quickly adapted and used for evaluating other STCR systems. The framework will be verified in the case study of onsite facade installation performed by the cable-driven robot developed in the Hephaestus project. The results of the case study can help determine whether the Hephaestus robot is worth investing in for construction companies. More importantly, this framework can be easily adapted to evaluate other STCR systems in various contexts. Furthermore, the results can provide evidence for the policy makers to decide how many resources shall be allocated or invested to the research and development of automated construction technologies.

3. Methods

As mentioned above, this research aims at proposing a simplified method for performing the economic evaluation for construction robots. In this section, the analytical framework and cashflow analysis table for calculation are proposed in general, which, later, is applied to the case study thereafter.

3.1. Analytical Framework for the CBA

In order to compare the STCR solutions to the conventional construction methods, the following simple and practical analytical framework for CBA is proposed (see Figure 1). The CBA in this article will follow this analytical framework.

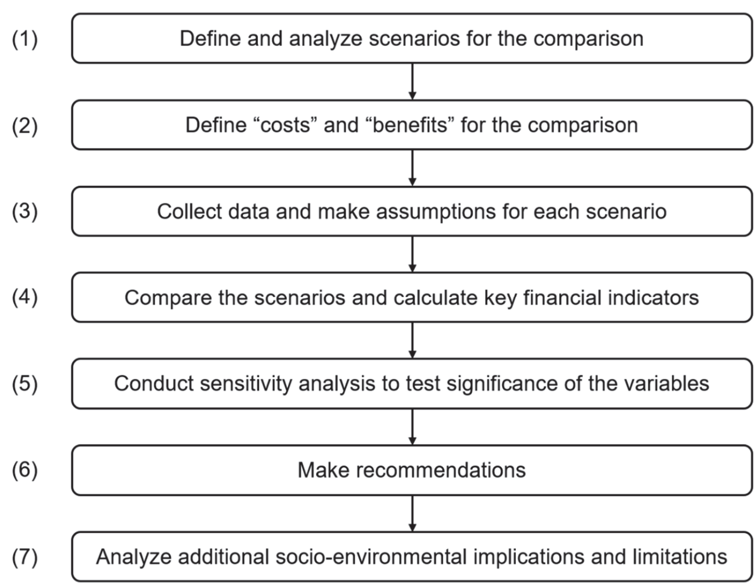


Figure 1. The analytical framework of cost–benefit analysis (CBA) applied in this research.

3.2. Cashflow Analysis Table

In the calculation process of the CBA, all relevant factors that affect the main stakeholder need to be considered. Normally, the cashflow analyses for CBA range from at least three (small-scale projects) to more than ten years (e.g., large-scale public projects) [7,12,13]. The five-year calculation period here is mainly because the engineering partners in the project estimate that the lifecycle of such types of construction robots will likely be approximately five years. More importantly, for individual companies as the key beneficiaries, the investment will not be attractive for them if the payback period is longer than five years (e.g., 10 years or above). Therefore, five years is a reasonable time horizon for economic evaluations of STCRs. As a result, a comparison table between conventional methods and STCR solutions is designed which takes every factor during the onsite construction task into consideration in a five-year period (see Figure 2).

Cashflow analysis to compare novel STCR solution and conventional method							
Key stakeholder/beneficiary							Operating region
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Total (€)	Explanation and remarks
Central - hardware costs							
Central - software costs							
Central - network costs							
Central - utility costs							
Central - operation							
Central - maintenance							
Central - other							
Per robot costs - hardware							
Per robot costs - software							
Per robot costs - network & utility							
Per robot costs - training							
Per robot costs - transport							
Per robot costs - installation							
Per robot costs - operation							
Per robot costs - disassembly							
Per robot - maintenance							
Per robot - other							
Total outflow							
Savings - equipment							
Savings - labor							
Savings - utility							
Savings - operational							
Savings - maintenance							
Savings - other							
Total savings							
Net annual cashflow							
Net cumulative cashflow							
Coefficient of productivity							
Annual wage increase							

Figure 2. Template of the cashflow analysis.

In this template, the light grey cells indicate the cost and saving aspects that need to be taken into consideration, whereas the white cells are used to input values for each cost and saving aspect in the respective year. Each line of item is followed by an "explanation and remarks" cell to describe the respective item in detail (e.g., explanation, calculation, additional information, etc.)

In particular, in the cash outflow category, the "central" rows indicate the indirect costs that a construction company needs to bear in their headquarters in order to run each robot system for a specific task each year, whereas "per robot costs" rows indicate the direct costs of each robot system each year. The "savings" rows indicate the costs of conventional construction method to conduct the same task each year. The "explanations and remarks" row can be used to explain how each row is calculated. If by, or before, year 5 the net cumulative cashflow turns from negative to positive, it suggests that the STCR system is likely to be worth investing in. Furthermore, based on the result of this table, key financial indicators can be calculated accordingly.

In the next section, a case study of an STCR project for facade installation is conducted, and a CBA of the STCR system is performed, based on the proposed framework, in order to verify the method.

4. Case Study

After the comparison framework is defined, a case study comparing the conventional curtain wall installation method and the alternative Hephaestus cable-robot solution is conducted, as follows.

4.1. Curtain Wall Installation Process

A curtain wall is an exterior envelope of the building that does not carry any vertical loads of the roof or floor. It supports its own weight as well as other imposed loads, such as wind, and transfers these forces to the building structure. It provides benefits such as daylight shading, insulation, and weight reduction [14]. Normally there are two types of curtain wall installations: (1) the stick system, where the assembly of the curtain wall components such as frames and glass panes, takes place on site; (2) the unitized modular system, where the prefabricated curtain wall modules (CWMs) are installed onsite. Due to the scope of this research, only the unitized prefabricated module system is considered. The standard CWM installation consists of four main steps, which are (1) bracket installation, (2) lifting the CWM, (3) CWM installation with position adjustment, and (4) CWM unit fixation (see Figure 3) [15].

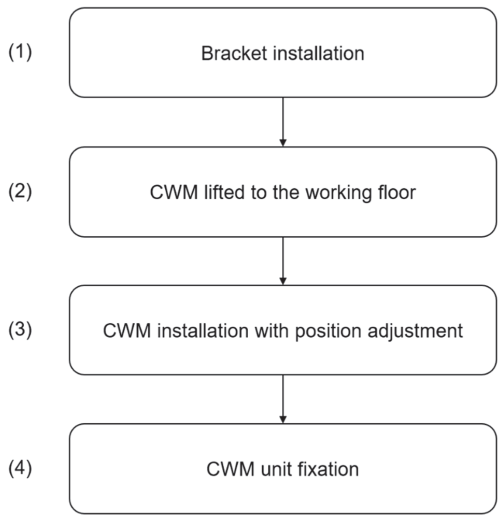


Figure 3. Four main steps in the curtain wall module (CWM) installation.

4.2. Conventional CWM Installation

In the first step of installation, the brackets will be manually installed to the building floors. There are two main techniques for bracket installation: the cast-in channel technique and the drilling technique. In the cast-in channel technique, the channels are welded onto the rebars of the framework before pouring the concrete, whereas the drilling technique requires drilling holes based on pre-measured drilling points which avoid rebars underneath. In the context of this research, only the drilling technique is involved. During the bracket installation process, the position of the CWM will be checked and controlled by using measurement systems such as a total station. The placement of the brackets is critical and will likely not be readjusted later. In the meantime, the modules will be transported to the construction site and stored after being unpacked and assembled. In the second step, the CWM will be lifted by the crane to the working floor (or, alternatively, in some cases, be elevated to the working floor through an elevator if possible). In the third step, while the crane holds the weight of the CWM, workers on the working floor minutely adjust the position of the CWM to ensure its installation to the brackets. Finally, after the position of the CWM is correctly confirmed, workers on the working floor fix the unit and the next CWM installation starts (see Figure 4) [15].

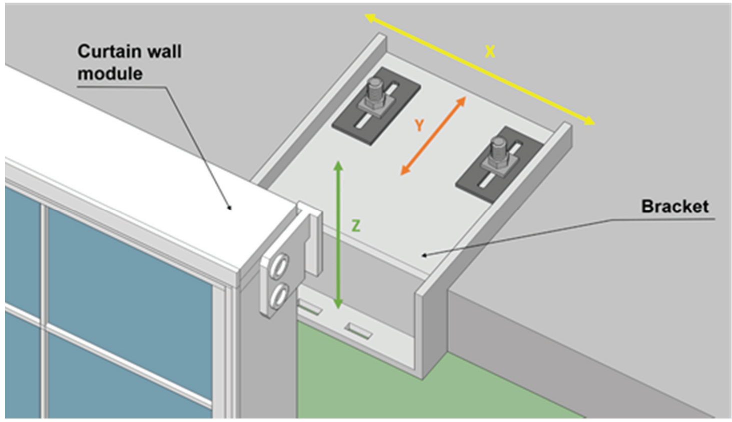


Figure 4. Schematic diagram of a typical bracket on the concrete building floor and its connection with a CWM module (the drilling technique).

Therefore, in the conventional CWM installation process, all the four steps are done manually by workers with the help of certain machines. The installation of brackets is completed by workers one by one manually, which is highly time-consuming. As demonstrated in Figure 5, the manual method normally involves several workers to work together at height, creating high labor costs and potential danger for these workers (e.g., injuries caused by machinery, back injuries from heavy lifting, falls from height, hearing loss from long-term exposure to loud machinery, etc.). In addition, workers on the ground, for component handling, and a tower crane, for CWM positioning, are necessary as well.

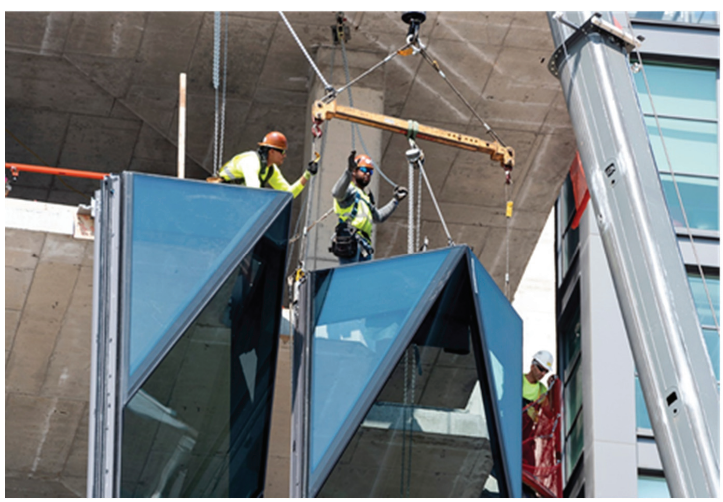


Figure 5. Several workers working at height during the CWM installation process (facade installation in Solar Carve Tower, New York. Facade engineered and manufactured by Focchi Group; photo by Timothy Schenck).

4.3. Automated CWM Installation

There are several existing instances of automated curtain wall installation. For example, a patented method developed by Brunkeberg Systems AB uses a dedicated railing system to automatically install specially-designed CWMs from the outside of a building [16]. However, the railing installation process is manual, and might not apply to certain types of buildings. Other researchers reported a mobile robot that can perform facade installation from the inside of the building, but it only managed to automate the third step, which is positioning the CWM. Činkelj et al. developed a hydraulic telescopic system that installs facade panels to the building from the outside. However, this semi-automated, tele-operated system is specialized for handling facade panels rather than CWMs, and there is also a height limitation due to the use of a telescopic handler [17]. In addition, researchers also proposed other novel solutions for the automatic installation of the facade, but many are still at conceptual level [18–21].

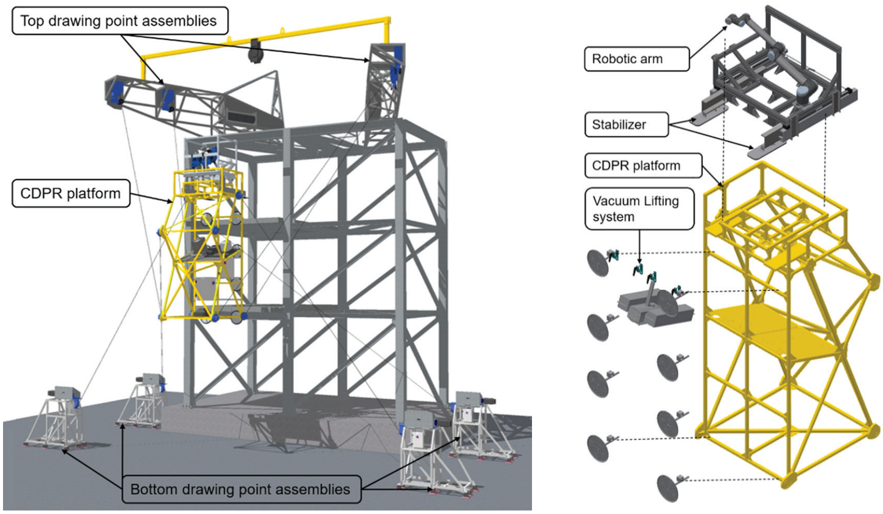
Therefore, the Hephaestus cable-driven robot was primarily developed for the CWM installation task, although various functions can be achieved by reprogramming the robot and replacing the end-effector. It is arguably the first cable-driven parallel robot (CDPR) in the world that is designed, built, and deployed specifically for curtain wall installation.

The CWM installation, as explained above, consists of four main steps: bracket installation, panel lifting, position adjusting, and panel fixation, which are the main tasks of the Hephaestus robot. The advantages of the robot are the large range of workspace, high payloads, reconfigurability, and modularity, making the system easily transportable and highly adjustable to adapt to various situations.

In terms of geometry, a CDPR is a configuration of cables with variable lengths connecting a drawing point attached to the base frame, and a fixing point attached to the mobile platform. The geometrical design of the CDPR can be defined by the following parameters: (1) number of cables, (2) geometry of the structure, (3) geometry of the platform, and (4) cable configurations. Previous studies indicate that CDPR driven by eight cables will have appropriate performance, thus the number of cables was chosen [22]. The geometries of the structure and platform were determined by the positions of the drawing points and attachment points, respectively.

The Hephaestus CDPR consists of seven subassemblies. There are two drawing point assemblies on the top of the building, and four on the bottom, controlling the lengths of the cables (see Figure 6a). In the center is the working platform subassembly, featuring eight fixing points, as well as the power system and various tools for the modular end-effector. In the Hephaestus project, two major tasks need to be performed: (1) the fixation of the bracket onto the concrete slab, which is performed by the robotic arm (see Figure 7), and (2) the placement of the CWMs onto the brackets by a vacuum system attached to the bottom of the CDPR platform (see Figure 6b). In addition, a linear system with vacuum cups serving as a stabilizer is also integrated in the platform in order to stabilize the working platform subassembly (see Figure 8) [23].

In addition, the CDPR features a control room (i.e., a small movable container equipped with computers and other relevant devices) which serves as the "brain" of the system. Currently, the CDPR (prototype) does not directly integrate advanced digital construction technologies. The main tasks, such as bracket installation and CWM positioning, are preprogrammed based on traditional CAD drawings. However, since the CDPR is equipped with adequate hardware and software capabilities, it certainly has the potential to integrate digital construction technologies, such as building information modeling (BIM) and digital twin, in future iterations in order to enhance its speed and performance.



(a) (b)

Figure 6. (**a**) Design of the Hephaestus cable-driven parallel robot (CDPR) prototype; (**b**) detailed depiction of the modular end-effector of the CDPR system.

Figure 7. Robotic arm and its tools for bracket installation protected by weatherproof covers (photo: José David Jiménez-Vicaría).

Figure 8. Stabilizer attaching the robot platform to the concrete slab (photo: José David Jiménez-Vicaría).

4.4. Determining the Scenario for Evaluation

Based on discussions and communications with partners of the Hephaestus project, a presumptive scenario for comparison can be proposed, as below (see Table 1). In this scenario, it is assumed that the facade installation company (i.e., Focchi Group UK) owns the robot during its lifecycle, because the company generated 133.90 million US dollars in revenue in 2019, which is large enough to fully employ more than one Hephaestus robot system.

In the case of curtain wall installation, the service charge is highly case-dependent (i.e., not only decided by the working area, but also by the form and shape of facade, type of CWM, etc.) and thus not easy to determine broadly. Usually, the representatives at the construction company carefully evaluate the building and requirements and provide an offer to the client thereafter. Therefore, a situation is assumed where the two scenarios execute exactly the same amount of workload (thus yielding the same revenue) based on the productivity of one robot system. In this way, many uncertainties can be avoided in determining the revenue that the company can make in the two scenarios. Similar to the concept of a controlled experiment in biology, in this research the variable “revenue” is controlled. Then, the costs of adopting the robot system and the benefits of saving money by avoiding the conventional method are compared. In other words, the costs here equal the money spent to operate the robot system, and the benefits equal the money saved by not using the conventional CWM installation method.

Table 1. Conventional and alternative scenarios defined for the comparison.

Category	Scenario 1	Scenario 2
Name	Hephaestus cable-driven robot	Conventional facade installation
Key beneficiary	Facade installation company (Focchi Group UK)	
Business model	Owning the robot	Paid based on working area, etc.
Primary location for calculation	United Kingdom	
Investment period	5 years (the assumed lifecycle of the robot according to the engineering partners in the project)	
Main equipment required	1 cable-driven robot	1 crane for positioning
Estimated average area per job	540 m^2 (L30 m × H18 m; 1.5 m × 3 m per panel)	

4.5. Gathering Data and Proposing Assumptions for Calculating the Costs of the Conventional and Alternative Scenarios

The data needed for the calculation in the cashflow analysis table are collected by various means such as market research, online meetings, calls, and emails with key stakeholders (e.g., the facade installation partner, the robot developing partner). Based on the data-gathering activities, the following information, which is crucial to the calculation, is demonstrated in Table 2.

Table 2. Data collected for the cashflow analysis of the two scenarios.

Category	Scenario 1	Scenario 2
Name	Hephaestus cable-driven robot	Conventional facade installation
Number of workers	• 3 workers for system setup and disassembly; 1 worker for robot operation	• 1 for crane operation; 5 for curtain wall module handling
Speed/performance	• ~15 min for one bracket installation • ~15 min for one CWM installation	• ~30 min/m^2
Total time needed per job	• 123 h in total: • 55 h setup • 60 h curtain wall installation • 8 h disassembly	• 270 h
Productivity weight coefficient	1	2.20
Jobs finished per year	14	6.36
Downtime per year (e.g., holidays, operational, extreme weather, etc.)	8 weeks	
Median wage of construction worker in the UK	15.47 € (14.05 GBP) per hour	
Annual wage increase	3% (commonly applied in the construction sector)	
Discount rate	0.1% (in the UK as of October 2020)	
Annual equipment maintenance costs	10%	

Note: In addition, detailed explanations of Table 2 are listed as follows.

1. The main financial beneficiary is a curtain wall installation company operating in the UK, because the main market of facade installation for the key beneficiary is in the UK.
2. For the simplification of calculation, the table uses the median hourly rate of construction workers to calculate all the inputs related to labor costs.
3. The estimated cost of the robot system includes manufacturing cost, logistics, administrative cost, and profit.
4. The robot system does not cause extra administrative costs, compared to the conventional method.
5. A one-month training cost of 12,000 € (3000 €/person) is added, to train four workers for operating the robot system during the downtime of the first year. During the training month, these workers' salary needs to be covered by the company as well (9900 €). After the training, one worker will become a highly-skilled operator, thus earning 30% more salary than the average worker.
6. The annual total saving outputs equal the annual saving inputs multiplied by a productivity weight coefficient of 2.2, which means that the alternative robot system is 2.2 times as productive as the conventional method. Therefore, the productivity weight coefficient needs to be considered in the conventional method to keep up with the productivity of the alternative robot system in order to achieve the same gross revenue for fair comparison.

7. Regarding the central cost for the company, this robot system does not require additional special managerial efforts, compared to the conventional scenario. Therefore, central costs are not calculated in both scenarios.

5. Results

Based on the proposed comparison scenario and collected data in the case study, the following results can be presented, including cashflow analysis, key financial indicators, sensitivity analysis, and recommendations. According to the comparison of the conventional method and cable-driven robot method for facade installation, the cashflow analysis table can be filled in detail with corresponding numbers, as below (see Figure 9).

Cashflow analysis to compare novel STCR solution and conventional method							
Key stakeholder/beneficiary	Curtain wall installing company						Operating region: UK
Cash outflows	Year 1	Year 2	Year 3	Year 4	Year 5	Total (€)	Explanation and remarks
Central - hardware costs						0.00	
Central - software costs						0.00	
Central - network costs						0.00	
Central - utility costs						0.00	
Central - operation						0.00	
Central - maintenance						0.00	
Central - other						0.00	
Per robot costs - hardware	600,000.00					600,000.00	
Per robot costs - software						0.00	
Per robot costs - network & utility	3,000.00	3,000.00	3,000.00	3,000.00	3,000.00	15,000.00	
Per robot costs - training	21,900.00					21,900.00	
Per robot costs - transport	5,000.00	5,000.00	5,000.00	5,000.00	5,000.00	25,000.00	
Per robot costs - installation	35,735.70	36,807.77	37,912.00	39,049.36	40,220.85	189,725.68	
Per robot costs - operation	16,893.24	17,400.04	17,922.04	18,459.70	19,013.49	89,688.51	
Per robot costs - disassembly	5,197.92	5,353.86	5,514.47	5,679.91	5,850.30	27,596.46	
Per robot - maintenance	60,000.00	60,000.00	60,000.00	60,000.00	60,000.00	300,000.00	
Per robot - other						0.00	
Total outflow	747,726.86	127,561.67	129,348.52	131,188.97	133,084.64	1,268,910.65	
Savings - equipment	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	250,000.00	
Savings - labor	159,390.50	164,172.22	169,097.39	174,170.31	179,395.42	846,225.83	
Savings - utility	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	5,000.00	
Savings - operational						0.00	
Savings - maintenance	5,000.00	5,000.00	5,000.00	5,000.00	5,000.00	25,000.00	
Savings - other						0.00	
Total savings	473,859.11	484,378.88	495,214.25	506,374.68	517,869.92	2,477,696.83	
Net annual cashflow	-273,867.75	356,817.22	365,865.73	375,185.70	384,785.28	1,208,786.18	
Net cumulative cashflow	-273,867.75	82,949.47	448,815.20	824,000.90	1,208,786.18	1,208,786.18	
Coefficient of productivity	2.20						
Annual wage increase	1.03						

Figure 9. Cashflow analysis of the proposed robot system based on the UK market.

5.1. Key Financial Indicators of the Hephaestus Cable Robot

As mentioned above, the key financial indicators relevant in this evaluation can be calculated based on the results of the cashflow analysis (Figure 9), including benefit–cost ratio (BCR), return on investment (ROI), payback period (PBP), initial investment value (IIV), and net present value (NPV) [4]. The key financial indicators are calculated based on the following equations:

$$\text{BCR} = (|\text{present value of benefits}|)/(|\text{present value of costs}|) \quad (1)$$

$$\text{ROI} = (\text{total cost savings} - \text{total outflows})/(|\text{total outflows}|) \quad (2)$$

$$\text{PBP} = \text{n} + (|\text{net accumulative cashflow of year n}|)/(\text{net annual cashflow of year n} + 1), \quad (3)$$
n represents the number of the final year with negative net accumulative cashflow.

$$\text{IIV} = (\text{initial hardware cost}) + (\text{initial deployment cost}) \quad (4)$$

$$\text{NPV} = (\text{net annual cashflow})/(1 + \text{cost of money})^{\text{Years in the future}} \quad (5)$$

As a result, the key financial indicators of the Hephaestus cable-driven robot for curtain wall installation are calculated, as below (see Table 3).

Table 3. Key financial indicators of the proposed robot system when operating in the UK.

Key Financial Indicator	Value
Benefit–Cost Ratio (BCR)	1.95
Return on Investment (ROI)	95.26%
Payback Period (PBP)	21.21 months
Initial Investment Value (IIV)	747,726.86 €
Net Present Value (NPV)	1,205,040.19 €

Note: The definitions of the key financial indicators are listed as follows:

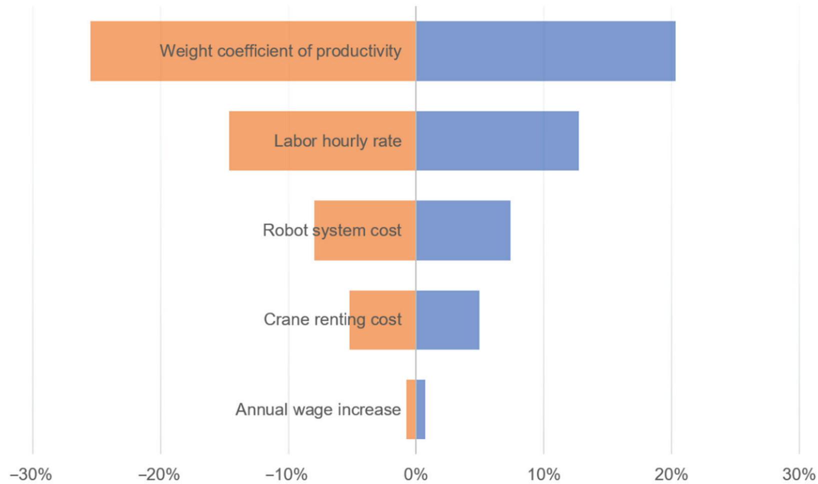
1. BCR indicates the overall relationship between the relative benefits and costs of a proposed project. In this case study, benefits refer to the money saved by not using the conventional facade installation method, and costs refer to the money spent to operate the robot system. If the value is larger than 1.0, the project is expected to deliver economic satisfaction to its investors.
2. ROI is a performance measure used to evaluate the efficiency of an investment.
3. PBP is the period of time required to recover the cost of an investment.
4. IIV is defined here as the amount of money needed for the total capital expenditures in the first year.
5. NPV is the current value of a future stream payments. Here it refers to the present value of the total net accumulative cash flow.

5.2. Sensitivity Analysis

Sensitivity analysis, also known as what-if analysis, is a financial tool which determines how target outputs are affected based on changes in input variables. This model is used to predict the result of a decision, given a certain set of variables. There are a wide range of uses of sensitivity analysis, which can be categorized into four main aspects: decision-making support, communication, increasing understanding of the system, and model development [24]. Based on this tool, the analyst will be able to understand which input variable is more consequential, and which one is less.

Therefore, a simple sensitivity analysis is conducted, regarding several major variables in the cashflow analysis. By adjusting each input variable 10% better and 10% worse, the total accumulative cashflow by the end of the five-year period will also change accordingly. Thus, the increase and decrease of total accumulative cashflow, compared to the original estimation, can be calculated. In this case, five main input variables, including annual wage increase, labor cost (hourly rate), robot system cost, crane renting cost, and productivity coefficient weight, are evaluated. The result is shown in Figure 10.

From the sensitivity analysis, it can be concluded that the outcome is most sensitive to the weight coefficient of productivity, followed by labor hourly rate, robot system cost, crane renting cost, and last, but not least, the annual wage increase. Other variables, such as utility cost and training cost, are not listed here due to their relative insignificance to the outcome of the analysis. The sensitivity analysis is especially important and insightful because many data acquired in this study are only rough estimations. It indicates that the most efficient way to improve profitability or benefits of the alternative system is to further improve the productivity and efficiency of the robot, although this objective might be difficult to achieve.



	Annual wage increase	Crane renting cost	Robot system cost	Labor hourly rate	Weight coefficient of productivity
Positive	1%	5%	7%	13%	20%
Negative	−1%	−5%	−8%	−15%	−26%

Figure 10. Sensitivity analysis of the CBA.

5.3. Recommendations

As mentioned in the beginning of this paper, the last part of CBA, usually, is to make a recommendation on whether the alternative option is worth considering. The results of key financial indicators indicate that the BCR is 1.95, which exceeds 1. Therefore, the investment of the Hephaestus cable-driven robot for CWM installation, based on the UK market, is projected to be economically acceptable and efficient. In particular, the investment of one Hephaestus cable-driven robot system could pay for itself in only 21.21 months when operated in the UK.

In accounting, the break-even point (BEP) refers to the point at which the total cost and total revenue are equal [25]. When adjusting the net cumulative cashflow to near zero in year 5, by adjusting the construction worker salary while keeping any other variables the same, it can be inferred that the investment of the Hephaestus cable-driven robot system will be worthwhile, in theory, if the local hourly wage for workers is higher than approximately 3.45 €/h. In other words, the proposed robot system for curtain wall installation task will be financially competitive in countries or regions where the median salary for a construction worker is above 3.45 €/h as of 2020, which is the BEP.

Furthermore, Table 4 demonstrates whether the Hephaestus cable-driven robot system is competitive in the G20 countries/regions (different currencies are converted to euros based on the exchange rates on 13 October 2020, according to Google). In this research, if the local median wage of construction workers is more than double the BEP, the investment will be defined as highly competitive; if the local median wage of construction workers is more than the BEP but less than double the BEP, it will be defined as competitive; otherwise, it will be considered as uncompetitive. Therefore, the table shows that the proposed system would currently be highly competitive, compared to the conventional method in most developed countries in the world, and it would be relatively competitive in many emerging economies as well, with a few exceptions such as Argentina, Brazil, China (mainland), India, Mexico, Russia, South Africa, and Turkey (according to www.salaryexpert.com as of October, 2020). However, as the economy continues to expand in these emerging markets and their average income of workers increases, it is predictable that the proposed system will become competitive in these countries as well in the near future.

Table 4. Median hourly rate of construction workers in G20 countries/regions, and indications on whether the robot is competitive in the respective country.

G20 Country or Region	Median Hourly Rate (in €)	Recommendation
Argentina	2.19 (198.68 ARS)	Uncompetitive
Australia	18.23 (29.93 AUD)	Highly competitive
Brazil	3.18 (21.07 BRL)	Uncompetitive
Canada	14.93 (23.23 CAD)	Highly competitive
China (mainland)	3.41 (27.25 CNY)	Uncompetitive
China (Hong Kong)	13.01 (118.60 HKD)	Highly competitive
France	14.15	Highly competitive
Germany	17.18	Highly competitive
India	1.15 (99.17 INR)	Uncompetitive
Indonesia	3.59 (62053.86 IDR)	Competitive
Italy	13.08	Highly competitive
Japan	14.66 (1826.55 JPY)	Highly competitive
Mexico	2.41 (60.66 MXN)	Uncompetitive
Russia	2.11 (192.16 RUB)	Uncompetitive
Saudi Arabia	8.69 (38.24 SAR)	Highly competitive
South Africa	3.12 (60.99 ZAR)	Uncompetitive
South Korea	10.18 (13,790.48 KRW)	Highly competitive
Turkey	2.51 (23,41 TRY)	Uncompetitive
United Kingdom	15.47 (14.05 GBP)	Highly competitive
United States	17.28 (20.29 USD)	Highly competitive

The results are important indicators for companies and policy makers in different countries and regions to decide whether the investment of the Hephaestus cable-driven robot is worth considering. Furthermore, as the manufacturing costs of the robot system drop and the global labor costs increase over time, it is foreseeable that the robot system will be competitive in even more countries worldwide.

6. Discussion

This research introduces a simple framework for economically evaluating single-task construction robots, based on a case study of a cable-driven curtain wall installation robot. The results indicate that the CDPR system in the case study is financially competitive in the UK, as well as in most developed countries or regions. The advantages and future validation of the methods, as well as the additional socioenvironmental implications, limitations, adaptability, and reproducibility, are further discussed in the sections below.

6.1. Advantages and Future Validation of the Methods

This paper mainly discusses the direct economic implications of STCR, using the proposed cable-driven robot for curtain wall installation as a case study. It will be one of the first CBA research instances focusing on STCRs, setting a valuable precedent for the field of construction robots.

The methodology is practical and helpful for the key beneficiary (e.g., the construction company) to make decisions about whether to invest in construction robots without acquiring large amounts of data. The calculation method is specifically designed to estimate the costs and benefits of an advanced solution for a specific task in a short amount of time.

Therefore, it does not require a large amount of time and effort of the key beneficiary, such as historical data collection and opinion survey.

Further, the proposed framework, as well as the results, can be further validated by the key beneficiary through a real-world pilot project in which the key performance indicators (KPIs) of the conventional and alternative scenarios (e.g., speed, performance, cost, etc.) can be more accurately measured.

6.2. Further Socioenvironmental Implications

The proposed methods mainly address the direct microeconomic evaluation of an STCR, compared to the traditional technique, through a simplified analyzing framework. However, more indirect socioenvironmental implications, other than productivity increase, are also worth noting. For instance, the STCR approach enhances labor safety. According to Eurostat, there were 3552 fatal accidents at work in EU-28 states during 2017, of which one fifth happened in the construction sector [26]. In other words, more than 700 accidental deaths took place within the construction industry in EU countries just in 2017. The reduction in the number of onsite construction workers at height, through applying construction robots, can substantially reduce the chance of fatal accidents and other injuries on the construction sites. Furthermore, the application of STCRs has a positive impact on construction quality through precise control and real-time monitoring, which potentially benefits the reputation and profitability of the relevant construction companies. Meanwhile, it also has a positive impact on resource consumption due to the precise automatic control system [2]. Moreover, the vacancy rate in the construction sector (excluding the real estate subsector) in the EU28 increased by 1.7% from 2010 to 2018, indicating growing labor shortages in the business. In particular, Germany observed 121,736 unfilled positions in the construction sector in 2018, compared to only 51,892 in 2010 [27]. The implementation of robots can help alleviate the growing labor shortages in the construction business. These aspects obviously make an even stronger case in favor of construction robots, although these additional socioenvironmental benefits are more difficult to monetize.

6.3. Limitations

Just like any other economic models, this initial CBA is by no means an impeccable process. The results reported in this section have certain limitations, summarized as follows.

1. The usability of the alternative scenario, currently based on a prototype, needs to be further tested and validated in real-world practice.
2. Many data for calculation are only rough estimations, and more accurate data might be possible in the future.
3. The manufacturing cost of the robot is only calculated based on prototyping cost in the EU market, thus cheaper alternatives, such as outsourcing, are not considered, and future mass production might be substantially lower.
4. Many long-term indirect socioenvironmental benefits are difficult to quantify and monetize. Also, the primary beneficiary in the case study is defined as the facade installation company. Therefore, the indirect socioenvironmental benefits are not included directly in the case study.

6.4. Adaptability and Reproducibility

As shown in previous sections, the case study provides a simple, but useful, tool to assess the benefit and cost of any given STCR system, which fills the gap in the economic evaluation of construction robots. The demonstrated process of CBA for STCR is highly adaptable and reproducible. Therefore, researchers, engineers, investors, and policy makers can easily follow and customize this method to assess the economic advantages of any STCR system, compared to traditional construction techniques and methods.

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Digital Simulation for Buildings' Outdoor Thermal Comfort in Urban Neighborhoods

Yingyi Zhang [1,*] and Chang Liu [2]

1 School of Architecture and Urban Planning, Beijing University of Civil Engineering and Architecture, Beijing 100044, China
2 Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China; liuchang9098@gmail.com
* Correspondence: zhangyingyi@bucea.edu.cn

Abstract: Buildings' outdoor thermal comfort influences environment quality and human behavior in urban neighborhoods. The Universal Thermal Climate Index (UTCI) has been broadly applied to the study of buildings' outdoor thermal comfort in urban areas. However, complex environmental conditions in climate-sensitive urban areas can make UTCI assessment complicated and ineffective. This paper introduces digital techniques into buildings' outdoor thermal comfort analysis for the improvement of the urban habitant environment. A digital simulation system is generated to facilitate the analysis procedure for buildings' outdoor thermal comfort assessment in urban neighborhoods. The analysis addresses the research question: "Can digital simulation techniques provide a modeling system to assess buildings' outdoor thermal comfort continuously and effectively?" Methods include a case study of neighborhoods in Beijing, qualitative and quantitative analysis based on digital processes, and parametric modeling. The results indicate that digital simulation techniques and tools have the capability to support the analysis of buildings' outdoor thermal comfort by providing three-dimensional models, algorithm-based analysis, and visual simulation. The findings include a critique of digital simulation as applied to architecture study and insights on potentially improving buildings' outdoor thermal comfort through human–computer interactions.

Keywords: digital simulation; buildings' outdoor thermal comfort; urban neighborhoods; UTCI

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1. Introduction

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment [1]. In urban areas, people can experience outdoor thermal sensation in outdoor areas of buildings, such as public gardens, streets, and markets. Buildings' outdoor thermal comfort analysis in urban space contributes significantly to human health [2]. The thermal complex is relevant to human health because of a close relationship between the thermoregulatory mechanisms and the circulatory system [3]. The assessment of outdoor thermal comfort has played an active role in promoting buildings' outdoor environments and public life, especially in intensive urban neighborhoods. Digital simulation has proved its efficiency in architecture and civil engineering industries [4]. Hence, this paper scopes the possibility of improving the approach of buildings' outdoor thermal comfort assessment by digital simulation techniques.

Early study on outdoor thermal comfort began with the analysis of British mines in the 20th century, and approaches have since developed over the decades. Developments in physics have resulted in a variety of approaches to the assessment of buildings' outdoor thermal comfort. A widespread consensus holds that direct sun falling on a person can substantially affect buildings' outdoor thermal comfort [5–8]. Nowadays, the differing models of outdoor thermal comfort assessment can be broadly delineated by two categories: thermal safety and thermal balance. Thermal safety models evaluate the safety of work environments. Variables include the physical index, air quality and subjective experiences.

The application of the thermal safety model began with endeavors to understand the indoor and outdoor thermal environments of office buildings—particularly those in tropical and subtropical zones. In 1919, the American Society of Heating and Ventilation Engineers first analyzed the influence of thermal comfort on human sensation and health. After that, Corrected Effective Temperature (CET) was created in 1930s to assess thermal safety using globe thermometer temperature instead of dry bulb temperature in those cases where the reading of the globe thermometer was higher than the dry bulb temperature [9]. With increasing demand for outdoor thermal comfort analysis, the use of Web Bulb Globe Temperature (WBGT) began in order to prevent thermal injury accidents in military training. In 1984, Steadman indicated that the equivalent Apparent Temperature (AT) could measure a building's outdoor temperature as perceived by humans by considering temperature, relative humidity, and wind speed [10]. The US National Weather Service simplified and converted AT into a multivariate statistical regression model and renamed it Heat Index (HI). HI indicates that a sustained wet bulb temperature of about 35 °C can be fatal to healthy people; at this temperature, our bodies switch from shedding heat to the environment to gaining heat from it [11]. WBGT, AT, and HI have been used evaluate human safety in harsh environments.

In contrast to the thermal safety model, the thermal balance model believes that physical human comfort is based on biological heat exchange mechanisms. Although sunlight has a greater impact than either wind or humidity on thermal comfort [12–14], thermal comfort also encompasses buildings' external environmental situation, breathing heat dissipation, and the thermal resistance of clothing. In 1970, Predicted Mean Vote (PMV) was developed by Fanger as an empirical measure of the human sensation of thermal comfort [15]. PMV uses a thermal sensation score to describe the vote of multiple participants. However, buildings' outdoor thermal environment is far more complex than an indoor one. The diversity of activities and increased metabolic levels complicate the measurement of outdoor thermal comfort. Physiological Equivalent Temperature (PET) was generated to specifically analyze outdoor thermal comfort. PET reflects a situation in which human skin and internal body temperatures are balanced with air temperature within a specific environment. As Matzarakis and Amelung stated, PET could measure how changes in the thermal environment can affect human well-being [3]. These well-documented thermal indices have varying foci but are essentially different combinations of the same set of important meteorological and thermophysiological parameters [16]. The International Society of Biometeorology recently proposed the Universal Thermal Climate Index (UTCI) meets the requirements for analyzing human biometeorology, individual characteristics, and valid evaluation procedures in all climates, seasons, and scales [17]. The UTCI is primarily concerned with balancing the temperature of human bodies [18,19] and generates objective thermal models which are applicable to architecture and urban design [20–22].

The urban neighborhood environment is currently more climate-sensitive than ever before. The assessment of the thermal environment is one of the main issues in climatic research, and more than 100 simple climatic indices have been developed to facilitate it thus far [17]. Increasing population, building density, and automobiles have created sensitive and fragile living habitats for humans. Inhabitants of urban areas witness air pollution, global warming, and flood disasters. The UTCI processes become complicated in the face of increasingly complex climate situations and sensitive living environments. Multiple factors, including air temperature, water vapor pressure, humidity, and wind speed, work together to calculate the UTCI value of a specified area. The resulting value represents a fixed instant that fails to represent the thermal situation over a continuous period of time. Moreover, current UTCI calculation results are presented as two-dimensional data. They do not intuitively indicate the outcome of multiple calculations.

This paper introduces the use of digital simulation technology to support buildings' outdoor thermal comfort analysis. Digital simulation utilizes computer-aided tools to redefine the relationship between building geometries and outdoor environments by considering variables as dynamic and mutable elements. Data calculations of UTCI are extended and presented as a year-round outdoor thermal comfort simulation with three-dimensional models. Parametric manners help to effectively evaluate buildings' outdoor thermal comfort with UTCI processes. The research question can be described as: Can digital simulation techniques provide a modeling system to assess buildings' outdoor thermal comfort continuously and effectively?

2. Methods

In order to address the research question, two urban neighborhoods of Beijing, China were selected as study samples. A method framework was built. It consisted of two parts. Firstly, data collection and UTCI calculation approach worked to understand the outdoor thermal comfort condition of the nominated neighborhoods. Methods included field study as well as qualitative and quantitative analysis. It tended to calculate buildings' outdoor thermal comfort stress as the standard that the UTCI indicates. Secondly, digital simulation worked to analyze and assess buildings' outdoor thermal comfort by providing three-dimensional models, algorithm-based analysis, and visual simulation. Rhinoceros 3D and Grasshopper 3D software (with plug-in Ladybug) were employed as digital simulation tools. Figure 1 presents the methodology framework.

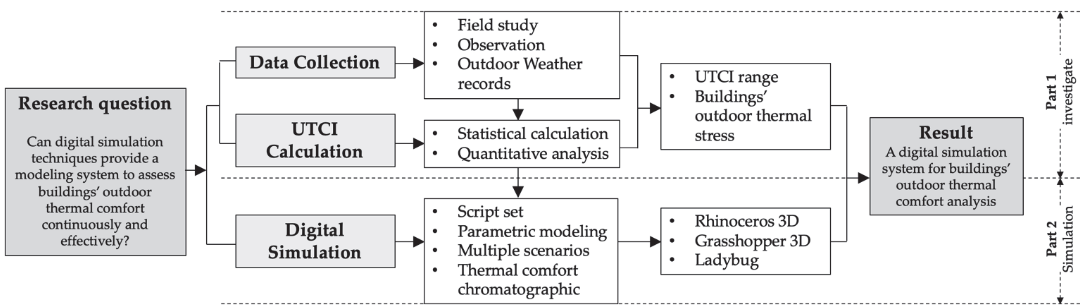

Figure 1. Research methodology framework.

The assumptions were that (1) UTCI calculation can work to analyze buildings' outdoor thermal comfort in the nominated neighborhoods in Beijing; (2) digital manners can provide a continuous and effective approach to analyze buildings' outdoor thermal comfort by embedding UTCI calculation into digital modeling platform. Part 1 of the methodology framework (Figure 1) targeted a response to the first assumption. Part 2 targeted a response to the second assumption.

2.1. Data Collection and UTCI Calculation

Two typical neighborhoods in Beijing were nominated for use as experimental cases. Beijing, the capital of China, has developed quickly in the last few decades. The increasing density of population and buildings make the city one of the greatest metropolises of the world. The nominated neighborhoods are located at Sanlihe East Road and Nanshagou Road, Haidian District. Both contain dense residential buildings and variously scaled street stores. The choice of these neighborhoods was two-fold: They are similar in location, building density and climate sensitivity. The two nominated neighborhoods were close to each other in location. The Sanlile neighborhood is located at 39.9065° N, 116.3305° E. The Nanshagou neighborhood is located at 39.9169° N, 116.3265° E. The similarity of the geographical location means they have similar humidity, climate situation, and wind condition in the semi-humid and semi-arid monsoon zone. Building functions, materials, and the age of the nominated neighborhoods are also similar. Most buildings in the Sanlihe and Nanshagou neighborhoods are both intended for residences, with brick–concrete building structures. The two neighborhoods were both constructed in the 1980s–1990s. The difference between them is the layout of building clusters. In the Sanlihe neighborhood, building cluster is presented as a mix of enclosure-type and line-type. In the Nanshagou neighborhood, building cluster is presented as a line-type. It is of benefit to control variables when assessing buildings' outdoor thermal comfort between different building cluster forms. Additionally, the chosen neighborhoods share spatial characteristics of residential areas in old city of Beijing. Experimental results can provide references for community and neighborhood renewal in similar areas.

In order to understand buildings' outdoor thermal comfort condition, data collection in the neighborhoods encompassed three types: average temperature, humidity, and wind speed. A thermohygrometer (type: ADT7461ARMZ-R7) worked to collect the temperatures and humidity data multiple times, then achieved average values. An anemograph (type: TSI9535) worked to measure wind speeds.

UTCI calculation was the foundational method used. Standard UTCI analyzed the sensible temperature of a human body with ideal conditions—where the wind speed was 0.5 m/s, the mean radiation temperature was equivalent to the air temperature, and the relative humidity was 50.0%. The experimental participant had specific physical features: they weighed 73.5 kg and had a body fat content of 14.0%. The conceptual equation of UTCI was presented as Formula (1). Basing on the Commission for Thermal Physiology of the International Union of Physiological Sciences, UTCI assessment has multiple categories ranging from extreme heat stress to extreme cold stress [23].

$$\mathrm{UTCI} = \mathrm{T_a} + \mathrm{offset}\ (\mathrm{T_a};\ \mathrm{T_{mrt}};\ \mathrm{V_a};\ \mathrm{RH}) \tag{1}$$

where T_a = average temperature (°C), T_{mrt} = mean radiant temperature (Kelvin), V_a = average wind speed (m/s), RH = relative humidity (%). V_a value is limited between 0.5 and 17 m/s.

According to the UTCI assessment scale and the collected data, the conditions of buildings' outdoor thermal comfort of the neighborhoods could be calculated.

2.2. Digital Simulation

Digital simulation was used as a novel method for the facilitation of buildings' outdoor thermal comfort analysis. It is rooted in digital animation techniques, and the latest refinements are based on advanced parametric design systems and scripting methods [24]. This paper used Rhinoceros 3D and Grasshopper 3D software (Robert McNeel and Associates. Seattle, WA, USA) to edit scripts and geometry constraints and to build digital models. Rhinoceros 3D and Grasshopper 3D rely on algorithm logic to create geometry with a visual programming language interface [25]. An algorithm is expressed within a finite amount of space and time and in well-defined formal language to calculate a function in mathematics and computer science [26]. It starts with an initial state and input then describes a computation that, when executed, proceeds through a finite number of well-defined successive states, eventually producing the output, then terminating [27].

The digital simulation procedure contained two aspects: input parameters and output models with quantified outdoor thermal comfort measurements. The input parameters included location, dry bulb temperature, relative humidity, direct normal radiation, diffuse horizontal radiation, horizontal infrared radiation, season, and solar-adjusted mean radiation temperature. These variables were embedded into the constraint script of Grasshopper 3D. The script contained three sections. The first step was to input parameters of physical built environment, such as neighborhoods' coordinates and building locations. The second step contained the input of thermal-related parameters, such as dry bulb temperatures, relative humidity and direct normal radiation. The third step was to input season parameters, such as a typical summer week. A typical summer week means the week containing the day of the summer solstice. Through automatic calculation with the parametric software, three-dimensional models of outdoor thermal comfort performance could be directly presented in Rhinoceros 3D. Ladybug, a plug-in of Grasshopper 3D, inputs climate data into the digital simulation system. The required input climate data, such as historic average temperature and mean radiant temperature, could be captured with open access of the

China Standard Weather Database. This procedure enables an outdoor thermal comfort analysis over a continuous one-year period. The scope of the digital simulation system includes a rational insight into how people of a building cluster can access and use outdoor space comfortably. It helps urban planners, architects, and civil engineering analysts to quantify thermal measurement and improve the planning and design process with due consideration to sustainability.

Digital tools helped to provide simulation results of buildings' outdoor thermal comfort of the nominated neighborhoods. Figure 2 presents the foundational climate situation over a one-year period (8760 h) in Beijing, as generated in Grasshopper 3D and its plug-in, Ladybug. Briefly, the simulation indicated that warmer months are between June to August and cold months fall between December and February in Beijing. Summer and winter are relatively longer than spring and autumn; sunlight and wind affect the sensible temperature. Different sunlight and wind climates create a curve fluctuation, and sunny days without wind result in a relatively comfortable outdoor thermal situation in spring and autumn.

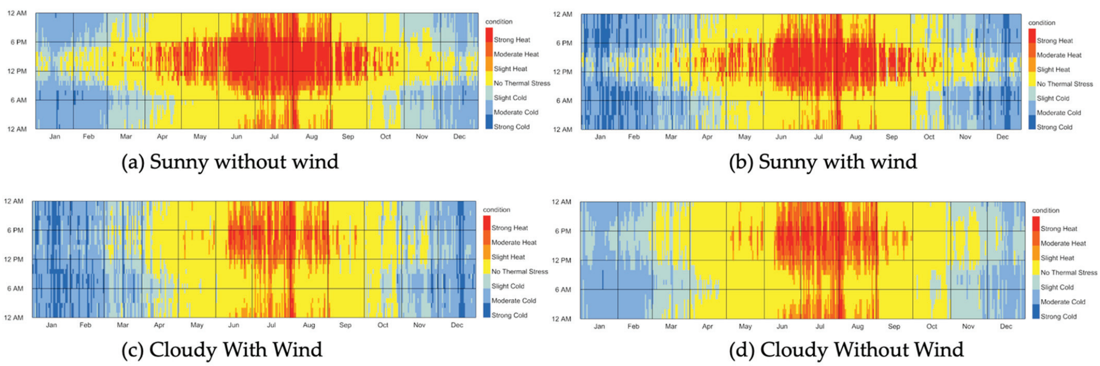

Figure 2. Examples of outdoor thermal comfort situations across one year in Beijing.

3. Results and Discussion

3.1. Buildings' Outdoor Thermal Comfort Simulation Results

In the nominated neighborhoods, building heights are multiple. In the Sanlihe neighborhood, the tall buildings have 12 floors with an approximate height of 36 m. They are located in the northern, middle, and eastern areas of this neighborhood. Medium tall buildings have six floors, with an approximate height of 18 m. They are located in eastern and western areas. Low buildings have two to three floors with approximate heights of 6 to 9 m. They are located in the southern area. In the Nanshagou neighborhood, buildings have four to seven levels, with heights of 12 to 21 m, approximately. The distance between buildings is not a necessary parameter in Rhinoceros 3D and Grasshopper 3D. As coordinates of the neighborhoods are provided, the software can automatically calculate the coordinates of each building. Grasshopper 3D uses the geographic coordinates to directly analyze the solar radiation situation rather than the distances. Typical days of each season represent the outdoor thermal comfort situation. A typical spring means the day of the spring equinox. A typical summer means the day of the summer solstice. A typical autumn is the day of the autumnal equinox. A typical winter is the day of the winter solstice. The Sanlihe neighborhood (39.9065° N, 116.3305° E) is a relatively complex residential area with multi-height buildings. Building layouts can significantly impact outdoor thermal comfort in terms of access to sunlight and experiences of wind speed. In this case, the tall buildings cluster in the middle, eastern and northern areas. The simulation result of the Sanlihe neighborhoods is shown in Figure 3. Presented in Rhinoceros 3D, the simulation indicates that outdoor thermal comfort varies across a one-year period. In spring, the perceived outdoor temperature ranges between 2 °C and 7 °C. Most open spaces are at relatively comfortable temperatures, excluding those areas shadowed by tall buildings. People can do outdoor activities such as strolling between buildings of western and southern areas as well as in courtyards. In summer, the perceived outdoor temperature is between 23 °C and 27 °C. Shadow areas are larger than in spring. People tend to use the shadows, especially in southern areas, for outdoor activities to avoid direct sunlight. In autumn, the perceived outdoor temperature is between 9 °C and 14 °C and the temperature of outdoor spaces is relatively balanced. Outdoor thermal comfort displays a mild feature with a mean temperature of 11 °C. In winter, the shadow areas become much larger. The perceived outdoor temperature falls to −5 °C to −10 °C. Outdoor activities and movement become uncomfortable. Only the southern and western parts of the neighborhood enjoy a relatively warm atmosphere.

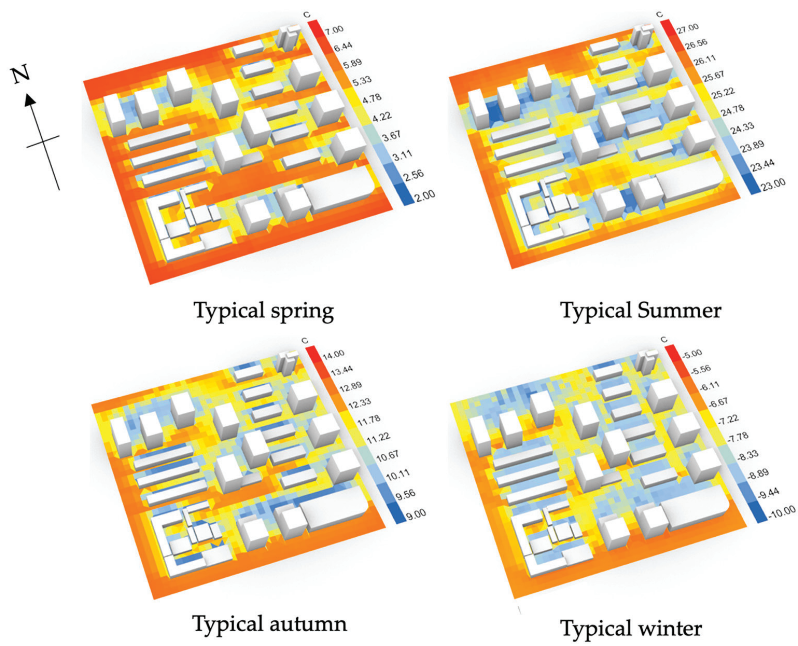

Figure 3. Digital simulation results of Sanlihe neighborhood.

Digital simulation also represents buildings' outdoor thermal comfort conditions of the Nanshagou neighborhood (39.9169° N, 116.3265° E). Building arrangement forms a regular matrix. Figure 4 presents the simulation results. In spring, the perceived outdoor temperature is between 2 °C and 7 °C. Open space areas in the southern and northern parts of the neighborhood are of relatively comfortable temperatures. Shadows occur in the northern parts of buildings, creating relatively cool sensations. In summer, the perceived outdoor temperature ranges between 23 °C and 27 °C. Outdoor thermal environments become warmer. Most areas are too warm for long periods of outdoor activity. People tend to stay in the shadows around buildings. In autumn, the perceived outdoor temperature is between 9 °C and 14 °C. The floor areas of warm and cold spaces are on a similar scale, with the southern region being relatively warmer than other zones. In winter, the perceived outdoor temperature falls to −5 °C to −10 °C, so the cold area grows. Solar radiation is an important factor affecting outdoor thermal comfort. Direct sunlight provides the southern area with a relatively warm atmosphere.

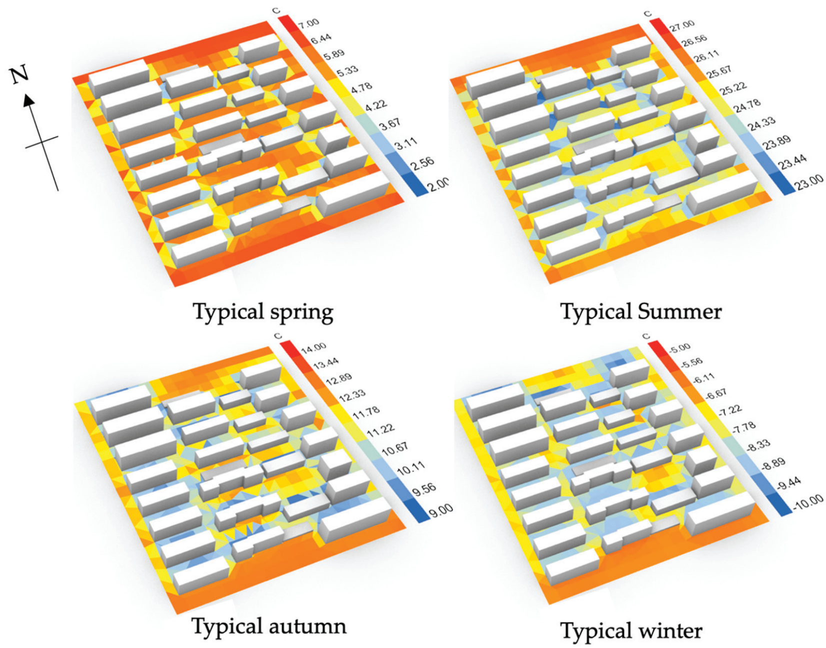

Figure 4. Digital simulation results of Nanshagou neighborhood.

The nominated neighborhoods of Beijing provide two types of residential layout for testing the digital simulation system. Digital simulation results in Figures 3 and 4 can reflect different building cluster types that affect buildings' outdoor thermal comfort. For example, it would be warmer both around the outside and inside (south-west area) of the Sanlihe neighborhood in spring. However, it would be warmer between buildings and outside (north and south area) of the Nanshagou neighborhood in the same season. The results demonstrate that UTCI calculation can work to analyze buildings' outdoor thermal comfort in the nominated neighborhoods in Beijing. Additionally, building geometries, locations, and cluster types can affect outdoor thermal comfort. Tall buildings lead to low perceived outdoor temperatures, considering the factors of solar radiation, wind speed and relative humidity. Areas outside the building clusters present warmer temperatures than areas between buildings. Enclosed building layouts form inner yards. Inner yards may create a cool atmosphere on summer days with favorable thermal conditions. The higher the distance between buildings, the warmer the emerging nodes. Residents desire intense sunlight and high temperatures in winter, but shadows and lower temperatures in summer.

3.2. A Digital Simulation System for Analyzing Building's Outdoor Thermal Comfort

Conventional approaches of analyzing buildings' outdoor thermal comfort rely on two-dimensional data calculations. It reflects outdoor thermal comfort conditions at specific points in time with temperature values. The present in situ results of buildings' outdoor thermal comfort analysis can be presented as numbers and brief text-based descriptions. No direct three-dimensional simulation or visual performance is presented. That makes the analysis results too abstract to guide real building projects. For architects and civil engineering researchers to appreciate thermal comfort over a continuous time period, a volume of climate data must be collected and calculated multiple times. The process requires a significant investment of time and human resources. Table 1 shows examples of thermal comfort condition descriptions.

Table 1. Outdoor thermal comfort description of the neighborhoods (April 2021, Beijng).

Neighborhood Name	Data Record No.	Average Temperature (°C)	T_{mrt}	Relative Humidity (%)	Average Wind Speed (m/s)	UTCI	Stress Category
Sanlihe neighborhood (39.9065° N, 116.3305° E)	1	23	0	38	15	8.7	Slight cold stress
	2	18	0	24	19	−6.3	Moderate cold stress
	3	14	0	20	24	7.2	Slight cold stress
Nanshagou neighborhood (39.9169° N, 116.3265° E)	1	24	0	39	16	9.7	No thermal stress
	2	15	0	25	20	−12.7	Moderate cold stress
	3	18	0	21	24	2.5	Slight cold stress

Based on data collection and UTCI stress category, the nominated neighborhoods have outdoor thermal comfort conditions of moderate cold stress, slight cold stress, and no thermal tress. General outdoor activities would be suitable in most public spaces outside buildings. Data were collected manually the Sanlihe and Nanshagou neighborhoods. Temperature, relative humidity, and wind speed were measured using a thermohygrometer (type: ADT7461ARMZ-R7) and anemograph (type: TSI9535) in the morning (8:00 a.m.), evening (6:00 p.m.), and at noon time (12:00 p.m.) the spring season (10 April 2021). The measurement is instantaneous by manual instruments. The height of temperature records is approximately 1.7 m. Average temperature, relative humidity, and average wind speed come from the mean value of the three records from morning to evening. Putting data into Equation (1), calculation results show in column UTCI of Table 1. They are examples of traditional UTCI manners that analyze buildings' outdoor thermal comfort. The more accurate the UTCI calculation result is, the more data should be collected. According to the Commission for Thermal Physiology of the International Union of Physiological Sciences, the thermal comfort situation is described briefly, such as slight cold stress or moderate cold stress. UTCI calculation can only reflect the thermal characteristics but no corresponding physical edge.

However, digital simulation results are more dynamic and accurate than traditional ones. As Figures 3 and 4 indicate, three-dimensional models contain more information regarding building environment, accurate construction edges, and thermal comfort rates of each coordinate point. For example, in the typical spring simulation of Figure 3, the UTCI calculation results by Grasshopper 3D range from 2.00 to 7.00. It means the buildings' outdoor thermal comfort has the characteristic of slight cold stress. The data come from a year-round database of the China Standard Weather Database. Digital tools operate big data instead of manual work. Digital simulation methods are used to improve the calculation approach by generating three-dimensional models. These models can reflect exact physical edges that show where thermal comfort zones are and where not. Model-based results have the capability to guide real-life construction practice in architecture and civil engineering.

This paper introduces digital manners to thermal comfort calculation and generates a digital simulation system to improve methods of buildings' outdoor thermal comfort analysis. Human–computer interaction tools provide a process for combining algorithms with UTCI analysis. Grasshopper 3D and Rhinoceros 3D work as digital tools for translating a variety of parameters, such as wind speed and relative humidity, into visibly demonstrable command components. Digital techniques simulate buildings' outdoor thermal comfort. The simulation presents algorithm-based three-dimensional models. Thermal comfort is shown as chromatography based on the three-dimensional models. Clear building clusters and outdoor thermal comfort edges are shown in direct visualized models. The results indicate that digital manners can provide a continuous and effective approach to analyze buildings' outdoor thermal comfort through embedding UTCI calculation into the digital modeling platform of Rhinoceros 3D and Grasshopper 3D. Additionally, urban alternatives may be simultaneously generated at a low computational cost and may be easily formulated within existing building and zoning boundaries [28].

Although parametric techniques can support procedures of buildings' outdoor thermal comfort analysis, they are not a panacea resolving all issues pertaining to evaluating bodily sensations of temperature. This paper uses digital operations to chromatographically depict thermal comfort conditions. All results are based on limited parameters related to physical sensations of temperature. However, many more factors may impact buildings' outdoor thermal comfort and human sensations of temperature. These may include the geographic situation, the landscape, and individual differences between human beings. Additionally, subjective sensations have not been factored into the digital simulation system. Overemphasizing digital techniques in physical environments may limit the success of addressing urban challenges. The digital simulation proposed in this paper can thus provide references for buildings' outdoor thermal comfort evaluation, rather than a complete picture.

4. Conclusions

This paper experimentally generates a digital simulation system for analyzing and improving buildings' outdoor thermal comfort in urban neighborhoods. Two neighborhoods of Beijing were nominated as research areas. Conventional UTCI measurements can reflect buildings' outdoor thermal comfort situations by manual calculations and text-based descriptions. It calculates outdoor thermal comfort at a specific time point. Digital simulation uses more parameters to compute a volume of data (for example, climate records of one year-round period) to reflect a more accurate thermal comfort analysis. In this paper, conventional UTCI measurements and digital simulation both work on the nominated neighborhoods. The UTCI calculation results of the two approaches tend to be in accordance, while digital simulation provides a more visualized, effective, and continuous manner. Simulation experiments demonstrate the feasible application of that technology to support buildings' outdoor thermal comfort calculation for achieving sustainable climate-sensitive territories. It proves simulation techniques that can provide a modeling system to assess buildings' outdoor thermal comfort continuously and effectively. Conventional thermal comfort analysis procedures largely rely on a plethora of climate information and complex calculation with two-dimensional data. Digital techniques have the capability to present quantified thermal comfort operation results over a 12-month period. They also provide an alternative method that simulates buildings' outdoor thermal comfort in an automatic and effective manner. Digital tools, Grasshopper 3D and Rhinoceros 3D, are used to create scripts and three-dimensional models. The results indicate that digital techniques can provide a three-dimensional modeling system to analyze buildings' outdoor thermal comfort continuously and effectively. They do not necessarily result in a complete analysis of outdoor thermal comfort; however, the results work well as a reference for the study of outdoor thermal comfort. Longer-term, digital techniques have the potential to support architectural analysis and civil engineering study. They are convenient and effective methods for supporting the study of climate-sensitive communities and neighborhoods. Further research on digital simulation facilitating buildings' outdoor thermal comfort analysis is indicated.

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buildings

Article

Design of Islamic Parametric Elevation for Interior, Enclosed Corridors to Optimize Daylighting and Solar Radiation Exposure in a Desert Climate: A Case Study of the University of Sharjah, UAE

Aref Maksoud [1,*], Emad Mushtaha [1], Zaid Al-Sadoon [2], Hala Sahall [1] and Ahmed Toutou [3]

1 Department of Architectural Engineering, College of Engineering, University of Sharjah, Sharjah 27272, United Arab Emirates; emushtaha@sharjah.ac.ae (E.M.); U15100490@sharjah.ac.ae (H.S.)
2 Civil and Environmental Engineering Department, College of Engineering, University of Sharjah, Sharjah 27272, United Arab Emirates; zalsadoon@sharjah.ac.ae
3 Department of Architectural Engineering, College of Engineering, Alexandria University, Alexandria 21544, Egypt; eng-ahmed.toutou1318@alexu.edu.eg
* Correspondence: amaksoud@sharjah.ac.ae

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Abstract: This study used innovative computational design tools to improve a corridor's visual and environmental conditions, such as solar radiation exposure and optimal daylighting, at the University of Sharjah's (UoS) campus in the United Arab Emirates. The research methodology used computational design software to develop two sets of codes. The first set was dedicated to conducting environmental study simulations that assessed the corridor's performance and classified site-dependent parameters such as sun path analysis and wind rose diagrams, and pattern-dependent parameters such as solar radiation analysis and shadow study diagrams. The second code set generated Islamic geometric patterns, following the design scheme of the University. Varying typologies were produced using the two parameters to change the pattern's porous size, shape, and gradient.

Keywords: computational design; corridors; energy performance; environmental behavior; grasshopper; Islamic pattern; parametric design; University of Sharjah; visual comfort

1. Introduction

Over the years, designers have had different opinions on corridors and their importance in a building regarding their functionality and aesthetics. Historically, when corridors were not yet typical features in architectural designs, people moved from one room by crossing through adjoining rooms, which could be disruptive and intrusive.

When corridors were introduced towards the end of the 17th century, their use was heavily influenced by socioeconomic factors, and they were often used to ensure that people from different socioeconomic classes did not have to cross paths. However, modern corridors are considered a key feature in building design, both for their function and aesthetic contribution [1]. Although corridors serve similar purposes, they should be tailored to fit specific standards based on a building's size and function.

Two main features define the function and design of a corridor. The first feature concerns the entrance or the opening, which has different types including: (1) unshaded, open exterior corridors; (2) shaded, semi-open exterior corridors, and (3) closed interior corridors.

The second category concerns access points and their distribution in a corridor, such as: (1) a connector corridor with no access points; (2) a single-loaded corridor with access points along one side, and (3) a double-loaded corridor with access points along both sides [2]).

Energy performance, solar radiation, and daylight are crucial environmental factors in a desert climate, and they present design challenges in terms of environmental comfort and air flow when including open and semi-open corridors. Much of the United Arab Emirates is characterized by a hot and humid climate, so architectural design that provides both aesthetic appeal as well as adaptable thermal control and environmental comfort has been a significant challenge [3].

In educational facilities, especially at universities, corridors influence the productivity and behavior of students, educators and staff. At institutions of higher education, corridors are typically one the most active spaces at different times of day, as they connect multiple rooms or buildings; therefore, an efficient, practical layout for aesthetic and thermal comfort is essential [4].

At the University of Sharjah, the semi-open corridors require climate-responsive screens that can take advantage of available natural light throughout the day while maintaining energy efficiency and thermal comfort according to programmed parameters. This study employed parametric modeling to investigate these goals and ensure that the university's corridors are comfortable and can attract more foot-traffic than alternative routes between buildings and rooms. Improvements in the energy performance were verified by the Estidama Pearl Building Rating System.

2. Research Background

Given the University of Sharjah's location and challenges due to harsh climate conditions, achieving optimum energy performance is crucial. For example, natural lighting including direct sunlight can affect visual comfort due to glare, shadows, dramatic changes in light levels, and reflections. These factors may cause headaches, fatigue, and nausea, as well as itchy and watery eyes. Without adequate environmental awareness and controls in "daylighting" designs, interior temperatures may increase or decrease too quickly and result in discomfort for the building occupants [5].

The use of specific parametric designs can help with thermal control and the impact of daylight on a building's interior temperatures. Parametric designs using dynamic façades that respond to the sun's movement and weather employ dynamic screens that control the amount of natural light admitted throughout the day. These screens could be applied to windows or as shading in semi-open corridors [6]. Any design considerations and improvements should be compared against the existing thermal strategies and outcomes as well as validated according to the standards set by the Estidama rating system.

2.1. Case Study: The University of Sharjah

The University of Sharjah is one of the largest universities in the United Arab Emirates, with 14 colleges offering different academic degree programs, of which 55 are bachelor's degrees, 17 are master of science degrees, and four doctoral degrees. The university currently has 16,982 students enrolled in the various academic programs. All the colleges have been accredited by multiple national and international accreditation boards and have been holistically accredited by the Commission for Academic Accreditation (CAA) of the Ministry of Higher Education and Scientific Research in the United Arab Emirates [7]). The university compound consists of four campuses: a female campus and a male campus, where each provides access to different colleges, as described in the site plan in Figure 1.

The existing corridors were categorized into two types: single-loaded corridors with an approximate length of 55 m, and double-loaded closed corridors with an approximate length of 30 m. The university has connected the buildings by enclosing all the single-loaded corridors from the male to the female campus (Figure 2). Accordingly, the corridor connecting the three engineering buildings (M8, M9, and M10) on the male campus was taken as a reference for the study due to its close location to the College of Engineering, one of the busiest corridors at the university. This corridor is approximately 45 m in length by 4.5 m in width, and it provides access between M8 and M10, where temporary facilities and kiosks are most likely to be located (Figure 3). Given these circumstances and the fact that this was one of the most active corridors on campus, it was essential to improve the environmental performance of this corridor, along with other corridors at the university, to create a walkable campus [8].

Source: Google Earth

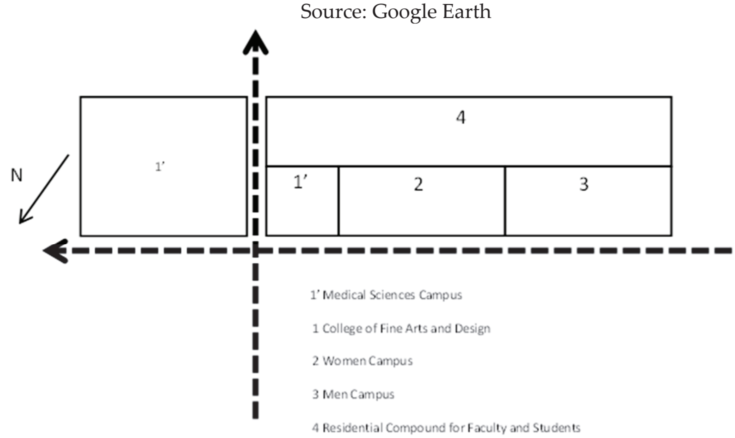


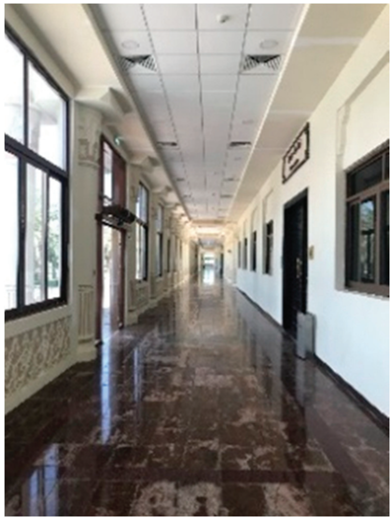
Figure 1. The University of Sharjah site plan (Source: Authors).

2.2. Parametric Design

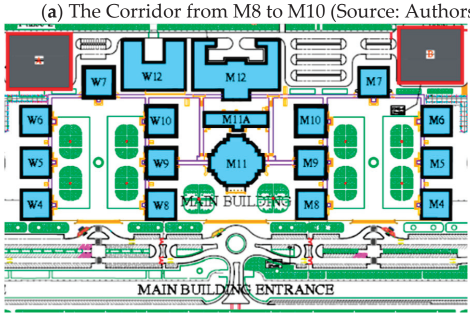
The term "parametric design" refers to the practice of digitally modeling a series of design variants whose relationships to each other are defined through one or several mathematical relationships (i.e., parameters) to form a parametric space that may comprise dozens or thousands of related but distinct factors [9].

Rhinoceros 3D (version 6 and 7, Robert McNeel & Associates, Seattle, WA, USA) is a robust modeling software platform produced by McNeil, which can produce geometries based on lines. Rhinoceros 3D provides accurate performance due to its mathematical definition of lines, as compared to other 3-D modeling software such as Autodesk's 3ds Max (Max version 2021) [10].

Grasshopper is a script-based modeling algorithm that offers designers a novel way of specifying their design and controls the design process and automation by defining geometry through mathematical functions. Parametric model generation allows rapid, significant changes to be made to the initial model and to quickly obtain complex shapes through geometrical iterations [10].



(**a**) The Corridor from M8 to M10 (Source: Authors)



(**b**) Site Plan

Figure 2. The selected single-loaded corridor from M8 to M10 and the site plan (Source: Authors).

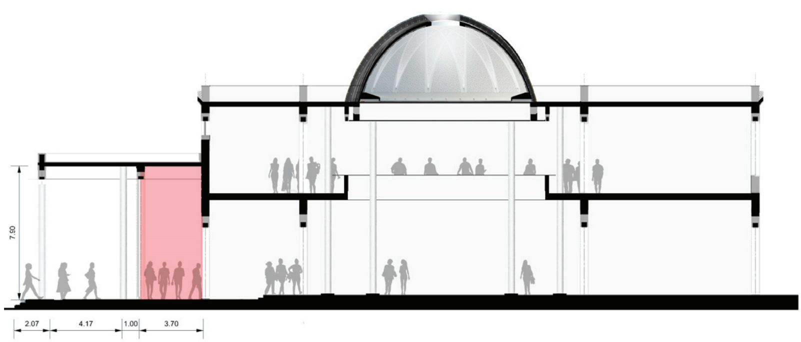


Figure 3. The selected single-loaded corridor section through the M8 building (Source: Authors).

2.3. Environmental Specifications

To achieve ideal energy performance and design, and an energy-efficient parametric screen, multiple codes were written to assess variable environmental factors such as sun path, shadows, solar radiation, and wind direction.

The sun is the most significant source of daylight; therefore, it was necessary to understand its movement and positions in the sky as well as its influence on thermal conditions in the corridor. The sun path is a diagram that indicates the sun's position as it rises and sets throughout the day, providing an estimate of how much daylight a location receives as the earth orbits around the sun [11].

The sun path diagram in Figure 4 was obtained via the azimuth and altitude lines that provided an approximation of the sun's exact location. The annual sun path diagram offers an approximation of the sun's position throughout the year; therefore, it indicates the peak summer months for which a design should account [12] (Muneer, 2004).

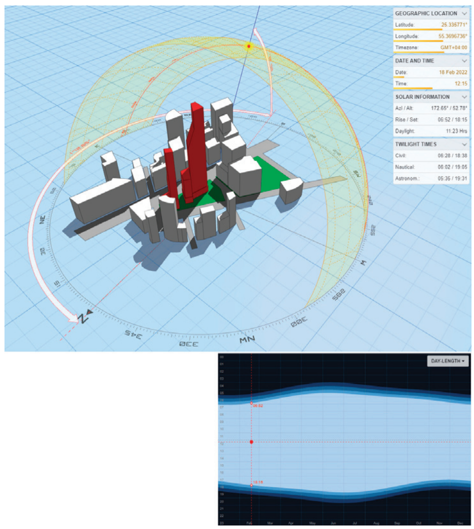


Figure 4. Sun path diagram.

Sun radiation (Figure 5) combines electromagnetic waves varying from infrared radiation to ultraviolet radiation. Within this spectrum are the wavelengths referred to as "visible light". The sun radiation diagrams provided an estimation of the amount of daylight the studied space received. As previously mentioned, the sun is the most significant light source, so it is crucial to understand how to optimize its benefits while minimizing its negative impacts [13].

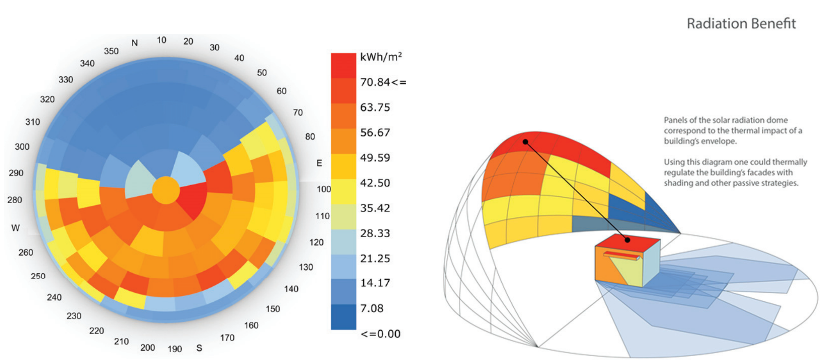


Figure 5. Sun radiation diagram.

The wind analysis diagram in Figure 6 displays wind speeds and directions at a given time [13]. In the United Arab Emirates, the prevailing winds have a northwest orientation.

In this study, the selected corridor is at a 35° counterclockwise tilt from the north, which is advantageous in terms of wind direction. In order to ensure an optimal design, the openings on the façade were strategically sized to improve the energy performance, solar radiation impact, and daylight exposure of the corridor [8].

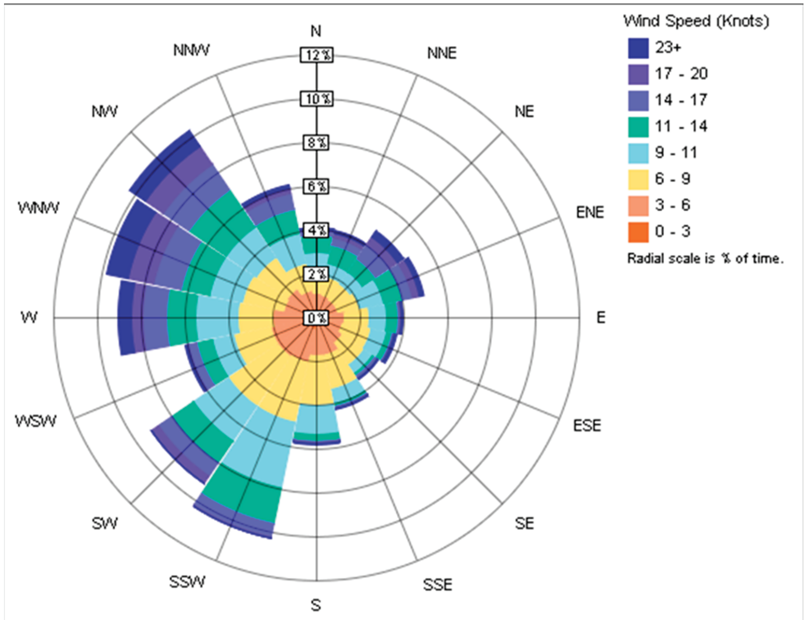


Figure 6. Wind rose diagram.

3. Research Methodology

By analyzing the key factors in parametric and computational design, the environmental performance of the chosen corridor and its compliance with Estidama regulations could be assessed to achieve optimal performance.

First, we connected Rhinoceros 3D and its Grasshopper plug-in with another tool, Ladybug for Grasshopper, that analyzed weather files and generated specific environmental diagrams. The Ladybug tool consists of Dragonfly, Butterfly, Honeybee, and Ladybug. Each specializes in a particular field and analyzes certain factors. For example, the Dragonfly tool analyzes large-scale factors such as climate change parameters and performs further analysis through other Ladybug tools. The Butterfly tool performs advanced fluid-dynamics simulations, while the Honeybee tool analyzes daylighting and thermodynamics through EnergyPlus and other environmental design engines [14]. Moreover, the Ladybug tool is a comprehensive tool used to validate simulation engines and translate them into computer-aided design interfaces. Using this interactive plug-in for Grasshopper allows the user to visualize slight variable changes and to make instant modifications at any stage of a design based on the feedback of Rhinoceros 3D [15]).

For our study, Ladybug also provided climatic graphs of the path of the sun, solar radiation, the shadow studies, and the wind diagrams, which indicated the energy performance of the screen. Figure 7 shows the software workflow when using Ladybug for Grasshopper [15]. Once the coding was written, the energy performance of the screen was demonstrated by diagrams obtained through Ladybug and showcased in Rhinoceros 3D. These data were either direct outcomes or required calculation methods to reach specific outcomes. The sun path and wind rose diagrams, for example, illustrated direct outcomes that did not require further calculations. As for the shadow study and solar radiation diagrams, the results required additional calculations to obtain possible estimations [15].

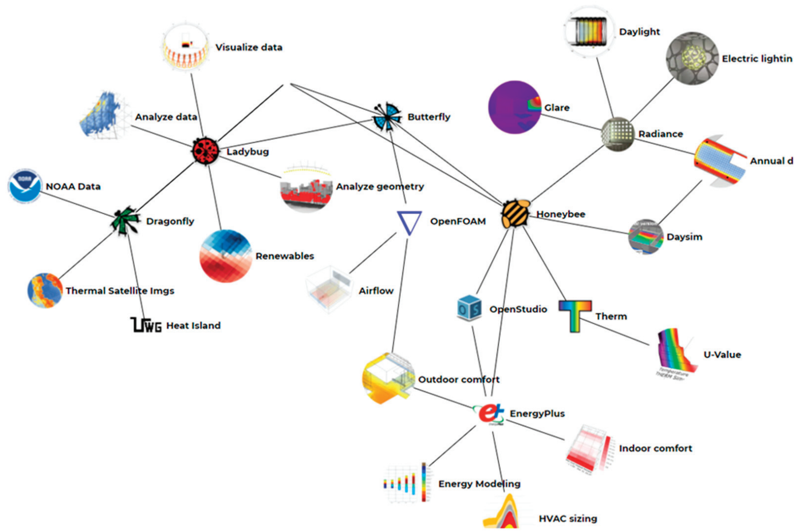


Figure 7. Software workflow.

4. Preparing Parametric Design Model with Parametric Logics

Since this study focused on the visual and thermal comfort of the corridors at the University of Sharjah, multiple parameters were tested to achieve an ideal design in terms of energy efficiency. A set of codes was written to evaluate the corridor's performance due to various environmental factors. These environmental specifications fell under two categories: (1) site-dependent parameters such as the annual sun path and the wind direction that were static factors including the site location and building orientation [13], and (2) pattern-dependent parameters that varied with each generated pattern, which included the shadow study and the solar radiation analysis [16].

4.1. Site-Dependent Parameters

The annual sun path diagram allowed us to identify the sun's position during the hottest months of the year, namely June to August, during which summer courses were offered. In addition, we could track the sun position throughout the year, including the fall semester (i.e., September to December) and the spring semester (i.e., January to May). This developed our understanding of how much shading of the corridor would be required to ensure thermal comfort, along with the shadow study, which was a pattern-dependent parameter. The direction of the openings would be determined based on the shading coefficient provided by the screen [15]).

Wind analysis indicated both the wind speed and the wind direction. It was necessary to consider these, as they play a significant role in improving the environmental conditions in the corridor. This diagram identified potential opportunities for cool breezes, resulting from the pattern of the prevailing winds throughout the year, specifically during the hot summer months. Considering these factors, the positions of varying opening sizes were determined to maximize airflow and bolster the stack effect [13].

4.2. Pattern-Dependent Parameters

The pattern-dependent parameters are environmental factors that are influenced by the geometric pattern on the façade. These parameters include the shadow study and the sun radiation analysis.

The shadow study provided explicit assumptions based on the analysis of the visual performance of the corridor. The second pattern-dependent parameter was the sun radiation analysis that evaluated how much exposure to daylight the corridor received. The solar radiation analysis was a core specification as it estimated the amount of artificial lighting that would be essential in the corridor, and the cooling load that would be required to compensate for the additional heat gain. Along with the shadow study, it suggested a preliminary number of openings with varying sizes for the screen [17].

4.3. Data Inputs and Analysis

For the generated codes to function, specific parameters were fed into Grasshopper to perform the simulations. The aforementioned environmental specifications had similar inputs, in addition to a few varying inputs, that allowed the program to predict potential values and indicate the energy performance, precipitation, solar radiation, sun path, and the building orientation impact. The varying inputs impacted the time duration of specific simulations, whether it was the peak hours of certain days, a specific week, or a range of months in a year.

The annual sun path diagram code (Figures 8 and 9) was written to demonstrate the path in which the sun orbits around the earth on a given day, highlighting the sun's position during varying hours, starting at sunrise and ending at sunset. The simulation exhibited the sun's position and its path on the 21st days of June, September, and December. These three months specifically mark the start of the summer, fall, and winter seasons, respectively. In June, the sun path started from sunrise at 6:00 a.m., when the sun offered less heat, as compared to that of sunset at 7:00 p.m. However, in September, when the transition between summer and winter occurred, the morning temperatures were cooler. In December, the sun was hot at noon and started to cool at 3:00 p.m. Although the sun in December was fairly hot through noon, it was still cooler when compared to other days of the year. This indicated that the screen should consider the radiation during the months June to September, in which the sun was at a higher angle and extra shading would be required to protect against excess heat gain.

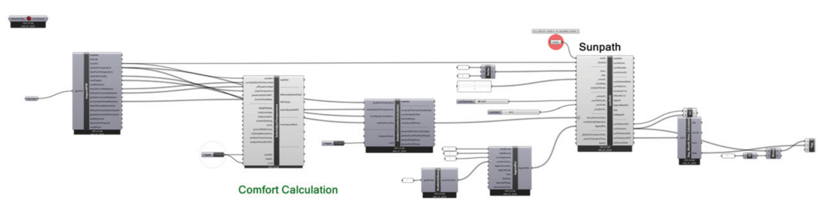


Figure 8. Annual sun path code.

Wind analysis codes (Figure 10) were written to generate a wind rose diagram that indicated the direction and speed of the wind during a specific period. During the fall semester, the wind blew southwardly 8% of the time at a minimum speed of 3.9 m/s and a maximum speed of 8.01 m/s, as illustrated in Figure 11. The wind blew eastwardly approximately 6.4% of the time with a minimum speed of 4.27 m/s and a maximum of 6.86 m/s. The wind blew northwestwardly 4% of the time, at a minimum of 4.43 m/s and a maximum speed of 4.56 m/s. For the spring semester, the wind was more likely to blow westwardly with an 8% probability with a minimum wind speed of 5.8 m/s and a maximum speed of 8.26 m/s. The wind blew southwardly with a 7.2% chance with a minimum wind speed of 4.55 m/s and a maximum of 7.86 m/s, as illustrated in Figure 12. The lowest wind direction frequency was towards the north-northwest with a possibility of 4% and a maximum wind speed of 4.63 m/s.

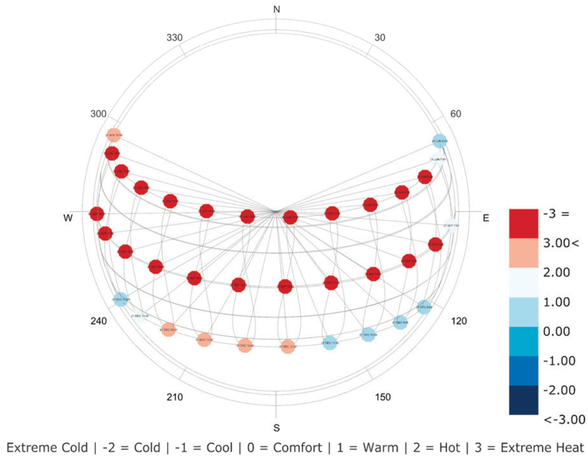


Figure 9. Annual sun path diagram.

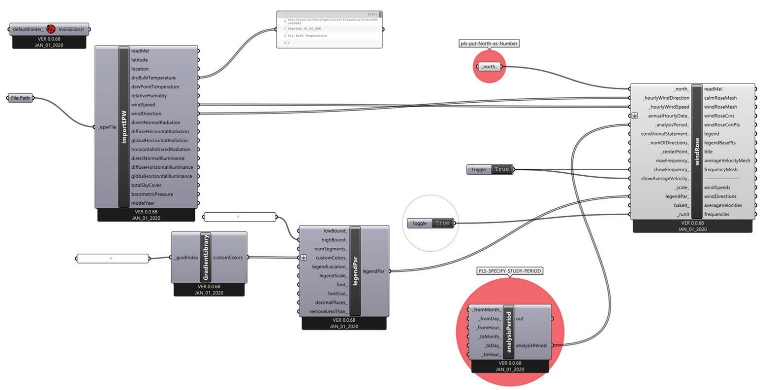


Figure 10. Wind analysis code.

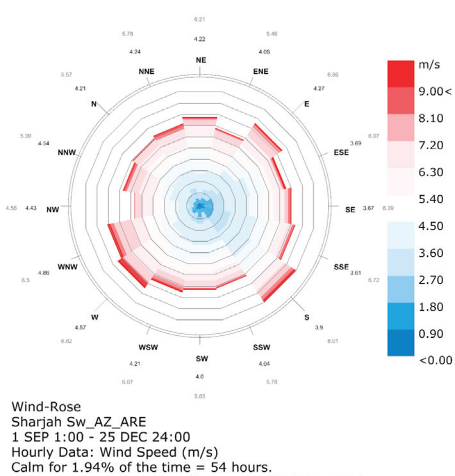


Figure 11. Wind rose for fall semester (1 September–25 December).

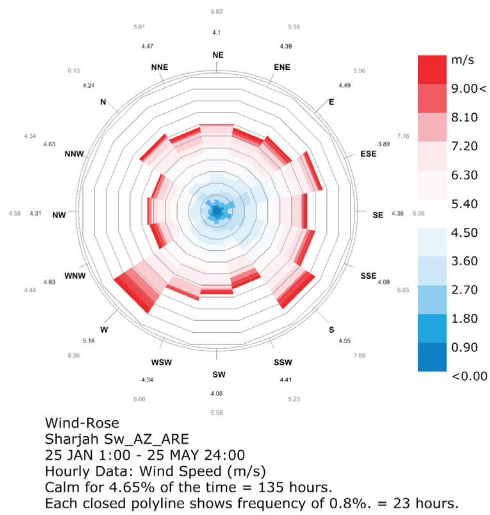


Figure 12. Wind rose for spring semester (25 January–25 May).

The codes written to run the wind analysis simulations highlighted the peak months in which higher cooling loads were required. In the fall semester, the months of September to November were considered when testing the performance of the parametric screen. In the spring semester, the month of May was when temperatures began to rise; therefore, the screen's performance was assessed during this month. As for the peak summer months of June to August, the screen was designed to specifically improve the thermal conditions of the corridor in response to the drastic increases in temperatures and compensate for the decreases in wind frequency and speed.

The shadow study codes were written (Figures 13 and 14) to estimate the brightness levels and the shadows cast on the corridor due to neighboring buildings. It illustrated the number of hours during which the corridors and their surroundings were exposed to daylight. As shown in Figure 14, yellow indicates the longest period of 13 h, and blue the lowest with no hours of sunlight.

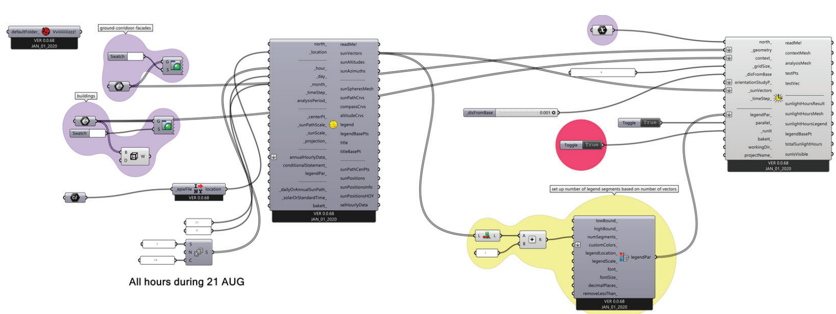


Figure 13. Shadow study code.

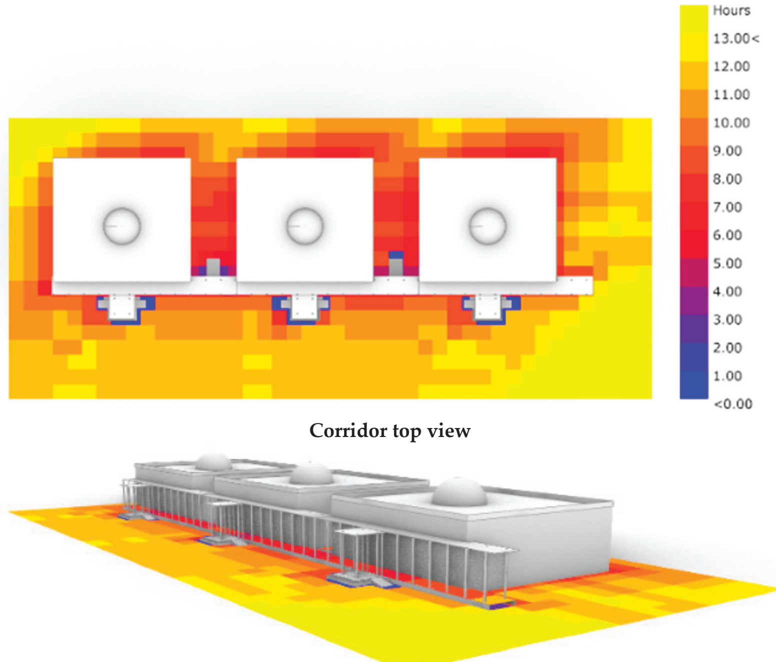


Figure 14. Shadow study analysis.

This environmental specification was a pattern-dependent parameter, meaning that its performance would be influenced by the screen design. As stated by Estidama regulations, the corridor should be shaded for a minimum of 75% during the daytime, which was at least 10 h. This had to be considered when designing the screen to ensure an energy-efficient performing corridor.

The second specification influenced by the pattern design was the solar radiation analysis. A set of codes was written to illustrate the radiation analysis at a given time, the annual radiation analysis, and the cumulative radiation analysis.

The first code, as in Figure 15, was written to demonstrate the radiation analysis between June and September during the peak summer months. It illustrated the diffuse radiation, direct radiation, and total radiation in kWh/m^2. For this specification, the north direction and space were the input values to generate the radiation analysis, as shown in Figure 16. During the hot months of the summer and given that the United Arab Emirates has a desert climate, most of the direct solar radiation reached more than 1100 kWh/m^2 in the southeast and southwest directions, as illustrated in Figure 17. There was not much overcast solar radiation.

The second set of codes illustrated in Figure 18 was the total radiation depending on the building orientation. As illustrated in Figure 17, the north direction received adequate radiation levels of approximately 340 kWh/m^2; for the south direction, where the sun was perpendicular to the ground at noon during peak summer months, there was an estimated level of 1134 kWh/m^2.

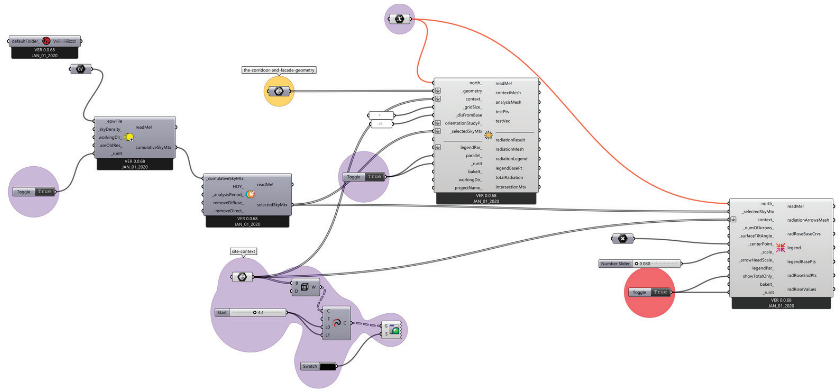


Figure 15. Solar radiation analysis code (June–September).

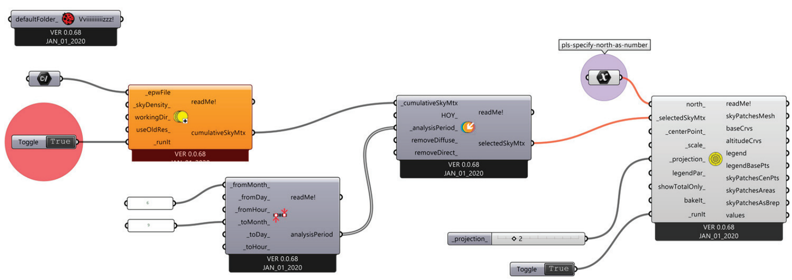


Figure 16. Solar radiation analysis (June–September).

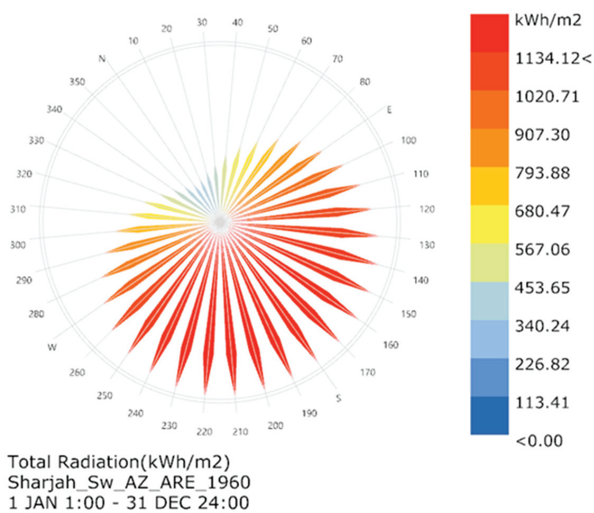


Figure 17. Total annual solar radiation analysis.

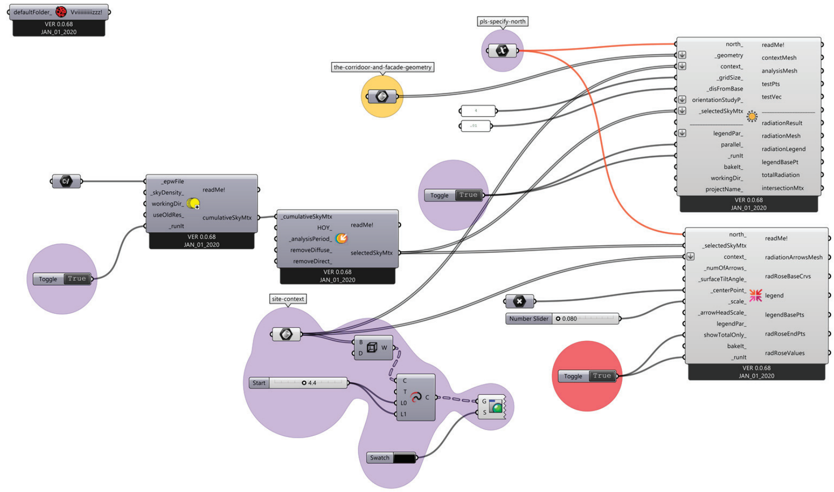


Figure 18. Total annual solar radiation analysis code.

The final set of codes, Figure 19, demonstrated the cumulative solar analysis radiation with the average daylight received annually. The colors in Figure 20 show much light the corridor received from the sun, with red being the highest and blue being the lowest. Certain parts of the corridor received sufficient daylight, compared to surroundings. Therefore, the screen would be designed to improve the visual performance of the corridor and the conditions influenced by the high solar radiation received.

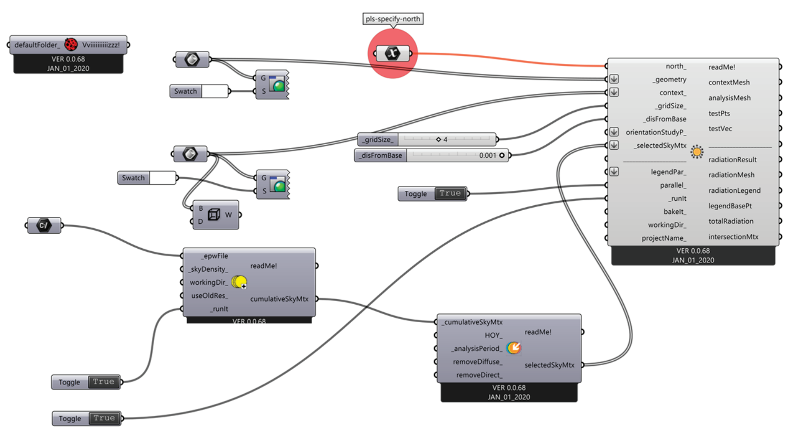


Figure 19. Cumulative solar radiation analysis codes.

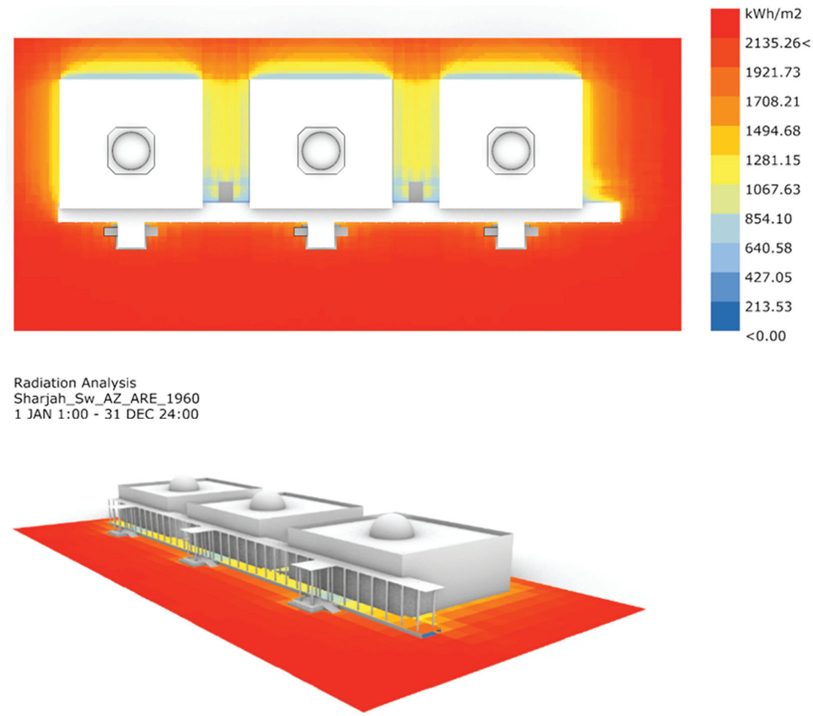


Figure 20. Cumulative solar radiation analysis.

5. Screen Design

In addition to these results, a screen was designed for implementation at the University of Sharjah, being the "cultural capital" of the United Arab Emirates, with architectural identity leaning more towards oriental and Islamic designs to create an aesthetically pleasing addition and to blend in with the existing architecture.

The following section discusses design philosophy and how Rhinoceros 3D and Grasshopper were utilized to achieve the desired model, as well as the analysis of the generated patterns' thermal and visual performance according to environmental specifications.

5.1. Phase 1: Screen Design Concept

Geometric patterns are a significant characteristic of Islamic architecture typically found in countries such as Spain, Iran, Morocco, and Turkey. These ornate patterns, as shown in Figure 21, can be defined as triangular-based polygons that often occur as star shapes and are often engraved on building facades or assembled from latticework and terracotta tiles. This style is referred to as "zellij" [18].

There is no historical evidence as to how these patterns were designed. Given that Islamic scholars had mastered mathematics and had an exceptional understanding of geometry, these patterns may be formulaic in design. With technological advancements and programs dedicated to mathematical formulation, it was practical to utilize these resources to generate further formulas developed by the Islamic scholars to provide the desired ornate star-shaped geometric patterns [18].

The University of Sharjah employs arcs, domes, and geometric patterns as part of its design scheme, as shown in Figure 22. These geometric patterns are typically found as engravings on walls, shading screens covering windows, or as outdoor shading elements [19]. This categorization sets clear benchmarks for the design approach and concept when designing the shading screen.

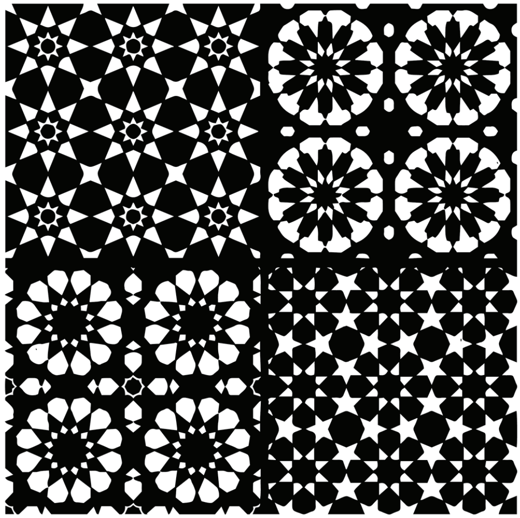


Figure 21. Islamic patterns.

Figure 22. Islamic pattern in the UoS Campus.

The basic shape of the pattern was chosen to match the current design and appearance of the university building. The script was designed in Grasshopper as a parametric design with the chosen pattern that would maintain daylighting performance in this corridor. In order to achieve sufficient comfort levels, these patterns were designed in varying shapes, sizes, and distributions according to the basic understanding of thermal sciences.

The script shown in Figure 23 can generate an infinite number of alternatives based on the same basic shape of the main pattern. This shape was differentiated based on two parameters. The first was the porous percentage to be detailed in phase 2. The second parameter was the gradient range that would control the porous arrangement in the pattern to be detailed in phase 3.

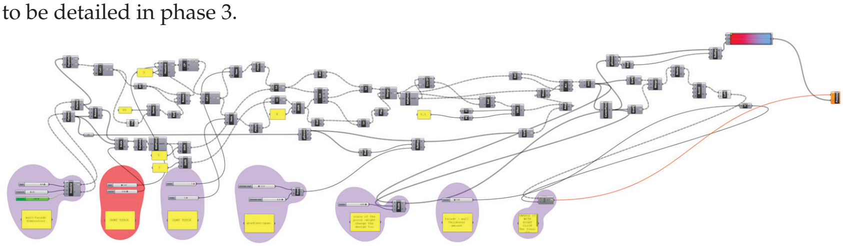


Figure 23. The designed set of codes to generate the performative pattern.

5.2. Phase 2: Generating Performative Patterns of the Façade Design

A code set was written to generate different pattern typologies that had various porous sizes and followed a vertical gradient. Figure 24 shows the codes, as written on Grasshopper, where specific parameters were input, creating different design options. The first parameter required the façade's height and length. The second parameter controlled the gradient span, which determined the number of times the porous size transitioned and reoccurred. The second parameter influenced the porous size scale, which was influenced by the gradient span. These factors resulted in a change of the porous size vertically along the screen. Lastly, a thickness was an input factor for screen depth depending on the material used, which allowed for accurate assumptions when analyzing the pattern's energy performance.

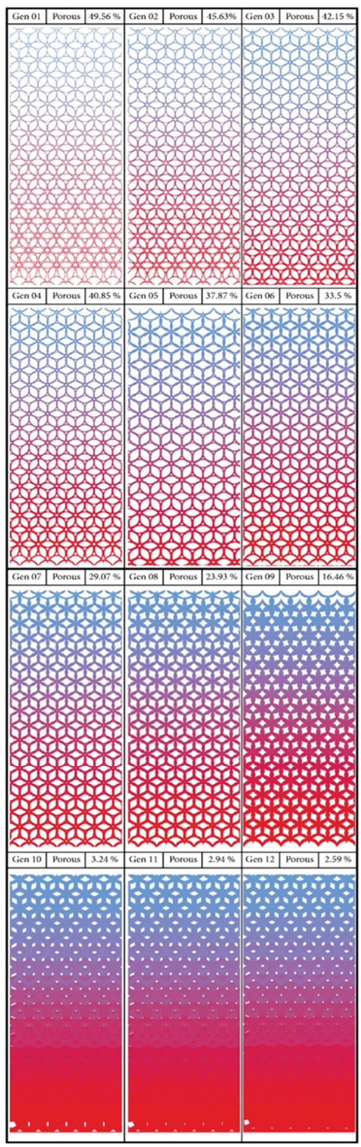


Figure 24. Generated patterns using the set of codes.

Twelve pattern generations, divided into three similar sections, were created based on a porous percentage from approximately 49.6% to 2.6%, according to the shape of the corridor. Only one section was tested to reduce the computational time and effort of modeling and simulation.

5.3. Phase 3: Analyzing the Performance of Generated Patterns

The third phase was focused on the environmental performance of the generated screen and to analyze its influence on the visual and environmental conditions of the corridor.

For comparison, and to ensure optimal environmental performance, the corridor and its surroundings were modeled in Rhinoceros 3D. The initial environmental performance of the corridor was then assessed through the environmental specification codes, as shown in Figure 25.

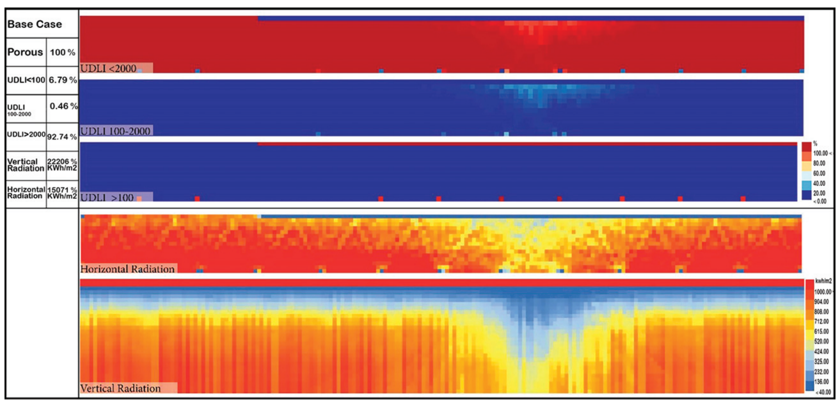


Figure 25. Daylight and radiation analysis of the current status of the corridor.

Based on the annual sun path diagram, we concluded that the screen should consider the solar radiation exposure of the corridor during the peak summer months of June to August. The wind rose diagram demonstrated that the temperatures rose in May, while the wind speed decreased, peaking in June to August. The screen was designed to utilize the prevailing winds during the summer months.

The Rhinoceros 3D model was defined in the Grasshopper code to run the solar radiation analysis regarding the pattern-dependent parameters.

In this phase, the current generations of the pattern were assessed based on the two indicators, daylight and solar radiation, to optimize the corridor's performance concerning visual and solar radiation and thermal comfort.

5.3.1. Daylight Analysis

Daylighting performance analysis was based on the useful daylight illumination (UDLI) indicator, which referred to the percentage of time during the active occupancy hours that the test point received daylight illumination. As per a previous classification [20], the illuminance in the study was classified as the following:

- Daylight illuminance below 100 lux (i.e., E < 100 lux) was considered inadequate as either the only lighting source or as a remarkable contribution to artificial lighting.
- Daylight illuminance between 100 and 500 lux (i.e., 100 < E < 500 lux) was considered as efficient lighting levels that may still require additional artificial lighting sources.
- Daylight illuminance between 500 and 2000 lux (i.e., 500 < E < 2000 lux) was perceived as either advisable or at least acceptable.
- Daylight illuminance of more than 2000 lux (i.e., E > 2000 lux) was considered as causing both visual and thermal discomfort.

The illuminance levels between 100 and 2000 lux could be merged into one layer as acceptable and advisable illuminance levels to be utilized in the space.

The main advantage of this indicator was the division into three layers. The first layer was UDLI < 100 lux. This layer was below the required illumination levels, which needed to be minimized; however, its effect could be eliminated by providing artificial lighting. The second layer was UDLI = 100–2000 lux. The second layer was the target for the daylighting analysis, which needed to be maximized to optimize the visual comfort in the corridor. The third layer was UDLI > 2000 lux. The third layer was the required illumination level, which increased the glare levels and needed to be minimized, and it was the most critical part as it could not be maintained in the same generation.

Daylighting Analysis for the Current Status

By conducting the daylighting simulation for the current condition of the corridor, we found that the useful daylight illumination levels were very low. As seen in Figure 25, UDLI 100–2000 lux was only 0.46% while UDLI > 2000 lux was 92.74%, and UDLI < 100 lux was only 6.79%. That indicated that the corridor occupants would experience an uncomfortable glare until later in the day, when the lighting levels had to maintained using artificial sources. This result showed that the corridor could be enhanced with shading devices that could reduce the potential glare without increasing the insufficient daylight levels. When the designed patterns were tested, there was no way to minimize UDLI < 100 lux below 6.79% except with material reflection or artificial lighting.

Daylighting Analysis for Pattern Generation

The generated pattern number 1, as shown in Figure 26, had a porous percentage of 49.57% and showed some improvement at the UDLI (100–2000) levels, compared to the current evaluation of the corridor. UDLI (100–2000) was increased from 11% to 11.47%, UDLI (<100) value was the same by 6.28%, but UDLI (>2000) was reduced by 10% to reach 82.25%.

Generation numbers 2–9 listed in Table 1 revealed that the porous percentage was reduced gradually from 45.63% to 16.46%. This reduction caused a gradual optimization in UDLI (100–2000) from 13.45% in generation 2 to 54.2% in generation 9. Meanwhile, the UDLI (<100) maintained the same value in all generations by 6.28%, while UDLI (>2000) continuously decreased from 80.37% in generation 2 until it reached 39.52% in generation 9.

Table 1. Values of UDLI based on the porous percentage.

Generation/UDLI	Gen1	Gen2	Gen3	Gen4	Gen5	Gen6	Gen7	Gen8	Gen9	Gen10	Gen11	Gen12
Porous %	49.56	45.63	42.15	40.85	37.87	33.5	29.05	23.93	16.46	3.24	2.94	2.59
UDLI (>2000)%	82.25	80.37	78.48	76.72	73.08	67.13	60.67	53.2	39.52	16.14	16.07	16.03
UDLI (100–2000)%	11.47	13.45	15.42	17.00	20.65	26.59	33.05	40.52	54.20	55.04	54.78	54.19
UDLI (<100)%	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	28.31	29.14	29.77

In generation 10, the porous percentage was 3.24%, which affected the UDLI (100–2000) (55.04%), the peak value in all the generated patterns, while it had a major increase on UDLI (<100) , which reached 28.31%. The UDLI (>2000) was reduced to 16.14%.

In generations 11 and 12, the porous percentages had lower values of 2.94% and 2.54%, respectively. The UDLI (100–2000) was gradually reduced to 54.78% and 54.19%, respectively. While UDLI (>2000) continued to decrease, the UDLI (<100) continued to increase, each reaching 29.14% and 29.77%, respectively.

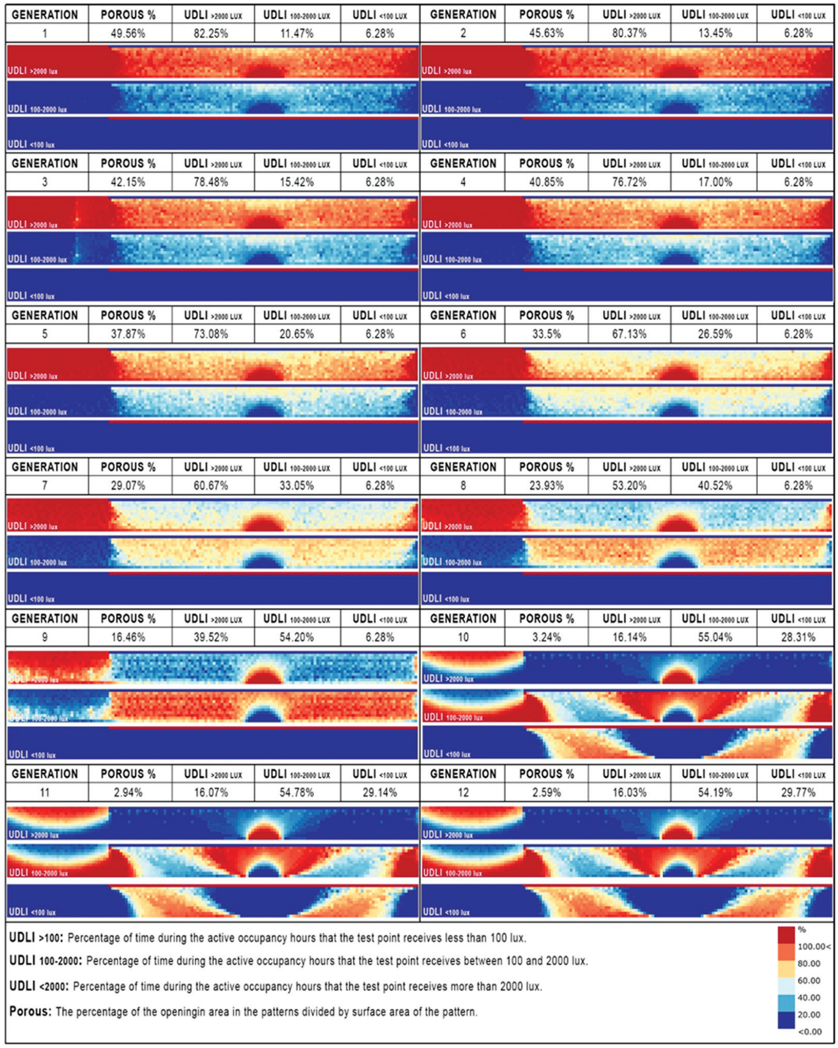


Figure 26. Daylighting analysis of the pattern generations.

5.3.2. Solar Radiation Analysis

In this analysis, two types of radiation analysis were considered. All patterns were assessed based on the radiation exposure of the corridor flooring. Afterward, the vertical radiation was estimated using a vertical test plan located in the corridor center. The horizontal and vertical radiation served as indicators for the thermal comfort of the corridor resulting from radiation. The less radiation received on the horizontal and vertical tested surfaces, the more assured the thermal comfort would be. It was considered thermally comfortable if the humidity and wind speed factors were fixed.

Radiation Analysis for the Current Status

The radiation analysis shown in Figure 26 indicated high levels of radiation exposure both horizontally and vertically. The horizontal radiation exposure was 15,071 kWh/m^2, while the vertical radiation was 22,206 kWh/m^2. These values suggested that shading devices were needed to disrupt the high rate of radiation exposure, which negatively affected thermal comfort in the corridor.

Radiation Analysis of the Pattern Generations

Generated pattern 1, as shown in Figure 27, was installed in the corridor, which reduced the horizontal radiation exposure, where the horizontal radiation showed a sharp decrease to 5254 kWh/m^2. Similarly, the vertical radiation also received less radiation and decreased to 12,864 kWh/m^2

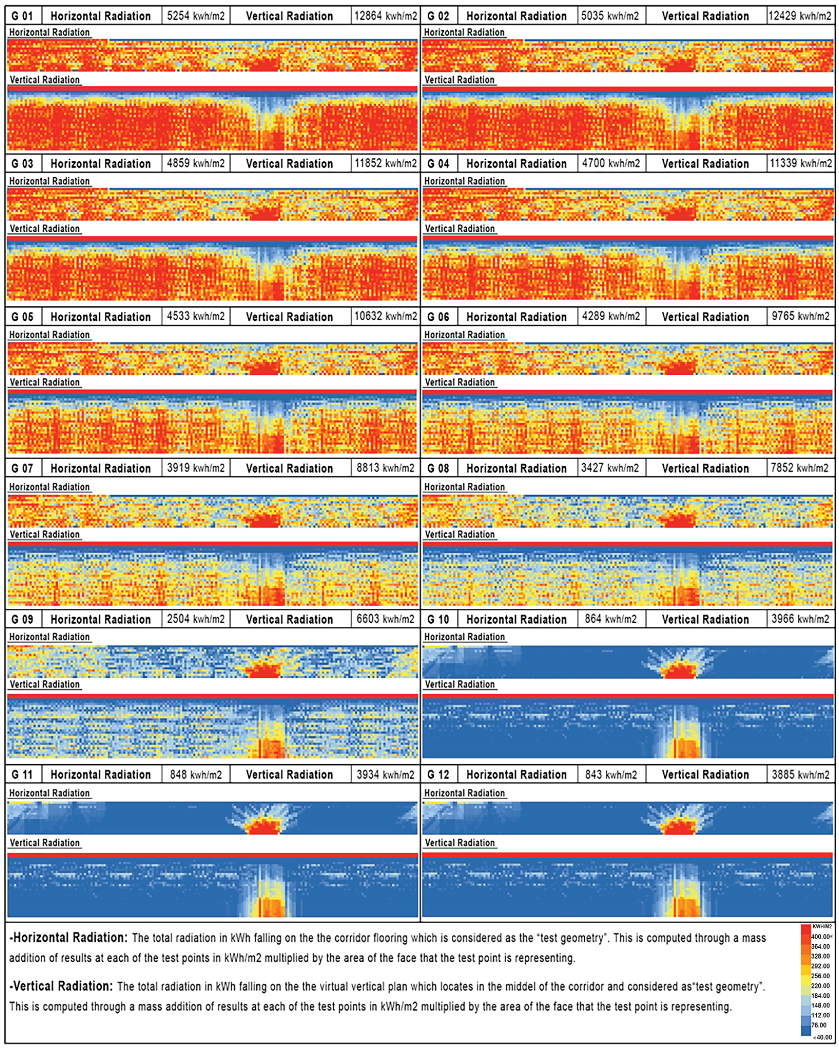


Figure 27. Radiation analysis of the pattern generations.

Patterns 2–9 showed a gradual reduction in horizontal and vertical radiation values, as seen in Table 2. The horizontal radiation in pattern 2 was 5035 kWh/m^2, and gradually decreased to 2504 kWh/m^2 in pattern 9. Similarly, the vertical radiation was 12,429 kWh/m^2 in pattern 2, and then declined until reaching 6603 kWh/m^2 in pattern 9.

Afterward, a significant drop in pattern 10 showed that the horizontal and vertical radiation exposure levels were 864 kWh/m^2 and 3960 kWh/m^2, respectively.

Table 2. Values of vertical and horizontal radiation based on the porous percentage.

Generation/ UDLI	Gen1	Gen2	Gen3	Gen4	Gen5	Gen6	Gen7	Gen8	Gen9	Gen10	Gen11	Gen12
Porous %	49.56	45.63	42.15	40.85	37.87	33.5	29.05	23.93	16.46	3.24	2.94	2.59
Vertical Radiation "kWh/m^2"	5254	5035	4859	4700	4533	4289	3919	3427	2504	864	848	843
Horizontal Radiation "kWh/m^2"	12,864	12,429	11,852	11,339	10,632	9765	8813	7852	6603	3966	3934	3885

In patterns 11 and 12, there were no significant achievements in the radiation results; horizontal radiation was 848 kWh/m^2 and 843 kWh/m^2, but the vertical radiation was 3934 kWh/m^2 and 3885 kWh/m^2, respectively.

5.3.3. Porous Gradient Parameter

As an outcome of the previous analysis and results, different alternatives were ranked to obtain the best generation. Patterns 10, 11, and 12 were found to have the best UDLI results. At the same time, the three options received a low radiation rate in the horizontal and vertical analysis. The computational process was used to change the porous gradient and test it for all options. The porous gradient for the three top-ranked patterns was changed to examine the extent of the enhancement in the alternatives' performances. Two different patterns were generated from each one of these three patterns and classified as two versions, "a" and "b", with different porous gradients.

All versions were assessed for their performance in daylighting and radiation, as shown in Figure 28. Versions of "a", shown on the left side of the figure, scored lower results of approximately 42% in UDLI (100–2000), while versions of "b", on the right side, showed remarkable achievements in the daylighting performance, exceeding an 18% improvement and reaching around 70% in the UDLI (100–2000).

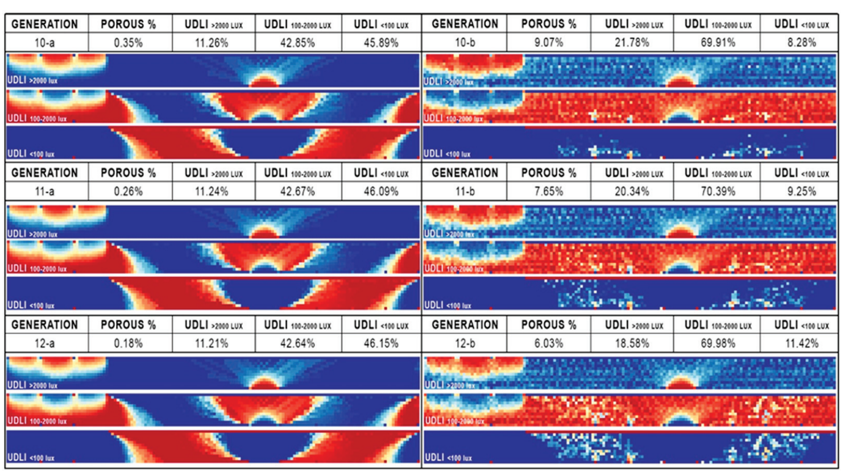


Figure 28. Analysis of the porous gradient-based patterns.

The daylighting values of the three "b" alternatives were similar as they varied between 18.6% and 21.8% for UDLI (>2000) and between 8.3% and 11.4% for UDLI (<100). They achieved values between 69.9% and 70.4% for UDLI (100–2000). Generation 12-b was considered as the optimum performance for daylighting and radiation together, as shown in Figure 29. However, the UDLI (100–2000) of pattern 12-b was lower than 11-b by 0.5%, and the potential glare value of pattern 12-b was smaller by 1%. In addition, the vertical and horizontal radiation values were smaller than pattern 11-b by 356 kWh/m^2 and 49 kWh/m^2, respectively.

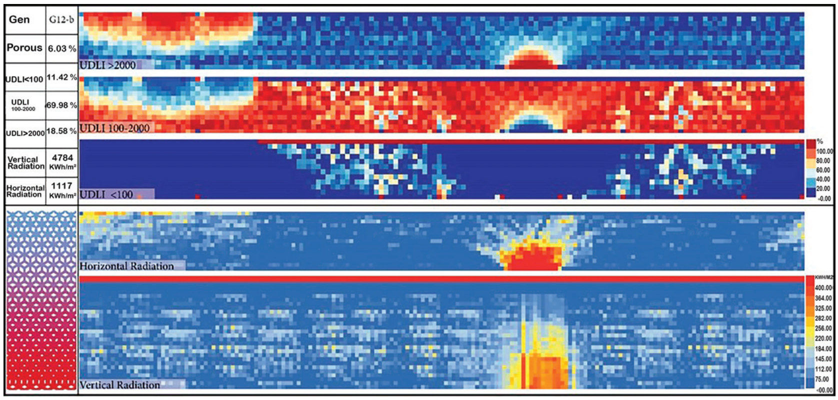


Figure 29. Best-case pattern parameters and analysis (G12-b).

6. Results and Discussion

Environmental specification simulations were conducted using the Ladybug tool, a plug-in for Grasshopper, in which the weather of the United Arab Emirates was studied to provide an estimation of the modeled corridor's performance. This section discusses significant findings regarding the influence of the generated patterns on the corridor performance, in which the screens demonstrated a wide range of results that improved, stabilized, and exacerbated the corridor's visual and environmental conditions.

The baseline corridor performance was assessed and compared to the performance of all trial screens. These screens were designed following an Islamic traditional geometric pattern, reflecting the design scheme of the University of Sharjah. Specific parameters were coded and analyzed using the Ladybug tool to provide an estimation of the screens' performance and impact on the chosen corridor's visual, solar radiation, and daylight conditions.

Particular environmental parameters, such as the sun path and wind rose diagrams, were evaluated to demonstrate the peak summer months where the solar heat gain would be at its peak, and the wind speed would be the lowest. This allowed us to define the study period according to the harshest conditions in an effort to design a screen model that would account for the most crucial period in the year.

The Ladybug tool analyzed the screens' performance in terms of solar radiation analysis diagrams, and estimated solar heat gain and produced shadow study diagrams. The diagrams obtained through Grasshopper's plug-in Ladybug, and further illustrated in Rhinoceros 3D, showcased the potential influence of the screen on the corridor's performance. Assessment of the solar radiation performance of the screen occurred during two phases. The first phase consisted of changing the porous size of the pattern and generated in 12 different patterns. These patterns were assessed for daylighting and radiation performance to identify the best three patterns. In the second phase, the porous gradient of these three patterns was adjusted to study the performance when changing the gradients.

Furthermore, a significant improvement in UDLI (100–2000) was found, as compared to the current status of the corridor, with an increase in excess of 54% being reported, while there was a significant decrease in vertical and horizontal radiation exposure.

In phase 2, there was a reasonable increase in the UDLI (100–2000) by more than 18%, as compared to the first phase. In addition, there was an effective reduction in the potential glare at UDLI (>2000), which minimized the potential glare by more than 9%.

7. Conclusions

An Islamic geometric patterned screen that matched the design scheme of the University of Sharjah was designed and modeled to improve the visual and thermal conditions of a selected corridor on campus. The parametric design of the screen generated several alternatives. The first phase of the study involved generating 12 different design options based on the change in porous size percentage for all screen designs. Daylighting and radiation analysis were simulated to classify the generations and to choose the best three. The top three alternatives were gen10, gen11, and gen12, with UDLI (100–2000) values of 55.04%, 54.78%, and 54.19%, respectively, and horizontal radiation exposures of 864 kWh/m^2, 848 kWh/m^2, and 843 kWh/m^2, respectively. In the second phase, each of the three chosen patterns generated two different patterns based on the different porous gradients. All the generated patterns were simulated and classified to identify the optimum screen design, which was gen12-b. This showed a significant development in daylighting performance, as the UDLI (100–2000) increased by 69.52% compared to the current design of the corridor and showed a significant reduction in radiation values as the horizontal radiation was minimized by 13,954 kWh/m^2. This research showed that the generated screens 10-b, 11-b, and 12-b were potentially successful and reliable.

The same approach could be generalized in the other corridors in the UoS and in many different screen designs for corridors with similar climates and functions.

8. Future Studies

The appropriate selection of screen materials for the fabrication process could be studied further, particularly in terms of thickness, strength, and thermal properties. In addition, virtual reality and mixed-reality techniques aided by artificial intelligence software and strategies could be applied for optimum screen design, and as an important part of the digital fabrication process.

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buildings

Review

The Decline of Architects: Can a Computer Design Fine Architecture without Human Input?

Joanna Kołata and Piotr Zierke *

Faculty of Architecture, Poznan University of Technology, 61-131 Poznan, Poland; joanna.kolata@put.poznan.pl
* Correspondence: piotr.zierke@put.poznan.pl

Abstract: Architects are required to have knowledge of current legislation, ergonomics, and the latest technical solutions. In addition, the design process necessitates an appreciation of the quality of the space and a high degree of creativity. However, it is a profession that has undergone significant changes in recent years due to the pressure exerted by the development of information technology. The designs generated by computer algorithms are becoming such a serious part of designers' work that some are beginning to question whether they are more the work of computers than humans. There are also increasing suggestions that software development will eventually lead to a situation where humans in the profession will become redundant. This review article aims to present the currently used, implemented, and planned computer technologies employed in the design and consider how they affect and will affect the work of architects in the future. It includes opinions of a wide range of experts on the possibility of computer algorithms replacing architects. The ultimate goal of the article is an attempt to answer the question: will computers eliminate the human factor in the design of the future? It also considers the artificial intelligence or communication skills that computer algorithms would require to achieve this goal. The answers to these questions will contribute not only to determining the future of architecture but will also indicate the current condition of the profession. They will also help us to understand the technologies that are making computers capable of increasingly replacing human professions. Despite differing opinions on the possibility of computer algorithms replacing architects, the conclusions indicate that, currently, computers do not have capabilities and skills to achieve this goal. The speed of technological development, especially such technologies as artificial superintelligence, artificial brains, or quantum computers allows us to predict that the replacement of the architect by machines will be unrealistic in coming decades.

Keywords: decline of architects; future of designing; computers control; algorithms; artificial intelligence

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1. Introduction

The architectural profession combines science, engineering, and art. It is an occupation that requires knowledge of current legislation, ergonomics, or the latest technical solutions and the need to assess the quality of space and creativity. However "the profession of the architect has never been stable" [1] (p. 8). The role of architects has evolved over the years and while they are still responsible for the quality and shaping of the space and "for the visual appearance of buildings and structures" [2], "demiurges [. . .] controlling the whole creative processes, consistently seeking to achieve a goal" [3] (p. 35), this profession can be also "characterised by a continuous transformation of its conditions and characteristics" [1] (p. 8). Architects are right now "the so-called mediators between different professions and they have to monitor the progress of the project from its initial stages onwards" [4] (p. 41). Over past few years they are also "challenged to take a public role, share their knowledge of space, their imagination of possible futures, and their intuition to grasp and affect a specific site or condition. The architect not only draws the lines and limits of space but also deals with the world and the people in it." Recently "new techniques of communication and modeling [. . .] extensively affect the architect's work" [1] (p. 7). This is caused, among other things, by the development of information technology, especially BIM (building information modeling), BLCM (building life cycle modeling), parametric design, or AR (augmented reality). By offering architects new design possibilities, they influence space. At the same time, they make work faster and easier in many aspects. However, questions arise as to whether computer algorithms are not starting to interfere too much in the creative process of architects and whether projects created as a result of this cooperation are not becoming more works of computers than humans. At the same time, there are concerns that the trend of computer programs taking over architects' work will continue and, eventually, a human being will become redundant in this profession.

This is a scoping review article. It aims to present current, implemented, and planned computer technologies used in the design and discuss how they affect and will affect architects' work in the future. Due to the nature of this article, a research query was conducted on the opinions of a wide range of experts. The selection of statements was based on the occupational criteria of the commentators. These include architects, scientists, developers of computer aided design software, but also writers, journalists, and even philosophers. The authors wanted to select opinions that represent different approaches to the possibility of replacing architects by computer algorithms. These comments, due to their different attitudes towards the aforementioned possibility are presented in the "Yes" and "No" subsections of this paper. The selection of opinions was also based on the different reasons that guided the commentators in forming their judgements, e.g., the development of particular technologies or limitations affecting computers and algorithms. The selection was not limited to the most recent commentaries, but the older ones from early computer development were also cited. The selection of opinion makers was focused on their experience and prestige. As a result, among representatives of scientists dealing with the described problem in their research work, opinions of professors predominate. Architects are mostly represented by a group of recognised and awarded designers, including those from well-known design studios. Design aid software manufacturers are dominated by representatives of leading companies from all over the world. This manuscript also contains statements of less known professionals. However, in the opinion of the authors, they contain important information on the described subject, which shows other, sometimes not obvious, points of view and enables a look at the described topic from a different perspective.

In the following part of the article, the obtained data are synthesised and an attempt is made to identify the patterns appearing in them. This will help to define the skills that computer algorithms would need to acquire in order to theoretically be able to replace architects.

The ultimate goal of the manuscript is an attempt to answer the question: will computers eliminate the human factor in the design of the future?

The answers to questions posed in this manuscript will contribute not only to determining the future of architecture but will also indicate the current condition of the profession. They will also help us to understand the technologies that are making computers capable of increasingly replacing human professions. Therefore, the problem described is multifaceted, and its complex character touches upon IT issues and sociological and even philosophical matters presented in this article.

2. Current Capabilities of Computers in Architectural Design

The initial use of the computer in architectural design was limited to replacing the drawing board, as exemplified by the widely used AutoCAD software. Dedicated CAD (computer-aided design) software was undoubtedly a great improvement on tedious manual work. Nowadays, there are more advanced programs such as ArchiCAD, which allow block design using predefined building components such as walls and ceilings. The design software continues to improve. Autodesk's Dreamcatcher is supposed to be the next generation of CAD. It is "a generative design system that enables designers to craft a definition of their design problem through goals and constraints. The system generates thousands of design options that meet specified goals, allowing designers to explore trade-offs between many alternative approaches and select design solutions for manufacture" [5]. The MaRS Innovation District office and research building in Toronto was designed using Dreamcatcher software. The design of the building was generated based on the needs and wishes of future users. "Software made it possible to take all of these factors into consideration to find a set of optimal options that satisfied as many criteria as possible" [5]. The benefits of generative design and examples of building forms created with this technology in Kiruna, Sweden, were presented among others by Jani Mukkavaara and Marcus Sandberg [6] (pp. 8–16).

System extensions and the introduction of the third dimension into CAD software have made it possible to integrate the various elements of a project into one thing. In recent years, BIM software, which uses "a modelling technology and associated set of processes to produce, communicate and analyse building models" [7] (p. 13) have been gaining popularity. Denis Neely noted that "design professionals are moving to BIM three times faster than the transition from hand drawing to CAD" [8], and in 2011 "BIM use reached the 50% mark among design professionals" [9] (p. 6) These programs significantly improve the work of architects, but professors Wojciech Bonenberg and Oleg Kaplinski also noted that BIM unexpectedly raises an architect's professional prestige [10] (p. 9). For instance, "the Sichuan Provincial Architectural Design and Research Institute used AECOsim Building Designer's BIM advancements to enhance information exchange among disciplines and ensure timely collection, update, management, and data application. The software enabled the institute to shorten the project period by 60%, reduced design errors by 80%, and increased design depth by 50%" [5]. Professors Oleg Kapliński and Wojciech Bonenberg consider the implementation of BIM technology (especially BIM as a process) and integrated project delivery (IPD) as "important elements conducive to the integration of architectural and engineering activities" [11] (p. 5), fundamentally affecting the work of architects in the future.

At the same time, parametric design programs are appearing, which enable the creation of ready-made structures based on parameters proposed by architects. They treat "the geometric properties of the design as variables", resulting in a design that consists of "relationships that are maintained between the various elements of the composition" [12] (p. 1). "By far the most widely used parametric design software is "Grasshopper" developed by the David Rutten for Robert McNeel Associates and first released in 2008" [12] (p. 5). Grasshopper is a platform closely integrated with Rhinoceros—McNeel's 3-D modeling tool, "to deal with this generative algorithms and associative modelling" [13] (p. 4). It also enables integration with sensors and software based on machine learning and artificial intelligence technologies. [14] (pp. 6–7). Therefore, it should come as no surprise that an increasing number of projects are based on this technology, which can be seen, for example, in the design of offices by Frank O. Gehry or Zaha Hadid. In 2021, a building design was presented by a Japanese architectural studio called Laboratory for Explorative Architecture and Design (LEAD) that was entirely generated by a computer program based on an algorithm prepared by the studio [15]. In addition to improving the work of designers and facilitating the design of complex, sculptural building forms, parametric design has had a significant impact on the architecture of cities such as Dubai, Doha, and Bilbao.

Currently, the most hopeful developments in computer-aided design are in "the fields related to machine learning (ML), including data mining, machine vision, computational statistics and other sub-fields of artificial intelligence (AI)" [16] (p. 14) as well as mobile robotics and computerisation in manual tasks. Frey and Osborne note that "machine learning algorithms running on computers are now, in many cases, better able to detect patterns in big data than humans" [16] (p. 16), which is exemplified by the aforementioned generative design technology, but they then admit, that "robots are still unable to match the depth and breadth of human perception" [16] (p. 24). Besides, as Yaser S. Abu-Mostafa notes, "Machine learning does not create information; it gets the information from the data. Without enough training data that contain proper information machine learning will not work" [17] (p. 81).

When it comes to AI, "in 2016, Google in the US developed the artificial intelligence (AI) applied in the field of graphic design" [18] (p. 2) called Alpha GD, which Wu Shan perceives as "a great threat to people engaged in graphic design" [18] (p. 2). Professor Duc Truong Pham notes "that there is a wide range of techniques which are capable of enhancing traditional CAD systems with advanced reasoning abilities thus increasing their prospect of being tools for intelligent design" [19] (p. 24). These include, among others: deep knowledge, non-monotonic, qualitative and geometric reasoning, uncertainty handling, and object-oriented representation [19] (pp. 15–24). Despite the increasing use of artificial intelligence in the construction industry [20,21] and design, as well as the aforementioned concerns about the future role of AI programs in design process, so far "it can only imitate the existing board, but cannot achieve independent innovation." [18] (p. 2).

In summary, computers and computer programs are increasingly influencing the work of architects. Increasingly sophisticated algorithms are being developed which can generate the forms of buildings or help to make decisions about, for example, their functional scheme or construction. However, these technologies are still not able to replace architects. One could even say that they are nowhere near it. This is supported by Frey and Osborne, who find that the level of complex perception and manipulation skills, creativity, and social intelligence necessary to design buildings [16] (p. 27) are tasks beyond the capacity of current computers. But will they be able to replace architects in the future?

3. Will Computers Replace Architects?

Eight years have passed since Carl Benedikt Frey and Michael A. Osborne estimated the probability of the architectural profession being replaced by computers in the next few decades at only 1.8% [16] (p. 58). In the past, however, different points of view have clashed, assuming, on the one hand, the 'death' of the architectural profession, and on the other, the impossibility of its replacement by machines. Let us consider how others—architects, planners, sociologists, philosophers, architectural software developers, architecture critics, or visionaries—view this issue.

3.1. No

It appears that among predictions concerning the possibility of computers replacing humans, skeptical opinions prevail when it comes to architectural design. The concerns are related primarily to the lack of perception and feeling of the world through the senses, which those expressing them believe are an indispensable element of design. The famous Swiss architect Peter Zumthor believes that: "The strength of good design lies in ourselves and in our ability to perceive the world with both emotion and reason. A good architectural design is sensuous. A good architectural design is intelligent" [22] (p. 65). In his essays on architecture, he points out that design is constant cooperation between feelings and reason. Each design is an expression of fleeting feelings, longing, desires to which the architect is subject and which are only creatively transformed by reason. Design, therefore, stems from inspiration but is also subject to change at every stage and as a result of each line drawn. The perception of the design and consequently the project itself changes as a result of the design process. It causes joy and excitement but is also the result of these feelings, which he compared to the effects of a drug [22] (p. 21). A similar opinion is expressed by Finnish architect Juhani Pallasma, who unambiguously claims that the lack of feelings, the inability to guess human emotions, or the possibility to create is the obstacle that will prevent architecture from ever being fully automated. Interestingly, he considers the perfect and repetitive execution of tasks by computers to be the biggest drawback in this respect. He believes that "creative work needs space to move. Too much precision is not good for creativity" [23]. This obstacle to designing is also noted by Andy Smith, Director, Product Management, Building Solutions, Bentley Systems, who "believes that computers are very good at solving specific tasks, such as engineering calculations, and can even make some quality assessments. But in the near future, computers will not be able to combine the five human senses and really understand the poetry of emotion that is a building" [5]. Interestingly, Andy Smith's opinion is quite common among representatives of design aid software producers. British Autodesk vice president Pete Baxter responsible for its architecture, engineering and construction operations in Europe, Asia and the Middle East believes that "technology won't destroy the profession, but it will, democratise it. There's a paradigm shift now: the one-man architect working from home with a bright idea now has access to an infinite amount of computing power in the cloud. That means a one-man designer, a graduate designer, can get access to the same amount of computing power as these big multinational companies. So suddenly there's a different competitive landscape. [. . .] The architectural profession absolutely will still exist. [. . .] I think what's happening is we're getting a more collaborative approach. But ultimately somebody still makes the decision" [24]. Autodesk CEO Andrew Anagnost, adds that "Each era of automation, from the first industrial revolution through the present digital era, has created more jobs, not less. Why should we assume the new machine age—the new era of automation—will be any different?" [25].

The Australian philosopher Elizabeth Grosz also draws attention to another characteristic that an architect should have, that is the capacity "for exploration and invention, in recognition of the roles of architecture and knowledge as experimental practices" [26] (p. 171). It is a capacity in which the architects, looking at the world, "try to enhance what seems to be valuable, to correct what is disturbing, and to create anew what we feel is missing" [22] (p. 24). Thus, they react to the constant changes of the context, trying to capture the beneficial elements from it and constantly correcting those that are unfavorable. It appears that design, which to such a large extent is the result of feelings that hinder the designer and influence the shape of the building, is an insurmountable obstacle for machines. What is more, it seems to be an extremely difficult, although possibly simpler, task to react to changes in the context or design trends.

Artificial intelligence is a technology whose future development and refinement make it possible to consider the actual replacement of architects by computers. However, it is worth noting the opinions that "computers don't come up with innovations. People do. Even the computer itself is a human innovation. [. . .] A.I. facilitates the idea. It makes the idea possible. However, it doesn't come up with the idea in the first place. [. . .] The artificial intelligence itself cannot exist without the ingenuity of the people that created it. A.I. needs maintenance and updates, otherwise, it becomes outdated in its own time" [27]. The current quality of artificial intelligence, as well as the readiness of computers to perform very complex tasks related both to the design itself and to relating the designed buildings to the surrounding context, causes many people to doubt the possibility of developing it in such a way that it would be able to replace humans in particularly complex fields such as architecture. Polish architect Aleksandra Wasilkowska shared the following excerpt from her conversation with the so-called Cleverbot—an intelligent computer program that passed the Turing test:

"– What is the architecture of the 21st century?
– People are close to revolt.
– What can it be?
– The song of angry men.
– What will it be?
– I don't know, because I won't be alive then" [28] (p. 356).

The answers are perhaps disturbing in the context of the social role of architecture. However, they may just as well sound rather random and, in this case, indicate that the intelligence of modern computers still has a long way to go before they can not only design a building but create architecture. It is now more akin to the cryptic words spoken in ancient Greece by Pythia, which were ambiguous, confusing, and unclear, and the priests had to give them the correct interpretation. Overstating the role of design software while downplaying the role of architects is pointed out by Reinier de Graaf, an architect, architectural theorist, urbanist, and writer, who states that "computer programs have been developed that allow you to design boxes in an increasingly sophisticated way: Microstation, AutoCAD, Rhino, Revit, BIM [. . .] However, the final form is still given to the box in Excel" [29] (p. 84).

The growing role of artificial intelligence is also noted by the authors of the "Technology and Innovation Report 2021" who believe that this technology "can also use modelling and a lot of data to make predictions that mimic human intelligence. This alters the nature of jobs by increasing or reducing the number of tasks. Some jobs will disappear, but others will emerge—such as those requiring empathy, inventiveness and ethical judgements that need to be made by humans" [30] S. 38. It seems, therefore, that according to the authors of the report, the profession of architect, which requires creativity and ingenuity, is not threatened, at least for now. Currently, technology has a great influence on tools used by architects and thus indirectly influences architecture, and although many contemporary design solutions are possible due to technological progress, "technology doesn't have an impact on thoughts, ideas or decisions" [31] (p. 194). This stance is echoed by Reinier de Graaf, who believes that "the information revolution—the turning point of our time—has not changed buildings, only the way we use them, so its impact on architecture is limited. By breaking the link between buildings and what happens in them, digital technologies [. . .] do not elevate the status of architecture; they actually lower it" [29] (p. 81).

Another problem that currently prevents computers from taking over the tasks of an architect is the poor relationship between computers and humans and the lack of interaction. This seems to be confirmed by the words of German architect Walther Gropius, who already in the 1940s said that "architecture requires strong convictions and leadership skills. Its form cannot be determined by clients or opinion polls. The results most often boil down to a desire to preserve what everyone already knows very well" [32] (p. 128). Gropius himself, moreover, believed that "the artist is the prototype of the 'complete' man; his freedom and independence are relatively intact. Intuitive sensing should be the antidote to mechanisation gone too far, ideally working to bring life back into balance and give a human dimension to machine influences [. . .] The contribution of the creative artist, whose art can more fully express the visual as well as the human appeal of planning, is essential" [32] (pp. 218–219).

People who express their opinions on the future of the architectural profession are undoubtedly aware of the continuous and unstoppable development of computer technologies, which will have an increasing impact on the design process. At the same time, they very often exclude the complete takeover of the architect's tasks, postulating that computers will be an increasingly effective complement to the architect's skills, allowing for more efficient, faster, and more accurate work. Dale Sinclair, Director, Architecture, Technical Practice, AECOM, agrees that "by automating aspects of the design process, such as creating multidisciplinary digital libraries that contain fabrication-ready information, more time can be spent on the design effort that makes a building unique in response to the client's brief and relevant to its environment" [5]. He compares the art of design to music, in which "musicians have embraced new instruments from the electric guitar to synthesisers and onwards to automated composing tools, as delivery of their outputs has shifted from albums to streaming. Yet the role of the composer remains unaltered" [5]. There are also claims that despite the significant developments in computer technology and artificial intelligence, "it doesn't have to mean that it causes job losses. As with any new technology, it's likely that A.I. will create just as many jobs as it displaces" [27].

There is another indication that the rise of computer technology will not result in the end of the architectural profession. As reported in the National Council of Architectural Registration Boards' annual survey, the number of licensed architects has grown in the USA by 1% from 2018 and by 10% from 2010 [33]. "While the number of architects licensed in the United States has risen over 13% in the last decade, the total U.S. population has risen just 7%, according to data from the U.S. Census Bureau" [34]. There is even more significant growth in the number of architects in Europe. Between 2008 and 2018 "the total number of architects has grown by 24%" and "reached in 2018 the number of 562,000" [35] (p. 4).

Although the above data does not cover the whole world, it shows that in highly developed countries, where e.g., the use of BIM technology is mandatory in a large proportion of projects and the percentage of construction companies that use BIM ranges from 20% (Austria) to 73% (United Kingdom) [36], the number of architects is increasing. This is despite the fact that in recent years there has been a rapid development of design support technologies like BIM [37], which originated in the 1980s [36].

3.2. Yes

Despite the prevailing view that the computer will not—at least for the time being—be able to replace people in the field of architecture, there are, however, also those who predict a more or less imminent end to the architectural profession. As early as 1943, Walter Gropius noted that "more than 80% of all American buildings are erected without the involvement of an architect" [32] (p. 112). Therefore, in theory, an architect is not needed to design buildings or even fine architecture. Many famous designers never received an architectural education. These include Mies van der Rohe, Le Corbusier, Louis Sullivan, Peter Zumthor, Luis Barragán, Buckminster Fuller [38], and Tadao Ando [39] (p. 131). Moreover, in some countries, e.g., Ireland, the opening of an architectural design studio depends on the payment of appropriate insurance, not on the possession of an architect's diploma. De Graaf also cites the example of the automated architecture of housing estates in the GDR, where "architecture ceased to be a matter of individual talent (and thus the exclusive preserve of the lucky few blessed with this gift), it came down to the mastery of certain know-how, from an innate skill to an acquired one. [. . .] East Germany [. . .] eliminated the need for the architect as a great builder and turned the entire surface of the country into a great exhibition of achievements made possible by his absence" [29] (pp. 61–62).

Despite the turbulent history of building design, the architectural profession continues to exist and, despite the onslaught of information technology, it seems safe for the time being. Nevertheless, some architects like Krzysztof Ingarden believe that "further technological development, in particular the automation of design and construction processes, may go so far that it will be possible in the near future to replace man by machines, both at the design and construction stage" [40] (p. 23).

Ian Keough, CEO of HYPAR in his foreword to Randy Deutsch's book *Superusers: Design Technology Specialists and the Future of Practice* links the future of the architecture profession to so-called superusers, who believe that "much of what we do in architectural practice can and should be automated, but they work in a profession which has its roots in an artistic tradition spanning hundreds of years. This tradition assumes [. . .] erroneously, that the act of 'design' is irreducibly human" [41] (pp. xi–xii). Admittedly, Keough does not say that computers will be able to completely replace humans, but he doesn't rule it out either. Randy Deutsch agrees with him and says "that the architecture profession and design industry will look radically different by 2030; and design technology specialists—a particular high-performing, high-functioning, highly connected, and highly motivated vocal minority here called Superusers—represent the near future of our industry" [41] (pp. xix–xx).

The greatest hopes for the development of design capabilities by computers are related to the evolution of artificial intelligence, especially the emergence of strong AI, also called artificial general intelligence (AGI), which, according to some researchers, will lead to the creation of the so-called artificial superintelligence. "As estimated by recognised AI scientists such as Kurzweil and McCarthy, once the strong AI is achieved, it will not take a long time for them to surpass human intelligence. The key point of strong AI is that it will be able to learn by itself, and therefore upgrade itself on its own, without any instructions from human agency" [42] (p. 18). Computers would then gain something akin to a human brain, although currently, the human organ is still full of mysteries. A better understanding of its properties may in the future be used to create computer programs that not only work on algorithms prepared by humans but also create them themselves. Wasilkowska gives the example of work on the BMI (brain–machine interface) and suggests that "if we perfect the method of a more precise mapping of our thoughts on the basis of brain activity, we will be able to transfer this information to the receptors of mechanised and intelligent architecture. Maybe knowledge about our state of consciousness combined with robotics could in the future allow for a wider definition of architecture" [28] (p. 357).

It seems that without achieving the advances in the development of computer algorithms described above, it will be impossible to eliminate the work of architects even though technologies are now emerging that allow the computer to perform some of the architect's tasks. They are becoming increasingly visible in reading the context for future buildings and suggesting very preliminary blocks, devoid of actual architectural expression, which nevertheless meet spatial and legal requirements. Their further processing remains the domain of architects. Nevertheless, there are claims that "applied mathematics can decipher the architectural context of space" [43] (p. 88).

Describing the latest technologies designed to make architects' work easier and faster, it is worth mentioning that the company Flux has prepared a modeling tool in which parametric buildings are automatically adjusted to the site constraints and official requirements resulting from the spatial context. This creates design "'building seeds' which generate different buildings in various contexts" [44]. "In the software they managed to automate the import of building and urban codes, therefore on the basis of contextual information the application is also able to generate 'buildable envelopes on the site'" [45] (p. 113). Although the object generated in this way fits in with the surroundings in terms of scale and mass, it still cannot be said that the program has succeeded in shaping architecture. Dana Nidal believes "that AI will be less likely to replace architect, and in terms of architecture practice it will provide new methods that adopt to future demands of people" [46] (p. 2).

Certainly, the growing computational possibilities in the future will make it possible to adjust the urban planning parameters so that they meet one of the most important criteria for the client, i.e., maximum return on investment. Mechanisms of learning or remembering may consequently allow for a preliminary rejection of such solutions, which are currently considered 'pathological' despite meeting formal requirements. This means that computer programs could make it possible to create better architecture coherent with the environment, independent of human weaknesses and temptations, e.g., financial ones. The preliminary building forms created in this way could also become the basis for further design processes that would be performed by computer software, especially for parametric or generative design. After all, it is already possible to create multiple variant concepts by generating sequential spatial sequences without requiring hours of work by a team of people. Nevertheless, the final decision as to the choice of the final version of the building's architecture that best meets the requirements of the spatial order, as well as the expectations of the client and the users, is up to the architect at the moment.

However, developments in AI may change the situation described above. Some architects and architecture critics believe that parametric design already takes away part of the creative process from the architect, sometimes leaving the human only to choose the best option proposed by the algorithm. Reinier de Graaf mentions this when he says that "by partially ceding the creation of form to computers, the antibox has elevated the production of extravagant shapes beyond any imaginable limits. What was still a conscious reflection on the concept of form in the early boxes has turned into a lottery. The question of authorship has become relative—since creation has been taken over by algorithms, the main joy offered by the antibox is the surprise it gives its designers" [29] (pp. 94–95). If he is right, then we are closer to replacing architects with computers than many pessimists think. This point of view is moreover echoed by Randy Deutsch AIA, LEED AP, Associate Director, Graduate Studies, School of Architecture, University of Illinois Urbana-Champaign, who notes that current "generative design has its own aesthetic, and for many it's is an acquired taste [. . .] Here, there is nothing for us humans to do but to accept the aesthetic of optimisation (however defined by those providing the computer input) because ostensibly what the machine generates is perfect—and it is up to us humans to allow the aesthetic to grow on us" [5].

The ease with which algorithms can generate further variants can be alongside or completely outside of the usual patterns to which the machine is not attached in any way. Thus, the probability of an original result is increased, at least early in the computer-designer's career. The competition and the number of objects created so far in each of the considered architectural scales are so large that it is difficult for the author to create original solutions all the time, which is currently a prerequisite for success in this industry. The computer can help solve this problem, but in some cities, the extravagance level of modern buildings is often so high that architecture hitherto perceived as 'boxy' becomes, according to De Graaf's aforementioned 'antibox' claim, a form of denial of previous achievements. Computers that will be deciding on architectural forms in given locations in the future will have to know the difference between acceptable and sometimes desirable originality of form and a block that does not fit into the context and introduces spatial chaos. Legal issues also remain, and who would actually have the copyright to the computer-generated designs—the owner of the software license, its manufacturer, or the software itself.

For now, it seems that the acceptable participation of the computer in the design process concerns automated processes that merely assist the architect but leave the architect with the final decision on the architecture. Allowing algorithms to be more intrusive in the design process will require a change in people's mindsets and readiness to accept such generated architecture. However, we cannot fool ourselves into thinking that architects these days only create good designs. Reinier De Graaf gives a very harsh assessment of the quality of most buildings currently under construction. He notes that "most of the buildings being erected today are stunning in their indescribable ugliness. They make up an endless collection of cheaply made buildings, harnessed to an endless bloodless competition to earn the highest possible return on the lowest possible budget" [29] (p. 25). It is possible that the acceptance of the new, computerised aesthetics will not be such a big problem for human buyers, especially since the final approval of the design, at least for now, is made by people—the investor and officials.

4. Theoretical Requirements for Computers to Replace Architects

According to Frey and Osborne, computers that are to replace humans in the future must be able to perform tasks that include simulating human perceptivity, human movements (manipulation tasks), must be able to handle creative intelligence tasks and social intelligence tasks [16] (pp. 24–26). While the ability to simulate human movements is not necessary to replace architects in design, the other skills seem essential. The senses enable architects to feel their surroundings. Without the senses, the concept of genius loci would not exist, i.e., the idea of the spirit of a place, which is expressed by "giving individual quality to particular places—objects, houses and complexes, cities, gardens and whole landscapes" [47] (p. 228). The senses are also essential to be able to experience beauty which is an indispensable component of architecture. Computers, that have no senses, could be capable of designing buildings but it is unlikely that they would ever be able to consciously design works of architecture.

Technologies that deal with computer perception have been under development for many years and, as a result, there are algorithms created that enable facial and voice recognition or that make it possible, still in a limited way, to communicate with devices. The latter group includes i.e., the so-called virtual assistants such as Siri developed by Google, Alexa by Amazon, Cortana by Microsoft, S Voice by Samsung and Google Assistant. In the field of architecture and urban planning, algorithms are now becoming better at dealing with such tasks as object recognition and categorisation, 2-D and 3-D modeling, or tracking and visual servoing. There still remains a challenge to properly understand the spatial context and draw conclusions to be able to create a design. It seems that improving the ability to recognise and characterise the environment is not a big difficulty at this point, as it most likely only requires improving the existing algorithms, increasing the power of processors and the amount of memory to collect enough spatial data. The real issue, still unsolved, remains the lack of sensitivity of computers to beauty. The above is a complicated task as the concept eludes measurable criteria and, at this stage, there is no mathematical formula that could be used to enable the computers to take over.

Another necessary requirement that would enable replacing architects with computer algorithms is to design creative intelligence to translate sensations and experiences into the language of architecture. Designing is, after all, an act of creation. While one can see increasing progress made in the field of artificial intelligence in such areas of art as literature, painting, and music [48]. "AARON, a drawing program, has generated thousands of stylistically-similar line-drawings, which have been exhibited in galleries worldwide. Furthermore, David Cope's EMI software composes music in many different styles, reminiscent of specific human composers" [16] (p. 26). It is still rather a collaboration between a machine and a human being than independent action. John Spacey believes that to end this dependence in the future, it will be necessary to develop a superintelligence with elements of consciousness such as intentionality, which theoretically can be developed with the use of recursive, self-improving program [49]. Self-adaptive systems will likely do very well in the field of architecture because they are inherently creative, their adaptations are unique and useful because of the unique situation to which they respond [50] (p. 10). Superintelligence is "foreseen as the last step of AI technology, it is considered as the milestone of the technological singularity in the future. At these further steps, it might be possible for artificial intelligence to develop an advanced form of artistic creativity" [42] (p. 77). However, Frey and Osborne find that "generating novelty is not particularly difficult. Instead, the principal obstacle to computerising creativity is stating our creative values sufficiently clearly that they can be encoded in a program [...] Moreover, human values change over time and vary across cultures [...] Thus, even if we could identify and encode our creative values, to enable the computer to inform and monitor its own activities accordingly, there would still be disagreement about whether the computer appeared to be creative" [16] (p. 26).

This also raises the question, which coincides with the concerns of architects Peter Zumthor or Juhani Pallasma, expressed in previous chapters, that "if there is no initial intention to express a feeling, an aesthetical point of view, or any personal statement per se, can we still mention the existence of an artistic creativity" [42] (p. 72)? This is an important question, because even when computers will be able to design buildings on their own, there may be voices saying that this is still not architecture, since it was created without emotions. However, Deniz E. Kurt believes that "despite the absence of an initiative emotional expression of the maker, the flow of affect will occur through a bottom-up perspective, and the 'feeling' of an artwork will be shaped through the emotional attachment of the human spectator" [42] (p. 73). Thus, in such a case, "AI is the actor who generates the artworks by using its own interpretation" [42] (p. 74). "Hence, for AI artworks to be recognised as artistically creative, they should correspond to the human taste of aesthetics and human emotions. The absence of human emotions in a machine is an intrinsic feature that gives the aura to the artwork of that machine" [42] (pp. 75–76).

Questions also arise about the copyright of designs created by computer programs [42] (p. 58). However, it must be acknowledged, that controversy is also associated with projects created by people. Peggy Deamer in her works points out many problems concerning employment in architectural firms. She also notes that architects are responsible for an important, but limited, part of a building's design. "In architecture, unlike the other arts no one person actually makes the object. Not only is there the significant distinction between designer and builder, or the multi-layered group of designers in an office, but the designers/manufacturers of the myriad of products used for a project bring the history of their own making with them" [51] (p. 17). Another issue is the multi-discipline nature of building design, where only part of the process falls to architects, but there are also structural engineers, installation designers, road engineers, etc. This contributes to the complexity of design and makes it difficult for computer algorithms to take over all of their skills. Nevertheless, design is a process that requires social intelligence. In this case, it is used, among other things, during the usually lengthy arrangements and negotiations with the client. They take place not only before the design work begins. Instruction changes occur even at an advanced design stage and are often necessary even during construction. Assuming that a computer algorithm would be responsible for the entire design process, which would eliminate the experts, technologists, and collaborators working with architects, social intelligence would still be indispensable for the reasons above. This view is supported by Frey and Osborne, who noted that computers that would design buildings must be able to talk to clients, have negotiation skills, and perhaps manage human resources [16] (p. 27). Andy Smith, Director of Product Management, Building Solutions, Bentley Systems, agrees with this sentiment, saying that the architect, after all, "needs to communicate the design intent to the client, explain why he or she chose certain things, and then evaluate the responses of the client's emotions and business sense to the design. That is a human interaction that needs to happen" [5]. In addition to negotiation skills, human social intelligence includes skills such as persuasion and caring [16] (p. 26). While computers "can now reproduce some aspects of human social interaction, the real-time recognition of natural human emotion remains a challenging problem, and the ability to respond intelligently to such inputs is even more difficult. Even simplified versions of typical social tasks prove difficult for computers" [16] (pp. 26–27).

At this point the problem of ethics also arises, which means the ability to take actions focused not only on a specific goal, such as making money or completing a project at any cost, but also responsibility for the users of the designed building and its impact on the environment. Benjamin Kuipers believes that "artificially intelligent creatures (AIs) [. . .] may increasingly participate in our society over the coming years. In effect, they may become members of our society" [52] (p. 98). Ronald C. Arkin and Alan R. Wagner make this eventuality contingent on robots recognising such moral emotions as dignity, guilt, trust, or even the ability to deceive. [53] (pp. 1–46). And although the basic laws of robotics were defined by Isaac Asimov as early as 1950. [54], and work on so called roboethics is now being undertaken by research institutions [55,56], robots and computer programs that control them are still unprepared to function in society. Kuipers believes that "the problem of providing robots with morality and ethics [. . .] draws on many different research threads in cognitive science, artificial intelligence, and robotics. These and other problems to be solved are difficult, but they do not appear [. . .] to be unsolvable. In the visible future, robots and other AIs are likely to have sufficiently useful capabilities to become essentially members of our society" [52] (p. 103).

As with creative intelligence, the greatest hopes for developing this technology are specifically related to the development of artificial intelligence. However, current estimates suggest that full human brain emulations should be possible before mid-century [57] (p. 81). The development of computer-aided design tools, as well as technologies that are likely to be developed in the future, are shown in Table 1.

Table 1. Development of software and technology for computer design.

Timeline	Type of Software/Technology	Software/Technology Capabilities
Past	2D Designing Software	drafting software to replace freehand drawing
	3D Designing Software	software enabling the creation of spatial structures used to generate particular parts of a design study
Present	Parametric Design	designing 3D structures and patterns following given parameters
	Generative Design	results-oriented design
	Building Information Modeling	3d modeling related to building model production, communication and analysis kit
	Building Life Cycling Modeling	modelling various aspects related to the life cycle of a building
	Augmented Reality	transferring virtual projects into real space using dedicated tools
	Neural Networks	forecasting phenomena based on initial data
	Machine Learning (ML)	collecting data and learning to use it under human supervision
	Artificial Intelligence (AI)	advanced machines and software based on neural networks and machine learning capable of solving complex problems
Future	Active Augmented Reality	real-time creation of spatial models in augmented reality
	Artificial General Intelligence (AGI)/ Strong Artificial Intelligence (SAI)	advanced machines and software based on neural networks and machine learning capable of solving complex problems
	Artificial Super Intelligence	highest form of computer intelligence that will enable the replacement of humans by machines, including architecture

5. Conclusions

The material presented in this manuscript shows recent developments in computer technology and their impact on the work of architects. It also provides deliberations of a wide group of experts on the future of that profession. It represents a rare group of papers that collects and interprets information about the impact of a wide range of technologies on the work of architects, and attempts to predict how this development will affect the profession in the future. Its novelty also lies in its effort to define requirements that could theoretically contribute to the elimination of architects' work. Although this paper is about the future, and thus cannot provide definite answers, it allows us to extract information that is certain and that may help us understand the future of this problem. A summary of this information is presented in the following items.

(a) The architectural profession, unlike some other occupations now being displaced by computer algorithms, requires wide-ranging competencies and skills, such as creative and social intelligence. Currently, computers do not have such capabilities, and thus do not have the potential to replace the work of architects.
(b) The future will see further development of computers and technologies such as machine learning, artificial intelligence, superintelligence and most likely others as yet undefined.
(c) The current development of computer technologies is not aimed at replacing architects, but at supporting, facilitating and speeding up their work. Therefore, it is difficult to expect that technologies which could replace architects' work will appear in the near future.
(d) People who accept the possibility of computers replacing the work of architects in the future, associate this eventuality with the development of such technologies as artificial superintelligence. It may be that the introduction of fully self-learning software will come closest to the goal discussed above, but it may also simply bring further, even more advanced improvements to the work of architects that will continue to be controlled by humans.

(e) Currently, it seems that occupations requiring creativity and social skills could be eliminated only as a consequence of creating an artificial brain with capabilities not inferior to the human organ.
(f) Although research on the human brain is now extensive, and we have increasing information about how it works, a complete understanding of its capabilities and limitations is beyond the reach of modern scientists. Without learning these principles and translating them into the language of computers, it is difficult to think of replacing architects with machines. Computers lacking the aforementioned skills or the ability to interpret information generated by the senses would, therefore, perhaps be capable of designing buildings but it is unlikely that they would ever be able to consciously design works of architecture.
(g) In view of the above considerations, it seems that the replacement of the architect by machines will be unrealistic in coming decades.

It seems that opinions coinciding with the above observation prevail among those presented in this paper. While usually more definitive, the no votes are nevertheless partly expressed by people who have never used computers, if only because of the times in which they lived. Individuals who are professionally involved in information technology are more likely to express the opinion that, however, in the future, algorithms will be refined enough to be able to replace humans in the design process. They see this opportunity primarily in the development of technologies such as machine learning and artificial intelligence. Computers that base their architecture on living matter, such as DNA or quantum computers, will get completely new capabilities. In 2009, In a *Scientific American* article, Martin Campbell-Kelly wrote that “no one knows what the computers of 50 years hence will look like. Perhaps their abilities will surpass even the powers of the minds that created them” [58] (p. 8). Such a scenario cannot be ruled out especially since “the pace of change seems likely to accelerate as a result of digitalisation and advances in ’frontier technologies’ such as artificial intelligence (AI), robotics, biotechnology, and nanotechnology (SDGs)” [30] (p. 3). However, even if computers do, in fact, eliminate architects in the future, it is still worth listening to the voices of the present and past skeptics. Sometimes, they also express concerns about the future of the human race in the clash with the growing role of computers or even about losing control over our lives. Those involved in computer technology should also take these voices into account and program computers with humility in such a way that they are a help to people, not a threat. It seems that due to the complex and multi-criteria nature of the architectural profession, replacing humans with machines will not be possible in the coming decades. However, it is likely that, eventually, technological developments will allow it. Until then, they should complement their work, which—at least for the time being—accelerates it and achieves greater and sometimes also innovative design capabilities.

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Contemporary Odeon Buildings as a Sustainable Environment for Culture

Kazimierz Leonard Butelski

Department of Architecture, CUT, Cracow University of Technology, Warszawska 24, 30-233 Cracow, Poland; kbutelski@pk.edu.pl

Abstract: The subject of this study is contemporary odeons in Poland, where 11 covered amphitheaters (odeons) have been built since 2005. The odeons were selected from a wider collection of 57 functioning amphitheaters. The study collected data on location, form, function, and construction. The data sources included the literature, archival research, design documentation, and competition entries. Descriptive and graphical comparative analyses of the phenomena, based on the statistics for completed structures and on design experiments in the case of unbuilt structures, were the two main research methods used in this study. The emergence and development directions of the typology of open cultural spaces from amphitheaters to odeons are presented in a global and regional context. Their interrelationships, affecting form and function, were also analyzed. The influence of high-end materials that were used to create these complex, large-scale spatial structures, and their impact on the environment, has been presented. The contemporary roofs covering the entertainment and stage complex were analyzed in relation to environmental factors, determining the location of the odeons. The functional aspects of these buildings and their cultural significance on a local, regional and global scale were discussed. The odeon in Biała Podlaska, built in 2019, was chosen as a case study to show, in detail, the complexity of the formation of contemporary odeons. In the discussion on the direction of the further evolution of open spaces for culture, an example of an unrealized competition design proposal of mobile roofing forms for the eighteenth-century amphitheater in the Royal Baths Park in Warsaw, Poland, was presented. The conclusions emphasize the environmental, spatial, functional, social and economic values of the establishment and functioning of contemporary odeons as open spaces of culture that are compliant with the principles of sustainable development.

Keywords: odeons; buildings; membranes; canopies; sustainable environment; open culture; spaces; evolution; adaptation; acoustics

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1. Introduction

Odeons appeared as public buildings in ancient times, as a part of an evolution in the typology of amphitheaters. This evolution consisted of covering the audience and the stage of the amphitheater with a roof. Their creation was closely related to Greek, and, later, Hellenistic and Roman culture. Most researchers define the original function of odeons as that of a musical theater. Some also believed that they could have served as a place for meetings of city councils in those cities that had no bouleuterions [1]. Thus, they were buildings that were associated with culture and democratic power. In the historical process from antiquity to modern times, the disappearance of political and administration functions in favor of those related to culture can be observed. However, contrary to the democratic genesis in antiquity, in the 1930s in Germany, amphitheaters were used for totalitarian Nazi propaganda. As part of the Thingplatz program, 1200 such venues were planned, of which 45 were built; the first was built in Halle in 1934 [2].

The siting of amphitheaters and odeons was most often connected with spatial pretexts, resulting from natural landscape features. One example of this is the ruins of Pericles' odeons from 442 BC and those of Herod from 115 AD on the slopes of the Athenian Capitol, and Agrippa's odeon from 15 BC on the Athenian Agora. The forms of odeons were based on the assumptions of open amphitheaters, and they differed from amphitheaters by covering the stage and the audience with a roof. In the conditions of the Mediterranean culture, with a mild climate, the reason for covering amphitheaters with roofs was mainly the acoustics [3].

As the typology of public buildings, such as amphitheaters, spread to other regions of the world, with less favorable climates, roofs became a necessity. Roofs made it possible to disregard rainfall and to use the space offered by the amphitheaters for longer. To be independent of temperature, walls also appeared, and the process of making buildings independent of the external conditions was completed. In this way, new typologies of cultural buildings were created, such as theaters, opera houses, concert halls, multifunctional halls, conference centers, and cinemas (in some countries of Western Europe and in the USA, nowadays called ODEONs). All of these public buildings that are dedicated to culture are among the most specialized structures that people create. The costs of their production and functioning are exceedingly high, hence they appear in the most developed and rich societies. The functional offering of these closed spaces of culture is varied and addressed, both to a narrow group of recipients and to the mass audience. In the latter case, the function of the events of culture and sport interpenetrates, hence the creation of, for example, multifunctional halls that are not infrequently intended for 20,000 visitors [4]. At the same time, however, one of the important values of odeons, which is contact with the natural environment, has been lost.

Today, amphitheaters and odeons, as open landscape spaces of culture, coexist with these highly specialized public buildings that are dedicated to culture.

The next stage in the development of open cultural spaces in the twentieth century was music festivals and religious events on a massive scale. During these events, the relationship between the audience and the stage, or multiple stages, benefited from the spatial experience of historic amphitheater systems supported by sound systems. Only temporarily built portable stages are covered with roofs. Events of this type generate the creation of ephemeral forms that exist for only for a few days. Due to the scale of these events, no odeons are built, because it is not possible to cover the audience dedicated to such a large number of people (mass cultural events in recent decades are as follows: 400 thousand people attended the rock festival at Woodstock in the 1960s, and in recent years in Poland (Kostrzyn and Odrą) 650 thousand spectators [5]. Six million pilgrims were in Manila, Philippines in 2015 [6], during the papal visit, and 2.5 million in Poland in Krakow in 2002).

The number of participants at such events many times exceeds the number of seats that were provided in all 57 of the amphitheaters analyzed in this study, which totals 114,816 spectators. These data indicate a significant relationship between the scope of the functional program and the sustainability of the form over time. Therefore, this paper omits large outdoor concerts and religious meetings, the spatial analysis of which requires a separate study because it does not correspond both functionally and spatially to the analyzed structures of cultural spaces, such as amphitheaters, and their final form of evolution—odeons.

Over the last 15 years, 11 odeons in the classical sense of this typology—i.e., in the form a stage and an auditorium covered by a roof or several roofs—have been built in Poland. The importance of odeons as open cultural spaces for sustainable cultural development in Poland is the subject of this paper. This work is holistic in nature, and deals with the environment in cultural, technical, and landscape aspects.

2. Materials and Research Methods

The main research material consisted of 57 amphitheaters built in Poland, from which a group of 11 odeons was selected. This selection was based on the definition of an odeon as an amphitheater in which the stage and auditorium are covered with a roof. Therefore, buildings with a covered stage, but no covered auditorium, or with an auditorium only partially covered were rejected. This was based on a review of the literature, in situ studies of completed buildings and projects. To show the delayed genesis of this spatial form, the historical development of open cultural spaces in Poland, starting from democratic political meetings to elect the king, was discussed. Relevant geographical conditions specific to the study area in relation to the creation of odeons have also been presented. A descriptive and graphical comparative analysis of phenomena for completed buildings based on statistics and an analysis based on design experiments in the case of unbuilt buildings are the two main research methods used in this study.

On the basis of the case study of the completed odeon in Biała Podlaska Figure 1, the paper presents the characteristic elements related to the complex approach to the construction of this type of object. A discussion based on unbuilt competition designs was also undertaken about contemporary trends on the example of transforming the oldest eighteenth century amphitheater in Poland into an odeon. On the basis of the materials gathered in this way and the research methods applied in their preparation, final conclusions were formulated in the aspect of the odeon as a contemporary example of a cultural open space created in conditions of sustainable development. This study focuses on the period after 1989 because it was a turning point in modern Polish history, which gave input for the creation of many open cultural spaces, such as amphitheaters and odeons.

Figure 1. Cultural environment of the odeon in Biała Podlaska, aerial view. Photo: Stanisław Butelski 2019.

2.1. Historical Analysis of the Development of Amphitheaters and Odeons on the Territory of Poland

Cultural diversity in a globalized world is a value, worth of preservation. The culture, geography, and history of Poland are fundamentally different from those of Greece, where the odeons originally arose. The contemporary forms of odeons in Poland are therefore the result of a long evolution and a process of architectural enculturation. Odeons were popularized by Roman culture, especially in the Western Empire. This phenomenon is well illustrated by Figure 2, which shows the distribution of amphitheaters in the Roman Empire [7]. Poland was never part of the Roman Empire, and the appearance of amphitheaters and odeons on its territory was significantly delayed relative to their time of origin. We can look for the first odeon-like buildings in connection with the political system. The origins of the Polish state date to the tenth century AD and are associated with the adoption of Christianity from the west. From the sixteenth to the end of the eighteenth century, Poland, through a personal union with Lithuania, was a European power. The state system was democratic, and the monarch was elected.

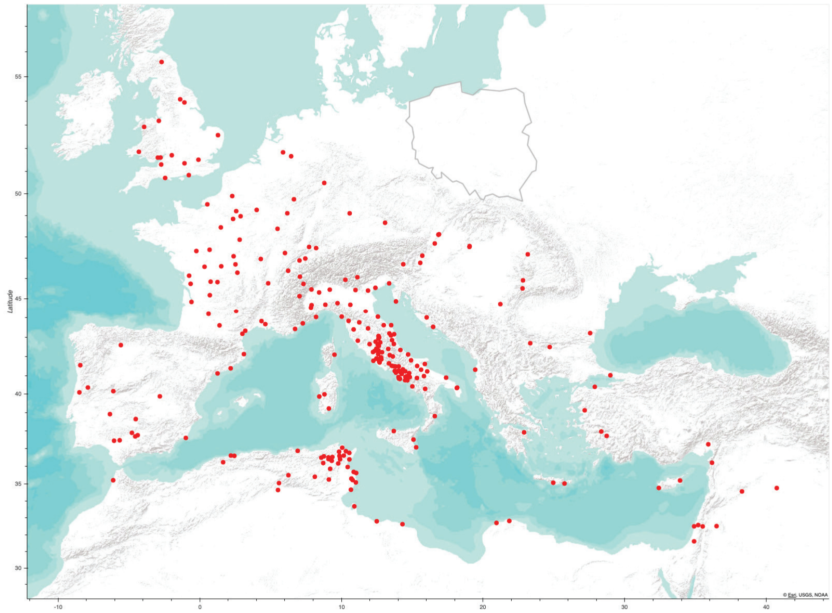


Figure 2. Distribution of amphitheaters in the Roman Empire. Adapted from ref. [8].

The election of regional representatives in individual provinces took place in churches (as public places were likely to gather the largest number of people), while the king was chosen in the electoral field. The electoral field, together with its associated temporary buildings, can be considered as one of the prototypes of modern odeons corresponding to the function of ancient buleuterions. The number of voters taking part in the election ranged from 12,000 to 50,000, so spatial organization was crucial in those times to hold a smooth presentation of issues, debate, and vote, as shown in Figure 3.

If we are talking about buildings for cultural purposes, then the Operalnia is considered to be the first permanent theater facility built specifically for this purpose in Poland. It was built in 1725 (the Operalnia building existed from 1725 to 1772 in Warsaw on Królewska Street) in Warsaw [9] on the initiative of King Augustus II the Strong of the House of Wettin. The author of the Operalnia building remains anonymous.

The first and most famous amphitheater in Poland, as presented in Figure 4, was opened in 1791 and is located in Warsaw in the park called the Royal Baths. The Royal Baths Park was created in 1764 on the initiative of King Stanislaus August Poniatowski as the surroundings of the royal summer residence, the so-called Palace on the Isle, and was an exemplification of the modernizing and modern concepts advocated by the last Polish king. The author of the amphitheater design was Jan Chrystian Kamsetzer, who had been born in Dresden. This building, which was a part of the park layout, in its architecture, referred to the ruins of Herculaneum and the Roman Forum [10]. One characteristic feature of this Romantic and Classicist complex was the location of the stage on an island, thanks to which the water separated it from the audience and constituted a background for the stage. Poland lost its independence at the end of the eighteenth century and remained partitioned throughout the nineteenth century. As a result of the First World War, Poland regained its independence. After the Second World War, it fell under Soviet occupation and lost its independence and territory in the east and reclaimed territories in the west. Several amphitheaters from the German Thingplatz program have been preserved in this western part, e.g., one of the largest for 20,000 spectators on St. Anne's Mountain. The totalitarian system came to an end in 1989 and since 2004, Poland has been a member of the European

Union. The year 2005 can be considered the cut-off date for the increase in the number of amphitheaters and odeons in Poland. There are currently 954 cities in Poland, 60% of the country's population lives in cities, and the population density is 125 people/km2. As many as 556 cities are under 10,000 population. The largest city is Warsaw (population: 1,790,658) and the smallest is Opatowiec (population: 338) [11].

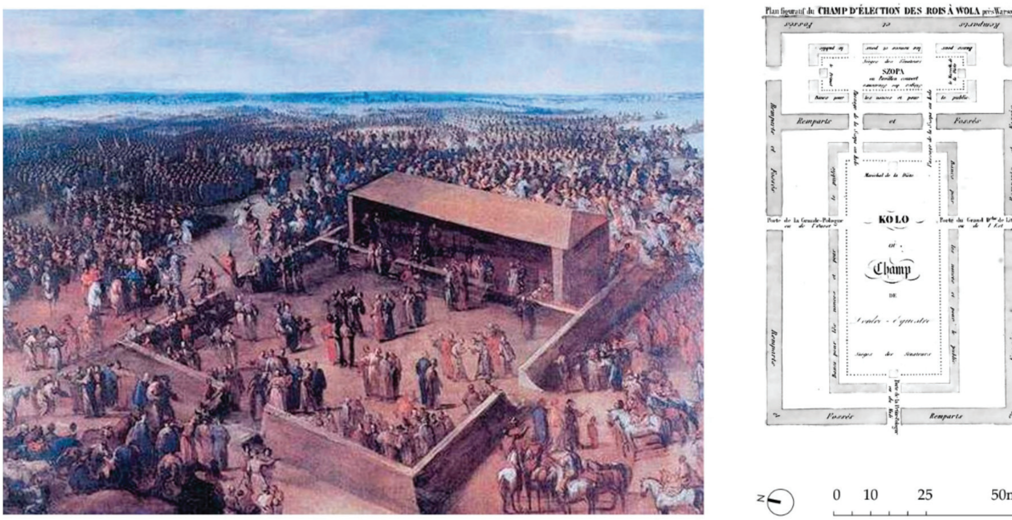


Figure 3. The author's graphics—the electoral field with a temporary building for senators called "The Shed", based on the painting *The electoral field of 1764* Author Jean-Pierre Norblin de La Gourdaine. Adapted from ref. [12]. Adapted from ref. [13].

Figure 4. *Amphitheatre in the Royal Baths Park*. Jan Piotr Norblin, watercolor, 1789–1791. Reprinted from ref. [10].

2.2. Directions of Typological Evolution, from the Amphitheater to the Odeon

The group of open cultural spaces such as amphitheaters and odeons can be divided into the following:

a. The simplest buildings, with an uncovered auditorium and stage;
b. Of medium complexity, where only the stage was covered;
c. Highly complex, i.e., odeons, in which both the audience and the stage are roofed.

Originally, 57 amphitheaters were listed in Table 1. The amphitheaters and odeons were selected and compared with respect to certain features for the analysis of form, function, and construction and the mutual relationship between these elements to determine the relationship with the sustainable development of open cultural spaces in Poland. Moreover, in the urban and cultural scope, the size of the towns in which these objects were built, the date of construction or reconstruction, and the authors of the objects were determined. From a group of 57 objects of open cultural spaces in Poland, 11 odeons were distinguished, in which both the auditorium and stage are covered with a roof, supplementing the following tabular research data: the number of inhabitants of the locality where the object is located, the surface of the roof, the type of roofing, the typology of the construction of the form, the symmetry and asymmetry of the form, the graphic illustration of the location, the construction system used.

Table 1. Fifty-seven amphitheaters in Poland ordered by number of spectators. Number 1 in the cell means that the described factor exists. Author's research. Amphitheaters are shown on the map in Figure 5 following the numbers in column one.

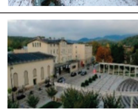
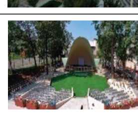
No.	Name	Place	Spectators	Year	Image of the Object	Maximum Roof Span	Roof over Audience and stage	Roof only over Stage	Roofless	Location	Typology
1.	The Concert Shell Jelenia Góra	Jelenia Góra	100	2008				1		Park	Amphitheatre
2.	Amphitheatre Opera Nova Bydgoszcz	Bydgoszcz	200	2006					1	Opera	Amphitheatre
3.	Amphitheatre Michałów	Michałów	210	2008				1		Lake	Amphitheatre
4.	Forest amphitheater in Lipnik near Bielsko Biała	Bielsko Biała	216	2021					1	Forest	Amphitheatre
5.	Amphitheatre Wałbrzych	Wałbrzych	216	2010					1	City center, Theater	Amphitheatre
6.	Summer Amphitheatre Tarnów	Tarnów	275	2018				1		City center	Amphitheatre

Table 1. *Cont.*

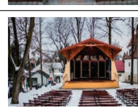
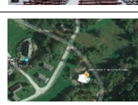
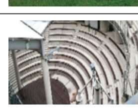
No.	Name	Place	Spectators	Year	Image of the Object	Maximum Roof Span	Roof over Audience and stage	Roof only over Stage	Roofless	Location	Typology
7.	Amphitheatre Konstancin Jeziorna	Konstancin Jeziorna	306	2009				1		Park	Amphitheatre
8.	Coloseo Zator	Zator	360	2014					1	Amusement Park	Amphitheatre
9.	Amphitheatre Bochnia	Bochnia	380					1		Park	Amphitheatre
10.	Amphitheatre Wilkasy Giżycko	Giżycko	400					1		Lake	Amphitheatre
11.	Amphitheatre Cekcyn	Cekcyn	400	2012				1		Lake	Amphitheatre
12.	Amphitheatre Bolesławiec	Bolesławiec	400	2017				1		Park	Amphitheatre
13.	Amphitheatre at Stary Dwór	Stary Dwór	432	2010				1		Lake	Amphitheatre
14.	Amphitheatre Gardeja	Garedja	450	2012					1	Lake	Amphitheatre
15.	Amphitheatre Tuchów	Tuchów	480	2013				1		Park	Amphitheatre
16.	Amphitheatre Zubrzyca Górna	Zubrzyca Górna	500					1		Open–Air Museum	Amphitheatre
17.	Amphitheatre in Wygiężłów Ethnographic Park	Wygiężłów	500	2011				1		Park	Amphitheatre
18.	Amphitheatre Podlasie Opera and Philharmonic Białystok	Białystok	550	2012				1		Opera	Amphitheatre

Table 1. *Cont.*

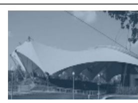
19.	Amphitheatre Park Zadole Katowice	Katowice	800	2005				1		Park	Amphitheatre
20.	Amphitheatre Piotrków Trybunalski	Piotrków Try-bunalski	800	2014				1		Park	Amphitheatre
21.	Amphitheatre Wąbrzeźno	Wąbrzeźno	840	2018				1		Lake	Amphitheatre
22.	Amphitheatre Siemianowice Śląskie	Siemianowice Śląskie	900					1		Park	Amphitheatre
23.	Amphitheatre Czeladź	Czeladź	900	2019					1	Park	Amphitheatre
24.	Amphitheatre Ustronie Morskie	Ustronie Morskie	900					1		Park	Amphitheatre
25.	Amphitheatre in Łazienki Królewskie-Warsaw	Warszawa	950	1791					1	Park, Pond, Island, Palace	Amphitheatre
26.	Michel Jackson Amphitheatre Bemowo Warsaw	Warszawa	960	2008		60	1			Park	Odeon
27.	Amphitheatre Biała Podlaska	Biała Pod-laska	1000	2019		45	1			Park, Palace, Fortress	Odeon
28.	Amphitheatre Zamość	Zamość	1000	2012					1	Fortress	Amphitheatre
29.	Amphitheatre Hajnówka	Hajnówka	1000	2015				1		Park	Semi Odeon
30.	Amphitheatre Szczyrk	Szczyrk	1000	2012				1		Ski jump	Amphitheatre
31.	Amphitheatre Władysła-wowo	Władysła-wowo	1100					1		Amusement Park	Amphitheatre
32.	The concert shell in the Saxon Garden Lublin	Lublin	1155	2019				1		Park	Amphitheatre

Table 1. *Cont.*

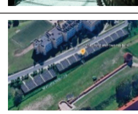
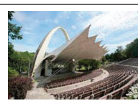
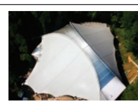
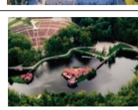
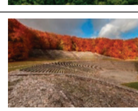
33.	Proszowice Town Amphitheatre	Proszo-wice	1200	2020				1		City Centre	Amphitheatre
34.	Czesław Niemen Amphitheatre Olsztyn	Olsztyn	1250						1	City, Castle	Amphitheatre
35.	Amphitheatre shell Sosnowiec	Sosnowiec	1700	2020				1		Park	Amphitheatre
36.	Amphitheatre Augustów	Augustów	1714	2013				1		Lake	Amphitheatre
37.	Amphitheatre Wejherowo	Wejherowo	1800						1	Park	Amphitheatre
38.	Amphitheatre of the Wolski Cultural Centre in Sowińskiego Park in Warsaw	Warszawa	2000	2019		70	1			Park	Odeon
39.	Amphitheatre of the Virgin Mary, Star of the New Evangelization and Saint John Paul II in Toruń	Toruń	2000	2016					1	Church, river	Amphitheatre
40.	Amphitheatre Świecie	Świecie	2000					1		City Centre	Amphitheatre
41.	Amphitheatre Ostróda	Ostróda	2500	2012		78	1			Lake	Odeon
42.	Stanisław Hadyna Amphitheatre Wisła	Wisła	2500	2009		58	1			Park	Odeon
43.	Amphitheatre in Ustroniu	Ustroń	2500	2008		55	1			Park	Odeon
44.	Marek Grechuta Amphitheatre Świnoujście	Świnoujście	2700	2010		58	1			Park	Odeon
45.	Open Air Auditorium Malbork	Malbork	2880	2010					1	Castle	Amphitheatre

Table 1. *Cont.*

46.	Amphitheatre in Boyen Fortress Giżycko	Giżycko	3200	2018				1		Fortress	Amphitheatre
47.	Amphitheatre Płock	Płock	3500	2008		63	1			River	Odeon
48.	Millennium Amphitheatre Opole	Opole	3800	2011				1		River, Island, castle	Semi Odeon
49.	Ignacy Jan Paderewski Amphitheatre Koszalin	Koszalin	4500	1976		106	1			Valley, Park	Odeon
50.	Helena Majdaniec Summer Theatre Szczecin	Szczecin	4500	2021				1		Park, pond	Semi Odeon / Odeon
51.	Amphitheatre Kołobrzeg	Kołobrzeg	4500	1968				1		Fortress	Odeon
52.	Anna German Amphitheatre Zielona Góra	Zielona Góra	5000	1970				1		City centre	Amphitheatre out of service
53.	Forest Opera Sopot	Sopot	5047	2012		107	1			Valley, Forest	Odeon
54.	Amphitheatre on Lake Czos Mrągowo	Mrągowo	5280	2012				1		Lake	Amphitheatre
55.	Amphitheatre Kadzielnia Kielce	Kielce	5500	2010		90	1			Quarry, Forest	Odeon
56.	Amphitheatre in Dolina Charlotty	Słupsk	10,000	2007					1	Valley, lake	Amphitheatre
57.	Monument and amphitheater on Mount Saint Anne	Góra Świętej Anny	20,000	1934					1	Quarry, Forest	Ruin

Odeons are the most typologically advanced among amphitheaters and are characterized by covering both the stage and the audience. In addition, an intermediate group can be distinguished, in which the entire stage and part of the audience is covered. One of their noticeable and characteristic features is the lack of buildings with only the auditorium covered. The evolution from simple open structures through medium complexity to the final form of odeons, where the auditorium and the stage are covered with a roof, is a clearly observable evolution trajectory. There have been many iterations of this process, during which, as spatial complexity increased, the existing elements of the auditorium and stage were adjusted and sometimes completely remodeled when the roof was built. In the case of the two largest Polish odeons in Koszalin and Sopot, the existing roof covering was also remodeled. The reconstruction of a previously functioning large amphitheater into a completely enclosed building, an example of which is the intention to build a concert and conference hall for about 1800 people in Zielona Góra, is an extreme case.

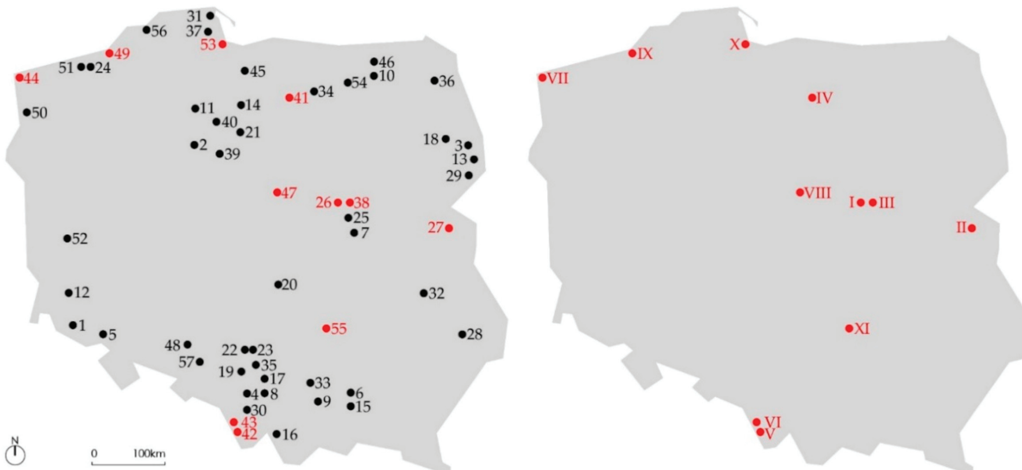


Figure 5. (**Left**): location of 57 amphitheaters and odeons in Poland (number following Table 1, odeons marked red). (**Right**): location of 11 odeons (numbers follow Table 2). Original research.

All the odeons analyzed are characterized by being outside city centers in relation to the landscape. We can compare their functioning with concert halls located within the city structure. In concert halls, we can often notice a strong relation between the space of the concert hall foyer and its foreground, which extends the influence of such buildings beyond their physical boundaries. In the case of odeons, there is no foyer, whose function is taken over by the open landscape, leading to a strong integration of these structures with the surrounding nature. Just as concert halls and their forecourts are often part of city space, in the case of odeons they are part of the surrounding landscape. In this arrangement, the canopies of the odeons are merely the culmination of the performance space. Transport service in odeons is connected with this issue. The access to odeon facilities has therefore a different landscape character than in the case of concert halls, and parking spaces for odeons are a part of parking spaces dedicated to a larger area, e.g., a park, and not for a single facility, similarly to public transport services. As a consequence, we have to deal with the dispersion of traffic streams over a considerable area, helping to discharge them without culmination, in short intervals of time.

2.3. Aspects of Odeon Siting

Poland is located in the moderate climate zone, with influences of air masses from the Baltic Sea stabilizing the temperature. Terrain is flat except for the mountains in the south, on the border with the Czech Republic and Slovakia. In the western part, the climate is slightly warmer, with Atlantic influences, and in the east, it is colder and more continental. The climatic differences between Greece, where odeons originated, and Poland are important from the point of view of the subject under discussion. In a preliminary study, the possible length of use of amphitheaters was determined considering average monthly temperature. Assuming a minimum temperature of 18 °C, the season for outdoor performances in Greece lasts for 8 months from April to November, and in Poland for

5 months from May to September. This data should be contrasted with rainfall data. The amount of rainfall in Greece is high at the beginning and the end of the outdoor season, but in the middle of the season it almost disappears. In Poland, on the other hand, the amount of rainfall at the beginning and the end of the shorter 5-month season is high, but in contrast to Greece it increases and reaches its absolute maximum in the middle of the outdoor season. Therefore, roofing outdoor stages and auditoriums in Poland is a necessity if they are to function during the season without getting wet.

Even the territorial distribution of amphitheaters is shown on the map of Poland in Figure 5; even the territorial distribution of amphitheaters indicates that there are no regional differences in the occurrence of this function. Among the localization factors, there are various spatial pretexts, both natural and cultural. Natural pretexts include, e.g., the geomorphology of the terrain in the form of valleys, mountains, lakes, forests, rivers, islands, and lagoons. The cultural pretexts for locating amphitheaters and odeons include city centers, fortifications, quarries, churches, opera houses, palaces, parks, castles, but also such structures as ski jumping platforms—see Table 1.

The location is always accompanied by at least one of the indicated factors, often there are several of them, which increases the attractiveness of the objects. An example of such a location with multiple pretexts is the oldest known Polish amphitheater in the Royal Baths Park in Warsaw, located in the park near the palace on the island and the lagoon. The most common pretext for siting amphitheaters is in parks, which was the case in 24 of the surveyed cases, and by lakes or rivers in 15 cases. Contact with nature and making use of its values is therefore one of the basic values when making a siting decision about building an amphitheater or odeon.

In terms of detailed analysis in relation to odeon locations, their orientation in relation to the direction of the world was also studied Figure 6. As a result of this research, it was found that there is no uniform rule in this regard. In the case of the Forest Opera in Sopot, the stage is on the north side of the odeon, in Koszalin, on the southeast side, in Ostróda on the west side, in Płock on the south side. The direction the stage faces in relation to the cardinal direction is determined by the shape and attractiveness of the surroundings and not by its location in relation to the cardinal directions. Additionally, it should be noted that the roofing function can be used to correct lighting conditions, especially regarding the glare resulting from the unfavorable position of the audience in relation to the sun. Moreover, some of the activities hosted by odeons occur after dark, so this issue does not arise.

The distribution of odeons in Poland concerns cities of different size—as demonstrated in Table 2—such as Kielce with a population of almost 200,000, Płock with about 100,000, and Koszalin with about 60,000, and 30,000 in Biała Podlaska, Ostróda, Sopot, Świnoujście, or small ones with populations between 16,000 to 11,000 such as Ustroń and Wisła. The exceptions are those located in Warsaw's districts of Bemowo and Wola. However, if we compare the number of inhabitants of districts such as Bemowo and Wola, it turns out that they are similar to the number of inhabitants of Płock or Koszalin, oscillating around 100,000. In this context, the largest city in which an odeon is located is Kielce with its nearly 200,000 inhabitants, and the smallest is Wisła with its 11,000 inhabitants. There is no direct relation between the number of spectators in an odeon and the size of the city, although the biggest odeon for 5500 spectators is in the biggest city, at the same time in the smallest city we have an odeon for 2500 spectators. Thus, other factors determine the size of the odeon. Apart from Warsaw, there are no odeons in cities where there are a number of facilities intended for participation in culture, such as concert halls, congress halls, theaters, or multifunctional rooms. This indicates an important role to be played by odeons in smaller peripheral centers, where there are no cultural facilities in the form of professional concert halls. On the other hand, on the scale of a large city or agglomeration, these facilities help in providing equal access to cultural events to the inhabitants of peripheral districts or parts of the agglomeration, as exemplified by Sopot and Warsaw. Summary of findings: a roof is a necessity in Polish odeons due to the weather; there are no regional differences in the distribution of amphitheaters and odeons; odeons are sited in the landscape taking advantage of its quality; the orientation of odeons is not related to the directions of the world; contact with nature is the greatest value; odeons played an important cultural role in peripheral centers and districts of large agglomerations.

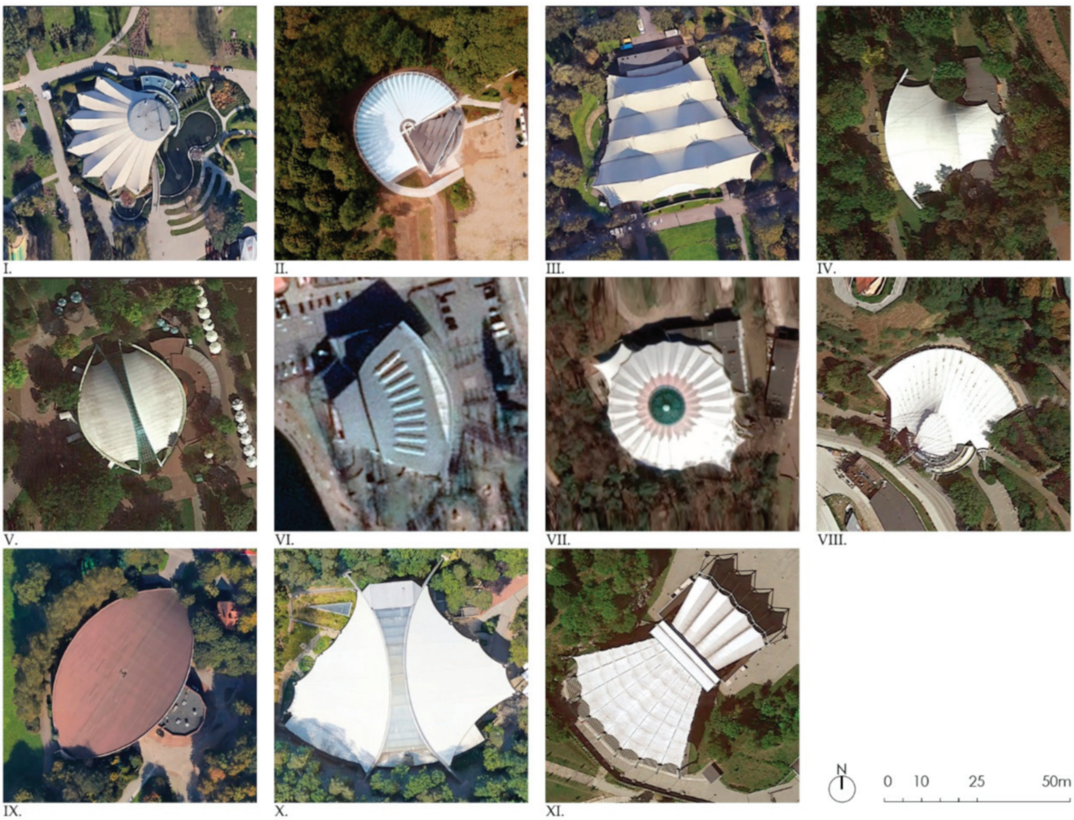


Figure 6. Form of odeons in Poland. Author's collection based on Google Earth. All pictures are presented to the same scale, with the north direction being the top of the page. Numbers follow Table 2.

2.4. Odeon Roof, Form, Construction, and Materials

Due to the geometric construction of the form, it is possible to distinguish categories of canopies with respect to the preservation of the axis of symmetry. Out of the 11 analyzed odeons, 2 are symmetric (Koszalin, Świnoujście), 8 are semisymmetric (assuming a difference of approximately 10 m in the length of the main structural arches of the roof is negligible for this qualification), because they keep symmetry along only one axis, and only 1 odeon does not keep symmetry with respect to any axis (Biała Podlaska).

In terms of surface typology, we can divide the roof forms into the following two groups: anticlastic and synclastic—see Table 2—nine of the eleven amphitheaters analyzed use the former typology, and only two in Świnoujście and Giżycko are synclastic. One important formal issue related to the functioning of canopies is the size of the division of the surface folds (foliation).

Table 2. Contemporary odeons in Poland, ordered by number of spectators. Original research. The odeons are shown on the map in Figure 5, following the Roman numbers in column one.

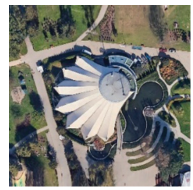
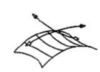
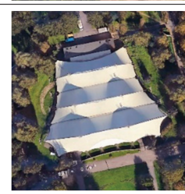
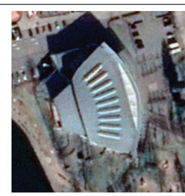
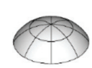
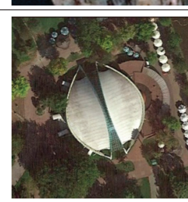
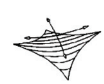
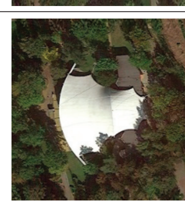
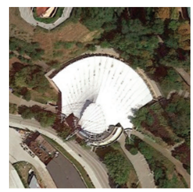
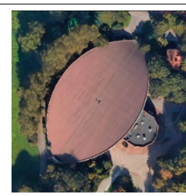
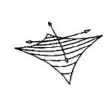
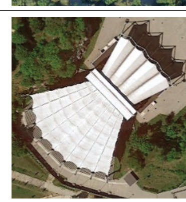
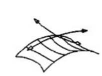
No. Table 1 | No.	Name, Place, and Author	City Inhabitants	Spectators	Year	Maximum Roof Span	Roof Surface	Roof over Stage or Mezzanine	Total Roof Surface	Material of Roof Covering	Location	Picture Presentation	Anticlastic or Synclastic Form	Cone, Arch, Hiperbolic, Logic
I. 26.	Michel Jackson Amphitheatre in Warszawa Bemowo, TiMRynek and Studio Architekt Juliusz Marcinowski	125,119	960	2008	60	1700	0	1700	Mambrane	Park			
II. 27.	Amphitheatre in Biała Podlaska, BP PROJEKT	59,280	1000	2019	45	1790	0	1790	Membrane Precontrain 1002 Serge Ferrari Fr, Mehler Texnologies Valmex Mehatop	Park, Castle, Fortification			
III. 38.	Amphitheatre of the Wolski Cultural Centre in Sowińskiego Park in Warszawa Wola, NN	141,407	2000	2019	70	3100	0	3100	Membrane Canobbio, Ps	Park			
IV. 41.	Amphitheater in Ostróda, Autorska Pracownia Architektury CAD	33,191	2500	2012	78	1880	359	2239	Wood	Lake			
V. 42.	Stanisław Hadyna Amphitheatre in Wisła, Pracownia Inżynierska PROJEKT s.c. Kręzel Marian, Kręzel Marta	11,132	2500	2009	58	1890	0	1890	Membrane	Park			
VI. 43.	Amphitheater in Ustroń, Andrzej Gałkowski, Marcin Gałkowski, współpraca Piotr Średniawa	16,073	2500	2008	55	1700	0	1700	Membrane Hp Gasser A.G. Sui	Park			

Table 2. *Cont.*

No. Table 1 | No.	Name, Place, and Author	City Inhabitants	Spectators	Year	Maximum Roof Span	Roof Surface	Roof over Stage or Mezzanine	Total Roof Surface	Material of Roof Covering	Location	Picture Presentation	Anticlastic or Synclastic Form	Cone, Arch, Hiperbolic, Logic
VII. 44.	Marek Grechuta Amphitheatre in Świnoujście, NN	41,516	2700	2010	58	2900	0	2900	Membrane Mehler Texnologies, Valmex Mehatop F	Park			
VIII. 47.	Amphitheatre in Płock, Czesława Korgul (główny architekt), Ignacy Bladowski, Wojciech Ryżyński, Henryk Nowacki, Henryk Sęczykowski	120,338	3500	2008	63	2770	0	2770	Membrane	River			
IX. 49.	Amfiteatr im. Ignacego Jana Paderewskiego in Koszalin, Marian Czerner, Andrzej Katzer, Jan Filipkowski	106,097	4500	1976	102	4500	0	4500	Trapezoidal metal sheet/ Membrane	Valley			
X. 53.	Forest Opera in Sopot, Paul Walther-Schaffer Paul Püchmüller, Janusz Kowalski	37,089	5047	2012	103	3520	1040	4560	Mambrne Tayio	Valley, Forest			
XI. 55.	Kadzielnia Amphitheatre in Kielce, Witold Gilewicz, Andrzej Lipski, Marek Borkowski, Wiesław Michałek, Adam Kluza	195,942	5500	2010	90	2500	1500	4000	Membrane over audience—Removable in winter, Mehler Texnologies. Valmex Mehatop F	Query			
	TOTAL	887,184	32,707		782	28,250		31,149					
	AVERAGE	80,653	2 973		71	2568		2 pnm m 832					

Related to this is the important issue of drainage of water from large surfaces at the lowest points of the canopy. In the case of homogeneous surfaces with a low degree of folding, there is a minimum number of drainage points. As a result, the highest accumulation of water per time unit occurs here, which requires an appropriate solution for its drainage without detriment to the structure and operation of the superstructure. In the analyzed examples, the smallest number of such points ranges from 2 in Szczecin to 38 in Biała Podlaska, where the roof surface is the most fragmented.

One important part of the membrane roof construction is the tendons and cables, which must meet the highest standards for strength, corrosion resistance, and fire protection. Foundations are an invisible part of membrane roof construction. Many times, they carry heavy loads with only a few points of support for the entire structure. For example, in the odeon in Koszalin, the main support is located at two points called abutments on the roof with an area of almost 4000 m^2. Two load-bearing arches of the roof are supported at their ends through spherical joints, by reinforced concrete abutments, which are monolithically connected to a reinforced concrete slab resting on 44 Franki piles [14]. In the Forest Opera in Sopot Figure 7, the main structure consists of two steel arches with a circular cross-section and a diameter of 1.3 m with lengths of 102.96 m and 93.20 m, respectively, founded on 12 m deep foundation blocks; additionally, 230 piles with lengths ranging from 12 to 12.5 m were made for the perimeter tension of the membrane. Membranes are the main material used for modern odeon roofs in Poland. Out of the 11 analyzed odeons, only two are not covered with membranes. Among the membranes used in the projects, there are French, Japanese, German, Swiss and Italian products (Canobbio IT, HP Gasser A.G. SUI, Mehler Texnologies DE, Serge Ferrari FR, Tayio JP). Each time an individual membrane assembly design is prepared together with a structural analysis of the stresses that occur during construction work. Membranes are not only a covering element, but also a structural element of roofs.

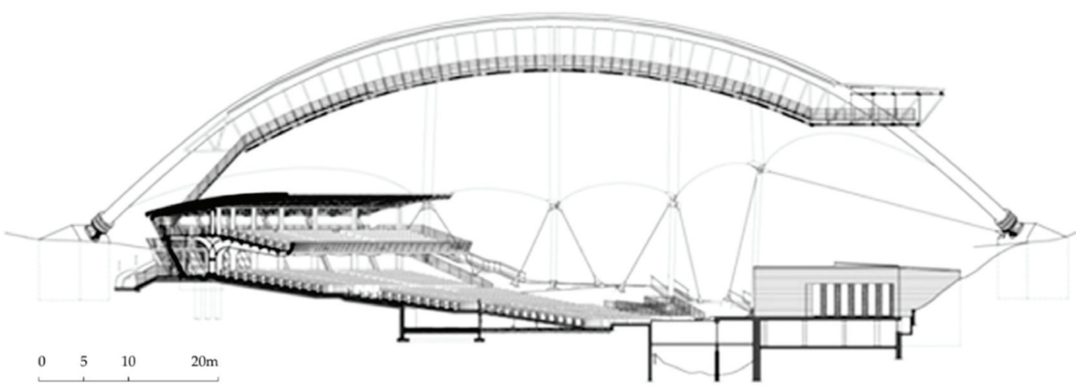


Figure 7. The scale of the main foundations of the load-bearing arch structure Forest Opera House in Sopot cross-section. https://inzynierbudownictwa.pl/stalowa-konstrukcja-z-motylim-dachem/10.05.2021 (accessed on 16 July 2021).

To shape the form of membrane roofs, the following two basic methods are used:

- The application and tensioning of the membrane on internal structural members in the form of arches, frames, or columns;
- Suspension and tensioning of the membrane on the overhanging structural elements of columns and pylons by means of cables and lashings.

The third method is a hybrid solution that combines those above. The use of membranes makes it possible to form geometrically complicated roof shapes on multicurve surfaces. In these systems, the steel structure is integrated with the membrane to form a complex structure.

In Europe, the development of tensile membrane structures is most often associated with the name of German architect Frei Otto and his most popular work, the 1972 Munich Olympic Stadium. This stadium, as well as the Millennium Dome built in London in the twenty-first century, has influenced many solutions in membrane roofing. Krzysztof Gerlic wrote [15] about the perception of these technologies on Polish territory, pointing to the freedom of shaping the architectural form inherent in this material. As a result, each of the 11 completed Odeon projects, 10 of which use membranes, have their own original architectural and engineering solutions. The oldest odeon in Koszalin was built when membrane technologies were not yet common in Poland. This structure refers to the famous sports hall in Raleigh, in the USA, from 1952, designed by Maciej Nowicki [16]. It was one of the first projects in which the structural and formal logic of modern architecture was materialized by showing the possibilities of membrane tensile structures. Currently in Koszalin the existing steel sheeting is being replaced with membrane roofing. The original construction was created by a special patent of prestressing the structure, and the covering created an anticlastic surface similar to a parabolic hyperboloid. In addition to the strength and durability, the ability of light to penetrate without creating additional illuminating elements is an important feature of the membranes. This property ensures good uniform daylighting over the entire auditorium. This property can also be used at night for multimedia projections, integrating the events taking place inside the Odeon with the surrounding environment. The membranes make it possible to regulate the inflow of light to individual Odeon elements. In the case of stage roofing, it is possible, for example, to use membranes with reduced light penetration or those that are completely opaque. A temporary folding roof occurs only in the case of one odeon in Kielce and applies to the part above the audience. The membrane over the stage is fixed permanently, and over the audience it is mechanically stretched during summer thanks to a special construction, and it is retracted over the stage portal for winter.

Summary of findings: the forms of most odeons are semi-symmetrical; from a typological point of view anticlassical solutions prevail; the size of the division of the fold of the roof surface is an important issue from the point of view of water drainage; membranes are the most commonly used roofing and construction material of odeons; two basic methods are used to shape the membrane roof; permanent membrane solutions prevail, but temporary projects are also possible.

2.5. Audience Form, Design, and Materials

The form of the auditorium in each of the analyzed cases relates to historical solutions and is a section of a circle approximated by a regular polygon—as displayed in Figure 8. The auditoriums in most of the analyzed cases were within the angle of 180 degrees that is characteristic for classical Greek amphitheaters, only in one odeon in Biała Podlaska is this angle greater. As a result, the visibility curves intersect in the center of the figures forming the audience at the place where the stage is located. Consequently, one-way shows are most often realized in odeons. Comparing the auditoriums for about 5000 spectators of the two largest Polish odeons in Sopot and Kielce, the audience plan curve is significantly higher in the former. The same is true for the two smallest odeons for 1000 spectators in Biała Podlaska, where the curve of the audience plan is greater than in Warsaw–Bemowo. As a consequence of the greater curvature, the stage is closer to the audience and partially surrounded by it. Solutions in which the curvature of the auditorium is greater, result in an increase in the size of the roofed area for a comparable number of spectators. A pairwise comparison of the roofing areas of the odeons in Sopot and Kielce, and Biała Podlaska and Warsaw–Bemowo illustrates this principle, and amounts to 4560 m^2/4000 m^2 and 1790 m^2/1700 m^2, respectively. Increasing the curvature of the audience angle allows for greater integration of the stage and audience, and consequently for building stronger relationships of audience participation in the performance.

The odeon stands are most often made of reinforced concrete and are used as an auxiliary element for the foundation of the structure. Often there are also mixed cold-reinforced concrete structures, which create a more harmonious relationship between the object and the environment in which it is located. In the case of an odeon, e.g., in Płock, the construction of the audience was the element of a wider project concerning the strengthening of Vistula escarpment [17].

The primary difference in audience typology relates to the terrain on which the odeon is located. In flat terrain, grandstands are self-contained structures, as, for example, in Ostróda. In areas with varied terrain, grandstands are often a component of the terrain, taking advantage of the natural lay of the land, such as in Płock or Kielce. In these examples, the filling of the auditorium occurs at two levels, i.e., at the crown of the auditorium and the level of the stage, regardless of whether the terrain is naturally formed, or the auditorium is a purpose-built facility. Audience seating is fixed, unlike indoor concerts and multipurpose halls and is made of wood or plastic in the form of individual or continuous elements on which the audience sits. There are also many cases where the stage is below terrain level and consequently so is the auditorium. In such cases, the filling of the auditorium is also done from the middle of the level. Differences in audience height affect acoustics, visibility, and communication and evacuation issues. Auditoriums in amphitheaters at the stage or upper bypass level usually have special seats for the disabled. In one of the unusual amphitheaters in Malbork, intended for staging knightly tournaments, there is a possibility of doubling the capacity of the audience by means of moving tribunes. This idea of temporarily setting up a second mobile auditorium on a street parallel to the permanent one was not realized.

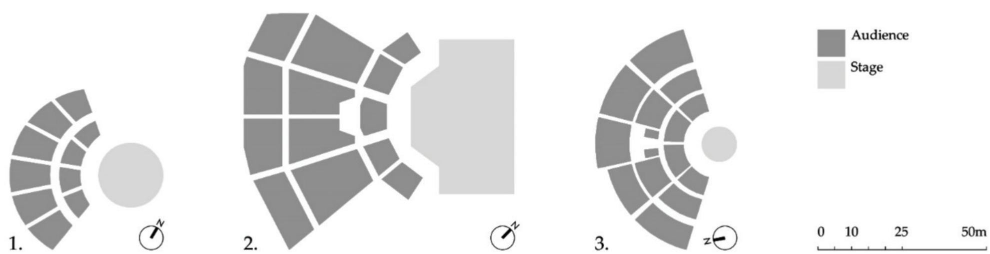


Figure 8. Plans of auditorium and stage in odeons: (**1**) Warsaw–Bemowo, (**2**) Kielce, (**3**) Płock. Original illustrations.

Summary of findings: the form of the auditorium refers to historical solutions in odeons; most often one-way shows are realized solutions in which the curvature of the auditorium is greater, causing an increase in the roofed area; increasing the curvature of the angle of the auditorium allows greater integration of the stage and the auditorium; the auditoriums are most often made of reinforced concrete; the basic difference in the typology of the auditorium is related to the shape of the land on which the odeon is located.

2.6. *Stage form Construction and Materials*

The scenes can be divided into two main groups with respect to the environment in which the odeon is located. The first group includes open landscape scenes, for which the background is an open landscape. The second group includes closed scenes, which create their own artificial in relation to the natural landscape background for the realization of the event. Examples of open scenes are odeons in Kielce and Ostróda. In the first χcase, the background is the remains of a quarry, and in the second it is the surface of a lake. In both examples, such background is the only a possibility because many times during the performance's decorations are introduced to the stage, blocking the view. In the other 9 cases, the odeons of the scene are closed, blocking views of the landscape despite its attractive nature. In the case of these formations, they are used for better propagation of sound by means of properly directing it to the walls and ceiling. Therefore, the materials used for stage construction are related to this requirement. Concrete and ceramic materials, traditional or thin-layer plaster, are the most commonly used materials for scenes enclosed by the landscape. Odeon stages, as opposed to canopies, are built using traditional (excluding the floor, which is most often wooden. This floor can be permanent or temporary variable depending on the type of show being performed) materials. During their operation, the acoustic conditions can change dynamically both due to the introduced scenery and decorations, but also depending on the number of performing artists and their placement.

One frequent reason for the construction of indoor stages is the functional need to create backstage facilities for artists. Therefore, in the functional program here, you can find dressing rooms and restrooms. In addition, the program can be complemented by storage spaces and workshops for the preparation of decorations. The size of the stage does not deviate from the standards in closed buildings of contemporary opera houses, theaters, and concert halls and is close to about 200 m^2. This size allows the placement of a large symphonic orchestra on the stage, and thanks to the deχorations, adjust the stage to a chamber orchestra, if necessary. A typical stage box in the case of opera is a module of 15 m × 15 m × 15 m, which gives an idea of the minimum size of the stage needed for the arrangement of a dynamic show such as a group dance. In the case of concert halls today, we usually speak of the following two typologies of halls: the box hall and the vineyard layout hall [18,19]. In the first case, the stage and the audience are on opposite sides of the premise, and in the second case the stage is surrounded by the audience. In the vineyard layout, the stage within the projection of an elliptical or near polygonal auditorium is located asymmetrically close to one of the foci of the ellipse. One example of this solution is the Philharmonic Hall in Berlin, which is still a model of this type of concert hall. These halls are characterized by the omnidirectionality of sound propagation and multidirectionality of the show because the viewer looks not only at the artists, but also at other spectators.

In the case of odeons, vineyard layouts are absent, and a box-like layout predominates. In this system, both sound and visibility propagation are unidirectional. This situation occurs in the case of stages, where the curvature of the audience projection is small and the distance between the stage and the audience is insignificant. In a few cases (Sopot, Biała Podlaska), when the audience has a larger curvature, an evolution towards a partially omnidirectional show can be observed. When the stage is partially surrounded by the auditorium, greater visual attractiveness of the show is achieved, analogous to concert halls in a vineyard layout.

Summary of findings: the stages can be divided into two main groups, open landscape stages and closed stages with artificial backdrops; the size of the stage does not deviate from the standards and is 200 m^2; in the case of odeons there are no vineyard layouts and a box layout predominates; the stage is partially surrounded by the audience, has a greater visual appeal of the show; the materials used for the construction of the stage are related to sound propagation.

2.7. Relationship of Roof Form to the Stage and Odeon Audience

The key issue concerning the architectural quality of odeons related to their roofing, is acoustics. Forms of roofs with predominantly asymmetrical solutions are mainly linked to their relation to the audience and the stage. The forms of the canopies follow the forms of the auditorium and the stage in asymmetric solutions, while in the case of symmetric roofs there is a discrepancy in the relation between the symmetry of the roof and the asymmetry of the stage and auditorium complex. Because of this contradiction, symmetrical solutions of odeon canopies deteriorate the architectural quality in terms of acoustics. Although it is possible to correct the acoustics with specialized designs, the relationship between the form of the roof and its material is decisive for this issue.

Because of the uniqueness and individuality of the solutions in the analyzed examples of odeon facilities, these issues should be analyzed separately on a case-by-case basis. Roofs, auditorium, and stage are the only elements that shape the space and at the same time serve to control the acoustic quality inside the odeon. Hence, excessively large openings between the auditorium and the canopy, and between the auditorium and the stage result in uncontrolled zones through which sound "escapes", which can cause unfavorable vocal phenomena. At the same time, however, these openings help in the spatial integration of the structure and the landscape. Therefore, a balance between these two contradictory aspects should be maintained in the design of odeons.

When discussing the size of odeons, we have to refer to two interdependent parameters, i.e., the size of the audience and the maximum size of the canopy. In the two largest odeons in terms of structural span, it is about 107 m; however, the size of the audience is different. The largest Polish odeon in terms of spectators is the one in Kielce, which has an audience of about 5500 with a maximum structure span of about 90 m. The smallest of the analyzed odeons are located in Biała Podlaska and in Warsaw in Bemowo, and are designed for about 1000 spectators. In Biała Podlaska the maximum structure span is 45 m and in Warsaw–Bemowo it is 60 m. The average size of the audience in the analyzed odeons is about 2500 spectators with an average span of about 70 m.

Finding's summary results: the architectural quality of odeons is related to their roofing and acoustics; the preferred form of roofing referring to the form of audience and stage offers asymmetric solutions; symmetric solutions of odeons roofing deteriorate the architectural quality in terms of acoustics; roofs, audience and stage are the only elements controlling acoustic quality inside odeons; audience size and maximum size of roofing are interdependent parameters.

2.8. Contemporary Functions of Odeons

On the basis of the analysis of the 11 existing odeons, including the odeon in Koszalin, which is being remodeled, it is possible to indicate the most frequently held events, which include the following: popular music concerts, cabaret performances, and classical music concerts. This type of activity is hosted in all mentioned odeons. These events are listed in order of occurrence. In some odeons there are also such events as the following: annual music festivals, theater performances, conferences, workshops for children and young people, meetings with artists, and special events. Annual music festivals of international scope are held today in the Odeon in Sopot. They have a long tradition of organization dating to the 1970s, during the communist period in Poland. At that time, apart from Sopot, there were also 3 such festivals held in Kołobrzeg, Opole and Zielona Góra (a competition for a concert hall at the site of Zielona Gora's amphitheater was decided in 2020). The festival in Opole is still taking place. It occurs in a facility that typologically is not an odeon, because apart from the stage it has only a roofed part over the audience. The other two festivals no longer occur; the amphitheaters have become decapitalized and have not been transformed into odeons. This shows a tendency for large artistic events to function only in amphitheaters converted into odeons or the disappearance of this function. In Sopot, where the variety of performances is the greatest, theatrical performances are also held, which distinguishes it from other odeons.

One interesting functional pretext for special events is the annual agricultural harvest festivals. They occur in many of the analyzed 57 amphitheaters, but they were also the reason for creating an odeon in Koszalin in the 1970s, and for its innovative roofing. Other special events that take place in odeons include fashion shows, and national and regional beauty pageants.

As the analysis of the event calendar indicates, concerts and cabarets as the most popular events occur in odeons between May and September, i.e., 5 months a year. The odeons' functioning outside the schedule of organized events creates a possibility of their use as a roofed place of year-round recreation and activities of inhabitants, i.e., organizing ad hoc events and nonprofessional performances. This is due to the fact that they are part of larger complexes, usually parks, and provide good conditions for both artistic presentation and expression as well as for viewing. Interesting data on the functions of odeons expected by the users are provided by a survey in Figure 9, conducted among the inhabitants of Koszalin in 2020 in connection with the odeon remodeling project currently being carried out [20].

It confirms the consistency of the data resulting from the aforementioned comparison of the activities of the currently operating odeons with the expectations of the audience. It also shows the proportion of expectations between great events of supra-local character and the opportunity to show the achievements of the local community of children, youth, and seniors. The size of the audience of odeons is related to the scale of influence of a given structure. The impact of the smallest odeons is mainly on a local scale and concerns the city and region, e.g., Biała Podlaska, or a district in the case of large cities, e.g., the odeon in Warsaw's Bemowo. The impact of the largest odeons goes beyond the local scale and is often associated with cyclical thematic festival events, such as the Sopot International Song Festival.

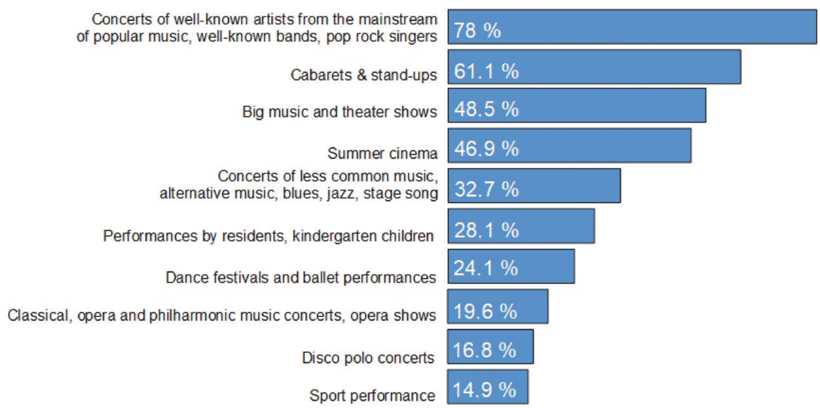


Figure 9. Survey on the expected functions of the new Odeon in Koszalin. Original chart based on [20].

Summary of findings: in odeons the most frequent events are pop music concerts, cabaret performances and classical music concerts; events occur between May and September; the functioning of odeons outside the schedule of organized events creates an opportunity to use them as a roofed place of year-round recreation and activity of the inhabitants; small odeons up to 2000 spectators have a local impact; the biggest odeons for 5000 spectators go beyond the local scale and are often connected with cyclic thematic festivals.

3. Case Study: Odeon in Biała Podlaska

To show, in detail, the complexity of the above-mentioned conditions, let us follow the case study of the odeon in Biała Podlaska.

3.1. Odeon and the Environment

The Park and palace complex of the Radziwill family is located close to the city center. It is a part of the estate of the famous Radziwiłł magnate family. The surviving earthen, fortifications and moat are dated to the seventeenth century, and were used to defend the palace, which has not survived, and the only remains of it are ancillary buildings. The surviving elements of the historical complex include the entrance gate, the entrance tower, three outbuildings, an eastern turret, the castle chapel of St. Josaphat, and earthen fortifications, which encircle the amphitheater. The entire complex features tall greenery that has the character of a park, yet has become overgrown over the past 400 years. The complex, after being adapted and remodeled, is now used as a cultural and community center by the city, which is located near the eastern border of contemporary Poland and inhabited by around 60,000 people. The complex features a city park, a Southern Podlachia Museum, a Public Library, a Musical School, the Biała Podlaska Culture Center, a Deux-Serves French Facility, the Biała Podlaska Chamber of Commerce, as well as an office of the National Health Fund, and a Psychological and Pedagogical Facility. The odeon was commissioned by the municipal authorities of Biała Podlaska. The historical Park Radziwiłłowski, which has been revitalized in recent years, has been enriched by it to include the odeon's contemporary form, and thus enhanced its functional offering.

The adaptation of the amphitheater into the odeon will allow the extension of the cultural season in Biała Podlaska, which is of fundamental significance to the city, as it is the largest building of its type in the surrounding region.

3.2. Development of Amphitheater Concept from 1950

The amphitheater is in the western section of the seventeenth-century earthen fortifications, on a site previously occupied by the first amphitheater, for an audience of several hundred that was built in the 1950s and gradually became completely decapitalized. It had been designed by Professor Gerard Ciołek, the founder of the Krakow school of landscape architecture.

The conceptual proposal of the extant amphitheater was selected through an architectural competition in 1993 (the author of the winning design was architect Kazimierz Butelski). In the years 1996–1997, a technical design was prepared, and in 2003, the amphitheater was opened. The key element of the conceptual proposal from the 1990s was the highly defined geometry of the earthen fortifications and the conservation requirements concerning the preservation of their geometry. To meet these requirements, the main focus was placed on solutions within the interior area of the fortification's sections, leaving their outline undisturbed. This solution allowed the construction of a theatre with a properly scaled stage covered with a triangular roof, with an ancillary building. The essence of the design proposal was changes to the geometry inside the bastion, together with lowering the terrain to build the audience and stage, enclosing the bastion with a stage building located at the border between the elevation differences and covering the stage with a triangular roof. The building was retained within the geometry of the fortifications, which was around 146 m above sea level, on the top of the embankment. It abutted the stage on one side, at an elevation of 141 m above sea level, and the entrance square from the side of the park, at an elevation of 143 m above sea level. The only element that protruded above the ordinate of the top of the embankment was the stage roof and its associated lighting bridge, whose ordinates did not exceed 150.5 m above sea level. The maximum height of the internal space was thus around 9.5 m, counting from the level of the stage to that of the roof, while the maximum span of the lighting bridge was around 52 m. The stage was placed on one of the axes of symmetry of the bastion, and the ancillary building was oriented perpendicularly to it. The entirety of the composition was contrasted with the east–west axis, which was accentuated by the form of the lighting bridge—as presented in Figure 10. The lighting bridge defined two curvatures of the audience, with 1000 seats inside the bastion, which was the diameter of one of them. This spatial concept was supported by material solutions that contrasted the soft plant materials of the external fortifications, and with the hard materials of the interior. The official opening occurred in 2003.

3.3. Design Idea Behind the Odeon

The design of the odeon from 2017 was a development of one of three conceptual proposals of roofing that had been presented to the developer. The conservation principles that were defined in the original design of the extant amphitheater, remained unchanged. As a result Figure 11, the conceptual proposal of a cable and membrane structure was developed, while respecting the principle of protecting the geometry, assuming the following three actions:

- The construction of a delicate steel open-work support structure at the top of the embankment, with the smallest possible height that would allow circulation in every direction and the drainage of stormwater from the roof;
- The construction of a cable structure between this support structure and the existing structure of the amphitheater, after its reinforcement;
- Construction of the membrane and tensing the entire structure.

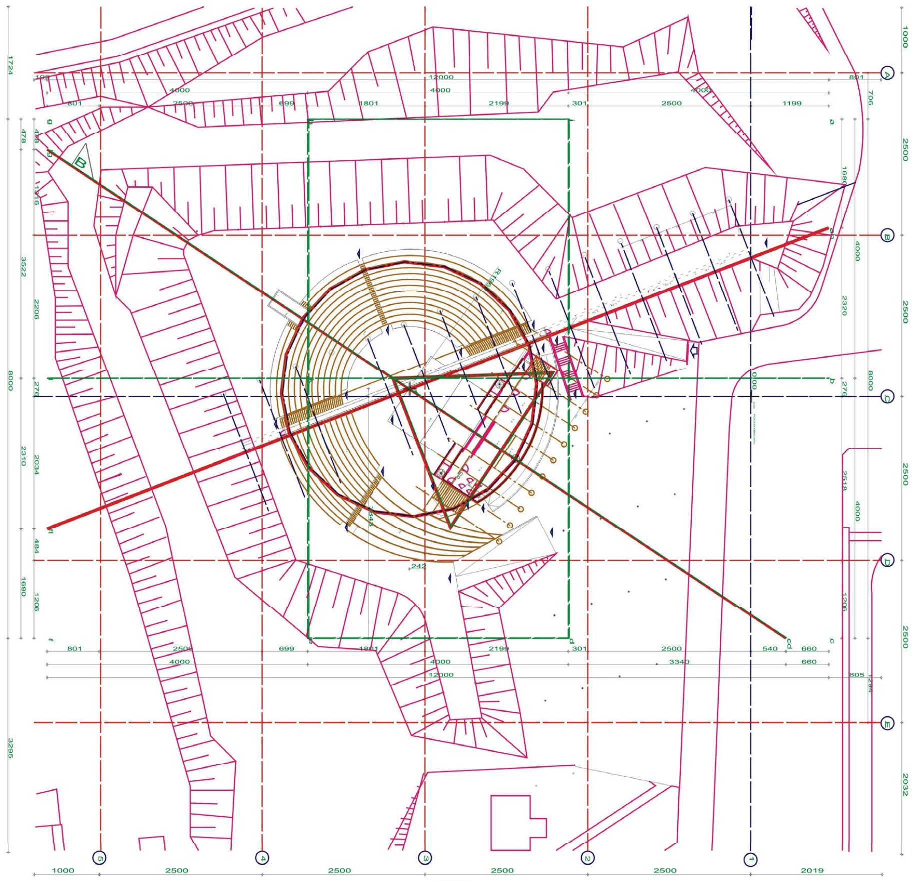


Figure 10. Geometrical concept of the amphitheater in Biała Podlaska. Source: BP Projekt.

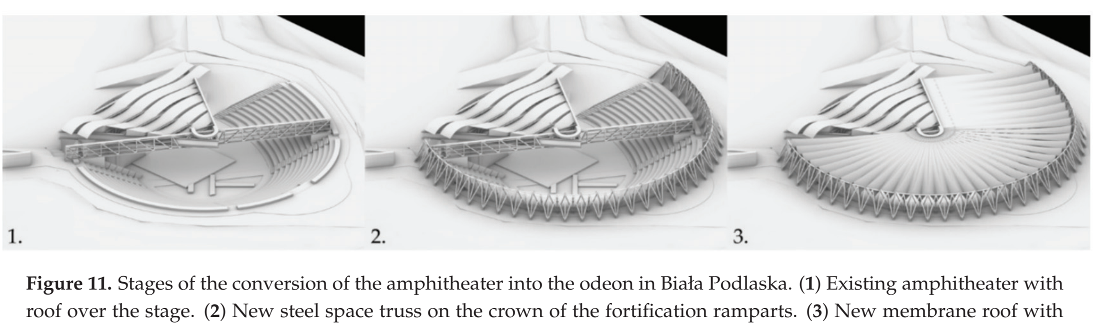


Figure 11. Stages of the conversion of the amphitheater into the odeon in Biała Podlaska. (**1**) Existing amphitheater with roof over the stage. (**2**) New steel space truss on the crown of the fortification ramparts. (**3**) New membrane roof with tensioned surface forming cables. Author graphics based on source BP Projekt.

3.4. Roof Design

Work on the form of the roof was conducted following the parametric design approach—as presented in Figure 12A. To find the optimal tensile distribution for the roof, the density of the structure, associated with the number of cables, its height, the cross-sections of structural elements, and the joints, were analyzed. The analysis also covered parameters such as the distancing of supports relative to the existing entrances to the audience, the height of the upper ring, and the distancing between the triangle bases that conditioned the possibility of freely passing between the spatial structure and the elevation of the wind cable fastening point that affected the roof pitch, and the stormwater drainage affected the ergonomics of the use of the solutions that were adopted. The main element of the design, which was the roof, was designed to feature cable and membrane technology—as seen in Figure 12B. The form of the roof is multi-ridged and has a delicate layout, which allows the drainage of stormwater along the external outline of the audience stands at the top of the embankment. The form of the roof reflects the geometric layout of the existing audience stands of the amphitheater. It is comprised of two parts that form a coherent whole, a part based on a semicircle and a side section in a layout similar to a rectangle—as depicted in Figure 12C. The roof has a peripheral structure, comprised of steel pipes that run along the top of the embankment and follow its shape. The spatial structure, to limit interference with the historical embankment top, has a pile foundation in the form of reinforced concrete piles. A section of the roofing, based on a semicircular shape, has a central layout that focuses on a steel ring that is fastened to the reinforced structure of the existing reinforced lighting bridge, to which the cables that tense the PVC membrane surface are anchored. The side part of the roofing is anchored perpendicularly to the bracing beam located at the southern side of the triangular-reinforced structure of the existing roof, to which PVC membrane tensing cables of this part of the roof are anchored. The steel peripheral space frame is made from pipes with a diameter of fi 159.0 mm and a thickness of 17.5 mm, from S355J2 steel, with horizontal braces with a diameter of 16 mm in the form of rods. In the semicircle, the first row of the structure's space supports is located flush with the last row of the concrete audience stand of the amphitheater, and its elements are spaced every 250 cm. There are 28 of such elements. The second row of space supports is located at a distance of 328 cm from the first row, in a running pattern relative to the first row, and features 28 elements that are spaced 287 cm apart. In the side section, the first row of space supports of the structure is placed flush, relative to the last row of the concrete amphitheater audience stand, and features 7 elements that are spaced 263.5 cm apart. The second row of space supports is located at a distance of 328 cm from the first row, in a running pattern relative to the first row, and features 6 elements that are spaced 284.5 cm apart.

The upper ring that tenses the structure is located at a distance of 150 cm horizontally, relative to the first row of supports, at a height of 401 cm relative to the floor of the upper walkway of the audience stands.

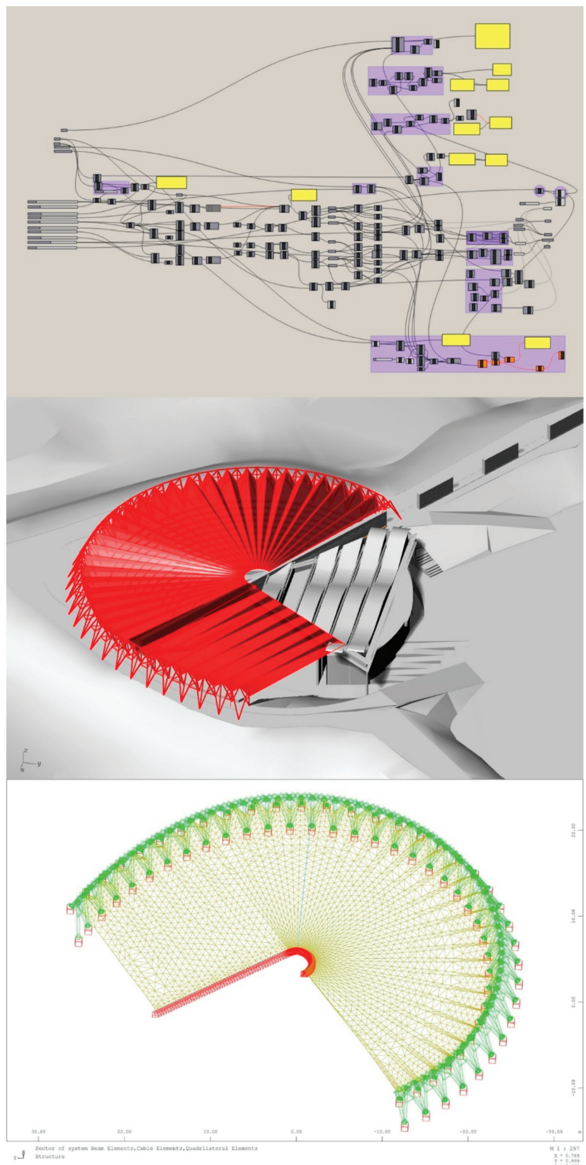
The spatial structure allows free circulation at the level of the upper peripheral walkway. All the structure's elements, except for the upper ring, are connected using mechanical joints. The upper ring is linked to the peripheral structure via on-site welding.

The cables that tense the membrane, both snow and wind cables, were designed as open steel cables, with a GALFAN coating, with a 1 × 61 weave (fi 31.3). The cables are linked to the structure using joint panels. The edge cables were designed as open steel cables with a GALFAN coating, 1 × 19 weave (fi 12.2).

The snow cables are fastened to the upper tensing ring. The wind cables are anchored to the central support in the first support row, at a height of 230 cm from the floor level of the upper walkway. The edge cables and tensors have a diameter of 12.2 mm. The cables on the semicircular section are anchored centrally to the steel ring (2 × HEM300), anchored to the newly designed reinforcement of the lighting bridge, while the cables in the side section are anchored perpendicularly to a C300 bracing beam at the southern side of the triangular roof. The combined length of the steel cables is 1743.8 m, while the total weight of the steel is 79,038 kg. The PVC membrane Precontraint 1002 Serge Ferrari roofing, with a total area of 1789 m^2, colored white, has the following parameters:

- Sunlight permeability: 19%;
- Protective coating: S2 PVDF/PVDF;
- Weight: 1050 g/m^2;

- Total thickness: 0.78 mm;
- Minimum tensile strength: 86/86 kN/m;
- Minimum tearing resistance: 0.55/0.50 kN;
- Minimum adhesion: 2.4 kN/m.



A. A parametric script, made to find a form in existing historical environment. Controls, roof surfaces density, geometry of external structure, heights cables mounts on building.

B. New final form shown as red.

C. Structural analysis of design proposal.

Figure 12. Parametric design of the shape (**A**,**B**) combined with structural analyze of the membrane and reaction of the foundations (**C**). Source: BP Projekt.

The second type of membrane, Valmex Mehatop, produced by Mehler Texnologies, with similar parameters, was used to cover “light bridges” inside the structure.

3.5. Acoustic Design

As a cable and membrane roof affects the building's acoustics, the following three types of acoustic correction elements were built after an acoustics analysis, as displayed in Figure 13, and built by Professor Tadeusz Kamisiński: the acoustic system behind the stage, the acoustic system underneath the triangular roof above the stage, and acoustic systems on the lower audience rows. The reflective systems behind the stage are wall fragments outside of the reach of the stage, shaped to direct the reflected sound towards the audience. They are formed from extruded polystyrene panels, finished with smooth silicon plaster. The system at the northern side of the stage, with a width of 592 cm, is comprised of 4 vertical strips with a width of 148 cm each. The system at the south side of the stage, with a width of 633 cm, is comprised of vertical strips with a width of around 158 cm each. The systems were designed along the entire height of the existing wall. The second type are reflective systems above the stage, in the form of membrane screens that are suspended from a peripheral steel structure, which are fastened between the existing triangular roof structure, between the bracing in three rows, to eliminate the parallelism of the stage and the ceiling.

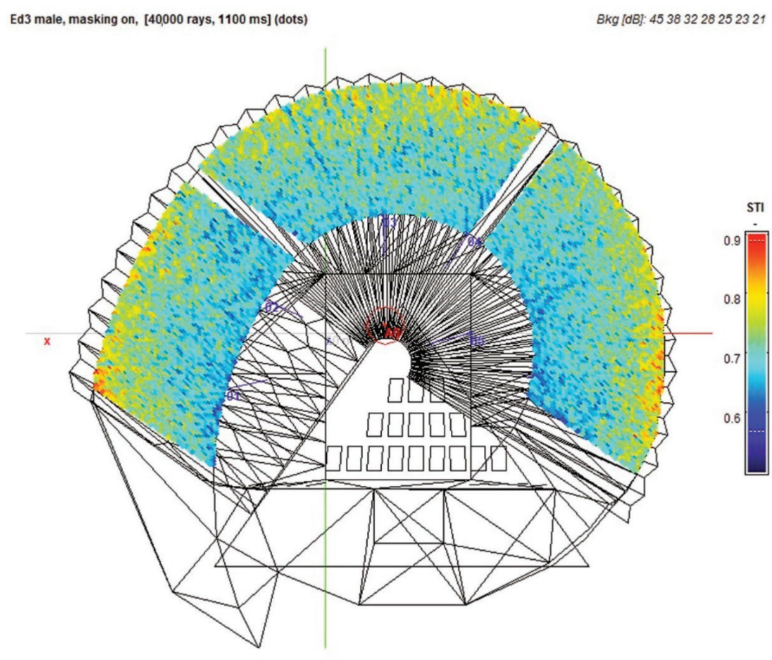


Figure 13. Audience acoustics analysis of sound distribution. Reprinted from ref. [19].

There are eight screens in the first row, six in the second, and four in the third. Each screen is 200 by 122 cm. The pitch of the screen along the longer axis does not change, and is 15°, while the pitch of the screen along the shorter axis varies between 4° and 16°. The height at which the screens are fastened varies, and is around 6 cm. The third type of sound-absorbing system was used on the vertical walls of the concrete audience stand in the first four rows.

The sound-absorbing material used here is mineral wool, with a glass veil that is 3 cm thick. Wooden profiles that reference the existing seating profiles were applied as masking elements. The profiles in the first row have a height of 55 cm, while in the remaining rows it is 46 cm. The profiles have the same width as the existing seating profiles—4 cm—and a thickness of 6 cm, with a narrow section with a thickness of up to 3 cm for mineral wool. Every profile is fastened at two points with masking joints.

3.6. Details

A range of renovation work on each of the amphitheater's elements was also performed, such as on its roof and its steel structure, along with painting of the audience (seating) and passages, approaches from the park, the stage, and the water drainage. New site development elements were also made, such as a new concrete path atop of the embankment.

The design also features a range of details, particularly the connection between the structure of the membrane and the peripheral support structure. An example of this includes the structure of the drainage valley. The water from the PVC membrane is collected in a steel valley near every node, with a snow cable. The water from the valley is transported outside the steel structure and introduced via an opening to the level of the pitched concrete floor on the top of the embankment. The water from the floor directly enters a linear drain that runs at the center of the peripheral pathway of the audience stands.

3.7. Result

This case study confirms all the previous odeon findings, in relation to location, orientation in relation to the world, typology and material of the roof form, typology and material of the audience and stage, the relationship between the roof and the audience and stage complex, and the functional program.

The application of modern materials and structural technologies enabled the construction of the odeon, by adapting the existing amphitheater building to the changing user needs. The contemporary formal solutions harmonize with the extant cultural and landscape heritage without mimicking or copying it. This contributes to the enhancement and development of culture, which leaves a material trace of its time at every stage of history, serving society and allowing it to read extant values anew.

The odeon, which protects against excessive sunlight in the summer and from rain in the autumn, forms a new type of multifunctional public space in Park Radziwiłłowski in Biała Podlaska, which corresponds to the scale of the city. The dialogue between the odeon's modern form, and the historical seventeenth-century park and palace complex in Biała Podlaska, was the main idea behind the project. Just as fortifications were an expression of contemporary ideas and technology in the seventeenth century, so is the odeon, built in the twenty-first century, an example of the ideas and technologies of its time, and, in this sense, it is a continuation of the site's past.

4. Discussion

As part of a discussion about possible directions of further development, we can discuss the results of the competition to transform Poland's oldest eighteenth-century amphitheater in the Royal Bath Park in Warsaw into an odeon. The topic was to convert the historic amphitheater at the Royal Bath Park in Warsaw into an odeon with a movable roof.

4.1. Environment and Conditions

At the moment, the site features an amphitheater with an auditorium and a stage, and a decoration in the form of ancient ruins. The area of the historic garden where the amphitheater is located is under legal conservation protection through an individual entry in the Register of Monuments. The auditorium and stage of the amphitheater are listed in the register of historical monuments. Due to the conservation status of the structures, it was imperative to protect the existing one historic landmark substance in and around the amphitheater area.

The idea of this two-stage competition was to create a temporary seasonal roof, covering the auditorium and the stage separately (used from April to October). After this period, it could then be completely dismantled, in such a way that no elements of its construction would remain visible.

It was necessary to design two independent canopies for the stage and the audience, separated by water, in a lightweight and demountable structure. Consideration had to be given to the staging phase, with the auditorium being covered at stage I, and the auditorium at stage II. The two main criteria for concept evaluation were as follows:

- Ability to fit into the historical context and conservation considerations;
- Quality and economy of design solutions [21].

The project has stirred considerable controversy, especially in the conservation community. "If this happens, we will be dealing with a real conservation scandal. The amphitheater is one of the most recognizable monuments of the Stanislaw August period"—Capital Conservator of Monuments Michał Krasucki argued this in August [22]. In the first stage, two works were selected and awarded participation in the second stage. In the second stage, no first prize was awarded, but one of the works received a second prize and the other received a distinction. In both concepts, membranes were used as the covering material. The works differed in the concepts of constructing the support structure.

4.2. Proposition One Using Eight Extendable Poles

The work of DiM'84 Czesław Bielecki's team, awarded with the second prize, was based on building a roof that was supported by eight telescopic columns. Four larger columns supported the roof structure over the auditorium, and four smaller columns supported the roof structure over the stage. These columns had different dimensions and were completely invisible during the period when the roof was to be dismantled. When the roof was installed, they served as support elements for the auxiliary perimeter structure, in the form of a semicircle in the case of the auditorium and a circle in the case of the stage. The membrane was attached circumferentially to these elements, and at four points inside each roof. Additionally, ropes were used as ties to stabilize the columns. The architects foresaw that the amphitheater roofing ring, after being assembled and fixed to the columns, would not be dismantled, but only lowered together with the telescopic columns into an appropriate, covered channel. The stage roofing ring, on the other hand, has been designed as a two-part system, with one half mounted permanently on the columns and the other half folded. The elements to be dismantled after the summer would be only the membranes and ropes with fittings [23].

4.3. Proposal Two Using Two Rotating Columns

The award-winning work by the BP Projekt team involved basing the roof structure on two spatial columns, with a fan-shaped expandable roof structure supported by spatial beams. This allows the roof to be spread over all the existing elements of the amphitheater and trees, without any collision. The membrane fastens the entire structure together. Both poles were placed outside the existing amphitheater, without interfering with its structure, which is an important structural element. The first pole was located on the axis of the composition on the empty square behind the audience, and the second was located asymmetrically on the island behind the stage. The main supporting elements, in the form of rotating spatial trusses, were placed on the pillars. There are five trusses above the audience, and four above the stage. The trusses are of composite construction, consisting of two parts that are separated by the axis of pole rotation. The structural thickness of the roof over the stage is 3 m, and over the audience it is 5 m. Under the columns and under the development area, there are reinforced concrete rims of circular cross-section, the radius of which is 4 m and the height is 2 m, supported, respectively, on piles drilled at an angle corresponding to the reaction of the spatial truss forces at the moment of the roof unfolding. When the roof was disassembled, only the foundation connection pieces remained on the surface. Storage of the assembled membrane and structure was to occur in boats on the water body surrounding the stage. The result was an asymmetrical composition of the free covering of the audience and the stage, with the possibility of various transformations of the elements forming the covering. Figure 14 shows the total membrane dimensions of 1547 m^2, consisting of a membrane over the auditorium of 1028 m^2 and over the stage: of 519 m^2.

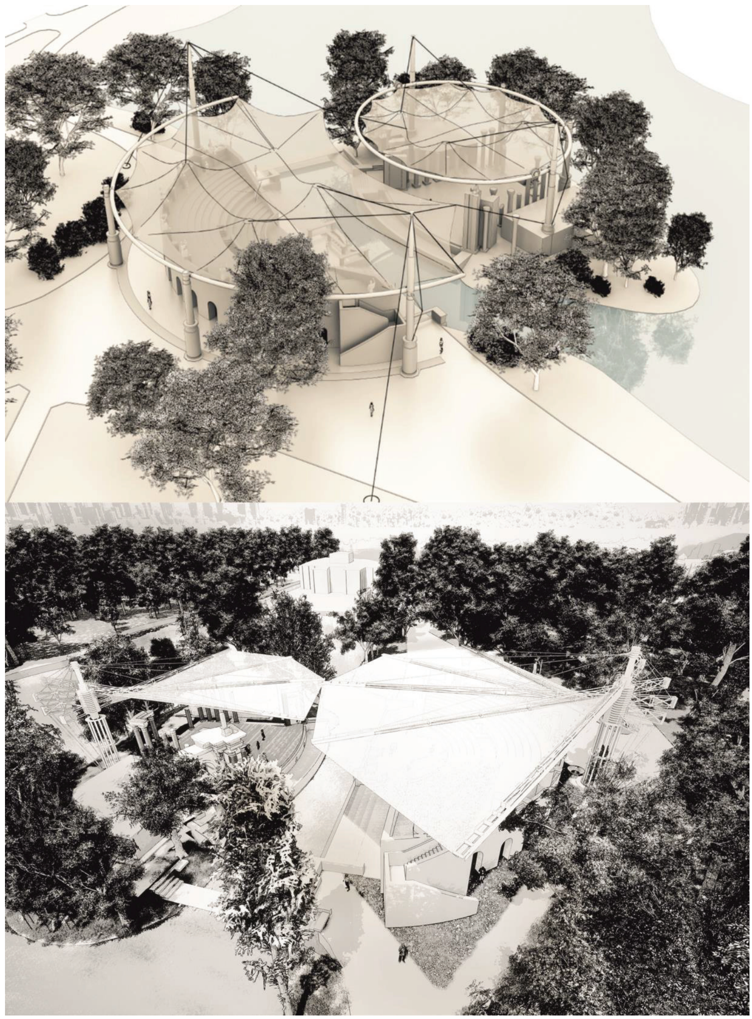


Figure 14. Competition entry team DiM'84 second prize. A first prize was not awarded. Reprinted from ref. [22]. Competition entry BP Projekt mention. Reprinted from ref. [24].

Neither of the two competition proposals could be realized, and, as such, they remained as voices in the discussion on the technical possibilities of transforming historic amphitheaters into odeons, by roofing them. Although both concepts are technically feasible, the decisive factor here is not the question of technical feasibility, but of conservation principles, which doctrinally assume the rejection of even temporary interference in favor of the purist preservation of the existing substance. This is understandable in a city that was completely destroyed during the Second World War. On the other hand, however, such an approach limits the possibility of creating new spatial and cultural values.

In the technical field, however, this poses the following interesting spatial problem that has so far been given little recognition: how to build an existing temporarily repeatable form without visual interference with the existing environment. Therefore, so far, in Poland, only the Kielce amphitheater has a roof that is partially folded in the part above the audience. This roof rolls up and develops into a stage portal that is connected to the fixed roof over the stage. When the roof is retracted, the buttresses of the supporting structure remain on the crown of the rampart. As a result, such a structure would not meet the requirements for this competition. The change and reconfiguration of space in various types of buildings is an interesting task; besides the mentioned technological and cultural aspects, it is also conditioned by economic aspects. An example of this is the Stade de France, whose reconfiguration from a football stadium to an athletics stadium costs about €40,000, and therefore occurs very rarely.

There are no financial data for a comparative analysis of the costs of the transformation of small venues, such as odeons. The costs of the construction and operation of odeons in the European model are covered by public funds from taxes. Therefore, their rational use, consistent with social needs, is an important issue. In the cost analysis, apart from the manufacturing costs, the maintenance costs of this type of facility also play an important role. The conversion of amphitheaters into odeons allows reduction in these costs and increase in income, by contributing to better use of resources.

5. Conclusions

Odeons, similarly to open cultural spaces, are interesting examples of architectural structures that follow sustainable development.

The formation of odeons is a process of evolution and adaptation of the existing built environment, involving the transformation of previously existing amphitheaters into more specialized forms. This transformation occurs gradually, and the resources previously possessed are thus used more fully. The result of covering the amphitheaters is their fuller utilization, by extending the artistic season. In Polish conditions, this extension is from two to five months.

In odeons, the quality of the space is better than in amphitheaters, thanks to the protection from rainfall, glare, and the improved acoustic conditions. Due to the open nature of odeons, and the lack of exterior walls, the quality of space is also improved over closed concert halls by the uniformity of natural lighting, natural ventilation, and ease of evacuation. The traditional foyer of a concert hall is replaced by the landscape, causing a strong integration of the surroundings and the interior of the performance space that is characteristic of odeons. In odeons, the disappearance of barriers between the inside and the outside results in an integration of space.

The construction cost of odeons, in comparison to the most similar concert halls, is significantly lower. This is due to the fact that less materials are used; some functional elements, such as, for example, foyers, are missing; there are no external walls; and there are no installations, such as heating, ventilation, and air conditioning. The lack of heating systems and natural ventilation results in a lack of pollution emission. Placement within a park means that large volumes of water that are collected from the roof surfaces are managed locally within the park, without overloading the neighboring areas, and therefore contribute to sustainable water management. The majority of odeons are built using membrane covers. Their use enables roof components to be completely recycled, and the short assembly and dismantling process contributes to reducing their carbon footprint.

Utility costs are significantly reduced because the building elements of the stage audience are not exposed to direct weathering, which increases their service life and reduces repair costs. This factor is the reason for the decapitalization of many unroofed amphitheaters, so covering them with a roof increases their durability.

Landscaped accesses to the odeons from various directions, from mass transit stops and parking lots through green areas, make these areas act as a de facto natural foyer. This contributes to the decongestion of traffic, and the natural contact between spectators and nature. This fits with the concept of biophilia.

Original characteristic forms of odeons have a social meaning that aids in promoting the place where they were created. They contribute to identification with the space, and open up new organizational possibilities for hitherto non-existent cultural functions, especially in small- and medium-sized towns. The permanent character of this spatial form in time favors the organization of cyclic events constituting a permanent cultural offer for the odeon's area. Depending on the events, this area can have a local, regional, or national character. Odeon's offer the social development of nonmetropolitan areas, where the odeons are mainly located. As a result, they are able to counteract the depopulation tendencies of small centers in favor of large agglomerations, by increasing their attractiveness. Further research in relation to open cultural spaces can relate to the phenomenon of large-scale events for tens of thousands of people in a short period of time, which is only hinted at in this paper. This may include both architectural and urban planning issues.

The various environmental, spatial, technical and social factors that were indicated above, jointly serve to build a sustainable cultural environment in Poland, responding to social needs at the current level of the country's development. The values in question are, however, universal and do not have to be limited territorially to the territory under analysis. In particular, open spaces of culture can be created in areas with similar climatic conditions, providing an alternative to classic closed objects with a similar function, which isolate humans from the natural environment.

Open cultural spaces significantly complement the variety of building forms for cultural development, by bringing people closer to the natural environment, and thus opening them up to new possibilities.

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Medieval Bourgeois Tenement Houses as an Archetype for Contemporary Architectural and Construction Solutions: The Example of Historic Downtown Gdańsk

Antoni Taraszkiewicz, Karol Grębowski *, Karolina Taraszkiewicz and Jarosław Przewłócki

Faculty of Architecture, Technical University of Gdańsk, 80-233 Gdańsk, Poland; antarasz@pg.edu.pl (A.T.); karolina.taraszkiewicz1@pg.edu.pl (K.T.); jprzew@pg.edu.pl (J.P.)
* Correspondence: karol.grebowski@pg.edu.pl

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Abstract: The basic urban tissue of medieval European cities consisted of brick townhouses. In the cities of northern Europe, these tenements were characterised by a block based on an elongated rectangular plan, covered with a gable roof with a ridge oriented perpendicularly to the street. The side walls of the tenement house were common for both neighbours and constituted a basic structural element. The gable façades were not loaded with ceilings, providing freedom in shaping them. The aim of this work is to determine the reasons why this method of shaping tenement houses in historical city centres has survived to the present day, becoming an archetype for contemporary architectural and construction solutions, despite the passage of time, numerous historical events, war damage, changing architectural styles, fashions and building techniques and technologies. The historical centre of Gdańsk has become the research material in this paper, where by means of such methods as historical source material analysis (iconographic), observation (operationalisation of preserved historical objects), comparative analysis of completed contemporary investments, and 3D modelling of structural systems, an attempt has been made to determine the main factors determining contemporary architectural and structural solutions. The reason for the extraordinary durability of this type of construction model can be found in the enormous rationality and efficiency of this solution. It allows for very intensive use of land, easy access of all front elevations to the main communication routes, cheapness of construction resulting from small spans and use of common structural walls for the neighbouring buildings, ease of shaping gable elevations, and fire safety. Aesthetic considerations are probably also important here, although it should be assumed that their significance began to grow only in the second half of the 19th century. However, it seems that the most important factor which made the model of the mediaeval bourgeois tenement house become an archetype for contemporary architectural and construction solutions is the timeless message contained in this model, a specific code allowing it to be unambiguously identified as a form of urban house—a place of safe living and at the same time a visible sign of the rich history of European cities, an element creating their cultural and spatial identity, a component of the living, constantly transforming urban fabric.

Keywords: contemporary architecture in historical context; archetype; bourgeois tenement house; cultural heritage

1. Introduction

Medieval towns in northern Europe were usually compact urban complexes surrounded by fortifications, whose basic tissue consisted of burgher houses. The term tenement house is defined in the paper as a brick, one-storey urban house, in a compact development, separated in terms of space and ownership, and co-creating with the plot a layout of a traditional urban block and a street [1]. The compact dense housing of many European cities evolved from detached houses due to the legal and spatial reorganisation of these cities as described in [2]. Such buildings did not aspire to the role of spatial dominance, leaving this role to the monumental edifices of cathedrals, churches or town halls, however, thanks to their huge mass, they determined the spatial expression of individual streets and squares, and sometimes districts and entire cities. The history of building plots in early and late medieval towns in the Baltic Sea basin is described in [3]. Studies on the house in the medieval and modern city in Europe are presented in [4]. The origins of the tenement house, its function and form in Central Europe, are presented, among others, in [5] while for Northern Europe, various aspects of the tenement are included in [6]. The breakthrough stage of the building's construction was replacing the walls of the timber-framed hallway house with a building with load-bearing brick walls. With time, the construction of the buildings changed from single residential buildings into compact buildings.

In the Northern European countries, from The Netherlands through southern Scandinavia to Latvia, Lithuania, and Estonia, the dominant type was that of the tenement house with its gable to the street, in which the side walls played an essential role and the façade was only a screen [7]. As a rule, the building block was based on an elongated rectangular plan, covered with a gable roof of a wooden construction. The construction of wooden roof trusses of tenements, their typology and development in the region of Central and Northern Europe, are described in [8,9]. The individual buildings differed primarily in the architecture of their façades [10,11]. The masonry side walls of the tenement house were common to both neighbours, constituting the basic structural element and, at the same time, the fire separation wall. The gable façades were not loaded with ceilings, providing freedom in shaping them. An important feature of bourgeois tenements was the fact that they were built as compact buildings, forming a clear element of the street or square frontage [12]. The bourgeois houses in the medieval cities of southern Europe looked different. These were usually buildings with a near-square ground plan, with low-pitched roofs and ridges parallel to the street. And although this model has survived in south Europe to the present day, it is not as expressive as the model of the bourgeois house in northern European countries.

The North European tenement form can be found in such cities as: Amsterdam (The Netherlands), Antwerp (Belgium), Copenhagen (Denmark), Lubeca, Frankfurt am Main, Bremen (Germany), Gdańsk, Toruń (Poland), and Tallinn (Estonia). For centuries, in those cities, next to Gothic tenements, Renaissance, and later Baroque, Classicist, or Eclectic buildings appeared, while the identical form of the structure and structural system described above remained unchanged [2,13]. An interesting study of tenement houses in modern times on the example of Gdańsk was conducted in [14]. The tenements were built on plots of similar widths and were of similar heights. The width of the plots ranged from several to a dozen or so metres, and their length reached even 100 m. They usually had from two to 4–5 levels and an attic. If someone wanted to enlarge the width of the tenement house, he had to buy the neighbours' plot. In this way, the bordering buildings were combined into one larger one.

Many publications have been devoted to the description of tenements in particular regions and cities of Northern Europe. For example, an analysis of housing estates in several European cities including Amsterdam can be found in [15]. The townhouses of the Klaipeda region (Lithuania) are described in [16], the architecture and reconstruction of the townhouses of Elbląg (Poland) is presented in [11], while various aspects of the townhouses of Gdańsk are given in [13,17–19], etc.

It is extremely interesting that this particular model of housing development managed to be maintained for six centuries (from the second half of the 13th century until the mid-19th century) in the cities of Northern Europe, in an almost unchanged form, despite the passage of time, changing architectural styles, and the admittedly slow, but progressive development of construction techniques.

In the 19th century, together with a rapid increase in the number of inhabitants of European cities and changing needs in relation to buildings situated along main streets, numerous attempts were made to replace the model developed in the Middle Ages with new, seemingly more adequate to the spirit of the introduced changes, forms of development. These attempts, however, ended in failure and the model of the medieval bourgeois tenement house, only functionally transformed into a tenement house, emerged from these attempts "victorious", remaining as the dominant one in the urban tissue.

A similar situation occurred after World War II [20]. The best example of this is Gdańsk, where after the destruction wrought by the war, despite many attempts to implement a completely new way of building, it was finally decided to shape the residential development on the basis of a modernised model, which, however, was still preserved from the Middle Ages.

All this brings us finally to modern times. The housing investments currently undertaken in Gdańsk, but also in many other European cities, located in the zone of historic city centres, are a modernised (however to a very small extent) model of a medieval bourgeois tenement house. The departure from the original is of course visible in the contemporary functional layout, execution technology and materials used, but it does not concern the most important, decisive elements of the building's spatial expression, such as its scale and the overground shape of its mass.

Historically, townhouses by their very nature had the simplest and most optimal structural system possible: wooden roof trusses and wooden ceilings supported on masonry walls placed directly on stone or brick foundations, or on wooden piles. In general, safety evaluation for historical constructions is recommended by ISO [21] and ICOMOS [22]. Principles for the analysis or evaluation of historic wooden structures are given in ICOMOS [23,24]. An interesting review of existing standards, guidelines and procedures available for the assessment of historic woodwork is presented in [25,26]. The most recent research on using advanced digital technologies (such as building information modeling–BIM, finite element method–FEM) in heritage preservation focuses on the analysing the current state of particular structures. This approach to the structural analysis of the tenement was used in [27]. BIM allows for excellent environmental sustainability results while helping to reduce design time and eliminate design errors. "To ensure that a project meets sustainability requirements, different software are used to verify energy consumption. These software take into account several factors such as thermal insulation, climate response, solar penetration, natural ventilation, mechanical ventilation HVAC systems, building dynamics and thermal mass" [28]. A complex assessment methodology and procedure for historic roof structures is proposed in [29]. Masonry structures are also most commonly analysed based on finite element methods. Reviews of methods applicable to the study of such structures have been presented in [30,31]. Unfortunately, there are few comprehensive studies devoted to the foundations of historical buildings [32,33]. Several examples of historical foundations, as well as past and contemporary preservation techniques, are also presented in the latter. Numerical analysis of stone foundations by the finite element method is given in [34]. A comprehensive structural analysis of the transformation of the tenement for the different building phases from the 13th to the mid-16th century was carried out in [35]. It considered a complex of three buildings on Mostowa Street in Toruń, which is one of the most interesting examples of bourgeois architecture, inscribed on the UNESCO World Heritage List. On the other hand, several cases of almost complete reconstruction of historical urban complexes are analysed in [36].

The model of the medieval bourgeois tenement has survived to the present day despite numerous historical events, war destruction, changing architectural styles, fashions, construction techniques and technologies [36], despite pro-environmental trends, the pursuit of sustainable development [37] and universal accessibility [38], and despite the progressive development of civilization and globalisation. The aim of the article is to determine the reasons for the great durability of this model, which has become an archetype for contemporary urban-architectural and structural solutions located in historical urban centres. The search for these causes was also based on the numerical structural analysis (FEM) of a medieval tenement house.

2. Materials and Methods

Among many elements of the current discourse on the protection of cultural heritage, one of the most important seems to be the problem of coexistence or dialogue between contemporary architecture and the existing valuable historical buildings. This problem is not new and seems to have accompanied architects and builders for centuries, during which they had to decide on the shape of new buildings adjacent to the existing ones. Nowadays, however, more than in the past, this problem has taken on a new, more pronounced meaning.

It seems that an excellent research material for this type of considerations is a model of a medieval bourgeois tenement house, which was and still is an archetype for many investment activities carried out in historical urban centres. In this paper, the historical centre of Gdańsk was examined. Using such research methods as analysis of historical source material (iconography), observation (operationalisation of preserved historical objects), comparative analysis of contemporary investments, and 3D modelling of structural systems, an attempt was made to determine the main factors determining the architectural and structural solutions of contemporary buildings.

3. Medieval Bourgeois Tenement House in Gdańsk

The type of bourgeois tenement house in Gdańsk was formed a bit later than in other northern European countries—only at the beginning of the 15th century—however it did not differ in any way from the Dutch or German model. This was because these buildings were constructed mainly by builders who came from other countries or by Gdańsk citizens who acquired their skills in constructing this type of buildings abroad. Thus, the burgher house in Gdańsk (like its foreign prototypes) was characterised by the body of the building based on a rectangular plan with a width of approx. 5 to ca. 7 m and a length of several to several dozen metres, adjoining the street along its shorter side (Figure 1).

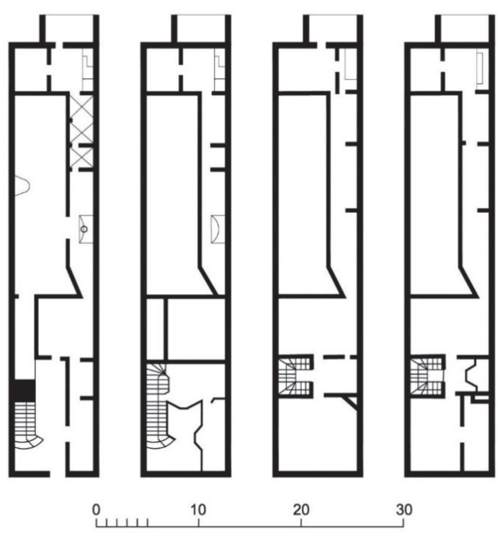
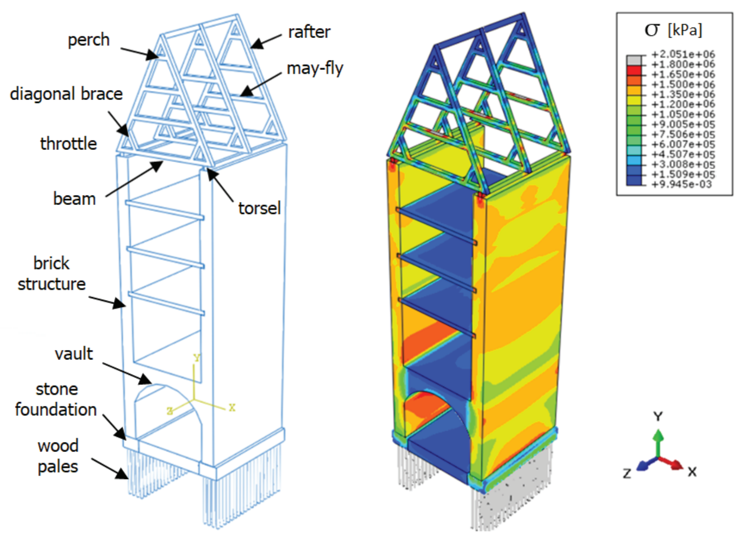


Figure 1. Uphagen House, Gdańsk, 12 Długa Street, ground floor plans, mezzanine, first and second floors [39].

The block was covered with a gable roof with an inclination of approx. 60° with a wooden structure usually covered with ceramic tiles and a ridge situated perpendicularly to the street. The side walls of the tenement were made of brick or earlier stone and common to both neighbours, providing the basic structural element on which the ceilings rested. These walls were also elements of fire separation for individual buildings. Gable elevations were not loaded with ceilings, providng freedom in their shaping. Due to the high level of groundwater in Gdańsk, the basements were shallow and the ground floor was elevated above the ground level.

In order to determine the load transfer in the medieval roof structure and to determine stresses in the brick walls, a numerical model was made in the ABAQUS software version 6.13, 2013 (Figure 2a). The analysis was performed on a 3D model of a medieval townhouse with dimensions of 700 × 800 cm and a wall thickness of 100 cm. The model was partitioned into 657,654 eight-node cubic reduced integration solid elements of linear shape function type C3D8R with a total number of nodes of 1,113,556. Calculations were performed for several finite element mesh sizes. The highest convergence was obtained for a grid with a side size of 10 mm. The load was modelled cinematically as an equal vertical displacement of the nodes of the upper surface of the elements forming the triple rafter roof framing. The load was collected from the entire roof area taking into account the dead weight of the elements and climatic loads.



(**a**) (**b**)

Figure 2. Medieval tenement house in Gdansk: (**a**) numerical model and description of the structural members, (**b**) results of maximum stress maps in (kPa).

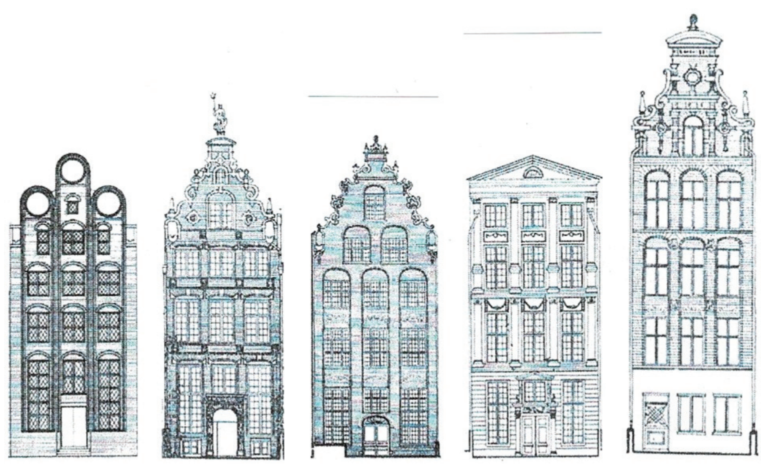
The numerical analysis carried out is intended to compare in a simplified way the static schemes and load transfer between medieval and modern roof trusses. The studies described in [40,41] were used to implement the wood input parameters. The following wood parameters were included in the model: longitudinal compressive strength X_C = 62.2 MPa, longitudinal tensile strength X_T = 140.0 MPa, transverse tensile strength Y_T = 8.5 MPa, transverse compressive strength Y_C = 10.9 MPa, shear strength S = 35.0 MPa, Young's modulus—length direction E_1 = 9715.0 MPa, Young's modulus—horizontal direction E_2 = 400 MPa, shear modulus G = 600 MPa, density ρ = 650 kg/m3, Poisson's ratio v_{12} = 0.316, v_{23} = 0.469, v_{31} = 0.023, initial yield limit σ_{0k} = 26 MPa.

The research described in [42] was used to implement the input parameters of a historical masonry wall. The elastic modulus of the masonry wall material was calculated using the homogenization algorithm described in papers [43,44]. In order to determine the stresses in the brick masonry, a plastic-degradation material with the following parameters was included in the model: Young's modulus E = 2600 MPa, Poisson's ratio v = 0.167, density ρ = 2000 kg/m^3, dilatation angle = 16°, eccentricity e = 0.07, biaxial/uniaxial compression plastic strain ratio 1.16, parameter κ_c = 0.667, viscosity 0.001, stress σ_c = 8.42 MPa inelastic strain ε = 0.009931, compressive degradation d_c = 0.99 in elastic strain ε = 0.00931, stress σ_t = 0.848 MPa in crushing strain ε_c = 0.00527, tensile degradation d_t = 0.97 in crushing strain ε_c = 0.00527 [45]. The current condition of the elements was also taken into account by lowering the value of the longitudinal modulus of elasticity. The results obtained during the numerical analysis in the form of stress maps are presented in Figure 2b.

On the basis of the obtained results, it was proven that the medieval triple rafter roof framing and brick wall would satisfy the ultimate limit state and serviceability conditions. Compressive stresses of 2 MPa did not lead to cracks in the structure of the elements, which would cause failure of the entire structure.

The elevation of the ground floor above the ground level meant that the ground floor was accessed by stairs through porches, which have become a characteristic element of this architecture. The height of buildings and the number of decorative elements applied on their façades depended on the social and, above all, material status of their owners. It should be noted here that the decorations were applied mainly to gable façades located on the street side. Gable façades located from the side of quarter interiors were not subject to decoration, and side façades were decorated only when they had no "neighbour" and were located along side streets. Very characteristic elements of the gable facades were (situated "at the meeting point" of the neighbouring buildings) often richly decorated containers for rainwater, connected with drain pipes running along the facades.

In spite of changing architectural styles and the development of building technologies, this method of building tenements was preserved in Gdańsk from the 15th to the middle of the 19th c. (Figure 3).



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 3. Elevations of Gdańsk tenement houses: (**a**) Gothic, (**b**) Renaissance, (**c**) Baroque, (**d**) Classicist, (**e**) Eclectic [46].

4. Gdańsk Tenements from the Mid-19th to the Mid-20th Century

The 19th century in Gdansk was initially a period of economic and construction stagnation caused by warfare. Later, mainly due to the industrial revolution, came a time of prosperity and thus a period of population growth and a boom in construction, including housing. However, this did not change the way buildings were constructed. The architecture of this period was full of historical borrowings and quotations, often based on very fashionable catalogues or architectural patterns. The style of the façades of the buildings was eclectic and the shape of the mass clearly continued the medieval traditions.

The end of the 19th century and the beginning of the 20th century in Gdańsk brought new challenges to the then urban development and a new look at the urban planning and aesthetics of the city. This prompted the citizens and authorities of Gdańsk to apply measures to modernise its appearance. Encouraged by the examples of other European cities, the citizens of Gdańsk began to undertake a number of actions aimed at "clearing" the urban tissue of buildings that did not meet the new challenges. A number of demolitions were carried out, unfortunately irrevocably destroying a significant number of valuable historical buildings. The demolished historical buildings were replaced with new ones, larger in scale and of a different, modern style, often characterised by flat roofs which were "alien here". The city authorities tried to control the emerging spatial chaos by organising architectural competitions for the "façades of Gdańsk buildings". These competitions were aimed at finding a solution or a model of a Gdańsk building realised in the historical area.

The most widespread competition among architects was organised in 1902. This competition attracted 110 entries from all over Germany and produced totally surprising results [47]. Despite enormous pressure from the proponents of modernity, the works submitted for the competition and awarded were solutions that very directly referred to the historical legacy, using neo-stylistics, mainly the Dutch Neo-Renaissance. The residential buildings presented in the competition were again traditional, medieval townhouses clad in neo-decoration (Figure 4).

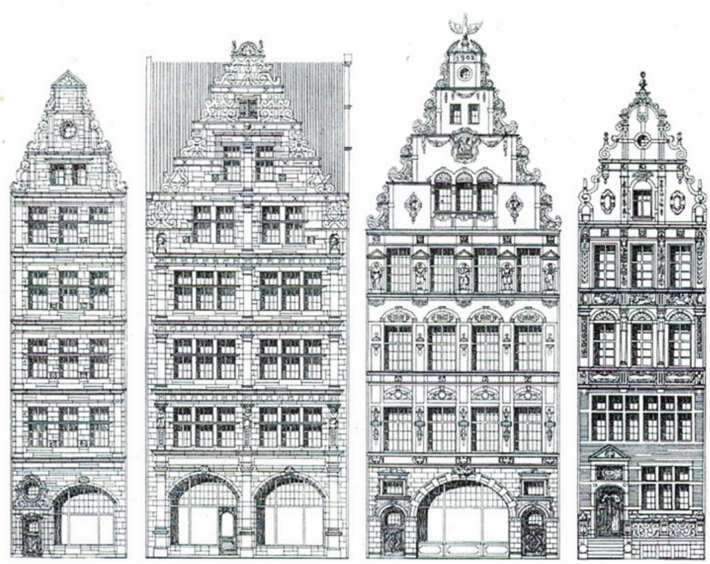


Figure 4. Tenement houses awarded in a competition for the facdes of buildings in Gdańsk, 1902 [46].

In the third decade of the twentieth century, the so-called "Project of Great Gdańsk" was being prepared. It was the first comprehensive zoning plan covering not only the historic downtown, but also its wide surroundings. Although this project generally assumed the preservation of the old buildings in the city centre, it allowed for the reconstruction of many historical parts of the city. The ideas of the modern movement in architecture and modernist design with flat roofs, columns, and strip windows began to "invade" the historic centre (Figure 5).

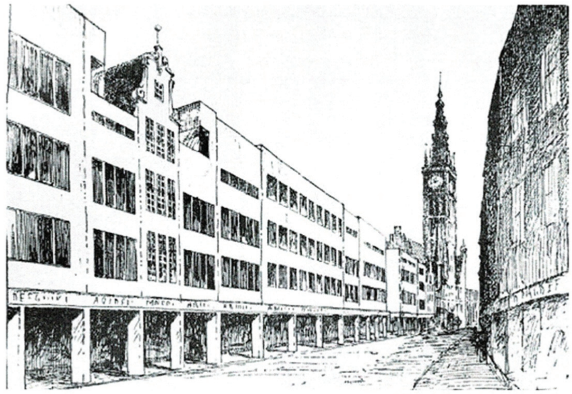


Figure 5. Frontage of Długa Street in Gdańsk designed by Martin Kiessling [48].

Historic conservation officers, architects and urban planners of the time were engaged in fierce disputes over the transformation of the face of the city. One of the proponents of introducing changes in the way of building was an architect and respected builder, Martin Kiessling [49], whereas his opponent and defender of historical building principles was professor and rector of Technische Hochschule Danzig (now Gdańsk University of Technology), architect Otto Kloeppel, who wrote in 1928: "For each city, there was a time when its proper style was constructed; this was the historical time when the most was built in a given city, thus creating its character. It was good if the newly constructed buildings were built in the same form language. Nevertheless, it is a fact that just as the various historical styles perfectly complement each other in our old cities, so there is also room for modern forms, provided that the essence of the spatial art of the old urban foundation is not violated" [48]. In the end, the traditional medieval townhouse won again. The space of the historic downtown of Gdańsk remained quite uniform in its historic style and the modernist visions of Kiessling and his ilk were not realised. Until the outbreak of World War II, the bourgeois houses located in the historic downtown of Gdańsk remained faithful to their medieval original (Figure 6).

Figure 6. Długa Street in Gdańsk, 1935. Source: Historical Museum of the City of Gdańsk.

5. War Destruction in 1945 and the Reconstruction of the City

Gdańsk is one of the European cities that suffered the most damage as a result of warfare during World War II. It is estimated that the degree of destruction reached as much as 90% of the buildings existing before the outbreak of war (Figure 7) [50].

Figure 7. Photograph of damage in Gdańsk after the Second World War [50].

The reconstruction of such a badly damaged city was not an easy task, especially as it was carried out in the atmosphere of many discussions and disputes concerning the way it should be done. There were also opinions that Gdańsk should not be rebuilt at all, but only turned into a huge park with only "islands" of the most important monumental buildings. In turn, modernist visions of rebuilding Gdańsk envisaged building in its place a modern residential district with wide, sunny streets, green areas and gardens. Towards the end of 1946, however, the vision of a historic reconstruction of the city began to prevail and its supporters began to draw up increasingly clear plans for its implementation. A great propagator of this idea was an architect, town-planner, and scientist, Władysław Czerny, the author of the first serious plan of rebuilding Gdańsk. He claimed that all reconstructions must be carried out on the basis of strict historical documentation, not allowing the creation of historical architectural fantasies. However, he allowed for the construction of tenement houses in contemporary forms provided that they could respect the "artistic custom and the custom of scale" [51].

Thus, the historic centre of Gdańsk was rebuilt, but this reconstruction was not a faithful and literal reconstruction of all of the pre-war elements. The most significant monuments were rebuilt, the main street lines were rebuilt, the city skyline was reconstructed, but at the same time, the urban tissue was radically changed, adapting it to the requirements of modern urban planning. A housing development has been built in the historic city centre. Therefore, during the reconstruction, the main emphasis was put on housing, i.e., again on tenement houses, which are the face of the city. These tenements, often built on historical foundations, in their general structure did not deviate in any way from the archetype of the medieval burgher house. They often had historical façades reconstructed on the basis of iconographic material, but even more often, they were buildings with a fascinating combination of historical structure and modernist and, in later years, socialist realist style [51].

Of course, it should be emphasised once again that it is the external spatial expression of these buildings and the basic layout of their structure that is at issue here, not the functional layout, which was completely transformed when adapted to the new requirements. It is extremely interesting that the "struggle" between the traditional form of the bourgeois tenement house and the new solutions lasted throughout the reconstruction of the city, i.e., until around 1960. However, the archetypical idea of a bourgeois tenement house was victorious in this struggle each time (Figure 8).

a) b)

Figure 8. Eastern frontage of Grobla I Street in Gdańsk: (**a**) modernist design from 1957 [51], (**b**) realisation in the form of tenement houses 1958. Source: compiled by A. Taraszkiewicz.

6. Second Stage of Reconstruction—An Archetype Still Relevant

Despite the successful reconstruction of the city in 1945–1960, today's historic downtown of Gdańsk still requires new buildings to fill in the vacant spaces and complete the quarters and street frontages destroyed during World War II. However, contemporary architects and urban planners operate in a very different reality than their post-war predecessors. The Venice Charter, adopted in 1964 by the Second International Congress of Architects and Technicians for the Construction of Monuments in Italy, changed the rules for the "handling" of monuments, and in particular drastically limited the possibilities for their restoration and reconstruction. The Charter calls for the protection and preservation of the original substance, structure and materials of historic buildings and for a clear distinction between all newly added elements and the original elements. Most relevant here is Article 9 of the Charter, which states: "The process of restoration is a highly specialized operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents. It must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp. The restoration in any case must be preceded and followed by an archaeological and historical study of the monument", and Article 10, which states: "Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience" [52]. The provisions of the Venice Charter significantly restrict the possibility of faithful reconstruction of historical buildings, especially the creation of stylised forms. In spite of this, between 1960 and 2000, many new tenement houses were erected in Gdańsk that deceptively resembled historical buildings. These buildings, although constructed with modern technologies and materials, are architectural fantasies on the theme of Gothic, Renaissance, Baroque, or Classicist bourgeois houses in Gdańsk (Figure 9).

Figure 9. Tenement houses on Stągiewna Street in Gdańsk. Source: A. Taraszkiewicz.

This situation, on the one hand, arouses objections of architects and conservators, who understand the incompatibility of these actions with the provisions of the Venice Charter and who are reluctant to create so-called "historic buildings". On the other hand, it is received with great satisfaction by the community of contemporary Gdańsk and the wider public, who perceive this type of development as fitting in perfectly with the historic landscape of downtown Gdańsk. As a result of the ongoing disputes, in 2004, on the almost 100-year anniversary of the 1902 competition described above, the city authorities organised an international architectural competition for the 21st century tenement house in Gdańsk. This competition was intended to provide specific guidelines for the implementation of contemporary housing located in the historic downtown. The competition was very popular. 94 applications were received from all over the world and 58 entries were finally submitted [46]. The jury awarded 3 prizes (two for projects from Poland and one for a work from Germany) and several distinctions. Surprisingly, all of the awarded and commended works are solutions presenting a "typical" Gdańsk bourgeois tenement house with its elongated, rectangular ground plan, body covered by a gable roof with its ridge situated perpendicularly to the street and a slender main façade situated along the street. The only difference from the historical original was the very contemporary, clearly international style solution of the front façade (Figure 10). It has to be clearly stated here that the architects taking part in the competition for the 21st century tenement house in Gdańsk decided that its basic spatial structure must derive from the historical pattern and, as it was done by artists of past epochs, only its front façade should testify to the time in which it was built.

Contrary to the expectations of its organisers, the 2004 competition did not provide clear guidelines for spatial activities related to the development of residential buildings located in the historic centre of Gdańsk. These activities are still carried out quite freely, creating solutions directly related to history (Figure 11) as well as referring to contemporary achievements, reflecting the spirit of the times in which they were created (Figure 12).

Structural solutions also vary, especially for elements such as roofs and basements. Roof slopes are still constructed as traditional, wooden rafter framing with the difference in relation to historical solutions that they are only one-tie structures. There are also lightweight steel rafters protected against fire with intumescent paint and even monolithic or prefabricated reinforced concrete slabs, laid with a slope of approx. 60° (Figure 13).

For particular roof construction solutions, i.e., wooden, steel and reinforced concrete rafter framing (all single-unit), as before, numerical models were made (Figure 13). The parameters and material properties of the different models were adopted analogously as in Chapter 3. An elastic-plastic model was considered for the steel truss model, while a plastic-degradation model of concrete was used to model the reinforced concrete slab roof. In contrast to the parameters of the medieval tenement house, the value of the longitudinal modulus of elasticity of the individual materials was not reduced. The results of the analyses are presented below in Figure 13.

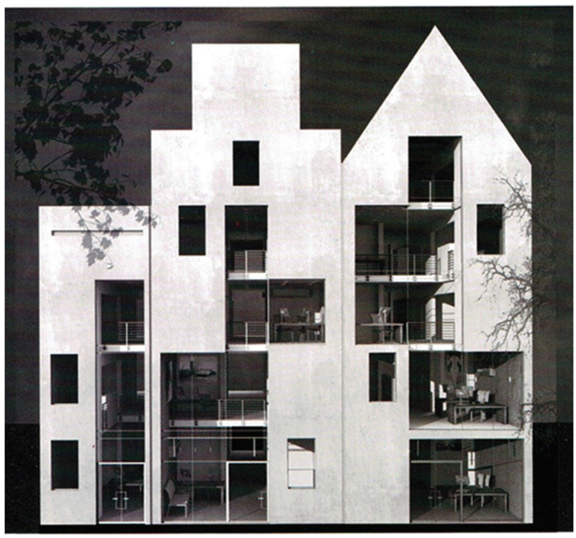


Figure 10. Awarded project of a tenement house in Gdańsk of the 21st century. Authors: B. Domsta, J. Raniszewski, K. Lipińska, M. Jaśkowiec [46].

Figure 11. Tenement houses in Św. The Church of the Holy Spirit in Gdańsk; designed by P. W. Kowalski [53].

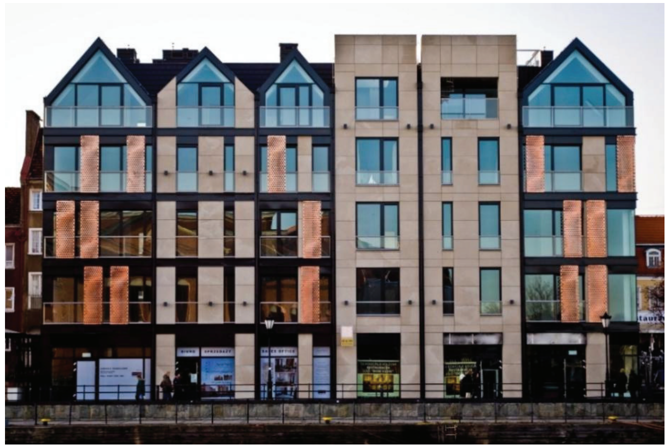
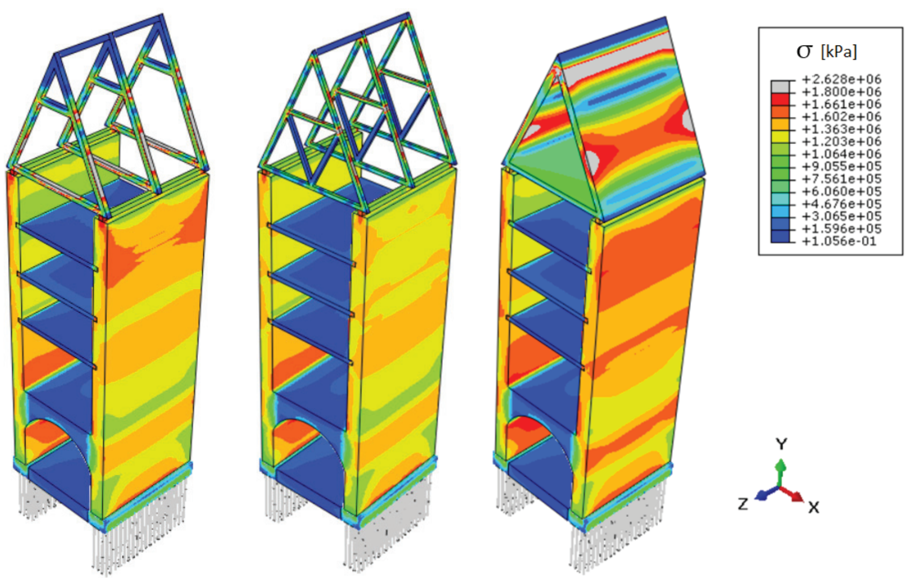


Figure 12. Tenement houses at Targ Rybny in Gdańsk; designed by Kurylowicz &Associates [54].



(**a**) (**b**) (**c**)

Figure 13. Numerical model of roof structures of modern tenement houses in Gdansk: (**a**) wooden rafter framing of one piece, (**b**) steel rafter framing, (**c**) roof made of reinforced concrete slabs; stresses in (kPa).

On the basis of the obtained results, it was stated that modern roof constructions fulfill the conditions of ultimate limit state and serviceability. The compressive stresses of 2 MPa are analogous to the results obtained from the analysis of the medieval roof. This allows us to conclude that for small spans, typically 5 to 7 m, the construction of roofs of tenement buildings carried out in the past (as well as at present) was economically justified and optimal for the safe transfer of loads.

Underground parts of contemporary Gdańsk tenements are also elements of very diverse construction solutions. Because modern engineers have acquired the ability to base buildings below the level of groundwater, the modern tenement house in Gdańsk no longer needs (which was characteristic for centuries past) to have the ground floor elevated above the level of the ground or to have shallow cellars. Today's engineers can deal with difficult ground and water conditions, which is why the basements of tenement buildings are usually realised as so-called "white bathtubs", made of waterproof concrete, realised with the use of cavity walls or sheet pile walls. A "white bathtub" is the general name for a reinforced concrete structure consisting of a foundation slab and walls made of waterproof concrete. It combines the supporting and sealing function and is one of the solutions to the problem of foundations in unfavourable ground and water conditions. A characteristic feature of such a structure is that, in part or in whole, it is externally loaded by ground water. The "white bathtub" as a description and solution has been refined for several decades, mainly in Germany and Central Europe [55]. This technology is used in both single and multi-storey buildings. It is supposed to protect the object from moisture without an additional sealing layer. Basements constructed in this way are often two or three storeys high and serve modern commercial functions such as fitness centres or clubs for the inhabitants, but they are also sometimes the space of underground car parks and the location of numerous technical rooms (Figure 14).

Figure 14. Cross-section through the quarter of buildings on Szeroka Street in Gdańsk; designed by A. Taraszkiewicz. Source: A. Taraszkiewicz.

One thing, however, remains unchanged—the architectural expression of the above-ground part of the building, designed and executed on the basis of a pattern developed in the Middle Ages. The power of this archetype is so great that so far it has not been broken by the changing styles, fashions and technical and technological progress over the centuries (Figure 15) [56].

The medieval bourgeois tenement house located in the downtown of Gdańsk, transformed in the 19th century into a tenement house and finally in the 20th and 21st century into a multi-family or even multifunctional building, as was mentioned earlier, has been and still is nowadays a background for monumental, historic religious buildings or centres of secular power as well as contemporary public utility buildings or collective housing.

However, the phenomenon of the tenement house archetype also manifests its power here, imposing its stylistics on larger objects containing a different function. Narrow, high and flat façades of medieval tenement houses in Gdańsk have become so strongly inscribed in the landscape of the historic city centre that none of the contemporary designers working in this area dare to disturb the existing order. And it doesn't just apply to residential development.

Completed in 2012 and awarded with numerous architectural prizes, the building containing the museum function of the Maritime Culture Centre in Gdańsk is one of many examples of contemporary implementation of the gable form of a tenement house in a building with a completely different function (Figure 16). However, this does not give the impression of artificiality or alienation in this so clearly defined space. On the contrary, by fragmenting the elevation and referring to the medieval way of shaping high and narrow façade divisions topped with pitched roofs, the building perfectly fits into the historical urban landscape. It creates a harmonious whole with it, and at the same time clearly emphasises its own modern distinctiveness through the use of contemporary materials and technologies and the application of minimalist architectural details (Figure 16).

Figure 15. Tenement houses on Szeroka Street in Gdańsk; designed by A. Taraszkiewicz. Source: A. Taraszkiewicz.

Figure 16. Maritime Culture Centre in Gdańsk; designed by Mirosław Frąszczak. Source: InfoGdańsk [57].

7. Conclusions

The spatial image of the European city is inextricably associated with a specific form of the urban house—the tenement house [6], the model of which originates from the Middle Ages, and despite enormous cultural, civilizational, and socio-economic changes, has survived until today. The reason for the extraordinary durability of this type of construction can be found in the enormous rationality and economic efficiency of this solution. Due to the continuity of the frontage, it allowed for very intensive use of the land. Thanks to the use of small construction spans and common for neighbouring buildings (up to today) construction walls (fire separation walls), it allows cheap and fast construction and fire safety.

Thanks to unburdening of the gable elevations, this building model also allows the gable façades to be shaped very freely, which is very important especially nowadays when the tenement house often gains additional, not only residential, functions.

The model of a bourgeois tenement house, thanks to a narrow street, paradoxically also allows for free shaping of the functional layout of the building. Inside the tract, limited by external walls, we are dealing with a "free plan", using modernist nomenclature, which we can freely shape. Even at the present time, when two or three tracts of tenement houses are functionally connected, the structural elements located at the border of the modules (again thanks to small spans) are very small in size, not interfering with the functional solutions. The possibility of easy access of each building to the main communication routes in the tenement model is also functionally very beneficial.

Also on the basis of numerical analyses, it was shown that the construction of roofs of tenement houses performed in the past, as well as in modern times, was and still is economically justified and optimal for the safe transfer of loads at small spans of 5 to 7 m.

Aesthetic considerations, i.e., the possibility of shaping the face of the city according to the patterns accepted in a given epoch and the ease of implementing elements testifying to the aesthetic views and the social and financial status of particular investors in the front elevation, are probably also important in the consolidation of the model of the bourgeois tenement house. It seems, however, that the most important factor which made the model of the mediaeval bourgeois tenement house become an archetype for contemporary architectural and construction solutions is a timeless message contained in this model, a specific code allowing it to be unambiguously identified as a form of urban house—a place of safe living and at the same time a visible sign of the rich history of European cities, an element creating their cultural and spatial identity, a component of the living, constantly transforming urban tissue.

The tenement seems to be a proven, flexible model of an urban building, perfectly fitting into the complexity of the downtown environment and possessing the features of a basic element of the urban-architectural composition of this environment. The building, both historical and contemporary, through its scale and archetypical form, fully respects the spatial context of its neighbourhood, forcing the designers to constantly reinterpret the legacy of past generations. The tenement house appears not only as a testimony to the magnificence of European culture, but through its contemporary architectural interpretations, it gives the inhabitants of European cities an opportunity to preserve their identity, cultural continuity and specific local character. Especially in cities such as Gdańsk, where cultural continuity was broken [58] not only by the destruction of the material substance but also by the exchange of society, where customs could not be passed from generation to generation and there was no natural inheritance of tradition, signs such as the urban tenement, inscribed in the city landscape, have become carriers of local tradition, bridging the gap between generations of old and new inhabitants [59].

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Influence of the Widespread Use of Corten Plate on the Acoustics of the European Solidarity Centre Building in Gdańsk

Wojciech Targowski [1] and Andrzej Kulowski [2,*]

[1] Department of Residential Architecture, Faculty of Architecture, Gdańsk University of Technology, ul. G. Narutowicza 11/12, 80-233 Gdańsk, Poland; wojtargo@pg.edu.pl
[2] Department of Technical Fundamentals of Architecture Design, Faculty of Architecture, Gdańsk University of Technology, ul. G. Narutowicza 11/12, 80-233 Gdańsk, Poland
* Correspondence: kulowski@pg.edu.pl; Tel.: +48-501-052-874

Abstract: This paper describes the relationship between a strong architectural vision that is difficult to balance, and user expectations in terms of acoustics. The focus is on the use of corten steel as the dominant finishing material on façades and interiors to achieve an expressive, symbolic message through program-based design. The architectural premises justifying the adopted solutions are presented, especially the universality and homogeneity of the material. Against this background, the influence of corten steel on the acoustics of the two largest rooms of the European Solidarity Center, which are the winter garden and the multi-purpose hall, was discussed. Remedial steps have been taken to reduce the greatest acoustic inconveniences resulting from the widespread use of metal sheet as a finishing material in rooms, i.e., excessive reverberation and a low degree of sound dispersion. A positive result for the acoustic conditions achieved in the winter garden was the presentation of a large body of classical music in the building.

Keywords: symbolic building; corten plates; tilted walls; winter garden; room acoustics; reverberation time; flutter echo

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1. Introduction

Developed as the result of a high-profile international competition, the European Solidarity Centre (ECS) in Gdańsk was opened in 2014 [1,2]. The purpose of the building is to document and promote the idea of Solidarity, a concept born in the Gdańsk Shipyard, the guiding idea behind the great socio-political changes in Central and Eastern Europe at the end of the 1980s. For understandable reasons, the symbolic aspect of the architecture was decisive for the design solutions and consequently for the verdict of the international jury [3]. The shapes and materials used are closer to sculptural forms than to utilitarian public architecture (Figure 1). A strong formal concept, however, sometimes entails disadvantages in the functional sphere, such as achieving the desired acoustic characteristics.

Widely used as an interior finishing material, the corten plate plays a special role in developing the symbolic code of architecture [4]. Devoid of any paint hiding the essence of the material, the raw surfaces perfectly reflect the spirit of the spontaneous protests by Gdańsk shipyard workers. The corroded surface of the façades, however, is only a complement to the primary formal idea behind the project, referring to the once existing steel stockpile required for shipbuilding—hence the consistent parallel alignment, and the inclination from the upright position of the rust-colored walls, so that they directly relate to the metal sheets leaning against the storage racks (Figure 2).

The aim of this paper is to show the possibility of reconciling the specific, difficult-to-balance, formal program of architecture with the requirements of the acoustic usability of the building (Figure 3).

Figure 1. Richard Serra, Memorial to the victims of the Nazi T4 extermination program, Berlin. Material: corten plate (photo by Wojciech Targowski).

Figure 2. Gdansk Shipyard, metal sheets warehouse for shipbuilding on the site of the future European Solidarity Centre (ECS) building (photo by Wojciech Targowski).

Figure 3. The south and west façade of the ECS, with structural walls which deviate from the vertical by 6.5°. The façades of the ECS are covered with 5 mm thick corten plates (photo by Wojciech Kryński).

2. Examples of Widespread Use of Corten Cladding in Public Utility Buildings

The use of corten steel in building architectural narratives dates back to the 1960s. One of the precursors of its application was the eminent American–Finnish architect Eero Saarinen. In 1964, after his death, the John Deere World Headquarters designed by him in Moline, Illinois, USA, was put into operation. In the symbolic code of the architecture of this building, an attempt was made to establish a dialogue of seemingly opposing values—industrial civilization and nature. According to the production profile, a large concern producing heavy agricultural machinery has gained a complex of offices and exhibition facilities made of steel blended into the organic landscape [5] (Figure 4).

The Mies van der Rohe award-nominated Raif Dinckok Cultural Center was opened in 2011 in Yalova, Turkey. The use of corten steel in the architecture of the building is an obvious reference to the industrial character of the city. It is also a tribute to the founder—a large industrial company, the Akkok Group. The impressive, openwork, steel structure, illuminated by flickering light, contradicts the perception of steel as a soulless, raw matter and, contrary to stereotypes, encourages the affirmation of the industrial landscape (Figure 5) [7].

Figure 4. John Deere World Headquarters Moline, Illinois, USA. Object completed in 1964, architects—Eero Saarinen and Kevin Roche [6]. Photo—public domain.

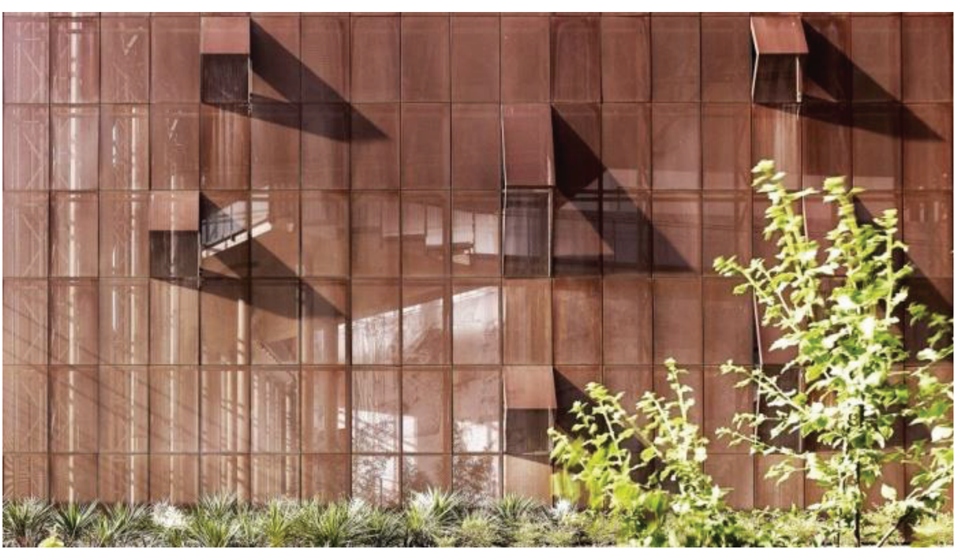

Figure 5. *Cont.*

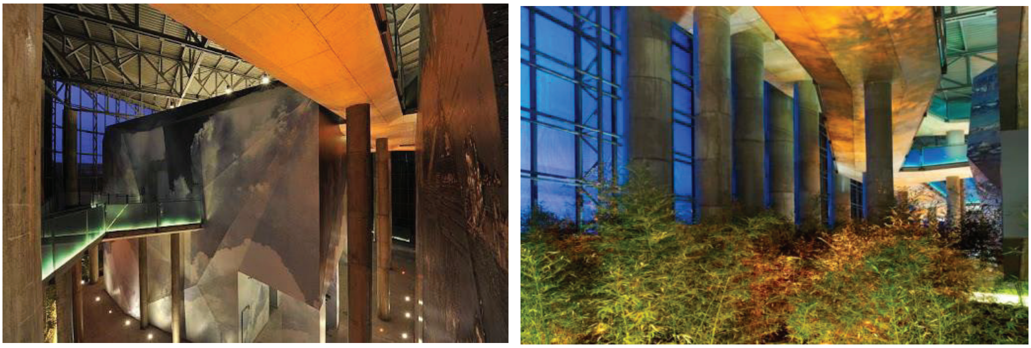

Figure 5. Raif Dinckok Cultural Centre, Yalova, Turkey. Object completed in 2011, architects—Emre Arolat, Gonca Pasolar and Rafat Yalmaz [8]. Photos by courtesy of emre arolat architects, Creative Commons Attribution-Share Alike 4.0 International.

The façades of the town museum building in Essen, Germany, which were built in 2009, and the city archives of Haus der Essener Geschichte—Stadtarchiv are completely covered with corten cladding. According to the authors' intention, the time-varying, maturing patina of corten steel sheets illustrates the passing of time, directly referring to the function of the building housing the documentation of the city's history. The brutal, tin block is also related to the landscape of the industrial complex of the Krupp steel plant—Kruppstadt Essen, for many years an essential condition for the city's existence (Figure 6) [9].

Figure 6. House of Essen History and City Archives, Essen, Germany. Object completed in 2009, architects—Frank Ahlbrecht, Hermann Scheidt [10] Photo—public domain.

The use of corten in architecture is good for building a symbolic aura. Architects fascinated by this material willingly use it to manifest programmatic references. Despite the aesthetic affinities with the above-mentioned projects, the building of the ECS is clearly specific. In this case, the designer took the risk of mass use of corten cladding as a finishing material in interiors with qualified acoustics. On the other hand, the unconventional use of large steel surfaces raised concerns that the interiors would show the acoustic properties of an industrial hall, and thus lose the acoustic comfort desired in public utility buildings [11].

3. Corten Plates as a Finishing Material

Corten steel (original name COR-TEN) is an alloy with a deliberately created corrosion layer replacing the need for a protective paint coating. It is obtained by the use of alloy additives that give the steel the desired metallurgical properties and form the corrosion layer (P, Cu, Cr, Ni, Si, Mo, Ti, V). Work on the production of corten steel began in 1933, with practical applications in 1959 [12].

In its basic applications, corten steel is a construction material. In the form of metal sheets, it is used relatively rarely, mainly due to its specific decorative value. In architecture, corten plates are mainly used as a façade covering for office and commercial buildings, cultural facilities, etc., as well as for artistic projects such as monuments, sculptures or other open-air installations. A special feature of the material is a long period of natural stabilization of the physico-chemical properties of the corrosion coating, lasting many years [13]. This is related to its change of color, as well as dusting and settling of the corrosion deposits on the surface of the ground [14]. For this reason, corten steel is mainly used in the open air. Due to the possibility of dusting, the use of corten sheet in rooms requires stabilization of the corrosion coating, e.g., by spraying with thin layer of clear varnish.

The article describes the use of corten steel cladding in the largest ECS rooms, i.e., in the winter garden and in a multi-purpose hall, along with the impact of this material on their acoustics. Corten plate is a finishing material that also dominates other ECS rooms (entrance hall, foyer, corridors). The rationale is a reference to the material uniformity of the façade and interiors, characteristic of large industrial facilities.

4. Use of Corten Plates in the ECS Interiors

A cladding made of 1 mm corten plate on plywood 15 mm thick was applied in all interiors of the ECS. Its sound absorption coefficient is comparable to that of plaster ($\alpha_w \approx 0.05$) [15,16]. The use of such material in the form of large, flat sheets causes the sound to be reflected in a mirror-like manner without loss of energy, which leads to a long reverberation time [17]. According to the designer's intentions, this is not considered an acoustic defect, but rather as an aid to the visual means shaping the mood of the major industrial interior.

These effects are mitigated to some extent by the use of a drawn mesh made of corten plate and perforated corten plates, moved away from the concrete wall, and the filling of the voids with mineral wool. When applied to the upper part of the wall, it preserves the homogeneity of the interior material and minimizes excessive reverberation, directing the auditory sensations of the users from the expected clear industrial monumentality to the acoustic neutrality typical of public spaces.

4.1. Winter Garden

The winter garden brings together the most important ECS functions, which are permanent and temporary exhibitions, reading rooms with libraries, offices, etc. They are accessible directly or through wide corridors, mezzanines with escalators and internal glass facades and window openings. As a result, the interior of the winter garden is largely fragmented, which in combination with large clusters of vegetation has a positive effect on its acoustics (Figure 7).

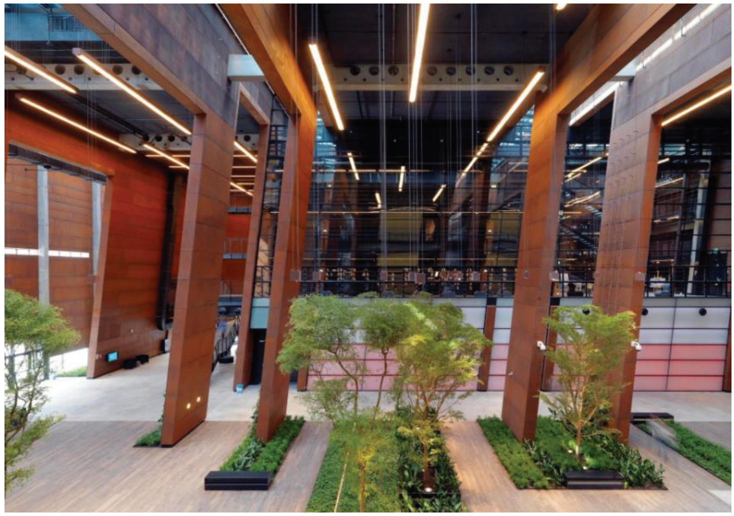

Figure 7. The ECS, winter garden (photo by Wojciech Kryński).

As it was said before, the interior of the winter garden is made of large, flat elements covered with metal sheets, reflecting the sound mainly in a mirror form, i.e., without dispersion and with negligible absorption. Occurring in sufficiently large groups, the vegetation has a positive effect on the acoustics of the room formed in this way by absorbing and dispersing sound [18].

There are two types of vegetation in the Winter Garden—trees growing in single pots and a green wall formed by plants climbing a frame next to construction poles. The sound absorption coefficient of detached trees is $\alpha = Gf^{1/2}$, where f is the frequency and G is a constant with values from 0.001 to 0.002 [19]. With the density of vegetation available in a room of the considered size (see Figure 4), a sound absorption coefficient α in the range from 0.06 to 0.18 for the frequency range f from 1 to 8 kHz can be expected. Similar values of α are reported in the literature for vegetation suitable for green wall formation (α from 0 to 0.2 for the frequency range from 200 to 1600 Hz) [20]. These are small values, but after reaching the target size by the mass of vegetation and combined with the effect of sound absorption by the air, also increasing with frequency [21], they will allow for a noticeable suppression of high sounds as intended by the designer.

Consciously used aesthetic effect should also be raised, expressed in exposing the rawness of corten combined with the softness of greenery, as well as improving air quality and bringing other benefits to various forms of activity conducted there [18]. At present, the vegetation in the winter garden is in the initial stage of growth, eventually becoming an element competing with the severity of corten. This applies at least to the lower part of the room, the total height of which is approx. 15 m.

The sound scattering and absorption effects produced in this way significantly reduce the feeling of reverberation that one might expect when entering such a large cubature. This refers to both the leading function of the winter garden, which includes meetings, exhibitions and occasional events, as well as special occurrences, such as the stage presentation of an opera (see Section 5, "Synergistic influence ... ").

The acoustic measurements of the winter garden were made without the presence of the public (Figure 8). This is a common practice to avoid audience noises that affect the measurement result. The influence of the audience on the acoustics of a room is usually taken into account by calculation. An estimate of the audience's influence on the reverberation time using a statistical method (the so-called Sabine method) is shown in Appendix A.

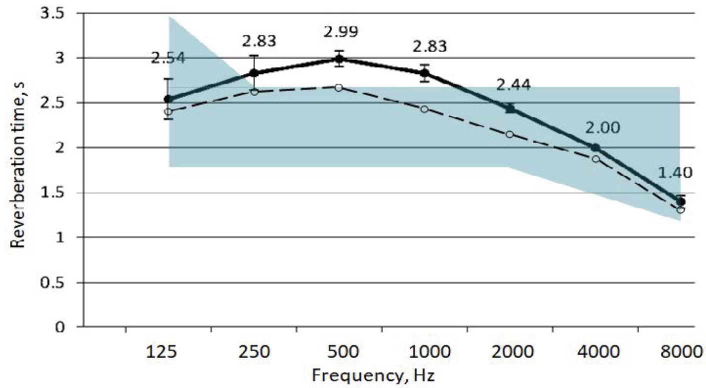

Figure 8. The reverberation time of the winter garden. Continuous line and numerical values: acoustical measurements (the average of 8 observation points, room without public). Measurements were made in accordance with the ISO 3382-2 standard [22], sound source—pistol shot. Dashed line—reverberation time taking into account the presence of the audience, choir and orchestra, see Appendix A. The range of recommended values of reverberation time for the occupied room is marked in blue [17].

Attention is drawn to the frequency characteristics of the reverberation time of the winter garden with the damping of the lower and upper parts of the band, due to the arrangement of the structural elements in the ceiling of the interior and the presence of large bodies of greenery, intended for further growth. In view of the varied nature of sound production, in line with the program-based multi-purpose character of the winter garden, this creates favorable conditions for the functioning of the sound system.

Dimensions of the winter garden—length × width × height: approx. 30 × 30 × 15 m, floor area—885 m^2, cubature, including acoustically coupled spaces—19,400 m^3, surface of the corten plates—approx. 2200 m^2, reverberation time at a frequency of 1000 Hz—2.8 s (Figure 8).

4.2. Multi-Purpose Hall

The multi-purpose hall is a room with a simpler form. As with the entire building, the main tool for creating the interior architecture of the hall is the corten plates, which completely cover the parallel aligned side walls. In accordance with the accepted formula of an industrial hall, the side walls are formed from large single-piece planes. This promotes the fluttering effect of the sound as it decays. In general, this phenomenon is due to the multiple mirror reflection of sound between spaced apart parallel surfaces, e.g., between walls or ceiling and floor, and is acoustically disadvantageous. Flutter echo can also arise between specifically shaped curved surfaces with insufficient absorption [17]. This phenomenon is local in nature, i.e., it is observed only in the area including the paths of reflected waves, at a specific location of the source generating sound pulses, e.g., percussion instruments.

The estimation of flutter echo formation is based on a geometric model of sound propagation. In this model the assumption is that the obstacle that reflects the sound, in this case the side wall, is large compared to the wavelength. This can be written as $l \geq K\,\lambda$, where λ is the wavelength, l is the dimension of the obstacle and K is a factor dependent on the ratio between mirrored and diffused energy. K can be taken as a measure of the audibility of a flutter echo. The greater the value of K, i.e., the larger the reflecting surfaces are, the more clearly the flutter echo phenomenon is audible. At low K values, the flutter echo becomes blurry because some of the reflected sound energy takes the form of the scattered sound. With the decrease of K and the appropriate arrangement of the fragmented elements, flutter echo turns into a smooth decay of the sound, beneficial for the acoustics of the room.

In the literature, the choice of the K factor is not free of some arbitrariness. Generally, the K factor is greater than one [23,24], though some authors accept smaller values (e.g., K = 1 [25], K = 1/2 [26] or even K = 1/3 [27]). This means that even a strongly blurred flutter effect, created with a share of diffuse reflections, is treated by these authors as an acoustic defect of the room. This can be the basis for taking remedial steps, such as dividing large areas forming a room into smaller ones, corresponding to small K values. An acoustically qualified division of large areas into smaller ones leads to the creation of acoustic diffusers.

In the multi-purpose hall, the area susceptible to flutter echo formation is the stage. In accordance with the architectural concepts, the walls of the building have been tilted. In this case, the strict formal guidelines had a positive effect on the room. The walls deviate so significantly from the vertical plane such that the flutter echo formation zone is shifted above the stage, severely reducing the degree to which it is perceived (Figure 9). As mentioned above, flutter echoes are usually eliminated by positioning the walls in a suitable plane or using sound-diffusing structures [17]. In this case, in order to emphasize the form of the industrial hall and to be consistent with the formula for the whole building, the parallel position of the walls and their flat form have been preserved, at the deliberate expense of a slight inconvenience in the sphere of utility.

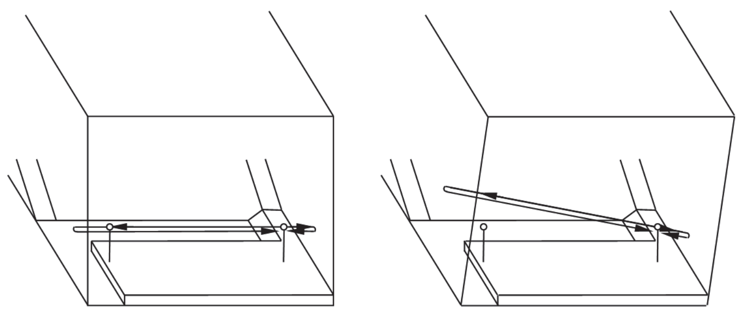

Figure 9. Shifting the zone of flutter echo formation (**left**) above the level of the performers' heads by deviating the side walls from the vertical (**right**).

4.3. Acoustic Tests of the Multi-Purpose Hall

Since the flutter echo consists of periodically repeated pulses, signal processing procedures can be used to detect their presence in the sound decay curve. Two methods are most commonly used, i.e., testing on the autocorrelation function and cepstral analysis. The autocorrelation function is a measure for the inner statistical relations of a signal and can reveal its stochastic or periodic components. In order to study the flutter echo, a property of the autocorrelation function that is called temporal diffusion was extracted [28]. Cepstral analysis is used when a highly condensed flutter echo is perceived as a coloration of sound. This method allows us to detect periodicity occurring in the sound spectrum, which is a symptom of its coloring [29].

The above-mentioned methods are an objective confirmation of subjectively unpleasant character of the reverberation, which, apart from fluttering echoes, consists of other irregularities in the sound decay curve. In many cases, a sufficient evaluation of the quality of the sound decay curve can be made using the auditory judgment. This applies especially to the audibility of the flutter echo in various types of sound production, i.e., speech, singing, musical sounds, etc., taking into account performance factors such as tempo, expression, the occurrence of pauses, type of instrumentation and others. The mentioned types of stimulation are different from the standard measurement signal. Therefore, it is helpful to include a competent judge, i.e., appropriately trained listener, in the auditory evaluation of these effects in the sound decay phenomenon.

In order to test the susceptibility of the multipurpose hall to the formation of flutter echoes, acoustic tests were carried out during the finishing works. They comprised an auditory evaluation of the degree of audibility of the flutter echo at various configurations of the absorbing material applied to the side walls (Figure 10). During the test, a comparison between the audibility of the echo to a listener positioned in the central part and at the edge of the stage was carried out, with and without sound-absorbing material. The source of the sound was a pistol shot, speech and selected musical instruments.

It was found that the inclination of the walls was a sufficient remedial step, shifting the area of the flutter echo formation above the level of the performers' heads. The level of echo was reduced to such an extent that it became unnoticeable. The echo remains slightly noticeable only at the edge of the stage, by the left side wall, which does not affect the convenience of using the room. Thanks to this, the covering of the lower parts of the walls with sound-absorbing material was avoided, which would have been clearly visible from the audience. Sound-absorbing material is applied only to the upper parts of the side walls as a means of reducing reverberation, without affecting the visual reference to the industrial character of the interior (Figure 11).

Figure 10. The multi-purpose hall during the acoustic experiment regarding the susceptibility of the room to the formation of the flutter echo. View from the audience on the stage, the left- and right-side walls are shown (photo by A. Kulowski).

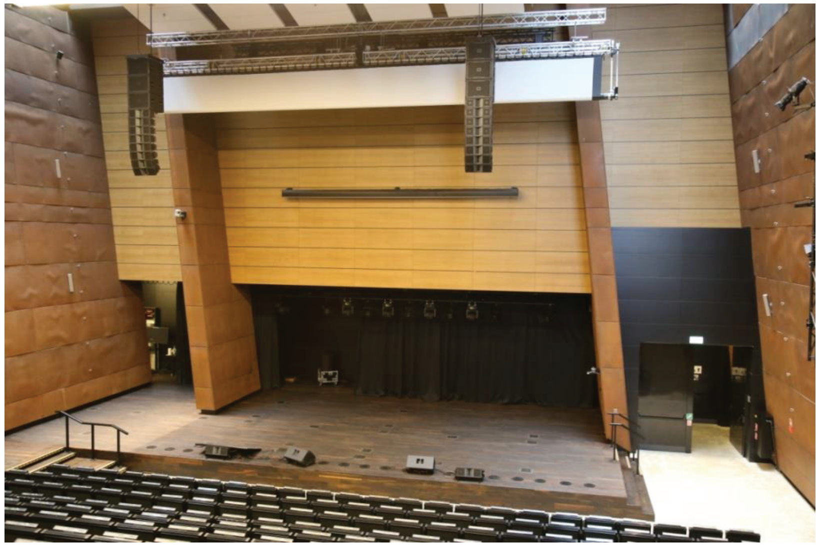

Figure 11. The multi-purpose hall, view from the audience on the stage (photo by Wojciech Targowski).

Dimensions of the multi-purpose hall—length × width × height—30.5 × 20.7 × 17.6 m; stage—length × width—15.3 × 9.1 m; floor area—483 m^2; cubature—5700 m^3; number of seats—433, surface of the corten plates—approx. 940 m^2; reverberation time at the frequency 1000 Hz—1.3 s (Figure 12).

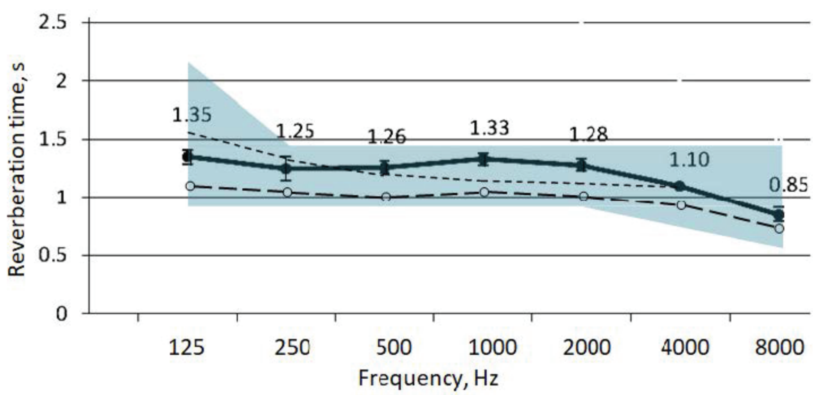

Figure 12. Continuous line and numerical values—measured reverberation time of the multi-purpose hall (the average of 6 observation points, room without public). The reverberation time measurements were made in accordance with the ISO 3382-2 standard [22], sound source—pistol shot. Thin dashed line—reverberation time according to the acoustic design. Thick dashed line—reverberation time in a occupied room, see Appendix A. The range of recommended values of reverberation time for occupied room is marked in blue [17].

5. Synergistic Influence of the Place of Presenting Art on Its Perception

The general aura of the surroundings—the spirit of the place—is important in terms of the perception of artistic events. We succumb to its charm when the architecture of the building crosses the barriers of the literary message. The emotional experience of the space can then be transferred to the assessment and impact of the events taking place within it [30].

The industrial setting and the resulting interior acoustics take on special meaning in the context of the artistic events presented at the ECS. It acts as a confirmation of the significant influence of the place of presenting art on its perception. One example of such synergy, noticeable in almost every meeting or artistic event taking place at the ECS, is the presentation of Ludwig van Beethoven's opera "Fidelio" in the winter garden on 30 August 2017 (Figure 13). The concert was performed by native musicians along with professionally educated artists who were immigrants and refugees from countries in conflict [31]. In this context, the ECS as a place for presenting art takes on special significance. Along with the ideological message of this operatic work, it refers to still-remembered or ongoing events with significant social consequences, including the mass protests that took place here in 1981, the changes in Poland and in Europe in 1989 and the current influx of immigrants and refugees into Europe. Art becomes then a clear carrier of the idea of solidarity, connecting these events.

Unrelated to the ECS, an eloquent example of a synergistic connection between the place of traumatic events and the content of the presented piece of art is the historical performance of Wolfgang A. Mozart's "Requiem" in Sarajevo in 1994 by the orchestra and chorus of the city of Sarajevo with world-class conductor and soloists (Zubin Mehta, José Carreras) [32,33]. The concert took place in the capital of the 1984 Winter Olympics, destroyed 10 years later during the civil war in Bosnia, among the rubble of the ruined National Library.

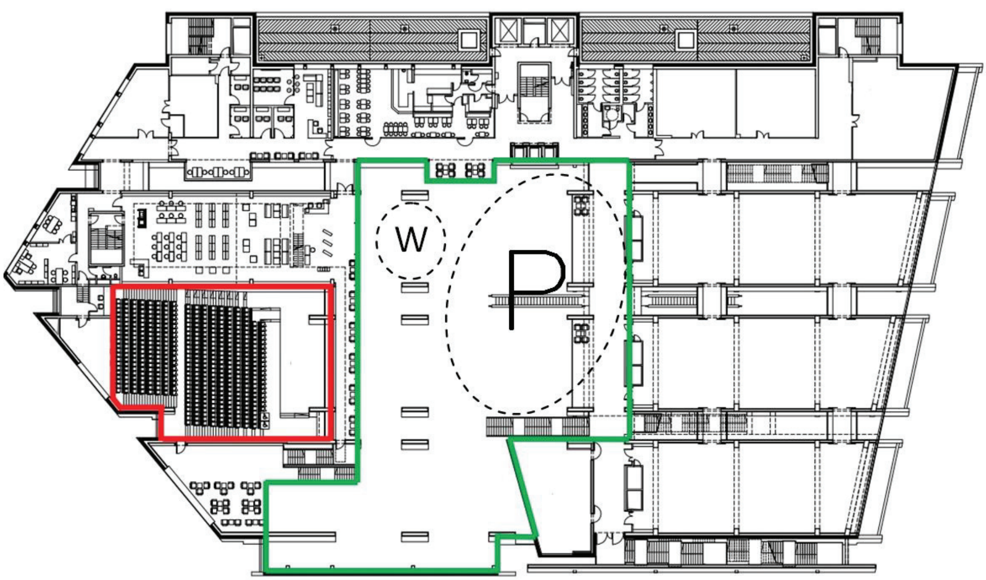

Figure 13. Location of the multifunctional hall and the winter garden on the ECS plan; the positioning of the performers (W) and the audience (P) during the stage performance of Ludwig van Beethoven's opera "Fidelio" in the winter garden is shown (own study).

6. Conclusions

The European Solidarity Centre is a public building, one in which the guiding idea of architecture plays a special role. Apart from formal procedures and numerous symbolic themes, the clear reference to industrial architecture serves to create the expected aura.

The primary means of expression are the shape of the whole, the interior layout and the uniformity of the finishing material, dominating on the façades and interiors. The building refers to the form of a large industrial factory building, with its high walls and vast, single-space assembly halls. The whole is finished with seemingly unattractive, raw in appearance, corten plates.

The main room of the ECS is a winter garden, which, together with the accompanying rooms, occupies most of the volume of the building. It was intended as a multi-purpose venue for various events involving large groups of participants. The consistent use of sheet metal as a finishing material in such a high and vast interior is a major inconvenience, leading to high reverberation, typical of industrial spaces. However, it was shown that architectural treatments can partially compensate for the demonstrable flaws. Particularly beneficial is the horizontal break in the interior, obtained due to mezzanines, the opening of the layout with wide and several meters high corridors, penetrating the whole body of the building, and the exceptionally richly designed clusters of greenery. The complementing of the whole with sound-absorbing fittings located in the upper parts of the room made it possible to achieve favorable acoustic conditions. In their current state, they allow for a variety of activities, from exhibitions, through various types of meetings, to qualified concert activities.

The multi-purpose hall, which is an important part of what the ECS program offers, was designed as a rectangular, hall-like interior, which is not conducive to good acoustics. In addition, it is completely encased in corten plate cladding. On the other hand, the tilted walls, as provided for in the project, effectively reduce the unfavorable effects and constitute the result of a desire to give the building a dynamic character, important with respect to illustrating the momentum and expansiveness of the political changes of the Solidarity era. Appropriate acoustic parameters were obtained in combination with the use of sound-absorbing materials.

The article shows that corten steel, a seemingly visually unimpressive and acoustically unsuitable finishing material, gains a new, attractive dimension through close cooperation between an architect and an acoustic specialist. The appropriate design decisions made it possible to reconcile the acoustic requirements with maintaining the clear ideological layer of the building. Furthermore, the interaction of the acoustic climate with the cultural climate of the place enhances the reception of both the values of the built space and artistic events organized in the ECS building.

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Appendix A

Table A1. Calculations taking into account the influence of the audience, choir and orchestra on the reverberation time during the stage performance of Ludvig van Beethoven's opera Fidelio in the winter garden.

No.	Acoustic Data	Octave Band, f, Hz						
		125	250	500	1k	2k	4k	8k
1	Measured reverberation time of the room without public, T, s	2.54	2.83	2.99	2.83	2.44	2.00	1.40
2	Sound absorption or the room without public, $A = 0.161 \times 19{,}400/T$, m^2	1230	1104	1045	1104	1280	1562	2231
3	Sound abs. coefficient, person sitting in an upholstered chair, α_1 [17]	0.16	0.35	0.42	0.47	0.52	0.53	0.54
4	Sound absorption of 400-seat audience as in No. 3, 2 persons per 1 m^2, $A_1 = 200 \times \alpha_1$, m^2	32	70	84	94	104	106	108
5	Sound absorption of an adult in light clothing, A_{20}, m^2 [17]	0.60	0.95	1.06	1.08	1.08	1.08	1.08
6	Sound absorption of a 30-person choir as in No. 5, $A_2 = 30 \times A_{20}$, m^2	18.0	28.5	31.8	32.4	32.4	32.4	32.4
7	Sound absorption of musician with instrument, A_{30}, m^2 [17]	0.12	0.24	0.59	0.98	1.12	1.12	1.12
8	Sound abs. of a 40-person orchestra as in No. 7, $A = 40 \times A_{30}$, m^2	4.8	9.6	23.6	39.2	44.8	44.8	44.8
9	Sound absorption of the occupied room, $A' = A + A_1 + A_2 + A_3$, m^2	1285	1212	1184	1270	1461	1745	2416
10	Reverberation time of the occupied room, $T' = 0.161 \times 19{,}400/A'$, s	2.43	2.57	2.64	2.46	2.14	1.80	1.30

Table A2. Calculations taking into account the influence of the audience on the reverberation time in the multi-purpose hall.

No.	Acoustic Data	Octave Band, f, Hz						
		125	250	500	1k	2k	4k	8k
1	Measured reverberation time of the room without public, T, s	1.35	1.25	1.26	1.33	1.28	1.10	0.85
2	Sound absorption or the room without public, $A = 0.161 \times 5700/T$, m^2	680	734	738	690	717	834	1080
3	Sound absorption coefficient of a person sitting in lightly upholstered theater chairs, α_4 [17]	0.56	0.68	0.79	0.83	0.86	0.86	0.86
4	Sound absorption of 433-seat audience as in No. 3, 2 persons per 1 m^2, $A_4 = 216.5 \times \alpha_4$, m^2	121	147	171	179	186	186	186
5	Sound absorption of the occupied room, $A' = A + A_4$, m^2	801	881	909	869	903	1020	1266
6	Reverberation time of the occupied room, $T' = 0.161 \times 5700/A'$, s	1.14	1.04	1.00	1.06	1.02	0.90	0.72

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buildings

Article

The Impact of Avant-Garde Art on Brutalist Architecture

Wojciech Niebrzydowski

Faculty of Architecture, Białystok University of Technology, ul. Oskara Sosnowskiego 11, 15-893 Białystok, Poland; w.niebrzydowski@pb.edu.pl

Abstract: Brutalism was an architectural trend that emerged after World War II, and in the 1960s and 1970s, it spread throughout the world. The development of brutalist architecture was greatly influenced by post-war avant-garde art. The greatest impact on brutalism was exerted by such avant-garde trends as art autre, art brut, and musique concrète. Architects were most inspired by the works of such artists as Jackson Pollock, Jean Dubuffet, Pierre Schaeffer, Eduardo Paolozzi, and Nigel Henderson. The main aim of the research was to identify and characterize the most important ideas and principles common to avant-garde art and brutalist architecture. Due to the nature of the research problem and its complexity, the method of historical interpretative studies was used. The following research techniques were employed: analysis of the literature, comparative analysis, multiple case studies, descriptive analysis, and studies of buildings in situ. The research found the most important common ideas guiding brutalist architects and avant-garde artists: rejection of previous principles and doctrines; searching for the rudiments; mirroring the realities of everyday life; glorification of ordinariness; sincerity of the material, structure, and function; use of raw materials and rough textures.

Keywords: art; construction engineering; cubature architecture; design method; design paradigms; brutalist architecture

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1. Introduction

It is hard to imagine greater integration of art and engineering than in brutalist architecture, especially in its beginnings. This connection did not only concern the architectural space, into which works of art (paintings, sculptures, tapestries) were introduced, nor only buildings decorated with ornaments, reliefs, and mosaics. Brutalists brought architecture into an existential relationship with art that went far beyond the mere function of beautification. In brutalism, integration between architecture and art took place at the most basic level. It was the level of rudimentary ideas, common foundations, the most deeply rooted principles and values from which architecture and art grew. These ideas also concerned strictly engineering issues, such as construction, materials, technical elements, and installations. Artist and architects considered their meaning, aesthetics, and ways of designing and exposing.

Brutalism was the architectural style that spread throughout the world after World War II. It reached the culminating point in the 1960s and faded away at the beginning of the 1980s. The architects who contributed most to the development of brutalism were Alison Smithson, Peter Smithson and Le Corbusier. They all collaborated with artists but also created art themselves. Knowledge of brutalist architecture is not sufficiently deepened. While the most famous works of the most eminent architects have been analyzed many times, the issues related to the theory of this style require further research. In particular, the relationship between brutalism and the ideas of avant-garde art should be explained.

When reviewing the state of the research field, significant publications and their authors should be identified. In this context, it should be stated that the most important researcher of brutalist architecture was Reyner Banham. He was at the same time a promoter, and even a co-creator, of the New Brutalism doctrine. Two of Banham's publications are of fundamental importance—the article "The New Brutalism", which appeared in December 1955 in "The Architectural Review" [1] and the book "The New Brutalism: Ethic or Aesthetic?" [2], which was published 11 years later. The analyses contained in the article concerned the beginnings of brutalism and included, among others, its definition. The book was largely their continuation and extension. Despite the passage of time, it is to this day the most important study on both brutalist architecture and the doctrine of New Brutalism. In the short chapter "Brute, non and other art", Banham mentioned the influence of avant-garde art on brutalism [2] (pp. 61–67). He also presented the issues of cooperation between architects and artists in articles about two significant exhibitions: "Parallel of Life and Art" [3] and "This is Tomorrow" [4].

Tight relationships between brutalist architects and representatives of various arts took place within the Independent Group. The literature on the work of this group is quite rich. The publications of Anne Massey, including the book "The Independent Group: Modernism and Mass Culture in Britain, 1945–1959" from 1995 [5], as well as a monograph edited by David Robbins, "The Independent Group: Postwar Britain and the Aesthetics of Plenty" from 1990 [6], should be mentioned here. An important publication is also the book "As Found: The Discovery of the Ordinary" by Claude Lichtenstein and Thomas Schregenberger, which was published in 2001 [7]. The authors presented the idea of As Found, which is essential to both brutalist architecture and avant-garde painting, sculpture, photography, and film.

In research on brutalism, the publications of its precursors are important. Alison and Peter Smithson were involved in intensive publishing work [8–11]. In the 1953 article "House in Soho", they used the term "New Brutalism" for the first time [12]. Significant publications on the brutalist phase of Le Corbusier's work were books from the "Oeuvre complete" series, especially volumes 5, 6 and 7 [13–15]. The achievements and ideas of other important architects related to brutalism are presented in monographs. Books about the following architects helped obtain research material: Denys Lasdun [16], James Stirling and James Gowan [17], Ernő Goldfinger [18], Louis I. Kahn [19], Josep Lluís Sert [20], Paul Rudolph [21], John M. Johansen [22], Kenzo Tange [23], Kunio Maekawa [24], Gottfried Böhm [25], Sigurd Lewerentz [26], Vilanova Artigas [27], Lina Bo Bardi [28], and Balkrishna Doshi [29].

The works and ideas of avant-garde artists are also presented in individual monographs or articles. These include books about two of the artists most connected with the New Brutalism doctrine, Nigel Henderson [30] and Eduardo Paolozzi [31]. The authors of articles relating to the influence of individual artists on brutalist architecture are Ben Highmore [32,33], Hadas A. Steiner [34,35], Alex Kitnick [36], and Dirk van den Heuvel [37].

The analysis of the current state of the research field has shown that so far, only fragmentary research has been carried out on selected issues, artists, and architects. There is a lack of studies dealing with the issue of the influence of ideas of avant-garde art on brutalist architecture in a holistic manner. The most important artistic ideas in this respect should be identified, characterized, and systematized. The research should also go beyond the theory aspect and include practice: architectural forms, building structure, architectural elements and details, and textures. It should be shown that architectural solutions show similarity, or even identity, with artistic and architectural ideas. Therefore, this article will present the fundamental ideas and assumptions of avant-garde trends in the art of the post-World War II period. It will be proved that the precursors of brutalist architecture not only adopted these ideas but also co-created them. Artists used the common creative principles in their works of art, music, and literature, and architects used them in their architectural doctrines and buildings.

This ideological connection between certain trends in art and brutalist architecture is evident, especially in the formation of brutalism, i.e., in the 1950s and early 1960s. A special place here is occupied by the theoretical activity of British architects of the young generation, which is led by the Smithsons. They developed the architectural doctrine of

New Brutalism, which left a deep mark on brutalist architecture. Another precursor of the brutalist style in architecture was Le Corbusier. His work and concepts were particularly analyzed in the study.

Summarizing this introduction, the basic hypothesis should be emphasized. Post-war avant-garde art and brutalist architecture shared common ideas. These ideas and assumptions influenced the spatial, aesthetic, construction, and engineering solutions characteristic of brutalist buildings.

The main purpose of the research was to identify and characterize the most important ideas and principles common to avant-garde art and brutalist architecture. The practical impact of these ideas on buildings was presented in terms of their forms, structures, functional and spatial solutions, aesthetic effects, elements, and details.

2. Materials and Methods

The subject of research was both brutalist architecture and avant-garde art. The term "brutalist architecture" should be understood as a global architectural style of the second half of the 20th century. This term is much broader than "New Brutalism", which was the architectural doctrine of young British architects. The term "avant-garde art" covers such post-war trends as art brut, art autre, and musique concrète, as well as the works of artists connected with these trends. The scope of the research problem included both the theory and practice of brutalist architecture and avant-garde art. The research period covered the years 1945–1980, although some aspects went back to the interwar period. The most focus was on the first phase of brutalism, which is the 1950s and early 1960s. As brutalist architecture spread around the world, the research concerned architects and buildings from many countries. Nevertheless, it should be noted that the origins of brutalism are largely related to the United Kingdom, and therefore, much of the research is devoted to this country.

The specificity of the science of history and theory of architecture requires extensive analyses of objects as complex as buildings and issues as multi-faceted as architectural ideas. In the case of brutalism, creative ideas were particularly diverse and included inter alia, artistic, social, technical, and economic factors. Due to the nature of the research problems and their complexity, the general method of historical and interpretative research was applied. The following research techniques were employed: analysis of the literature, comparative analysis, multiple case studies, logical interpretation, descriptive analysis, study of the buildings on the site.

The course of research can be divided into four basic stages:

1. Collecting research materials.

Books and scientific articles, as well as information from internet sources, were collected. Photographs and design drawings from publications and obtained from other authors were also collected. During the study visits, our own photo and film documentation of the buildings was prepared. On-site research was carried out, inter alia, in the United Kingdom, France, Germany, Austria, Lithuania, Slovakia, Poland, Turkey, and the USA.

2. Identification and organization of materials.

The collected materials were initially organized according to several criteria in thematic groups concerning, among others: avant-garde trends in art, the doctrine of New Brutalism, works and ideas of individual architects, and forms of brutalist buildings.

3. Assessment and analysis of the collected materials and their interpretation.

The collected materials were assessed in terms of their usefulness in research. Further research was carried out based on the most significant materials, using the remaining ones as needed. The main research technique at this stage of research was the analysis of the literature supported by comparative studies. The subjects of comparative analyses were, among others, ideas and principles of artists and architects, works of avant-garde art and buildings, and specific features of works of art and works of architecture (e.g., textures).

In the course of these analyses and interpretations of their results, the main ideas common to avant-garde art and brutalist architecture were identified.

4. Formulation of results and conclusions.

The final stage involved the formulation of results and detailed conclusions regarding the individual ideas and principles. The author also compared the results with his own research goal and working hypothesis.

3. Results

The most important ideas and creative principles common to the studied areas of avant-garde art and brutalist architecture are listed and characterized below. Tables 1–7 show examples of buildings representative of each idea.

Table 1. Examples of buildings representative of the idea of rejection of previous principles and doctrines.

Building	Architect	Year
Sugden House in Watford	Alison and Peter Smithson	1955–1956
Richards Medical Research Laboratories in Philadelphia	Louis I. Kahn	1957–1961
Bank of London in Buenos Aires	Clorindo Testa	1960–1966
Southbank Arts Center in London	Norman Engleback	1964–1968
Goddard Library at Clark University in Worcester	John Johansen	1966–1969

Table 2. Examples of buildings representative of the idea of searching for the basics.

Building	Architect	Year
Patio and Pavilion (installation)	Alison and Peter Smithson	1956
Maison du Brésil in Paris	Le Corbusier	1957
Kagawa Prefectural Offices in Takamatsu	Kenzo Tange	1955–1958
Kokusai Kaikan Building in Kyoto	Sachio Otani	1963–1966
Center for Environment and Planning Technology in Ahmedabad	Balkrishna Doshi	1968–1972

Table 3. Examples of buildings representative of the idea of reflecting the realities of life.

Building	Architect	Year
Golden Lane Housing Estate in London (project)	Alison and Peter Smithson	1952
Keeling House in London	Denys Lasdun	1957–1958
Halen Estate near Berne	Atelier 5	1957–1961
Park Hill Housing Estate in Sheffield	J. Lewis Womersley, Jack Lynn, Ivor Smith	1957–1961
Metteotti Estate in Terni	Giancarlo de Carlo	1969–1974

3.1. Rejection of Previous Principles and Doctrines

New art and new architecture were supposed to break with the existing rules as inconsistent with the post-war realities. Avant-garde trends, especially musique concrète and *art autre*, showed how radical this rejection can be.

Table 4. Examples of buildings representative of the idea of glorification of ordinariness.

Building	Architect	Year
House in Soho in London (project)	Alison and Peter Smithson	1949–1954
Maisons Jaoul in Paris	Le Corbusier	1953–1955
Langham House Close in London	James Stirling, James Gowan	1957–1958
Florist Kiosk in Malmö	Sigurd Lewerentz	1969
Casa Martirani in São Paulo, 1969–1974	Vilanova Artigas	1969–1974

Table 5. Examples of buildings representative of the idea of sincerity.

Building	Architect	Year
Secondary School at Hunstanton	Alison and Peter Smithson	1949–1954
Istituto Marchiondi in Milan	Vittoriano Viganò	1953–1957
Convent Sainte Marie de La Tourette in Éveux	Le Corbusier	1953–1961
Salk Institute for Biological Studies in La Jolla	Louis I. Kahn	1962–1965
Servico Social do Comercio in Pompeia	Lina Bo Bardi	1977–1982

Table 6. Examples of buildings representative of the idea of rough textures.

Building	Architect	Year
Unite d'Habitation in Marseille	Le Corbusier	1947–1952
Yale Art and Architecture Building in New Haven	Paul Rudolph	1958–1963
Sports and Recreation Center in Zürich	Hans Litz, Fritz Schwartz	1961–1965
Elephant and Rhinoceros Pavilion at London Zoo	Hugh Casson, Neville Conder	1961–1965
Sampson House in London	Fitzroy Robinson, and Partners	1976–1979

Table 7. Examples of buildings representative of the idea of As Found.

Building	Architect	Year
Upper Lawn Pavilion in Fonthill Abbey	Alison and Peter Smithson	1959–1961
Hotel Godesberg in Bad Godesberg on the Rhine	Gottfried Böhm	1961
METU Faculty of Architecture Building in Ankara	Altug and Behruz Cinici	1961–1963
City Hall in Boston	Gerhard Kallmann, Michael McKinnell	1963–1968
Boston Government Service Center	Paul Rudolph	1966–1971

The architecture that Banham referred to as architecture autre (other architecture) was also supposed to bring about such fundamental changes. The New Brutalism doctrine seemed to be the beginning of such architecture of another kind. This was confirmed by the first projects of the Smithsons and the buildings of other British architects. In place of devalued rules, brutalist architects introduced new ones: subordinating the form of a building to the circulation of people and their perception, articulation of internal functions in the form, sincerity of structural expression, strong contrasts, vehement juxtapositions of solids, and repetitive and disturbed rhythms. New ordering and unconventional forms of buildings were often incomprehensible to an ordinary user (Table 1).

3.2. Searching for the Basics

Avant-garde artists sought rudiments in the work of artistically uneducated people or primitive tribes. They created paintings and sculptures by drawing on their own basic emotions, which were expressed in a spontaneous, direct way.

In brutalist architecture, referring to rudiments was connected both with the simplification of forms and the use of local and natural materials, as well as inspiration with the works of uneducated creators of vernacular architecture, but most of all with reaching the most basic ideas and principles of architecture. The architects tried to reject stereotypes and established patterns in order to objectively assess the context. They had to start each design task from scratch. Inspiration by vernacular architecture led to a regional diversification of brutalism. The most relevant example of reinterpreting the solutions of the local architectural tradition was Japanese brutalism (Table 2).

3.3. Reflecting the Realities of Life

Avant-garde painters, sculptors, and composers saw their art as a manifestation of life, even its dark sides. Photographers photographed the everyday life of working-class districts and rural settlements to reflect the relationships between people, space, and time.

Brutalist architects were fascinated by vernacular architecture precisely because it was a direct response to the real needs and situation of users. The aspirations to link life and brutalist architecture were most fully expressed in the design of residential buildings and housing estates. The architects paid special attention to the spaces of social contacts. The most important solution in this respect was the street deck, which was a reinterpretation of the street in a traditional housing estate. Other spaces for establishing neighborly relations were galleries, courtyards, terraces, bridges between buildings, rues intérieures, and drying rooms (Table 3).

3.4. Glorification of Ordinariness

The connection of art and architecture with everyday life led to the fascination with ordinariness. The artists presented images of everyday objects in their works or used them directly, as found. They also employed prosaic, unattractive materials such as sand, asphalt, mud, and rubbish.

Brutalist architects acted similarly, using ordinary, readily available materials and extracting their artistic value. Among them were brick, stone, wood, sheet metal, and common plywood. However, the most popular was concrete, which offered enormous structural and aesthetic possibilities. The details, elements, and architectural forms were also simple and sometimes even primitive. However, in the later phase of brutalism, the ordinary was largely replaced by the extraordinary (Table 4).

3.5. Sincerity of Artwork and Building

Sincerity was an inherent feature of art autre and art brut. It manifested itself in the honest expression of the artist's emotions and the expression of the physical properties of the materials he used. The relationship between the material and the work of art was clear and unbreakable.

The results of the idea of sincerity and directness in brutalist architecture were use of raw materials, rejection of the aestheticization of the building's surfaces and any imitations, exposing the overall constructional system of a building and its individual elements, mirroring methods and stages of erecting a building in its form and surfaces, articulation of internal functions, and exposing and highlighting technical elements (Table 5).

3.6. Roughness of Textures

The works of avant-garde artists drew the attention of brutalist architects to the qualities of rough surfaces, bearing traces of the way they were made. Dubuffet claimed that the essential gesture of a painter is to smear, not to smooth. Paolozzi's bronze sculptures had an uneven texture composed of small objects.

Brutalist buildings usually had rough surfaces because the textures were supposed to be sensual. The uneven and heterogeneous surfaces were picturesque, and they produced variable visual effects depending on the distance and lighting. The architects did not strive for perfectionism but preferred ordinary building craftsmanship. Craft methods gave their works additional value of originality and uniqueness. In some brutalist buildings, defects of surfaces were not hidden but even emphasized, which can be described as the poetics of "magnificent ruins" (Table 6).

3.7. The Idea of as Found

The use of found objects was the essence of the work of many avant-garde artists. In the post-war years, these were often things found in the ruins of destroyed cities and later everyday objects, parts of mechanisms, and things of nature.

Influenced by artists, brutalist architects treated building materials as found objects. Sometimes, they also used real found objects in their buildings. It should be emphasized that the broad idea of As Found and the resulting design method became particularly important for brutalism. As Found contributed to an objective analysis of the context, searching for specific features of a place, and taking into account the conditions. The uniqueness of brutalist buildings resulted from the fact that architects treated the existing situation as a found object (Table 7).

Figure 1 presents the intensity of each idea in brutalist architecture (from 1950 to1980) (Figure 1). Research shows that the intensity of all ideas declined in the following decades, reaching the lowest levels in the final phase of brutalism. Only the idea of sincerity and, to a lesser extent, the idea of roughness remained of great importance throughout the duration of the style.

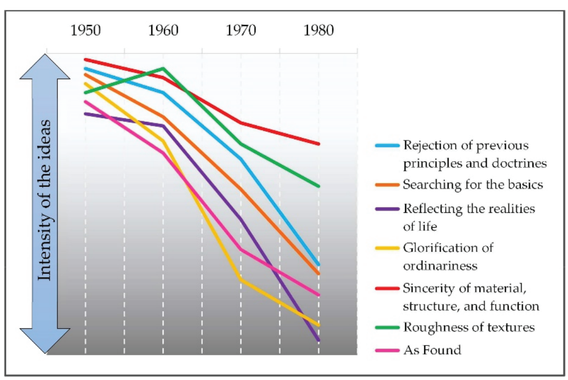

Figure 1. The intensity of the ideas in brutalist architecture (author: Wojciech Niebrzydowski).

Figure 2 presents the impact of the ideas on architectural solutions, forms, and aesthetic effects (Figure 2). The research shows that the idea of sincerity contributed the most to the development of the indicated attributes of brutalism. The other ideas were of similar importance in this respect.

IDEAS / Architectural solutions, forms and aesthetic effects:	Rejection of previous principles and doctrines	Searching for the basics	Reflecting the realities of life	Glorification of ordinariness	Sincerity of material, structure, and function	Roughness of textures	As Found
Simplification of forms and elements	++	+++	++	+++	++	+	++
Forms and solutions inspired by vernacular architecture	++	+++	++	++	++	++	+++
Vehement juxtapositions of solids and elements	+++	+	++	+	+++	++	++
Repetitive and disturbed rhythms	+++	++	+	++	+++	+	+
Highlighting circulation and communication elements	++	+	+++	+	+++	+	++
Exposing structural elements	++	++	+	++	+++	++	++
Exposing installations and technical elements	+++	+	++	+++	+++	+	+++
Ordinary materials	+	+++	+++	+++	++	+++	++
Raw materials	++	+++	++	++	+++	+++	+++
Poetics of "magnificent ruins"	++	+++	++	++	+++	+++	+

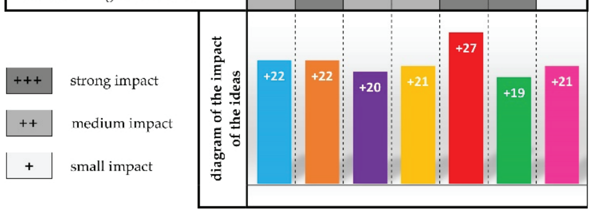

Figure 2. The impact of the ideas on architectural solutions, forms, and aesthetic effects (author: Wojciech Niebrzydowski).

4. Discussion

4.1. Artistic and Architectural Avant Garde after World War II

After World War II, a new political, economic, and social situation emerged in many countries. The war also had a great impact on art and culture. However, new artistic trends did not develop as dynamically as after World War I, when dadaism, surrealism, and purism emerged. Stagnation was also visible in architecture. At that time, such innovative architectural trends as those created thirty years earlier—modernism, expressionism, constructivism—were not developed. After World War II, modernism gained the greatest importance, but from the avant-garde trend, it turned into popular "soft modernism". In many countries, attempts were also made to use the threads of traditional architecture, albeit in a superficial way (e.g., New Humanism). In countries subordinate to the Soviet Union, socialist realism was introduced as the obligatory style. In fact, the primary task of architects everywhere was to rebuild cities and provide housing, not to search for new styles.

An example of a country stricken by the war, despite being victorious, was the United Kingdom. Many cities were destroyed, food was rationed, and the public mood was pessimistic and stagnant. British artists of the young generation were some of the first to wake up to this apathy. Some of them formed the Independent Group in 1952, which was extremely important for the beginnings of brutalism. The Independent Group gathered artists, writers, designers, and architects [5] (pp. 2–3) who met at London's Institute of Contemporary Art [38] (p. 6). It is worth noting that they also had similar political views, and most of them were socialists. The tragic events of the war left an imprint on both their psyche and creativity. The family of the painter Magda Cordell died at the hands of the Nazis. Nigel Henderson was dismissed from the Royal Air Force due to a nervous breakdown [7] (p. 92). The Italian family of Eduardo Paolozzi had lived in Edinburgh for years. When Italy declared war on Britain, they were arrested and deported to Canada on the SS Ambrosia ship, which was torpedoed and sunk [32] (p. 101). The radical and nonconformist stance of these young artists pushed art, literature, and theatre in the United Kingdom to new paths. At the root of these changes was the idea of searching for art that would correspond to the harsh post-war reality and situation of British society. William J.R. Curtis emphasized that they were involved “in trying to convey the rough grain of modern urban life in a new art” [39] (p. 530). They also drew inspiration from new trends in world art and works of other avant-garde artists.

Among the members of the Independent Group were also architects: Alison and Peter Smithson, James Stirling, and Colin St John Wilson. These young architects set themselves the goal of creating new, up-to-date architecture. Historian and critic Reyner Banham actively assisted in their efforts. They were disappointed with the trends prevailing in British and world architecture after World War II. They found these trends false and incompatible with the times and felt that “the majority of architects have lost contact with reality and are building yesterday’s dreams when the rest of us have woken up in today” [8] (p. 185). The Smithsons in particular played an important role in the development of brutalist architecture. They called their architectural doctrine New Brutalism, which was a reference to the term “Nybrutalism” used by Hans Asplund in 1950 to describe Villa Göth in Uppsala ([2] p. 10). They based it on several general ideas, including the objective perception of reality and the direct relationship between architecture and life. Moreover, architecture should evoke emotions, just as works of avant-garde art do. The Smithsons wanted the language of architecture to be moving, not just pleasant [7] (p. 125). They believed that thanks to this, architecture would help society recover from the war trauma and regain a sense of identity.

Architects searching for a style appropriate to the post-war era reached for ideas and principles on which the avant-garde trends in art were based. This was due to the fact that they did not find them in the pseudo-traditional architectural trends, the sentimental International Style, and the post-war buildings of the old masters of modernism. Instead, they had special relationship with art autre, art brut, action painting, pop art, musique concrete, and the works of Jean Dubuffet, Jackson Pollock, Pierre Schaeffer, Eduardo Paolozzi, and Nigel Henderson.

In 1952, the French art critic and curator Michel Tapié published the book *Un art autre* [40], in which he postulated that post-war art should correspond to the turbulent nature of that time and completely reject the old styles. As examples of art autre, he gave, among others, works of Pollock, Dubuffet, and Paolozzi, as well as such “anti-artists” as Jean Fautrier and Georges Mathieu [2] (p. 61). The works of art autre were characterized by expressiveness and anti-formalism. The spontaneously created works were a radical break with traditional notions of composition and order.

Art brut is a term coined by Jean Dubuffet. He defined it as art created by people without artistic education. The works of art brut showed the creative power inherent in every human being, which over time is suppressed by social norms or the educational system [41] (p. 34). Dubuffet gave examples of pictures painted by children and mentally ill people. However, art brut was also practiced by professional artists, such as Magda Cordell from the Independent Group “with the impressively violent style of painting in her Monoprints” [7] (p. 157).

Another artist, this time from the USA, who left his mark on brutalism was Jackson Pollock. Ben Highmore even argues that Pollock contributed more than anyone else to the formation of the New Brutalism doctrine [33] (p. 277). His action painting, the technique of spontaneous splashing liquid paint on canvas, fascinated young architects with its expressive effects and the rejection of compositional rules. According to Banham, Pollock became for them “a sort of patron saint of anti-art even before his sensational and much published death” [2] (p. 61).

Pierre Schaeffer composed experimental music in which he used random human voices or sounds recorded in the streets or factories [37]. The musical trend he initiated was described as musique concrète. It broke the classical rules of music in a way that was as radical as art autre broke the classical rules of painting and sculpture.

The Smithsons' closest associates in the Independent Group were not other architects, but two artists, Eduardo Paolozzi and Nigel Henderson. As members of one team, they created two exhibitions fundamental to the New Brutalism: "Parallel of Life and Art" (1953) and installation "Patio and Pavilion" (presented at the exhibition "This is Tomorrow", 1956).

Paolozzi's work was accompanied by aspects related to the most important ideas of the New Brutalism: As Found, image, and sincerity of the material. In the 1940s, Paolozzi made collages from newspaper clippings, and after returning from Paris to England in 1951, he focused on sculpture. He used ordinary materials, including cast concrete, which is so important for brutalist architecture.

After the war, trying to recover from his nervous breakdown, Henderson turned to photography. The artist experimented with variable exposure times, deformations, and blurring of human figures. Kenneth Frampton claims that Henderson's work "evokes at one stroke time, place, decay, and movement" [42] (p. 49). It should be emphasized that all these aspects, especially the movement and circulation of people, became the key problems of brutalist architecture. Henderson's photographs were used by the Smithsons to prepare the exhibition presented in 1953 at the CIAM (International Congress of Modern Architecture) meeting. In this way, they gained fame and became symbols of new thinking about architecture and urban planning.

It cannot be ignored that young architects also drew inspiration from the architecture itself. Early in their career, the Smithsons referred to Mies van der Rohe, Hugo Häring, and even Andrea Palladio. However, the real impact on their doctrine had one architect—Le Corbusier. He gained great respect in their eyes because he was able to make a radical turn in his work. Despite his status and widespread recognition for his earlier works, he did not follow the mainstream of post-war architecture, as most pre-war masters did. Similar to young architects, he wanted to create a new style that truly corresponded to reality [43].

Already in the 1930s, Le Corbusier's works showed signs of rejecting machine aesthetics in favor of more diverse textures and stronger articulation of solids in an architectural form. He decided to create more sensual and expressive architecture in which emotional experience plays a leading role. Le Corbusier was inspired by vernacular architecture, which he considered sincere and directly corresponding to the everyday life [44]. Finally, he began to implement his architectural credo, which was expressed already in 1923: "L'Architecture, c'est, avec des matières brutes établir des rapports émouvants" ("Architecture is, with raw materials, establishing moving connections") [45] (p. 4). As a result of this turn, he designed his first proto-brutalist buildings. They foreshadowed his new style and, at the same time, a style that appealed to so many other architects in the 1950s, not only the younger generation [46] (pp. 14–15). The following houses should be mentioned here: Maison de Mme de Mandrot in Le Pradet (1931), the holiday house Le Sextant in Les Mathes (1935), and Petite Maison de Week-end in Boulogne-sur-Seine (1935). Henry-Russell Hitchcock wrote that they all showed respect for local materials and simple country craftsmanship [47] (p. 518).

4.2. Rejection of Outdated Rules and Canons

World War II changed the world so much that progressive architects decided that architecture should also be radically different from the previous one. It should become an expression of a society in change [48]. The Smithsons were among the first to start working on a new architectural doctrine. The New Brutalism was to be based not on stylistic but ethical assumptions, such as truth, objectivity, sincerity, and directness. These features were also present in the avant-garde artistic trends of the time. Objectivity to the new reality required rejecting the previous rules and "to overthrow the classical tradition" [2] (p. 62). Young architects, together with artists, were involved in the anti-art movement.

4.2.1. Art Autre and Architecture Autre

Architects admired how avant-garde artists break the traditional principles of art—painting, sculpture, and music. The works of artists from the interwar period convinced them that the new order was possible. Among them was Paul Klee, for whom the form was the result of growth and change [49] (p. 77).

Dubuffet not only collected art brut works but also created such paintings himself. Primitivized, caricatured, made with the use of unconventional techniques giving a rough texture, they completely departed from the recognized canons of art. They seemed to emanate the ugliness, deformation, and randomness of the composition. Paolozzi, despite studying in many art schools, decided to reject academic art. His main idea and goal were to reflect the harsh living conditions without any compromises or embellishment. Schaeffer discovered previously disregarded sounds, including sounds of the city. He used their musical potential to create innovative musique concrète in which he abandoned the traditional kind of harmony, melody, and scale. He also manipulated the recorded sounds, distorting them in various ways.

However, the works of Jackson Pollock played the greatest role in the rejection of classical principles in brutalist architecture. Europeans first saw his spatter paintings at the Biennale di Venezia in 1950. British architects became acquainted with Pollock's works 3 years later at the exhibition "Opposing Forces" in the Institute of Contemporary Art in London. Banham wrote about them: "The impact of these pictures on the intellectual edifice which architects had built around classical theories of measure and proportion was to be extremely destructive" [2] (p. 61). The Smithsons, on the other hand, noticed in spatter paintings a revolutionary approach to artistic creativity and a new order in art [10] (p. 86). Jackson Pollock practiced action painting, radically subverting formalistic artistic conventions. This type of painting was primarily a notation of the creative process. It was also connected with the all-over principle, which involved painting in such a way that every fragment of the picture became important and expressive. Similar effects were followed by many brutalist buildings in which all elements were expressive and visually strong. An example is Boston City Hall (1963–1968). During its design, Gerhard Kallmann used his concept of "action architecture", which drew inspiration from Pollock's action painting and its critical reception [50] (p. 56).

Le Corbusier was also fascinated with action painting. Together with Tino Nivola, he developed a specific sculptural method called "action sculpture", which gives interesting textural effects. During his stay in the USA in the early 1950s, Le Corbusier lived by the ocean on Long Island. He and Nivola waited for the ebb of the ocean; then, they formed wet sand and poured plaster (gypsum) over it. Plaster sculptures made in this way were raw, their shape resulted from the possibility of forming sand—the material in which they were cast. At the same time, they had a rough texture reflecting the structure of sand. Similar features characterize Le Corbusier's brutalist buildings and their concrete surfaces with an imprint of the formwork material.

The concept of architecture based on completely new principles was promoted by Banham. He was searching for an architecture of another kind—une architecture autre (other architecture). This name was not accidental because "the term was coined by analogy with Tapie's concept of un art autre and was intended to stand for something equally radical" [2] (p. 68). Architecture autre ought to be as vehement and extremely expressive as the works of Dubuffet, as distant from the routines of classical composition as Pollock's paintings. It should also be based on "materials as found", as musique concrète is based on "sounds as recorded". Banham even predicted that in the future, it ought to abandon the idea that the most important role of an architect is to use structure to make space. He hoped that the New Brutalism would be such other architecture, or at least its seed. He appreciated the cooperation of architects and avant-garde artists. As a member of the Independent Group, Banham participated in meetings with artists from various countries. He was particularly moved by the meeting with Schaeffer in 1953 and wrote that musique concrète "gave a measure of the extent to which une architecture autre could be expected to abandon the concepts of composition, symmetry, order, module, proportion, 'literacy in plan, construction and appearance', in the sense accepted in the theory of architecture as taught in the Ecoles des Beaux-Arts, and piously preserved in the Modern Architecture of the International Style and its post-war successors" [2] (p. 68). Rhythms were the primary tool of music composers. Similarly, in the case of brutalist architects, rhythms—repeated or interrupted in unexpected ways, simple or complex—became the leitmotif of many buildings.

4.2.2. Breaking the Rules—The Smithsons and British Architects

Before the Smithsons began to make Banham's dreams of architecture autre a reality, they prepared two groundbreaking exhibitions, both in collaboration with Paolozzi and Henderson. The first, "Parallel of Life and Art" (1953), had a significant subtitle "Indications of a New Visual Order". The unconventional way of arranging panels with 122 photographs in space was one of the most important aspects of this exhibition. Each of the panels was an autonomous exhibit placed in a seemingly random manner in space. The panels differed in size and location, yet their arrangement gave the impression of a specific coherence. It was impossible to focus on just one image because the view of another was superimposed on it. In this way, the images lost their status as separate elements and established relationships with each other. The authors of the exhibition wrote in the catalogue: "In short it forms a poetic–lyrical order where images create a series of cross relationships" [51]. These relations were varied and depended on the visual similarity of the objects presented in the photos. Henderson, emphasizing the aspect of the interaction of the plates, compared the way of their installation to a cobweb that formed something similar to a nervous system [36] (p. 73). The arrangement of the plates made the observer move from place to place, positioning himself at the correct angle to individual images. The reduced resolution meant that to see the picture accurately, the observer had to move away from it or get closer to it. The exhibition "Parallel of Life and Art" was not only a milestone showing how new architectural order can follow new visual order. It also raised issues that will become key problems for brutalist architects: circulation of people, perception of architecture in motion, discovering spatial relationships and unconventional ordering rules, affirmation of ordinariness.

The installation "Patio and Pavilion" (1956) referred more directly to architecture, and as the name of the entire exhibition "This is Tomorrow" indicated, it referred to the future of architecture. The authors of the installation, using a rather enigmatic building, symbolic objects, and the limitation of space, created a virtually formless place with meaning understandable to people. It should be remembered that according to Banham, "formless buildings" were supposed to be the essence of architecture autre [2] (p. 68).

The idea of rejecting the previous compositional principles in architecture was implemented by the Smithsons in 1956 in Sugden House in Watford (Figure 3). This building was also a reaction to the white, abstract box-like houses of the International Style [38] (pp. 11–12). The Smithsons explained the concept of Sugden House: "From individual buildings, disciplined on the whole by classical aesthetic techniques, we moved on to an examination of the 'whole' problem of human associations and the relationship that building and community have to them. From this study has grown a completely new attitude and non-classical aesthetic" [9]. However, architecture critics were appalled by the building, especially the chaotic arrangement of its various windows. They condemned architectural illiteracy in plan, construction, and appearance [2] (p. 67). The Smithsons (and Banham) were actually satisfied with such opinions, as these words confirmed that they had managed to employ a new kind of architectural grammar.

The New Brutalism had a strong influence on British brutalist architecture. It is no wonder then that in this country, the tendencies to reject the classical principles were visible throughout the style—not only in its initial phase but also in later years. The following examples from London confirm this thesis.

In the 1950s, these were public buildings designed by Lyons, Israel, and Ellis (e.g., the Old Vic Theatre Annexe, London, 1958) or residential buildings designed by Denys Lasdun (Sulkin House and Keeling House, London, 1958). It should be emphasized that Lasdun's cluster blocks went beyond aesthetic and compositional principles, but also beyond the traditional way of functioning of a residential building. In the 1960s, the Southbank Arts Center was built. It included Queen Elizabeth Hall and Hayward Gallery (Chalk, Herron and Crompton under the group leader Norman Engleback, London, 1968). According to critics, the complex was deliberately unresolved in compositional terms and was a demonstration of the brutalist concept of "crumble" [52] (p. 117). In fact, "the quirky topology" [53] was the result of subordinating the form of the building to the circulation of people and their perception (Figure 4). The complex should be interpreted in an unconventional way as a system of places and visual events located along alternative paths. An example from the 1970s, the last decade of brutalism in England, was the Sampson House (Fitzroy Robinson & Partners, London, 1976–1979). The huge building was a kind of brutalist megastructure (Figure 5). Its alien, vehement form, bizarre details, raw materials, and textures shocked even artistically sophisticated Londoners. Due to the lack of acceptance (but also for economic reasons), the building was demolished in 2018.

Figure 3. Alison Smithson and Peter Smithson, Sugden House in Watford, 1955–1956 (photo: Joshua Abbott).

Figure 4. Norman Engleback, Hayward Gallery in London, 1968 (photo: author of the article).

4.2.3. New Ordering in Brutalist Architecture

Another type of ordering and composition in brutalist architecture was the principle of articulation of internal functions in the form of a building. One of its precursors was Le Corbusier, who showed functions on the facades in Chandigarh using variable patterns of reinforced concrete loggias and brise soleils. It was also practiced by Louis I. Kahn, exposing served and servant spaces in Richards Medical Research Laboratories in Philadelphia (1957–1961) [19] (p. 124).

Figure 5. Fitzroy Robinson & Partners, Sampson House in London, 1976–1979 (photo: author of the article).

These concepts were consistently developed by Josep Lluís Sert. His Law and Education Tower at Boston University (1960–1965) clearly reflects the idea of a "vertical city". It was a building that contains a multitude of functions, including urban functions, and articulates them in its form. The arrangement and mutual relations of the elements on the three-dimensional facade make it possible to read the meanings assumed by the architect, which would not be possible with a smooth facade. He applied similar solutions at the Holyoke Center in Cambridge near Boston (1960–1967). The articulation of the complex functions of the building is visible especially on its southern facade (Figure 6). Sert achieved a clear effect primarily through the varied rhythms of vertical reinforced concrete sun breakers, showing the location of hospital rooms, doctor's offices, seminar rooms, and the floor for patient recreation. Working on the integration of urban planning and architecture, Sert applied the principle of articulation of functions also in large building complexes and megastructures. Charles Jencks wrote about the Boston University Complex: "Sert breaks down a gigantic volume into several related forms and spaces which announce the differences in function. These differences are further articulated by using separate materials, and by making the construction apparent. All this rich articulation has the effect of explaining a diverse and possibly overwhelming complexity without falling into strident rhetoric or eroded symbolism" [54] (p. 115).

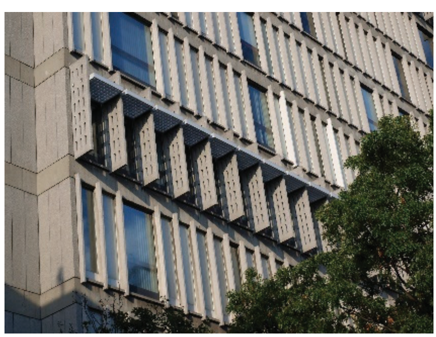

Figure 6. Josep Lluís Sert, Holyoke Center in Cambridge near Boston, 1960–1967 (photo: author of the article).

Other American buildings, such as Boston City Hall and Goddard Library at Clark University in Worcester designed by John Johansen (1966–1969), also articulated their functional structure in a very expressive way, using overhanging solids and different textures. The form of Goddard Library differs so far from conventional buildings that it evokes associations with a complicated machine that is only in the assembly phase. Johansen compared his work to a photocopier without a case and said that it was closer to a three-dimensional bubble diagram than a conventional building [22] (p. 14). He described his design of Goddard Library "likening it to assembling the required spaces—lobby, stacks, offices, reading rooms, study carrels, circulation stairs, and elevator shafts—within a large plastic bag and then drawing out all the air to reveal the building's form" [55].

The principle of exposing functions gave spectacular results in the USA, but it was also evident in brutalist buildings in other countries. Examples are Hotel Tokoen in Yonago (Japan, 1963–1964) by Kiyonori Kikutake and Caja Costarricense de Seguro Social in San Jose (Costa Rica, 1977–1979) by Alberto Linner. In Poland, brutalism was especially visible in religious architecture. In the forms of churches, various liturgical functions were articulated. An example is the Church of St. Jan Kanty in Poznań (1976–1980) designed by Jan Węcławski in which the rhythm of cantilevered solid housing confessionals was articulated (Figure 7).

Figure 7. Jan Węcławski, Church of St. Jan Kanty in Poznań, 1976–1980 (photo: author of the article).

Brutalist architects also applied other individual rules of order and composition. The rejection of classical principles has made this architecture difficult to understand. It is commonly believed that brutalist buildings are inhuman and ugly [56]. However, it should be emphasized that the goal of brutalist architects has never been to glorify ugliness. On the other hand, they also did not pursue beauty. Actually, they did not pursue any other aesthetic attribute. The brutalist building was supposed to provoke the senses, not satisfy any taste.

However, it seems that several architects were close to the effects assumed by art autre artists. About his sculptures from the 1950s, Paolozzi said: "I was trying to make a kind of anti-art object; really trying to make something which looked horrible. It was a reflection on the sensibility of that time" [32] (p. 103). A similarly shocking aesthetic effect in architecture was achieved by Clorindo Testa and SEPRA Studio. In the Bank of London in Buenos Aires (1960–1966), they used strange shapes, deformed elements, and bombastic corner to break with the traditional image of a building (Figure 8). In turn, Lina Bo Bardi, in her provocative statement about her building, Servico Social do Comercio (SESC) in Pompeia (1977–1982), "declared that she wanted the SESC to be even uglier than the MASP [Museu de Arte de São Paulo—her earlier building]" [57] (p. 152).

4.3. In Search of Rudiments

Avant-garde artists rejected the existing values in art and looked for new ones instead. They found these values in the pure minds of uneducated artists. They also found them in the works of primitive peoples, which were the result of the basic, simplest emotions. They discovered true principles at the basis of human culture. Dubuffet appreciated the value of works created without influences, without a specific purpose, and therefore spontaneous and sincere. "Those works created from solitude and from pure and authentic creative impulses—where the worries of competition, acclaim and social promotion do not interfere—are, because of these very facts, more precious than the productions of professionals" [58]. Paolozzi's figurative sculptures from the post-war period were simplified, primitivized, almost similar to archaic artefacts. For example, Paolozzi explored how far he can simplify a sculpture of a head so that it is still perceived as a head. He asked himself: "How far can the disintegration of the head go without the head losing its identity" [59]?

Figure 8. Clorindo Testa and SEPRA Studio, Bank of London in Buenos Aires, 1960–1966 (photo: Bogusław Podhalański).

Architects, similar to artists, looked for the basics in the works of uneducated people, which were free from imposed stylistic rules. These people were the builders of vernacular architecture. Brutalist architects believed that there are objective, eternal, deep-rooted values in such architecture. Contemporary vernacular buildings became important because direct contact with them and their authors was still possible, unlike with architects from past historical epochs.

Le Corbusier observed that the abstract forms of modernist buildings did not appeal to the common people. He noticed that people identify rather with buildings with traditional forms made of local materials. Le Corbusier realized how great artistic and emotional potential lies in vernacular architecture and primitive houses of rural builders. During his vacation in the countryside, he began sketching rural cottages, fishermen's houses, and their details. He also took measurements of such buildings [44]. As a result of analyses of vernacular architecture, Le Corbusier discovered the value of raw, natural materials as well as traditional steep roofs, massive walls, and narrow windows. However, it should be emphasized that in the works of ordinary builders, he was looking not for primitivism but architectural wisdom [60] (p. 6). He was convinced that the concept of contemporary architecture could be influenced by the experience of ancient cultures, especially from their origins [61] (pp. 345–346). Inspired by vernacular architecture, Le Corbusier fully developed his brutalist style in the post-war period. Direct references to the forms of traditional buildings were hardly noticeable in his works. Although they are clearly visible in the use of raw and natural materials such as stone, e.g., in the Maison du Brésil in the Cité Universitaire built in Paris in 1957 (Figure 9).

Other brutalist architects, seeking the basics, drew more direct formal inspiration from vernacular architecture. They often combined motifs of local architecture with brutalist elements and forms. This was particularly evident in Japanese brutalism, where architects used both eternal ideas and reinterpreted forms and solutions specific to vernacular architecture. Relevant examples are buildings in which reinforced concrete structures imitated the system, proportions, and sometimes even shapes of wooden construction elements. In the Tsuyama Culture Center built in 1965 according to the project of Kohji Kawashima, all structural elements replicate the wooden poles, beams, and corbels used in Japanese temples. Less direct references to the tradition can be seen in the Kyoto Kokusai Kaikan Building built in 1963–1966 according to the project of Sachio Otani (Figure 10). The form of the building is characterized by complexity, monumentality, and sloping walls [62] (pp. 78–79). The pioneers of Japanese brutalism, such as Kenzo Tange and Kunio Maekawa, also reached the roots of architecture. This is evidenced by buildings built in the 1950s: the Kagawa Prefectural Offices in Takamatsu (Tange, 1955–1958) and Harumi Apartment Building in Tokyo (Maekawa, 1957–1958). Frampton wrote about the first building that it was "a béton brut version of Daibutsu wooden style of the 12th century as we find this in the Todaiji precinct at Nara, which for Tange embodied the essence of Japanese national culture" [63] (p. 98).

Figure 9. Le Corbusier, Maison du Brésil in Paris, 1957 (photo: author of the article).

Figure 10. Sachio Otani, Kokusai Kaikan Building in Kyoto, 1963–1966 (photo: Stephen Smith).

Brutalism reached another Asian country, India, thanks to Le Corbusier. In the form of the Mill Owners' Association Building (1954), we can find references to the traditional wooden and stone architecture of the Gujarat Region [39] (p. 426). Frampton even suggested that the concrete roofs of the High Court in Chandigarh were a reinterpretation of roofs from Fatehpur Sikri—the capital of the Great Mughal [64] (p. 228). However, it should be emphasized that Indian native architects—Charles Correa, Balkrishna Doshi, and Achyut Kanvinde—really deepened the ties between brutalism and vernacular architecture. These include the Museum of Mahatma Gandhi in Ahmedabad (Correa, 1963) and the Center for Environment and Planning Technology in Ahmedabad (Doshi, 1968–1972), combining brick and concrete structures with local motifs [65]. In Turkey, Behruz and Altug Cinici referred to local architecture in the METU Faculty of Architecture Building in Ankara (1961–1963). The building has only two floors; its monochromatic form is fragmented and devoid of expressive elements, such as overhangs. These features were taken from the traditional architecture of Anatolia.

References to vernacular architecture are visible in Polish sacral architecture [66]. The steep, gable roof characteristic of rural residential and farm buildings was especially used. As the dominant element and in a very direct way, it was applied by Szczepan Baum in the Church of the Assumption of the Blessed Virgin Mary in Władysławowo (1958–1962) and Władysław Pieńkowski in the Church of the Blessed Virgin Mary, Mother of the Church in

Sulejówek (1972–1983). In addition to concrete, traditional materials such as red brick and field stones were used (Figure 11).

Figure 11. Władysław Pieńkowski, Church of the Blessed Virgin Mary, Mother of the Church in Sulejówek, 1972–1983 (photo: author of the article).

The proponents of the New Brutalism also drew from the vernacular architecture. In "Patio and Pavilion", they returned to the roots of architecture—a piece of the world (a yard) and an enclosed space (a house)—two necessities of human habitat. The Smithsons showed that these architectural rudiments will also be valid in the future [33] (p. 277). They emphasized this by using both traditional (wood) and modern materials (corrugated plastic, aluminum) in their installation. An appeal to fundamentals is visible in their analyses of social patterns of associations in primitive habitats. As a result of these studies, they concluded: "From pre-history to contemporary peasant society, each culture has thrown up a limited number of house forms. The culture expresses itself through these forms. Today's problem is to define that form unique to each culture group" [11] (p. 14). It is worth noting that Alison and Peter Smithson ended their program manifesto, published in January 1955, with a significant reference to the vernacular architecture: "What is new about the New Brutalism among Movements is that it finds its closest affinities, not in a past architectural style, but in peasant dwelling forms" [67]. They undoubtedly confirmed this idea in Sugden House. An important aspect of their searching for the basics was starting each design task from scratch. They always rejected all stereotypes, imposed patterns, and objectively assessed "realities of the situation" [2] (p. 87).

4.4. Art and Architecture as the Direct Result of a Way of Life

The linking of architecture with everyday life was one of the assumptions of brutalism. The vernacular architecture was also glorified because it was a direct response to the real needs of users. The connection of art brut and art autre with life, even its ugly and dark sides, also seems obvious. The Smithsons claimed: "Architecture, painting, and sculpture are manifestations of life, satisfying real needs; of man and not of each other" [68].

Henderson focused on life and "the everyday activities of people whose energies were mostly directed towards the basic needs of survival" [35] (p. 141). He was also inspired by the research of his wife Judith Stephen, who from 1945 conducted an anthropological project called "Discover Your Neighbour". Henderson's photographs, depicting the everyday life of Bethnal Green (where he lived) and other London districts, were not merely documentary photos. The artist analyzed human associations [49] (p. 105), relations between people and surroundings, and how these aspects change over time. Later, Henderson turned to X-ray and microscopic photographs which he treated as a metaphor of life. The artist had a great influence on the doctrine of New Brutalism. The existential nature of brutalist architecture was derived from Henderson and Paolozzi [64] (p. 263).

Just as Henderson photographed the everyday life of ordinary workers and their families in London, Pierre Jeanneret and Charlotte Perriand photographed old villages in the

Jura Mountains (in the 1930s) [69] (p. 24). They both collaborated with Le Corbusier, who used these photos when designing his proto-brutalist houses. According to Le Corbusier, "no architect could match the judgement and skill of the humble peasant who builds his own house around his daily actions" [70] (p. 48). He emphasized that rural builders, who are also users of houses, can build them better than professional architects.

Brutalist architecture was supposed to be a parallel of life. Its creators noticed that in the past, the architecture of traditional villages and cities was correctly related to life. The austere, post-war times and the changing way of life resulted in the need to search for new, appropriate architectural and urban solutions. Brutalist architects not only reached for completely new ones but also began to process and reinterpret solutions that previously functioned well in social terms.

Many brutalists based their creative credo on the link between architecture and the realities of life. Le Corbusier used to say that life is always right and architecture is wrong [71] (p. 79). Kahn wrote that before everything an architect does becomes a building, it must be appropriate for human beings. "You don't know yet what a building is, as long as you don't believe in its identity with people's way of life" [72] (p. 303). A similar attitude was presented by Gottfried Böhm when he spoke about architecture in which forms and functions life finds its reflection and explanation [73] (p. 346). The Smithsons declared: "We see architecture as the direct result of a way of life" [67]. Inspired by the work of Henderson, they started researching people's connections with home, street, district, and city. The Smithsons prepared their grille for CIAM 9 using Henderson's photos from Bethnal Green. This ground-breaking presentation, known as the "Urban Reidentification" grid, concerned design with social associations [34].

The pursuit of a complete environment for human beings was expressed by the Smithsons in the competition project for the Golden Lane Housing Estate in London (1952). In this project, "street decks" appeared for the first time. They were not only access galleries to flats but also served as spaces for social contacts. So, they were a reinterpretation of streets in traditional housing estates. The Smithsons believed that an important aspect of these "streets in the sky" [52] (p. 109) was their width (12 feet), providing space for meetings and other activities. They emphasized the relationship between architecture and everyday life in their design drawings, filling them with photographs of residents. In the perspectives of the estate, the human presence almost overwhelmed the architecture [1] (p. 360).

The idea from the unrealized Golden Lane project was applied in the Park Hill Estate in Sheffield (J. Lewis Womersley, Jack Lynn, Ivor Smith, 1957–1961). In Park Hill, street decks connect all the buildings and pass through the entire estate (Figure 12). At bends and intersections of street decks, there are spaces analogous to traditional street corners with intimate squares. They were supposed to be places of frequent meetings of residents. Here, people entered staircases and elevators and dumped garbage into the chute. The architects claimed that, in terms of neighborly relations, the chute was "the modern equivalent of a village pump" [2] (p. 132). Alan Powers wrote: "The street decks at Park Hill emphasized the new focus on circulation spaces and routes as a means of recovering the sense of community within this otherwise forbidding mass of structure" [52] (p. 114).

Lasdun designed a new type of multi-family residential building—the cluster block. In the cluster block, residential towers were attached to the central reinforced concrete circulation and service core (Figure 13). The connection was provided by short bridges leading into galleries and flats. The cluster block idea was fully implemented by Lasdun at Keeling House in London. The main place of neighborly contacts was not the gallery, but the central core in which the entrance hall and drying rooms (every second floor) were located. The architect proposed such a solution after analyzing the functioning of the traditional Bethnal Green buildings and the habits of their residents, such as meetings and gossip while hanging up the laundry.

In order to shape collective spaces, brutalist architects used such solutions as street decks, galleries, bridges (connecting buildings or their parts), rues intérieures, courtyards, terraces, and drying rooms. Virtually all of these spaces are associated with the circulation of people. The architects' intention was for people walking through these spaces to meet and establish relationships in a natural way. Therefore, circulation and movement became the essence of architecture (not only residential), as well as an element crystallizing the building's form and helping users to understand it.

Figure 12. J. Lewis Womersley, Jack Lynn, Ivor Smith, Park Hill Estate in Sheffield, 1957–1961 (photo: Sarah Briggs Ramsey).

Figure 13. Denys Lasdun, Keeling House in London, 1957–1958 (photo: author of the article).

These noble ideas did not always work properly. In large-scale buildings and housing estates, spaces intended for neighborly contacts sometimes became places of vandalism and violence. An example is the Harumi Apartment Building in Tokyo, where street decks were used by children during the day and by bullies at night. Japanese architecture critic Noboru Kawazoe expressed his opinion about Harumi: "To be a true building it must melt into the history of its time. A building does not really belong to the people unless it is capable of absorbing the shadier sides of life along with the more pleasant" [2] (p. 131).

4.5. Ordinariness

The connection of art and architecture with the everyday life of ordinary people led to the apotheosis of ordinariness. Dubuffet was fascinated by ordinary things. In the 1950s, he painted a series of works entitled "Landscape tables", which presented everyday objects: dishes, bottles, papers, etc. He also emphasized the artistic potential of prosaic materials: "I've found myself suggesting certain materials, not so much those with a 'noble' reputation like marble or exotic woods, but instead very ordinary ones with no value at all like coal, asphalt or even mud . . . in the name of what . . . does man bedeck himself with necklaces of shells and not spiders webs, with foxes furs and not their guts, in the name of what I'd like to know? Mud, rubbish and dirt are man's companions all the life; shouldn't they be precious to him, and isn't one doing man a service to remind him of their beauty" [74] (pp. 263–264)? Other avant-garde artists also used such unattractive materials as sand, gypsum, slag, and asphalt. Henderson photographed people in an ordinary London working-class neighborhood in everyday, unposed situations. In his other works, he used ordinary found objects. He also claimed: "I feel happiest among discarded things, vituperative fragments, cast casually from life, with the fizz of vitality still about them" [64] (p. 265).

Many architects were sure that they would be able to bring out exceptional artistic values from ordinary things and materials. The Smithsons rejected these fashionable and simulated ones. "Thus 'as found' was a new seeing of the ordinary, an openness as to how prosaic 'things' could re-energize our inventive activity. A confronting recognition of what the post-war world actually was like. In a society that had nothing. You reached for what there was, previously unthought of things" [6] (p. 201). Already in the installation "Patio and Pavilion", they demonstrated the intensity of the direct and ordinary [7] (p. 13). The harsh living conditions in Great Britain were reflected in both art and architecture. Anthony Vidler wrote that brutalism "was born out of the post-war culture of 'austerity Britain' [. . .] with almost everything either rationed or simply unavailable" [75] (p. 106).

Young architects, whose basic assumption was objectivity, had to take this austerity as a starting point. Thus, they began to use readily available materials. In England, it was primarily brick. Its advantage was not only commonness but also the fact that it was cheap. Brutalist architects were aware that for their understanding of architecture to be widely accepted, the buildings they proposed could not be expensive. In a difficult economic situation, the idea of simple and unspectacular architecture, which for many seemed a weakness, could become a decisive asset. Peter Smithson even claimed that he personally did not like brick, but he appreciated its qualities because of the prevailing conditions. In Sugden House, he used low-quality bricks of various shades. Such a material would be considered poor by most, but the Smithsons gave it artistic value. Other prosaic materials were also used in brutalism: stone, wood, sheet metal, common plywood, and blockboard [49] (p. 96). However, the most popular was concrete, which, apart from its ordinariness, also had transcendent features.

Architectural and construction elements, as well as details, were also ordinary, sometimes even primitive. It can be said that the steel structure used by the Smithsons in Hunstanton School (1949–1954) was a primitivized version of Mies van der Rohe's structure from the Illinois Institute of Technology. The steel frames were welded in the simplest way. They lacked elaborate details such as Mies's famous corner pillar. The Smithsons wrote about their House in Soho that it was supposed to have a simple construction as in a small warehouse [12]. Maisons Jaoul in Neuilly-sur-Seine (1953–1955) designed by Le Corbusier is an extreme example of the apotheosis of ordinariness in brutalism (Figure 14). Even very monumental works were erected from concrete and brick using primitive techniques, such as buildings designed by Kahn in Bangladesh.

The forms of buildings in the first phase of brutalism were also quite simple. The architects used a small number of solids and elements, and their compositions were not complicated. The emphasis was on clarity and coherence between material, construction, and form. However, over the years, the forms have become more complex and even bombastic. In the later phase of brutalism, the tendency toward the apotheosis of ordinariness survived in the works of a handful of architects. Lina Bo Bardi based on this tendency: "I was looking for simple architecture [...] I made the most of my 5 years in the northeast of Brazil, a lesson of popular experience, not as folkloric romanticism but as an experiment in simplification. By means of a popular experiment, I arrived at what might be called Poor Architecture" [57] (pp. 153–154). Undoubtedly, Bo Bardi was also influenced by the works of other Brazilian brutalist architects tending to the ordinary. These include the buildings of Vilanova Artigas (Casa Martirani in São Paulo, 1969–1974) (Figure 15) and Paulo Mendes da Rocha (Casa Millán in São Paulo, 1970). The forms of their buildings are simple concrete blocks with few windows. An equally radical example is the Florist Kiosk at the Malmö Cemetery (1969) designed by Sigurd Lewerentz [26] (p. 11).

Figure 14. Le Corbusier, Maisons Jaoul in Neuilly-sur-Seine, 1953–1955 (photo: author of the article).

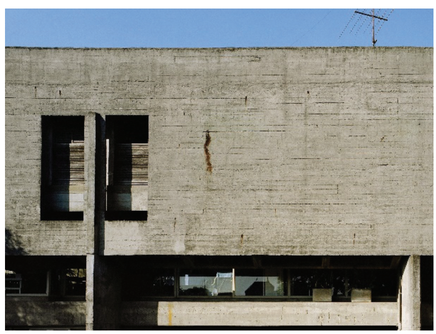

Figure 15. Vilanova Artigas, Casa Martirani in São Paulo, 1969–1974 (photo: Nelson Kon).

4.6. Sincerity of Material, Structure, and Function

Sincerity was an attribute especially valued in avant-garde art trends. The artists expressed their emotions in an honest and direct way—thanks to their independence from the prevailing cultural norms and current artistic trends. They also directly exposed the nature and properties of the material they used. This was characteristic of Paolozzi's works [59]. In some cases, a sculpture seemed to be almost a study of the properties of its material [36] (p. 63). Artists and then brutalist architects rejected abstraction and emphasized the importance of materiality.

The value of sincerity and directness in art brut and art autre inspired brutalist architects to honestly display the structure of buildings [9], but not only that. The form of the building answered four general questions.

1. What materials was the building made of?
2. What is its construction?
3. How was it built?
4. How does it work?

(1) Brutalist architects exposed raw, as found materials in their buildings. In this way, they showed their natural color, internal structure, and other features. They rejected the aestheticization of the building's surfaces and any imitations. They did not use plaster or cladding. The Smithsons emphasized: "We were concerned with the seeing of materials for what they were: the woodness of wood, the sandiness of sand. With this came a distaste of the simulated" [6] (p. 201). Each material was supposed to show only what it really is. Cast

concrete, the most important material in brutalism, was a doubly honest solution in the minds of architects. Béton brut reflected both the nature of the building material and that of the formwork. It should be noted that some concrete buildings have a similar character to the sculptures of Paolozzi. They show the enormous textural possibilities of concrete. A relevant example is the Hayward Gallery.

(2) Architects exposed an overall constructional system of a building and its individual elements, such as columns, beams, and floor slabs. They were visible in the facades, as no cladding or curtain walls were used. Reinforced concrete elements were usually exposed also in brick walls. Even in the facades entirely made of concrete, the constructional elements were distinguished, for example with the help of various textures. There was also a tendency to enlarge construction elements and give them sculptural shapes (against the idea of ordinariness). Thick, angular poles were used by Marcel Breuer in the Becton Engineering and Applied Sciences Center in New Haven (1969–1970). In turn, the curved supports in the Australian Embassy in Paris (1975–1977) was an idea of Harry Seidler (Figure 16).

Figure 16. Harry Seidler, Australian Embassy in Paris, 1975–1977 (photo: author of the article).

(3) Striving for truth in architecture, brutalist architects reflected the methods and stages of erecting a building in its form and surfaces. In the case of cast concrete, traces of the building process were especially the lines (striations) left by the edges of the formwork and the imprint of its surface. The holes left by the formwork assembly elements—nails, screws, spacers—were also exposed. One of the first architects who decided to leave circular holes produced by spacers was Antonin Raymond. In the walls of the Gunma Ongaku Center erected in 1955 in Takasaki, these marks form an additional pattern and are a badge of authenticity [76]. This was also the practice of Kahn, for whom the direct presentation of a building process was the essence of architecture: "An architectural volume is characterized by the fact that it shows how it has been made" [77] (p. 423).

(4) The articulation of internal functions in the form of a building was undoubtedly a way of showing how the building works. The display of technical elements and installations played a similar role. Water, sewage, electricity, and other installations were visible inside. Elements of water drainage from the roof (gutters, gargoyles) and ventilation elements (chimneys, air intakes) were exposed outside. The Hunstanton School was pioneering in this regard. Banham wrote about the sincerity of this building: "Water and electricity do not come out of unexplained holes in the wall, but are delivered to the point of use by visible pipes and manifest conduits. One can see what Hunstanton is made of, and how it works, and there is not another thing to see except the play of spaces" [1] (p. 357). Paul Rudolph, who later in his work rather hid installations, in the Blue Cross and Blue Shield Building in Boston (1957–1960) created a composition of ventilation ducts on the facades (Figure 17). Rudolph actually designed a heating, ventilation, and air-conditioning system with ducts placed within exterior concrete piers [21] (pp. 49–54).

Figure 17. Paul Rudolph, Blue Cross and Blue Shield Building in Boston, 1957–1960 (photo: author of the article).

4.7. Textures—Roughness and Defects

Most brutalist architects preferred rough, uneven textures. Dubuffet's paintings and Paolozzi's sculptures drew the architects' attention to the qualities of such raw surfaces, bearing traces of the way they were made.

Dubuffet emphasized that the texture of a painting is a means by which the painter expresses himself. He preferred the expressive, dynamic, and spontaneous application of painting material. The layer of paint or other matter was thick and expressive. Dubuffet believed that the essential gesture of a painter is to smear, not to smooth. In this way, he wanted "to imprint the most immediate traces that he may have of his thoughts and rhythms and impulses coursing through his arteries and running along the length of his nerve endings" [78] (p. 35). Therefore, the rough texture was an expression of emotions and mind. Dubuffet's ideas helped brutalist architects to justify the thesis that the use of rough and raw materials in architecture is not a regression, but an expression of avant-garde taste.

Paolozzi's sculptures also had rough surfaces. Using bronze or concrete, he finished their aesthetic development at an earlier stage than other artists. For Paolozzi, it was raw material not "artist's material" [59]. Some of Paolozzi's sculptures were large and monumental. Observed from a distance, they seemed coarse, as if roughly hewn. However, up close, their rough surface revealed details, small objects that made it up [32] (p. 88).

The massiveness and heaviness of solids and monumental forms became the hallmarks of brutalist architecture in the following years. In contrast, brutalist buildings, such as the sculptures of Paolozzi, changed depending on the distance of the observer. Only after approaching the building, the observer was discovering the structure of their surfaces—for example, an imprint of formwork and components of concrete. Rough surfaces prevailed in brutalism because the textures were supposed to be sensual. The uneven and heterogeneous surfaces were picturesque, and they produced variable visual effects also depending on the lighting. Smooth textures were also used, but most often to juxtapose them with rough surfaces, following the brutalist principle of contrast.

Picturesque brick textures were designed by Le Corbusier and the Smithsons, and even Rudolph (Yale Married Student Housing in New Haven, 1960–1961), who was known for his concrete textures. Le Corbusier hired unskilled Algerian workers using crude and primitive building techniques. In this way, he wanted to achieve the effect of sloppy and carelessly made brick walls. James Stirling admitted that he was shocked but also excited when he saw the Jaoul Houses within half a mile of the Champs Elysèes built in contrast to sophisticated constructional habits with the use of "ladders, hammers and nails". [2] (p. 86). In developing countries, primitiveness was an immanent feature of brickwork, and that is why such aesthetics is visible in local brutalist buildings, e.g., in the Center for Environment and Planning Technology in Ahmedabad (Figure 18). It was the same with concrete buildings. Many architects also opted for craftsmanship rather than precise prefabrication. They followed Dubuffet, who emphasized: "The more the artist's hand is apparent in the entire work, the more moving, the more human, the more eloquent it will be. Avoid all mechanical and impersonal means. The most meticulous typography and calligraphy are less alluring than a few hand-written, unpremeditated words scrawled by a devoted hand" [78] (p. 35).

Figure 18. Balkrishna Doshi, Center for Environment and Planning Technology in Ahmedabad, 1968–1972 (photo: Aurobindo Ogra).

Artisanal building methods, according to many architects, gave their works additional value. Unlike prefabricated buildings, they were original and unique. Each of their fragments was characterized by individualism and contained immanent features. The erection of a building from concrete placed on the site was an even more difficult and complex artisanal task than bricklaying. Max Bächer claimed: "Here is the very essence of 'hand-made' article. Here is task calling, if ever one did, for the fullest mental and manual skills of the dedicated craftsman" [79] (p. 64). In some brutalist buildings, defects of surfaces were not hidden, and even highlighted, as in Unite d'Habitation in Marseille (1947–1952) (Figure 19). Architects considered cracks, blisterings, and efflorescences to be an inherent feature of the material. In addition to Le Corbusier, this approach to concrete texture can also be found in buildings designed by Hans Litz and Fritz Schwartz. In the Sports and Recreation Center in Zürich (1961–1965), they used coarse wooden formwork with gaps between the boards and left all texture defects. John Andrews achieved a similar effect using metal sheet formwork in Scarborough College in Toronto (1963–1965).

Figure 19. Le Corbusier, Unite d'Habitation in Marseille, 1947–1952 (photo: Tomasz Basista).

As a result of exposing rough textures with defects, some brutalist buildings already on the day of completion looked as if they had been destroyed by time, as if they were almost ruins. It was a deliberate effect that was to add splendor to the building and bring it closer to the great works of the past that have survived for centuries. The building was to become "a magnificent ruin" [2] (p. 16). These poetics came from the surface of the building, it was inherent in its texture.

The fascination with ruins was related to the war trauma noticeable in the works of avant-garde artists. The installation "Patio and Pavilion" should be mentioned again, as it presented the image of a makeshift building erected on rubble among scattered objects. Fragments of buildings destroyed during the war were also visible in other works by Paolozzi and Henderson. Especially for Henderson, it was important to capture the problem of time, place, and passing in the photographs. He was interested in specific signs of space, defects in buildings, "slicks and patches of tar on the roads, the cracks and slicks end erosive marks on pavement slabs, the ageing of wood and paintwork, the rich layering of billboards" [7] (p. 94). The Smithsons were interested not only in ancient ruins but also in the ruins of industrial facilities. This was due to both the search for the basics and the rediscovery of the genius of the place. They wrote: "Our enjoyment of ruined places, liberated spaces intended for life but emptied by time, their clean yet evocative stones have, over the years, suggested to us we are on the threshold of a period of lyrical appropriateness" [49] (p. 325).

4.8. Found Objects and the Idea of As Found

The use of found objects was the essence of the work of avant-garde artists and influenced brutalist architects not only in terms of the way materials were used.

Paolozzi found everyday objects to make his works, as shown by the series of sculptures made using the lost wax method. This method allowed reflecting the shapes of materials and objects used to make the mold in the finished sculpture casting. The coarse bronze objects had rough surfaces from which broken toys, piano mechanisms, wheels, gun-sights, cogs, electrical parts, clock parts, broken combs, and bent forks emerged. Paolozzi described his artistic process as "the metamorphosis of rubbish" [32] (p. 87). Henderson placed objects and pieces of rubbish found in the ruins after the bombings in his photograms. He picked them up in London's bombarded East End and took them back to his darkroom. There, he lay them on light-sensitive paper to make what he called Hendograms [36] (p. 68). He also created collages with photos of found objects. Charlotte Perriand used found objects (objets trouvés) in her photographs. She described her works, often created together with Fernand Léger, as art brut. She especially liked driftwood, shells, and debris, lifting these objects out of obscurity and giving them the status of works of art [80]. She used her artistic experience while working with Le Corbusier and Ernő Goldfinger. Brutalist architects treated building materials as found objects. They used raw materials without any surface treatment, which has already been analyzed above. It is worth noting that they really used found objects as well as artefacts found at the construction site. Gottfried Böhm in the Hotel Godesberg in Bad Godesberg on the Rhine (1961) incorporated the stone walls of the ruined castle into the new architectural structure [79] (p. 40). Altug and Behruz Cinici in the METU Faculty of Architecture Building in Ankara have inserted an original historical wooden door called "han kapisi" (Figure 20).

However, As Found in brutalist architecture should also be understood as a broad idea and the resulting design method. The idea of As Found contributed to noticing various aspects of the context, searching for specific features of a place, and taking into account the existing conditions in the project. The uniqueness of the design solutions of brutalist architects resulted precisely from the fact that they treated the existing situation as a found object with all its immanent features.

According to the idea of As Found, the value of the thing was contained in the thing itself. The brutalists did not modify the thing itself but tried to change its relations with other objects and with people. Anette Busse noted: "As Found meant taking something existing and reinterpreting in relation to reality" [81] (p. 93). The design method used, among others by the Smithsons involved "picking up, turning over and putting with; a careful consideration of ordering and an appreciation of the ordinary" [7] (p. 194). In fact, it was a creative process transferred directly from the artistic experience of Paolozzi or

Henderson. An example was the Upper Lawn Pavilion in Fonthill Abbey (1961). First, the Smithsons assessed the situation and the place, analyzing the remains (foundations, stone walls, chimney) of the old house. Then, they reinterpreted it in relation to new needs, deciding to use some parts of the old structure. As a result, they developed the new building with significant preservation of the original artefacts.

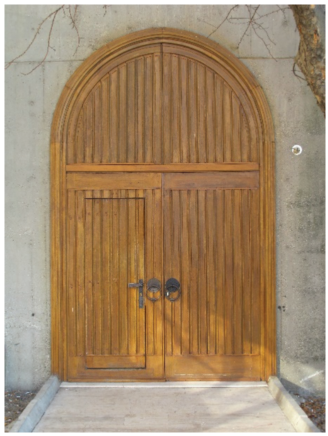

Figure 20. Altug and Behruz Cinici, METU Faculty of Architecture Building in Ankara, 1961–1963 (photo: Haluk Zelef).

Kallmann also followed the idea of As Found when creating his concept of "action architecture". He insisted on accepting the reality of established urban, social, and even political contexts. "If governments wanted to represent authority, then architects would oblige; if cities were threatening places, 'as found', perhaps buildings ought to be tough and defensive" [50] (p. 56). It is worth noting that many brutalist buildings, especially those from the 1960s (the period of the Cold War and social unrest), have defensive and heavy forms (Figure 21).

Figure 21. Gerhard Kallmann and Michael McKinnell, City Hall in Boston, 1963–1968 (photo: author of the article).

5. Conclusions

The greatest impact on brutalist architecture was exerted by such avant-garde trends as art autre, art brut, and musique concrète. Architects were most inspired by the works of Jackson Pollock, Jean Dubuffet, Pierre Schaeffer, Eduardo Paolozzi, and Nigel Henderson. This influence was most evident in the beginnings and the first phase of brutalism, that is, in the 1950s and early 1960s.

After the end of World War II, both avant-garde artists and architects searched for a new style that would correspond to the harsh reality and the changing way of life. They were convinced that the language of architecture and art should, first of all, be moving; it should evoke emotions. Young architects reached for the ideas of avant-garde art, as they did not find the right ones in the architecture of that time. In fact, the only architect of the older generation whose work inspired them was Le Corbusier.

The studies of brutalist architecture have shown that it was a very complex and heterogeneous style. There were various trends in it, changing over time, and many architects developed their own, individual manner. The regional differentiation was also characteristic of brutalism. Therefore, it should be emphasized that the ideas derived from avant-garde art did not apply to all architects and their works to the same extent. Moreover, some buildings and their features, especially those from the late stage of brutalism, seem to contradict these ideas. Nevertheless, the hypothesis that many brutalist architects drew from the post-war avant-garde artistic trends a number of assumptions and ideas is correct and has been confirmed. These ideas found their implementation in brutalist buildings. The most important ideas were:

- Rejection of previous principles and doctrines,
- Searching for the basics,
- As Found,
- Glorification of ordinariness,
- Reflecting the realities of life,
- Sincerity of material, structure, and technology,
- Articulation of internal functions in the form of a building,
- Roughness of textures.

These ideas contributed to the development of the following forms, solutions, and aesthetic effects in brutalist architecture:

- Simplification of forms and elements,
- Forms and solutions inspired by vernacular architecture,
- Vehement juxtapositions of solids and elements,
- Repetitive and disturbed rhythms,
- Highlighting circulation and communication elements,
- Exposing structural elements,
- Exposing installations and technical elements,
- Ordinary materials,
- Raw materials,
- Poetics of "magnificent ruins".

Among the architects who were largely guided by the ideas derived from avant-garde art were Le Corbusier, Alison and Peter Smithson, Denys Lasdun, James Stirling, Vittoriano Vigano, Louis I. Kahn, Paul Rudolph, Gerhard Kallmann, John Johansen, Joseph Lluís Sert, Kenzo Tange, Altug and Behruz Cinici, Vilanova Artigas, and Balkrishna Doshi.

The research showed that the idea of sincerity had the greatest impact on brutalist architecture. It contributed to the development of most of the architectural solutions and forms. Both at the beginning and the end of the style, its importance was great, especially in terms of the sincerity of the material. The remaining ideas were gradually devalued, which was one of the reasons for the fall of brutalism.

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Article

Unknown Suns: László Hudec, Antonin Raymond and the Rising of a Modern Architecture for Eastern Asia

Anamaria Andreea Anghel [1], Joseph Cabeza-Lainez [2,*] and Yingying Xu [3]

[1] Department of Architecture, Faculty of Architecture and Urban Planning, Politehnica University of Timisoara, 300006 Timisoara, Romania; andreea.anghel@upt.ro
[2] Department of Architectural Composition, University of Sevilla, 41012 Sevilla, Spain
[3] Department of Oriental Studies, University of Seville, 41002 Sevilla, Spain; xying@us.es
* Correspondence: crowley@us.es

Abstract: The purpose of this article is to disclose the strenuous efforts of László Hudec in China and Antonin Raymond in Japan and India to create a modern architectural stance by heralding an incipient space syntax. At the turn of the 19th century, for dynastic, political and economic reasons, Eastern Asia had very little modern architecture. It is a surprising fact that, out of happenstance, two European architects, Antonin Raymond and László Hudec, had to intervene to remedy this situation, to the point of becoming 20th century icons in Japan and China. Their fruitful careers spanned over thirty years and included locations like Tamil Nadu and the Philippines. The oriental territories were not an easy ground for the bold architectural achievements that they produced. Despite faraway strangeness and uncountable personal losses, in revolutions and wars, which eventually forced them both to leave for the United States of America and never to return, they were successful in the manner of establishing a broad avenue for modern Asian architecture which is still recognizable today thanks to their systematic approach. However, theirs is an endangered heritage and the intention of this article is to offer a just remembrance of the way in which such actions could be performed, how they predated by many years a syntactic approach to architectural composition and why their legacy should be preserved.

Keywords: modern architecture in East Asia; architectural design; László Hudec; Antonin Raymond; innovative architectural projects; space syntax; Asian traditions

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1. Introduction

A score of years ago one of the authors of this article was present when the late and famed architect Peter Smithson delivered a speech to a devoted audience of the Architectural Association of Seville.

When the turn came to explain his acclaimed project for the furniture factory Tecta in Germany, he produced a slide with a map of Europe. Then he showed that the latitude of the construction site near Kassel was very similar to that of London, roughly 50 degrees north. Then, with a smile of confidence, he uttered to the listeners' surprise: "This is a Known Sun . . . " and he went onwards explaining the particulars of his design.

With such a phrase, P. Smithson wanted to convey his great environmental concerns; he dared to work in this part of Germany because he deemed that the climate or at least the shadow casting of architectural forms were similar to that of his native London.

On the contrary, for Antonín Raymond and László Hudec, the eastern sun was a totally unknown one, no matter how hard they tried to appease its ruthless brightness.

Both Hudec and Raymond never chose such a challenge. For sundry vicissitudes, including exile and imprisonment, they were to settle and design for Eastern Asia. They soon realized that their duty and position was to adapt the innovations of modern architecture which they had known in Europe and America, such as Perret's, Wright's or Le Corbusier's oeuvre [1], to the incipient but firm building activity of the great Chinese and Japanese newly opened ports. Subsequently they extended this huge task to all confines of Asia, like India [2], the Marianas and the Philippines [3].

In this article, the authors will try to disentangle the subtle nuances and mechanisms of such extraordinary construction. Our main research objective is to demonstrate the relevance of the designs that they produced out of the significance and relevance for modern architecture. How they were able to develop new structures and typologies was deeply ingrained with the architectural traditions of Asia.

When China and Japan opened up to European markets and culture in the 19th century and began an amazingly rapid process of technological development, their traditional architectural culture was also fundamentally transformed. The two Eastern Europeans who contributed the most to this process of modernizing the architectural image of the Far East, blending local traditions with European influences and creating the foundations of contemporary architecture in both countries, were the internationally recognized Czech Antonín Raymond and László Hudec, yet to be rediscovered by posterity since basically their contribution is largely forgotten [4].

The careers of Hudec and Raymond [1,5] share considerable similarities. They were born geographically close to each other (Czechoslovakia), although under different circumstances, and ended up in a cultural environment foreign to their own. The two architects had an active and productive career, enabling them to form ties with the members of the local cultural and political elite. They both strived to find their own form of expression in the 1920s and clearly turned towards Functionalism in the 1930s, exerting a major influence on their respective environments, while they enjoyed international attention thanks to periodicals and other publications. This led them to make a fundamental contribution to the modern development of architecture in the metropolises of the East. After considerable research experience in East Asia, we have reached the conclusion that their legacy has been obliterated and such indubitable heritage faces undeniable risks that we intend to avoid by outlining the fundamental characteristics of their oeuvres.

2. The Material Milieu

2.1. A Parallel between Antonin Raymond and László Hudec

Raymond and Hudec, since the beginning of their lives, shared many similitudes; for instance, their birthplaces are very close, one in today's Czech Republic and the other in Slovakia; their years of birth, with a slight difference of about five years, 1888/1893; their dream to excel in architecture; their formation at the architectural academy; the First World War and their active participation in it; and their destiny in Eastern Asia (Figure 1).

Figure 1. Comparison between Hudec and Raymond's trajectory from Europe to Eastern Asia (Hudec's trajectory in red, Raymond's trajectory in orange).

As we can see in the map above, their trajectories start from similar places, but Hudec is going east and Raymond west. Both converge in Eastern Asia, one in Shanghai and the other in Tokyo. The big difference between the two is that Hudec arrived in China unwillingly, after escaping from a prison camp during the War [4], and Raymond came to Japan (with his family and Frank Lloyd Wright) with the precise aim of designing the Imperial Hotel.

As regarding their professional careers, immediately after finishing his studies, Hudec was enrolled in the army. The only previous experience he had was working for his father. This was a blessing in disguise for him; although he had to start practically from nothing in Shanghai, he rapidly progressed and evolved.

On the contrary, Raymond's work experience before arriving in Japan was ample. He had always combined two professions, architectural practice and painting. He worked for different architects and painted together with his wife. It was because of his talent that he was invited by Frank Lloyd Wright to help him with the design of the Imperial Hotel in Tokyo [6].

2.2. China and Japan in a Contemporary Review

China and Japan are situated in Eastern Asia and are geographically separated by a relatively narrow stretch of ocean. Japan was strongly influenced by China's writing system of characters, architecture, culture, religion, philosophy, and law.

In the mid-19th century, western countries forced Japan to open for trading. Japan moved towards modernization (Meiji Restoration) and started to view China as an antiquated and isolated civilization, unable to defend itself against Western forces, in part due to the First and Second Opium Wars resulting in Anglo–French expeditions from the 1840s to the 1860s [7]. Japan's long chain of invasions and war hostilities in China between 1894 and 1945 as well as modern Japan's attitude towards its past are major issues affecting current Japanese and Chinese relations.

2.3. Modern Architecture in Shanghai and Tokyo

Like every other style in architecture, Chinese architecture is a style that has become ingrained in Eastern Asia since the beginnings of Chinese civilization. The structural principles are almost the same; differences reside mainly in the decorative details. Chinese architecture had a major influence on the architectural styles of Korea, Vietnam and Japan.

In the 20th century, after the opening of China to the world, western-trained Chinese architects have tried to combine traditional Chinese design with modern architecture. This had limited success in big cities, like Beijing or Shanghai, and later proved impractical because of the pressure for urban development, which demanded new types of buildings. The appreciation for low-rise Chinese architecture declined in favor of modern architecture.

It is important to outline the main characteristics of traditional Chinese architecture, in order to analyse the buildings designed by the architect László Hudec, among the pioneers who brought modernism into design. These features are, from the point of view of space syntax [4]:

1. Symmetry—signifying balance and order;
2. Enclosure—this involves designing the building around an open space, like a courtyard, the spaces opening to the yard directly or through verandas;
3. Hierarchy—the placement of the building within a complex, taking into account the entrances to the different buildings;
4. Horizontal emphasis—the emphasis on breadth and less on the height of the buildings;
5. Cosmological concepts—the use of concepts, such as Feng-Shui and Daoism, for the organization and layout of the constructions. (In Japan, China, India and other countries, the disposition of buildings in relation to the surroundings followed an adroit strategy of natural balance related to geomancy, like Feng-Shui or Vastu, and to the observance of deeply rooted environmental rules [8].)

Shanghai gained its international identity and flourished as a hub between the East and the West during the period known as Old Shanghai, which dates from 1846 to 1945. Shanghai was then a free treaty port, witnessing the establishment of international settlements. During its internationalization period, Shanghai gained its cosmopolitan reputation through the intermixture of global and local residents with diverse social, economic and cultural backgrounds. This intersection of cultures is reflected in the mixture of multinational architectures and the coexistence of modern and traditional styles.

Historically, although Japanese architecture was strongly influenced by its Chinese counterpart, there are some important differences between the two. For example, the wood used in Chinese buildings is finished with bright painting, while in Japanese traditional architecture the wood remains exposed; Chinese architecture is based on a lifestyle that uses chairs, tables and beds, while in Japan the floor serves all these purposes [9], though this changed slightly during the Meiji Period (1868–1912).

László Hudec, in one of his letters addressed to his family, writes his opinion about Japanese and Chinese temples and the differences between them: "The concept of Chinese temples is absolutely beautiful and on a large scale, but shameful in the detail of its workmanship—while in Japan the details are like arts and crafts but the layout is weak. It is true that their asymmetrical arrangement is much more picturesque than the strict symmetry of the Chinese temples but the trees in the courtyards make the latter less boring" [4].

Traditionally Japanese architecture is characterized by wooden structures, slightly elevated from the ground, covered by tiled or thatched roofs and with sliding panels, translucent and covered by paper, which are called, respectively, shoji and fusuma. Rash mats or tatami, heavily modulate the space at a fixed area of 1.65 m^2, two tatami disposed in a square shape give 3.3 m^2, which is the actual unit of measurement, the tsubo. Even today, these are key elements of the traditional Japanese house and garden [10]. These sliding panels or shoji are elements particular to Japanese architecture, used instead of normal walls, and thanks to them each space can be customized for different occasions. Until the 20th century, tables, chairs or beds did not exist in any house or space, traditionally, the Japanese people used the floor for sitting or sleeping.

Architecture in Japan has been strongly influenced by the climate and this is reflected in the way homes are built. Summers in most of Japan are long, humid and hot. This is also the reason why the traditional houses are raised from the ground for letting the air circulate around and beneath the house [11]. Wood is the preferred material because of its properties—cool in summer, warm in winter, and its flexibility during the earthquakes.

In the 19th century, gradual changes began. Japan has slowly incorporated western modern architecture into the design of buildings. Today, Japan is a trendsetter in the field of architectural design and technology. Modern architectural techniques were introduced in Japan with the advent of the Meiji Restoration in 1868. Two major events in the history of Japan radically changed its architecture. The first event was the Kami and Buddhas Separation Act of 1868, which distinguished Buddhism (a foreign faith) from Shinto and Buddhist temples from Shinto shrines, breaking an association which lasted well over a thousand years. This caused severe damage to the nation's architecture for lack of state funding. The second event was the intense modernization Japan was undergoing in order to compete with other developed countries. For this, the first step was importing architects and styles from abroad. However, after a while, Japan taught its own architects who slowly began to design in their own modern style. Japan sent architects to the West to study and they returned home, introducing the International Style of modernism into Japan. International recognition came only after the Second World War with the work of architects like Kenzo Tange. In the four years of employment in the office of Kunio Maekawa (one of the most influential Japanese architects of his generation), starting in 1938, Kenzo Tange assimilated his practising experience. Maekawa had the privilege of working in the office of Le Corbusier in Paris [12] (being part of the team which designed the Villa Savoye and the Swiss Pavilion) and, once returned to Japan, spent five years at Antonin Raymond's office.

In the 1880s, a sudden reaction against the rush toward westernisation, ignited the support of Asian models, even in architecture. This changed again after World War I when the architects Frank Lloyd Wright (1869–1959) from the United States and Bruno Taut (1880–1938) from Germany arrived to work in Japan [13].

2.4. Interior Design Concepts for the Japanese Dwellings

The interior design of a Japanese house is very different from normal European interiors. It possesses its own rules, underlying deep notions based on tradition. In the past, a Japanese house consisted of an open space, even devoid of screens to make partitions for individual spaces. In time, particular areas and different functions (like eating, sleeping or dressing) became more and more present in the design. As a result of such new necessities, the use of self-standing screens started (first byobu, then shoji and fusuma). They were used to provide some degree of privacy, although they served less as sound barriers. These screens can be easily removed in order to open up the entire space [10].

The Japanese had a particular way of dealing with the interior and exterior of the house. Instead of seeing the interior and exterior as two distinct environments, they are considered continuous spaces. Therefore, they introduced the veranda (engawa), which plays the role of transitional space between inside and outside.

The traditional living space is designed for people who remain seated on the floor, not standing. The windows and doors are therefore placed low, so that the visual relation between the spaces is clear and everyone from the inside can see the garden or vice versa.

Although modernization has produced significant alterations in design, the traditional Japanese style has not vanished, and it is still in use. For example, even in westernized dwellings, it is likely that a room will be found whose floor is clad with tatami, and it is customary to remove one's shoes when entering the house.

3. Case Studies

3.1. Antonin Raymond and László Hudec—A Comparison of Early Works

The architects both lived and practiced in Eastern Asia for a long period of time, sufficient to allow them to become involved with the local people and culture. They had the advantage of starting their architectural practice in Japan and China, in the proper period, when these countries opened up to modernization; they were "in the right place at the right time". A timeline of their careers is offered in Figures 2–4.

In Raymond's case, he began just when Japan's pursuit of modernization slowly shifted from being based on the westernization model back towards native roots. Another important reason for Raymond's blossoming career was the fact that he benefited from the consequences of the Great Kanto earthquake and the following period of reconstruction [14].

László Hudec was much more interested in the use of modern materials, functions and technologies. This was the main reason of their encounter. When Raymond was finishing his design for the American Otis Elevator Company in Tokyo, Hudec had installed Otis lifts for the first time in Shanghai in his novel 22-storey Park Hotel. As Alessa Hudec De Wet recalls, Hudec met Raymond through the Asian representative of Otis. After the family's first trip in 1932 to Tokyo, a lasting friendship developed between the two and their families. From 1935 to 1941, the Hudecs spent their summer holidays in Japan in Raymond's house on a hill near Karuizawa [15]. This can be inaccurate in part because the Raymonds had to leave Japan in 1938.

On the other side, Antonin Raymond gained a deep insight into traditional building techniques, the use of materials and a wider view of Japanese culture. This allowed him to deal with the problematic issue of finding the perfect balance between traditional Japanese and western modern architecture, the necessary syntax for the creation of a modern architecture suited to Japan.

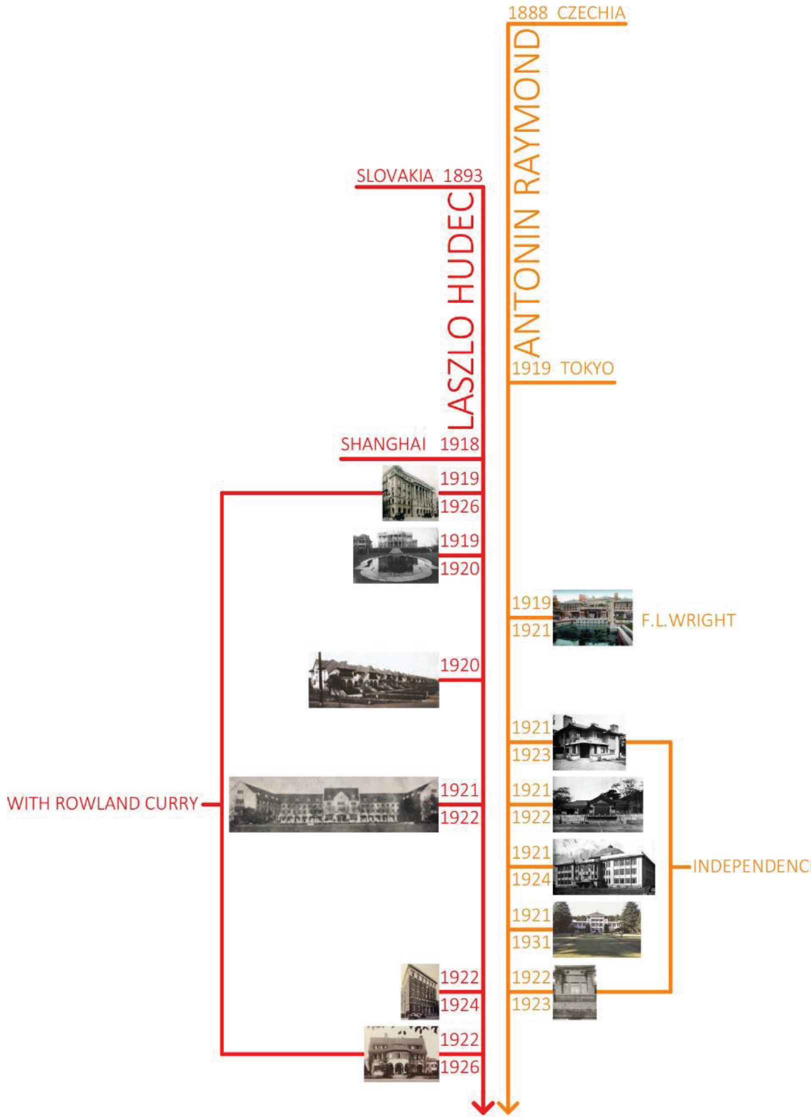

Figure 2. Timeline 01—Hudec and Raymond comparative designs.

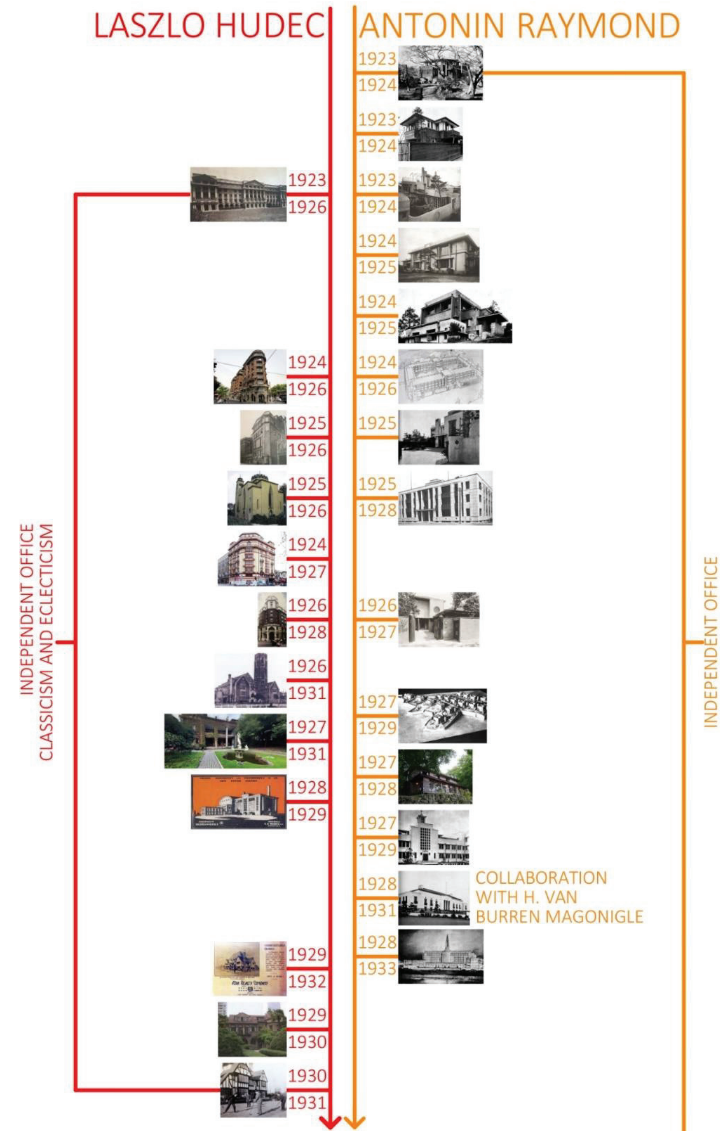

Figure 3. Timeline 02—Hudec and Raymond comparative designs.

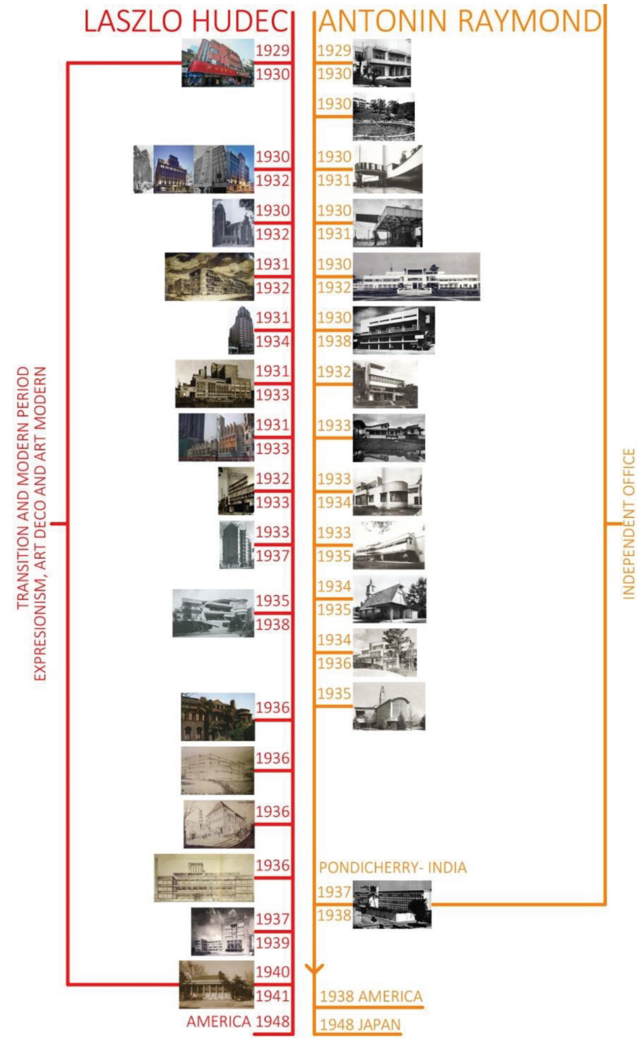

Figure 4. Timeline 03—Hudec and Raymond comparative designs.

3.2. The Private Houses of Hudec and Raymond

The authors believe that the best way for an architect to achieve full development is by reflecting on the design of his own house. The process often starts as an experiment that later becomes a representative project. In Raymond's case this happened more than once but the first occasion was with his Reinanzaka concrete house (Figure 5), which ended up being a real modern project, one of his masterpieces. Designing his own house or his Karuizawa studio, an architect gains all the necessary freedom to create art which incorporates most of his knowledge, beliefs and principles. Without compromises and restrictions, this is the way real art and architecture emerge.

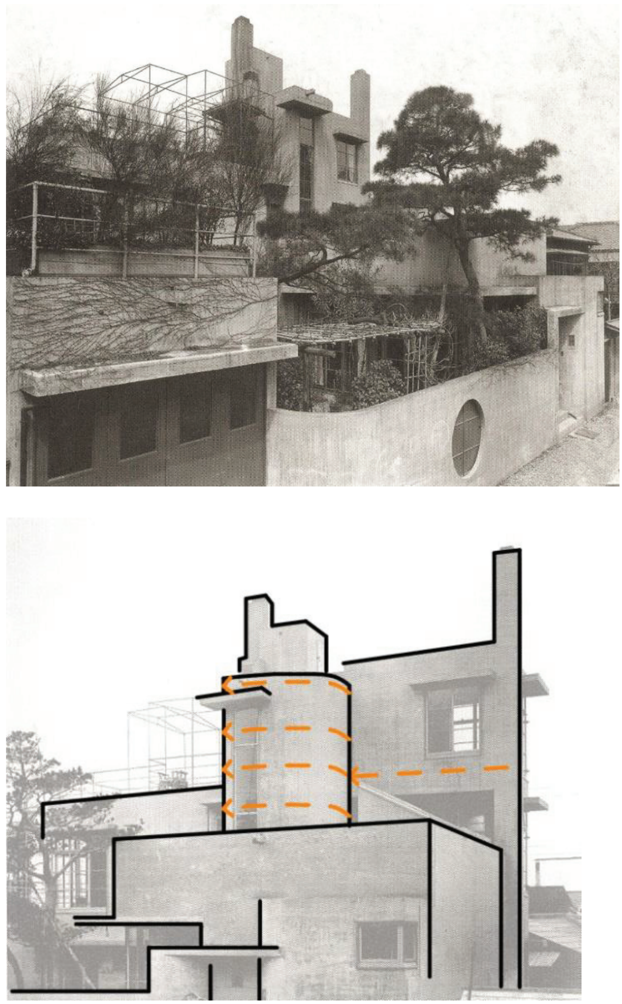

Figure 5. Reinanzaka house of the Raymond family (1924) and its concrete plasticity.

Built completely out of reinforced concrete, Reinanzaka House constituted a huge step forward and a liberation from Frank Lloyd Wright's mannerism, predating modern architecture. Like everything Raymond designed after the Kanto Earthquake of 1923, the house had an earthquake proof structure of reinforced concrete. The exposed concrete was not clad with cement mortar or any other finishes, which emphasized Raymond's belief that there is inherent beauty in concrete and that it has its own character if studied and understood [16]. He created a monolithic enclosure surrounding the house and garden. The configuration was striking because it was dissimilar to his former designs and also to local productions. For the organization and separation of the functions (the living areas from the servant's areas), he articulated three aisles under a U-shaped plan (Figure 6).

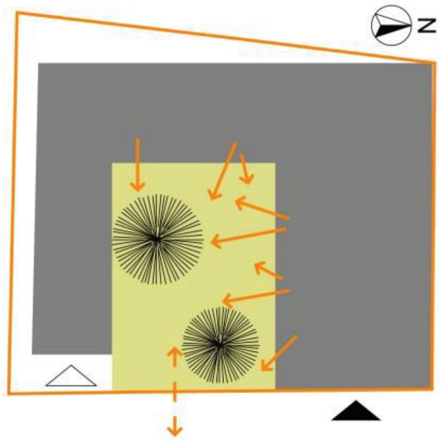

Figure 6. The U-shaped plan of the Reinanzaka house and openings towards the garden.

Raymond's own house was remarkable in a number of ways. It was one of the first occasions on which a concrete frame was enriched so as to recall traditional Japanese wooden construction, a mannerism which was to become the architectural touchstone of Japanese architecture after the Second World War [16].

Raymond explains that the flexibility and southern orientation of the living spaces, the position of the windows which provided good ventilation and natural illumination and the principle of using only natural materials without any processing, were all inspired by traditional Japanese examples. As every room had a proper orientation to the south and access to its own section of garden, the windows became quite important. There appeared some necessary details above the windows, "the overhang (eyelid)", which was not only aesthetic but had the main purpose of preventing direct sunlight in summer while admitting it in winter. Moreover, the design constituted a reinterpretation of the veranda (engawa), which has the combined role of a transitional space between inside and outside and a protection from the harsh weather. These concrete canopies or "eyebrows" situated over the windows became one of the principles of modern design [1]. In Raymond's attempt to integrate into his design elements extracted from the local vernacular, the rainwater was evacuated in a particular way, by means of ropes, instead of the usual western gutters prone to clogging. Apart from concrete, the house has metal fenestration and tubular steel trellises (Figure 7).

In 1933, the Raymonds decided to build a summer residence (Karuizawa) for themselves in order to continue developing some of the work in the midst of the hot summer of Tokyo. Raymond had a deep admiration for Le Corbusier's oeuvre. In the design of his summer residence, the main inspiration was Le Corbusier's unrealized Matias Errázuriz house for Zapallar in Chile (1929–1930). In fact, as Raymond says, "what better way to express an admiration for someone than taking one of his motifs of an unconstructed project and carrying it further on". Raymond's design borrowed the distinctive "butterfly roof and internal ramp circulation". "Except for the motif for the main room of the Karuizawa summer house, the building was conceived in an entirely original way. It has a very strong Japanese flavour, although it does not adopt any traditional Japanese forms." [17]. The Karuizawa summer house may be a key project to the intention of breaking completely from Wright's influence and embracing a new period, dominated by Le Corbusier.

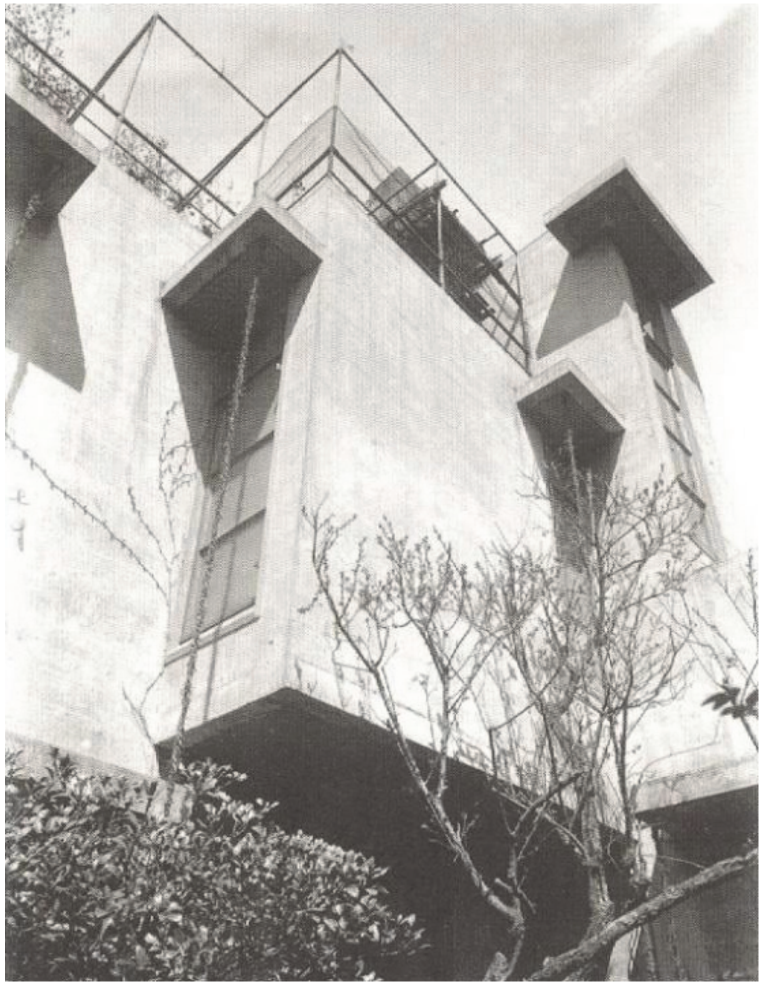

Figure 7. Reinanzaka house of the Raymond family 1924—detail of the concrete eyebrows and of the ropes for evacuating the rainwater, looking up from the garden.

Pointing out that on his turn other architects used to adopt or borrow details from his designs, in 1938 Raymond published his book entitled *Architectural Details*. The book was conceived with the aim of sharing his knowledge and information with all the interested architects "in the hope that they would use it" (like in his own case, when he was a student and first got his hands on a book presenting Frank Lloyd Wright's projects).

Raymond built a house suited to his family lifestyle (one of the fundamental principles advocated by the pioneers of modern architecture). His main design principles, "honesty", "simplicity", "economy", "directness", "functionality" and "naturalness", are guiding lines of the whole structure [14].

For the plan and interior organization of the spaces, Raymond followed the roles of Japanese traditional residential architecture regarding orientation. The plot has a pavilioned distribution. Raymond oriented the main house with the openings of the living room towards the south, facing the breathtaking view of the mountains and the pond (Figure 8).

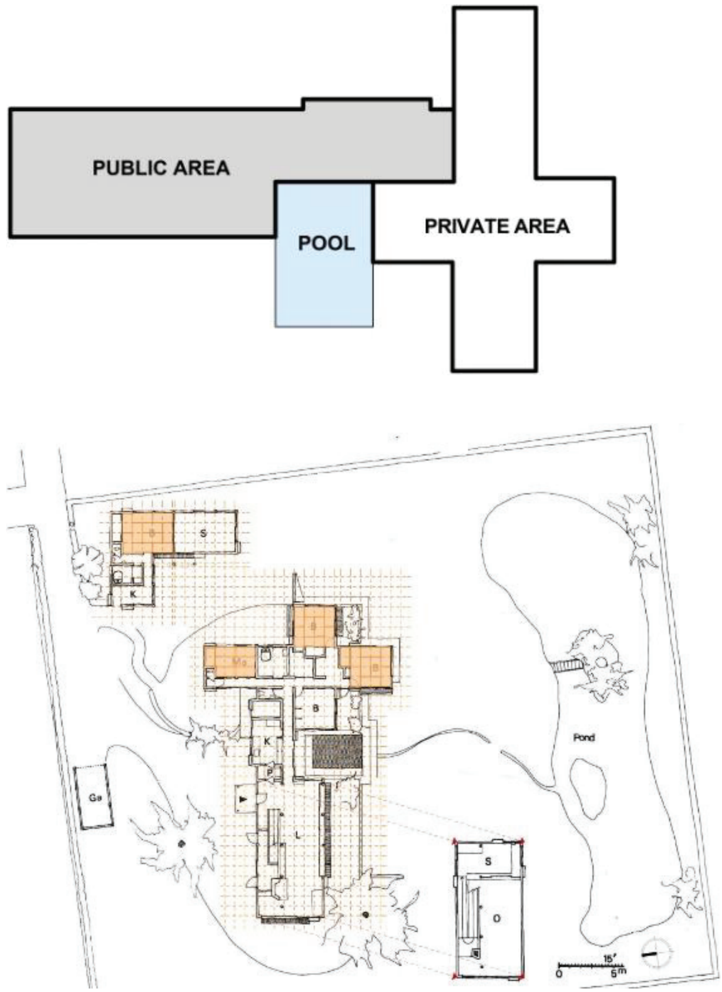

Figure 8. Karuizawa house—public and private area and the pool, plan and views.

The house is composed of two main areas—the public area (living and dining room, kitchen and studio) and the private area (which included the bedrooms and the maid's room). These two main zones are articulated by the pool, which serves as natural barrier between them two, creating a source of relaxation and fresh and moist air which invigorates the atmosphere during the humid summer.

The house stands upon elevated ground, artificially created from the soil extracted to make the pond (Figure 9). The circle of life is recreated by the fact that the water overflowing the pool is being let to the pond. In fact, the whole level difference allows better drainage of the ground below and around the house, for which the pond functions like a reservoir (Figure 10). The fact that is entirely supported by a series of short wooden posts facilitates the natural ventilation beneath the house.

Figure 9. Karuizawa summer house—lightness and transparency.

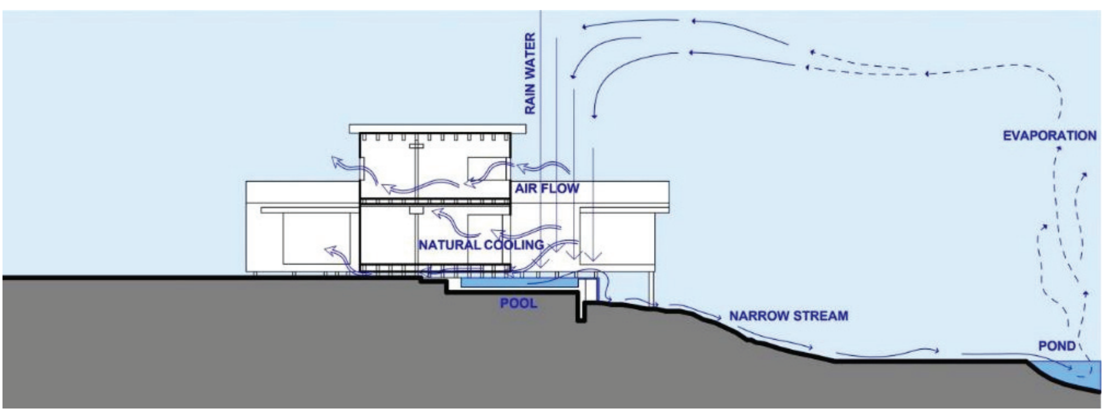

Figure 10. Karuizawa summer house—section, natural ventilation and water cycle = eco-friendly, sustainable house.

Raymond was eager to introduce the traditional Japanese syntax of the tatami in his design. In the summer house there are three tatami rooms in the main building, almost the entire private area. By placing a grid based on a three-by-three shaku (Japanese foot) module over the plan [18], we can observe that Raymond used the tatami as a syntactic resource for the overall composition of the Karuizawa house, highlighting the conversation between western and traditional Japanese (Figure 11).

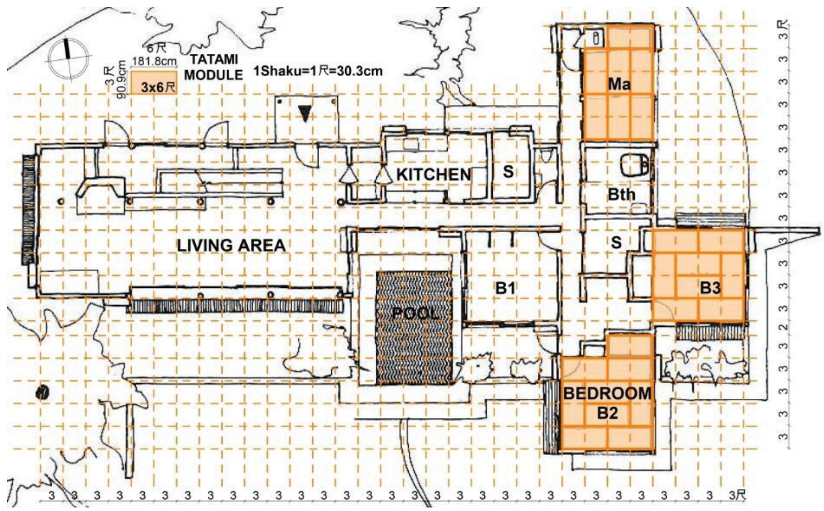

Figure 11. Karuizawa summer house—study of the tatami module over the plan.

This house "marked the new era in his design" in Raymond's own words. Actually, with this house, he completed a stage, summarizing all the knowledge gathered previously and it was the living result of the many years spent trying to find the perfect balance between western modern principles and Japanese traditions. The need to combine western and Japanese elements in his designs was not only due to practical issues but more an aftermath of his long studies and admiration of the Japanese roots and traditions. He began to develop this discovery from an early stage in his career. The Karuizawa summer house testifies to the strong impact this research had on him and his wife, Noemi Pernessin, who practically used them as the main inspiration for their ensuing designs. In the last period of their life they reconstructed the Karuizawa house in New Hope, Pennsylvania [19] under a loose key that permitted calling it a farm and that was sadly demolished recently.

For Raymond, the secret key to successfully blending modern with traditional Japanese architecture was the "wise handling of material that speaks to us". In this case he linked concrete from lava aggregate and wood from neighbouring forests. The structure of the building included only these two materials, an exposed concrete elevated base with a round lumber framework of sand-polished columns and beams [9] (traditionally, Japanese architecture is characterized by wooden structures, slightly elevated from the ground) [20].

A clever remark was made by Raymond when he saw architect Albert Kahn's own house on one of his business trips to America which he conducted in order to obtain a commission from Henry Ford to build a large assembly facility in Japan.

His work at that time was creative and modern in every way. I was, therefore, amazed to find that both his office and his home were designed in an entirely eclectic way. It was difficult for me to understand how those two things could be reconciled in one personality, as both aspects could not be the expression of a truly sincere conviction [10].

A similar situation is Hudec's experience; both of his houses were designed following the local trend of eclecticism and classic revival. He was somehow more aiming towards the comfort of the family in the detriment of the modern form and the development of new trends in the history of architecture. Hudec might have been influenced by his wife's wishes and classic stylistic preferences (as we can see in the numerous drawings and details of the furniture designed for Gisela's bedroom) and another reason could be his financial business skill, since he was very good in making investments and gaining profit after selling the property. The styles chosen for their family houses were not defining the architect's vision of a perfect, modern work of art, but may rather reflect the overall preference of future possible clients, proving that Hudec was more interested in business than creating outstanding designs. An exception was Hudec's Sun Ke's house [15]. It seems that the architect designed it in a freer, creative mood, perhaps because the house was originally meant for him, and some traces of shifting towards new modern trends were just around the corner. Since he did not have to please any client, he felt the freedom to indulge himself in experimenting with his own ideas. Since he got a very good offer from Sun Ke, he sold the house before it was completely finished, just another proof of his ambition for profits that may enhance his practice (Figure 12).

Figure 12. Sun Ke House—neo-Gothic (**first row**) and Art Nouveau (**second row**).

Hudec's second residence built in 1930 was one of Hudec's last projects belonging to his first period in his independent career, described as a constant continuity of classicism and eclecticism, for a variety of clients, of different nationalities (westerners and Chinese) and cultural backgrounds. The designs he made in this first phase of his career were all eclectic. This required extensive and vast knowledge. His theoretical background acquired in his university years helped him greatly. He was aware of Frank Lloyd Wright's activity and, like Antonín Raymond, he disagreed with the way he was imposing his designs and ideas, no matter the taste or real need of the client. Raymond and Hudec always designed their projects for and with the clients, analysing and filtering the requirements depending on environmental characteristics and wishes.

He felt at home with a wide array of architectural styles, always choosing the one that best suited the taste of his client. He worked like an extremely adroit tailor who makes bespoke clothes, in all sizes and designs, from any material and in any quantity. His ultimate aim remained the same throughout his career: "to satisfy his clients as best as he could". [. . .] Hudec believed that the architect must serve the client and the community [4].

Later on, he was to apply his novel ideas in Dr. Woo's house, which was recognised as an early and enduring influence by the Chinese architect I. M. Pei. On this occasion, Hudec's approaches were much more systematic (Figure 13).

Figure 13. Former residence of Dr. Woo.

3.3. The Grander Scale in Hudec's Work

In the early 1930s, Hudec's star was about to shine brighter with the construction of Shanghai's tallest skyscraper. He played a significant role in developing modern architecture in Shanghai, side by side with other prestigious architects of that time, who were slowly beginning to shift their neoclassical stylistic preferences in the direction of Art Deco or the so-called "modern". Shanghai became in the 1930s one of the major centres of Art Deco (still extant and well preserved), with a very large number of buildings around the Bund area. Shanghai's art deco is unique because of the traditional Chinese design elements that were incorporated.

His two designs developed almost in parallel, the Grand Theatre and the Park Hotel, which were situated in a centremost area, on the northern side of the racecourse, adjacent to each other. Figures 14 and 15, show the racecourse and the Shanghai Race Club, a building that we can visit today, designed in neo-classical style (1934) with effective eclectic details.

Figure 14. The racecourse with the Shanghai Race club and Grand Theatre, viewed from the Park Hotel.

Figure 15. View from the racecourse towards the Grand Theatre and Park Hotel.

The 22-storey hotel (91.4 m) was designed once again for the Joint Savings Society (after the previous success of the JSS headquarters). It was at that time and for many decades after the tallest building in the entire eastern hemisphere, from London to Tokyo. Until 1984, for more than a half century the new structure was to remain the highest residential construction of Shanghai and Asia [15]. It was a dream come true, not only for the architect but for the Shanghainese citizenship who were enthusiastically aiming toward modernization. Since the American skyscrapers equaled and symbolized the modernity and financial power of the city, Shanghai became very proud of its own achievement. Hudec's recognition extended to internationality, and he remained known until today as "the man who changed Shanghai".

Shanghai lies on very difficult alluvial soil on the River Yangtze Delta, composed of sand and mud. This was always problematic for the builders, because after a short time, all the constructions started to sink or lean. Building in height seemed almost impossible. It was only in the first decades of the 20th century that European engineers invented new technologies and methods of foundation suited to Shanghai's impractical soil condition, with the aim of reducing to a minimum the subsidence problem. In order to receive the permit to erect the hotel, the architects had to present a satisfactory foundation design that would prevent such constraint and reduce the sinking to a minimum.

The plan offered three special solutions: a deep foundation pit to be excavated, impermeable metal partitions to surround it, and the insertion of a dense system of piles. Four-hundred 33 m-long piles of Oregon pine were driven into the ground at a close distance in order to increase the friction coefficient between the piles and the soil to ensure an adequate transmission of the building loads [4].

Besides the already mentioned system of piles, Hudec and his team adopted another method, developed in 1920 in Germany, called Larssen pile profiles, which consisted of piles made with sheets of steel driven into the ground in order to stabilise a structure. Pile foundations had been previously employed in Eastern Asia since the early 1920s but never before for such a high building as the Park Hotel.

The building features 22 storeys above ground and two storeys below ground. Resembling the skyscrapers from New York, from the ground until the upper 21st floor, the layout and form is constantly changing, gradually decreasing, thus creating a truncated pyramid shape towards the sky that begins at the 15th level. The whole composition and syntax is based on a characteristic tripartite scheme used by the architect in most of his high-rise buildings:

3.3.1. Urban Connections and Entry Floors

The base of the hotel showcases modern details, such as an emphasis on the horizontal, dark finishes of polished black granite from Shandong and Qingdao, rounded corners and continuous windows following the same major curve of the road (a detail he previously included in 1928 for his neighbouring design, the Honisberg Garage, by virtue of the same architectural language which later became known through Erich Mendelsohn's work in Wrocław).

Thus, the architect managed to integrate the appearance of the lower levels of the hotel (Figure 16) with his previous design for the Honisberg Garage; it almost seems like the two building were meant to coexist. Unfortunately, the garage was recently demolished in order to accommodate a major expansion of the hotel.

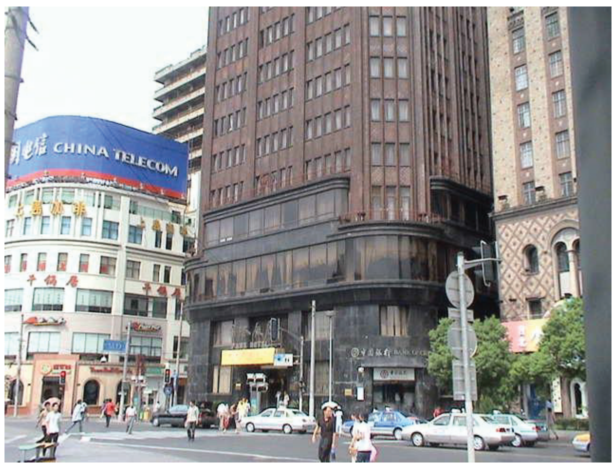

Figure 16. Lower levels of the Park Hotel.

3.3.2. Central Part of the Hotel Building

The middle section, entirely Expressionist in style, is clad with dark brown brick and ceramic tiles. Vertical elements that convert into rear pillars articulating and dividing the façade present at the same time a decorative and functional role; these elements provide grace and cause the building to look sleeker than it actually is.

Between the modern rectangular-shaped windows, the vertical brick faces are laid 45 degrees from the horizontal (a resource visible in the building of the Christian Literature Society for China). The ceramic enameled tiles covering the facades are rotated again by 45 degrees, creating interesting textures which vary in subtle accordance with the angle of the sun. Although Hudec resorted mainly to German Expressionism, his meticulous design with oriental furnishings proved a sensation, since buildings so hefty and monumental were yet to emerge at the time.

3.3.3. Adjustments and Influences for the Hotel and the Theatre

The upper section, purely Art Deco and Expressionist, bears finishing akin to that of the middle floors (dark ferrous brick and enameled tiles). The stepped pyramid of the upper part, which reminds us of Saqqara, emphasises the verticality and slender silhouette of the entire building. The windows use the same grid-like disposition. The attic recesses floor by floor until the top, where an observatory terrace was placed (Figure 17).

Figure 17. JSS Building (Park Hotel)—main view, detail of the façade decoration from the middle part and detail of the upper part.

In Figure 18, we present a succinct analysis of the façade's grammar and the vector-like interplay of tension lines. Such careful composition reveals the sheer evolution of Hudec's architectural thinking towards a modern idiom.

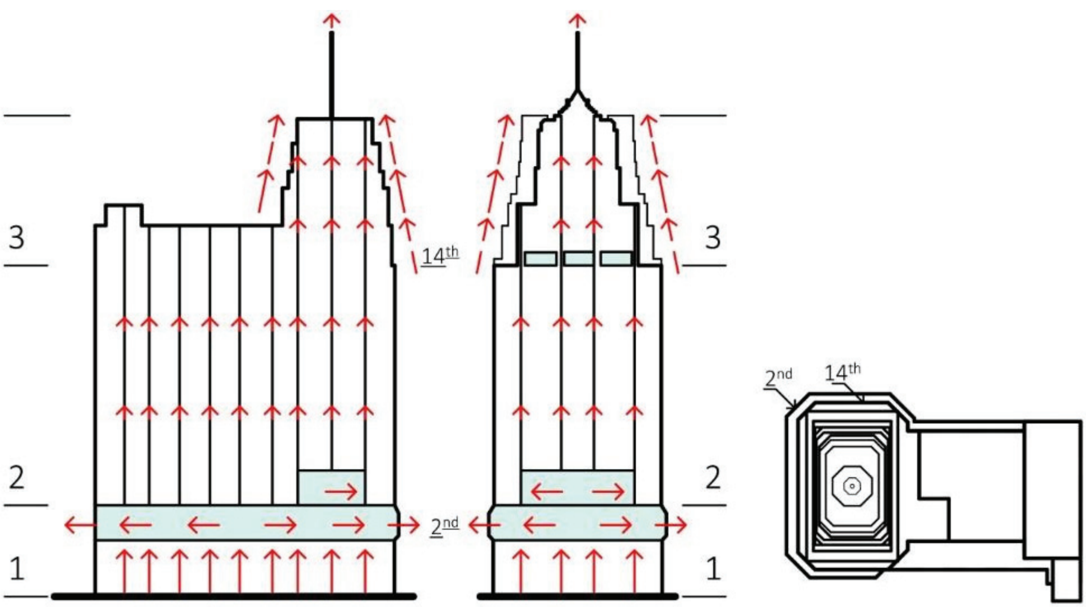

Figure 18. JSS Building—tripartite scheme and gradually decreasing plan, scheme of tension lines.

In 1931, Hudec was commissioned with the refurbishment of the Grand Cinema built in 1928. Initially, the design was meant to become a temporary facility. However, Hudec persuaded the clients to go ahead with the construction of a new, modern movie theatre, which resulted in his most significant design made for the world of entertainment.

The site was near to the Park Hotel, as the two buildings positively contributed to the definition of the cityscape of 1930s Shanghai. Art Deco and Modern in style, straight and curved tension lines mark the whole aspect of both the exterior and interior of the Grand Theatre (Figure 19).

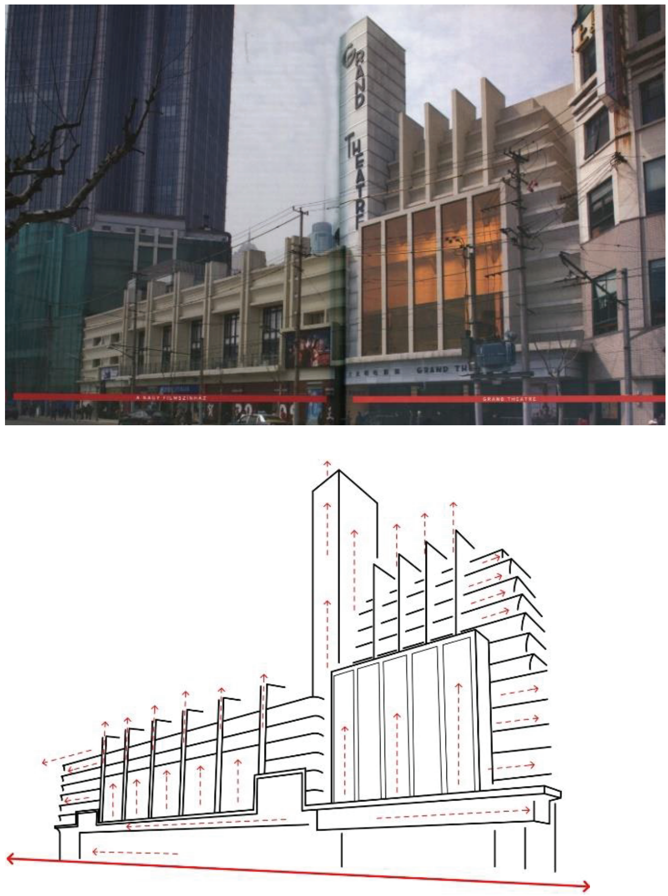

Figure 19. Grand Theatre—(**top**) main view from the former race course, (**bottom**) compositional study of the façade's grammar, Art Deco and International Style.

Perhaps facing fewer constraints that in the case of the Park Hotel, Hudec envisaged here a true liberation of forms towards a futuristic expression, one that encompassed the fascination of the Orient and advances in technique and which signified a real progress for Chinese architecture.

The architect's dexterity in fitting all the required spaces into such a difficult, quasi-triangular plot (long and asymmetrical) can be seen in the way he contrived to project the entire building.

The structure of the central hall's gallery was a sort of challenge for the engineers, but the result was satisfactory. Taking into account its dimensions, it constituted a real novelty in the Far East. The shape of the main hall and the reinforced concrete arch gallery ensure proper visibility and adequate acoustics from all the seats (Figure 20).

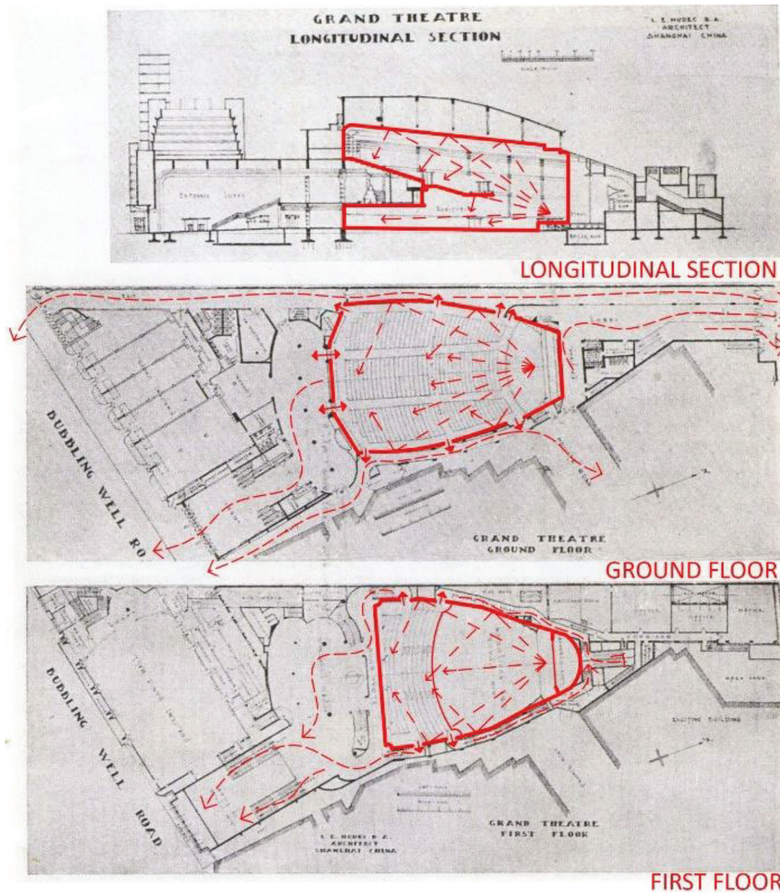

Figure 20. Grand Theatre—longitudinal section and plans; shape, acoustics, visibility and evacuation of the auditorium.

Carrier's air conditioning equipment (which amounted to 25% of the total construction costs) and fire control systems were installed in the entire building. By that time, it was the sole cinema in Shanghai equipped with synchronous interpretation devices integrated into each chair. For that reason, barriers of language were almost broken and everyone, even locals, could attend the latest foreign-language American and European films using individual earpieces. The programme changed in order to reflect the developments of the Chinese film industry only after the Pacific War, in 1949.

With the Grand Theatre's refined statement (Figure 21) and the landmark of the Park Hotel, Hudec returned to the spotlight, this time in the international scene of modern architecture, side by side with leading architects of the period, gaining recognition through sundry publications.

Figure 21. Grand Theatre—the entrance lobby and glittering pillars.

The September 1934 issue of *L'architecture d'Aujourd'hui* introduced the Grand Theatre in a lengthy article along with some designs by Le Corbusier, the Moscow Theatre designed by the Vesnin brothers and the famous London Zoo pavilion of Lubetkin and Tecton. The issue of May 1935 of *Der Baumeister* published the designs of the Park Hotel and the Grand Theatre side by side; the two buildings stand next to each other and together defined the skyline of Shanghai at the time. In December 1935, Dexter Morand wrote about the Grand Theatre in the Spanish journal *Obras*: "This new cinema is neither European, nor American, but Asian and Chinese. It testifies to the high standard of film theatre construction achieved in this country and is on a par with European cinemas. The layout and decoration of Shanghai's Grand Theatre (Figure 22) are as modern as any European or American design could be. Its appearance bears the marks of Modernism often seen in Europe" [4].

Figure 22. Recent view of the Grand Theatre.

4. Discussion

As seen in the projects and design intentions formerly described, Raymond's trajectory towards modern architecture was much more straightforward as compared with Hudec's long and winding road.

However, Hudec and Raymond's visions on how an architect should behave, converge as follows:

Independence and freedom are two important aspects, vital to an architect or artist, in order to protect their creative work from anything that might compromise it. A real architect must be an independent artist. He must have freedom and strength to stick to his principles [15].

Besides that, however, an architect has to be able to design beautiful and economical architecture even in the worst situation possible. "It is the architect's job to create beauty in every house, no matter what the economic level is" [15].

Discussing the relationships between architecture and engineering, we have to stress that both Hudec and Raymond enjoyed a similar polytechnic academic formation. The two central European universities, Budapest and Prague, belonged to the Austro-Hungarian realm and, as such, they were putting a great emphasis on the proper education, a preparation in engineering for their students. However, due to their different cultural context of living and designing, the two architects ended up having different orientations. Hudec is perhaps more of "the engineer" type and Raymond closer to "the artist", as can be perceived in their ways of thinking and designing.

Although this slight difference existed, both of them had considered vital the collaboration between the architect and the engineer. As Raymond stated, they must:

> "[. . .] work closely [. . .] from the beginning (of the project), in order to find not an extraordinary solution, but the simplest, the most direct and most economical solution of the problem". [21]

Soon, he realized that in order to eliminate any kind of constrains due to future possible confrontation with engineers, an architect had to become one with himself in order to achieve his aims, and more, in the technological present era, an architect needs to know the properties and technological processes of different materials:

The aim of the architect is to put once more his feet on the ground, to work naturally and from insight, to avoid external artistic and abstract influences, to become once more an "architect" which means "master builder". Designers, whether they are architects or designers for the industry, have, as a rule, little idea how their designs are to be executed [21].

This was enhanced by the context of Japan, where previously the profession of an architect did not exist and the carpenter or Daiku had the role of an architect and engineer at the same time [22].

Hudec, on the other side, regarded himself as an engineer rather than an architect. The technical aspects, structure and construction techniques were pivotal in the process of defining the architectural form, being equal in importance, always seeking for unity and interaction between them: "You will only be a good architect if you understand materials and construction. [. . .] Here buildings have either steel or reinforced concrete frame structure, walls are not considered structural elements but seen just as partitions" [4]. Such was his approach to modern structures, mainly because he had imbibed the Chinese traditions of complex wooden frames that harks back to the 13th century and treatises like the Yingzao Fashi. Later, this tome on wood construction was an explicit influence on Jorn Utzon.

The conscious pursuit by these architects of the oriental essence of building, the so-called Dao of architecture, led them to a spatial renovation that paradoxically coincided with some postulates of modern architecture, as recognised by Walter Gropius on a famous postcard to Le Corbusier in which he admitted, among other statements, that, "the Japanese house is the best and most modern I know of and truly prefabricated" [23].

By accepting the modularity and versatility of the oriental construction procedure which is based on the Jian or Ma system of intervals [10,24], as we exposed regarding the Karuizawa summer house, they paved the way for an early space grammar applicable not only in Asia but in the whole world, as Bruno Taut had justly foreseen during his stint of nearly three years in Japan. A fact later confirmed by Schindler, Bawa [25] and even Bernard Rudofsky in his acclaimed essay "The Kimono Mind".

Moreover, such a semiotic paradigm reached contemporary linguistic theories when Roland Barthes published in 1970 the book *Empire of Signs* about his experiences in contemporary Japan.

In his celebrated lecture "The Destruction of the Box", addressed to the AIA in 1954, Wright expressed his admiration with a vision of Laozi contained in *The Book of Tea* by K. Okakura.

He claimed that only in the vacuum lay the truly essential.

The reality of a room, for instance, was to be found in the vacant space enclosed by the roof and the walls, not in the roof and walls themselves.

It can be argued that in a similar fashion to their former icon, Frank Lloyd Wright, they adopted the following vision of Laozi about architectural space:

"Pottery needs to be hollowed so that it is useful, (otherwise it is just an irregular brick) a house needs to have some holes (e.g., door and windows) to be useful, (otherwise air and people cannot enter or exist). Thus, a certain level of nothingness is necessary to make an object useful" [26].

That is, they clearly understood that the void was, so to say, more important than the solid, a game-changer for architectural design, since Aristotle had postulated that the void was irrelevant compared with matter [27]. Conscious of this fact, they applied themselves to molding new materials, especially concrete, to embody their novel intuitions.

5. Conclusions

Hudec and Raymond are justly called pioneers of modern architecture because they were among the first western architects who came to Eastern Asia (a cultural context completely different to their native one), developed as modern architects and managed to guide, transform and implement a new way of thinking and design based on oriental philosophy [28].

Once in Japan, far away from his native Europe, Raymond had to adapt his design processes. He tried to define what he considered to be the principles of a true modern architecture, everything based on the synthesis between his own pre-Japan experience and what he had learned since his arrival in Tokyo: space, structure, modulation as the essential philosophy of Japanese traditional architecture.

Antonin Raymond, found himself in a relationship with Japan that offered him the best conditions for developing his stark and audacious principles [29]. Nature beckons beauty, and beauty, in the traditional Japanese houses, was to be found in pure simplicity and essence. It was only after years of experience and observation of the Japanese houses inside nature that he realized the easiest way to achieve beauty in architectural design. He used to say that it is through increased simplicity and elimination that the man of taste finds elegance.

Complementarily, Hudec's modernism lies in his architectural ability and complexity, as a man always ready to change his life drastically when confronted by dire events or facing necessity. He gained architectural experience in Shanghai (not as the leader of the architectural movements but as an actor always prepared to follow and to adhere to new trends and styles if his commissioners wished for them, constantly adapting to the fashion and introducing the latest western technologies in the Far East), had more pronounced diplomatic experience than Raymond during the Second World War (providing humanitarian aid, helping his compatriots and Jews escape from Nazi prosecution) and gained teaching experience in America (giving lectures on archaeological themes).

Hudec was not as avant-garde an architect as his trendsetting European contemporaries, who were concerned with reforming and creating new guidelines and manifestos in architectural design. However, thanks to his dexterity in articulating modern functions, spaces and shapes with the world's most advanced technologies, he became one of the leading architects of fashion in Shanghai, enjoying local and international recognition through his designs that deeply reflected the city's growth and cultural character in the constantly changing Chinese society.

Although they are now unfairly forgotten and their works lie mainly in neglect, we believe that Raymond and Hudec should be praised for their stylistic audacity that heralded a new understanding and appreciation of architectural space and contributed to the creation of a viable future for the development of Asia. This is the main reason why we have conceived the present article.

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Article

Historical Cultural Layers and Sustainable Design Art Models for Architectural Engineering—Took Public Art Proposal for the Tainan Bus Station Construction Project as an Example

Wan-Fang Liu [1], Chun-Ta Tzeng [1] and Wen-Chang Kuo [2,*]

[1] Department of Architecture, National Cheng Kung University, Tainan 70101, Taiwan; liu.design2014@gmail.com (W.-F.L.); ctmt@mail.ncku.edu.tw (C.-T.T.)
[2] Department of Arts and Creative Industries, National Dong Hwa University, Hualien 97401, Taiwan
* Correspondence: art.tra@gms.ndhu.edu.tw

Abstract: The concept of "historic buildings" is cultural with evolutionary characteristics, mainly constructed in the category of historical culture and people's living settlements. "Public art" is an artistic asset with aesthetic attributes in urban living spaces. It contains two connotations, "cultural landscape" and "cultural route", which form an artistic symbol of urban architectural space at the same time. Along with the progress of an urban renewal plan, a local culture characterized the urban landscape, making architecture a tool used to convey cultural identity spatially. Two coexisting issues can be seen through the accumulated structure and long-term changes of historic buildings, a region's appearance, and the content of the traditional architectural styles—cultural value preservation and modern urban renewal—which ferment and generate decision-making discussion of design subtly in every corner of a city. This study examines the extant literature and the design model of public art landscape setting to construct a design model that balances the cultural value of historic buildings, and the landscape of public art has been proposed as a result of this study.

Keywords: historic buildings; public art; sustainability value; case studies and projects

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1. Introduction

Little attention has been paid to small and tight spaces in urban systems, which are often fragmented and unorganized (e.g., small open spaces, green spaces, art deco building facades, and streetscapes); however, nowadays, they are formed by the influence of aesthetics and ecology and have gained a new dynamism driven by society and publicity. The dynamism is influenced by civic activity, referred to as a social ecosystem. This civic activity promotes sustainable design for public art, historical building renewal and demolition programs.

According to J. Becker (2004): "Public art is a multifaceted field of inquiry; it encompasses a wide variety of creative expressions in the public realm" [1].

Compared to current urban living spaces, the architectural styles left behind by history show a strong and more profound sense of belonging. In other words, their distinctive features and historical traces exist as the "local power" and urban public art, which is a display of architectural culture layers. Implementing public art can connect the characteristics of local culture and show the characteristics of urban blocks.

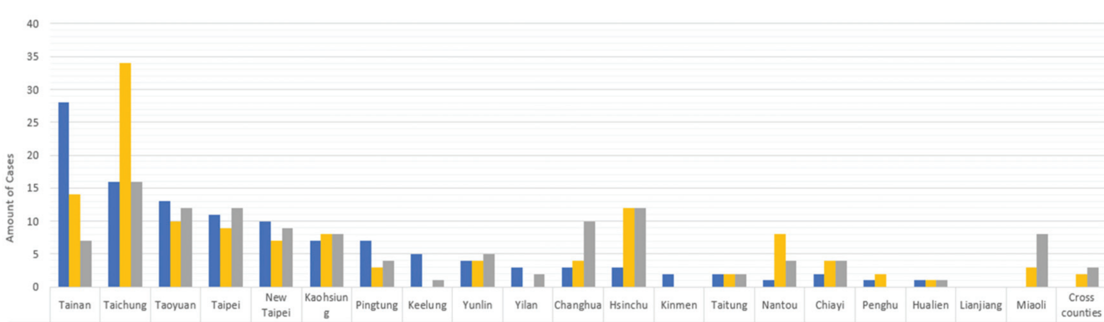
The common sustainability features of public art include public accessibility, public realm placement, community participation, and public process (including public funding); however, these works can be permanent or temporary. M.J. Jacob (1992) said, "Public art brings art closer to daily life" [2]. In 1992 and 1998, the Taiwan R.O.C. government promulgated the "Culture and the Arts Reward and Promotion Act" [3] (Taiwan version of Percent-for-art Program) and "Regulations Governing the Installation of Public Artwork" [4]. Since then, public art has become an important cultural and artistic indicator for Taiwan's urban public construction space. The design characteristic of sustainable public art determines how best to activate the images in the surroundings. The concept of "sustainability" arises in response to the perceived environmental deficiencies of a city. For example, A. Zittel's public art: "Indy Island", proposes issues of sustainability and sustainable living space that participants can actively participate in, which can be considered sustainable public art facing the challenge of public open space needs [5].

The "Cultural layer" refers to a layer of earth formed by the accumulation of human traces or remains of man's activities in the past. The historical and cultural patterns can be examined with this concept of time evolution and stacking of the older and newer cultural layers. Furthermore, through the interpretation of modern architectural design and public art, traditional buildings' value of historical and cultural sustainability can also be transmitted and preserved [6].

On the other hand, historical streets are the spatial pattern of historical buildings, which carry the historical information of the city and the memory of residents and a form of stacked expression of cultural layers. The designs of these stacked cultural layers in historical buildings are presented in the field of modern urban architecture through time, symbolizing the cultural assets of a living block. Making historic blocks follows the same nature as public art: "cultural landscape" [7], "cultural route" [8], and "intangible cultural heritage" [9]. These factors simultaneously form a design symbol of the image of a city.

The United Nations has promoted sustainable development programs in various economic, social, and ecological genres since the 1980s. In 2016, F. Ceschin proposed the "4 Innovation Levels" [10] of sustainable design, one of which is known as the "Spatio–Social innovation levels"; the context of this innovation is about the spatial and social conditions of human settlements and their communities. This can be addressed at different scales, from communities to cities. Therefore, through the forms of public art, the design style guided by the cultural layer of traditional buildings can be used as a wonderful method of sustainable urban design.

The most special requirement of the design characteristics for public art is the construction of interactivity. The setting environment of public art is the living space where citizens experience it with their five senses, and public art plays an important role in creating a community [1]; Figure 1 presents the statistical data of public art installations in Taiwan from 2018 to 2020 [11]. As shown, public art installations are mainly distributed in urban blocks with significant populations. This agglomeration phenomenon suggests that the number of urban construction and public art installation projects is proportional to the trend, and it also shows the coordinate phenomenon of public art for urban planning and artistic landscape. The form of public art has been transformed into a design concept in the space field, creative thinking that involves the historical building space, and an artistic landscape combined with the planning and resources of urban public building construction.



	Tainan	Taichung	Taoyuan	Taipei	New Taipei	Kaohsiung	Pingtung	Keelung	Yunlin	Yilan	Changhua	Hsinchu	Kinmen	Taitung	Nantou	Chiayi	Penghu	Hualien	Lianjiang	Miaoli	Cross counties
2020	28	16	13	11	10	7	7	5	4	3	3	3	2	2	1	2	1	1	0	0	0
2019	14	34	10	9	7	8	3	0	4	0	4	12	0	2	8	4	2	1	0	3	2
2018	7	16	12	12	9	8	4	1	5	2	10	12	0	2	4	4	0	1	0	8	3

Figure 1. Amount of public art installations in Taiwan in the past 3 years (2018–2020).

Public art refers to artwork installed in an open space. The primary considerations in evaluation have four design features: "Artistic expression in environmental space", "Locality", "Civilian interaction", and "Feasibility of safety structure". These four characteristics are related to the current reconstructed architectural styles in historic districts with the same essence and needs. Through evaluating traditional architectural design styles and using public art as a reconstruction method, the design elements of traditional buildings and the aesthetic needs of current urban planning can be obtained, which are the current selection focus of the urban public art landscape design and the decision-making for transforming traditional architectural space.

Artwork can be a feature of urban environmental education, especially when installed in the public domain [12]. Public art is an artistic asset with aesthetic attributes; it is the architectural space's image facade, representing the fashionable beauty of the design at the time, which simultaneously forms an artistic symbol. Historic building facades represent a style of stacking with the time of the cultural layer; with its unique style and function, it simultaneously shows the value of historical culture and the beauty of the public art landscape's design.

Therefore, this study analyzes the design elements of traditional historic buildings through the characteristics and proposes a design-involved method for the historical building space through public art. This study uses a design decision-making application model, matching sustainable design to provide artistic landscape planning of the future architectural environment.

In the 1970s, American cognitive psychologist J.J. Gibson proposed the "Environment affordance" theory, arguing that:

> *"Human beings must be able to perceive the space environment; the space environment it-self is perceived by people in the movement of the space environment, and the affordance of the environment is composed of elements provided by the environment to the users [13]. Architectural engineering design is a cultural activity of human society not only covering aesthetics but also exposing the inner essence and hierarchical structure of culture."*

Public art shows the artistic characteristics of modern architectural public space and the affordability of space environment design; it then creates the cultural place color of urban architecture.

Based on the above needs for the public space reconstruction of historical buildings and public art landscapes, the design evaluation involves quite a variety of levels. Comparative analysis needs to be carried out through an evaluation tool that can take into account the existing spatial elements and non-substantial design characteristics and can objectively analyze the characteristics of the overall elements. The research takes the historical building facade of Shennong Street, Tainan City, Taiwan, as the research object, through its facade design patterns, design elements, and the perception level of representative models, to conduct a questionnaire survey on the design characteristics of relevant research objects. In the end, the following results are proposed:

1. An evaluation and extraction method for the design elements of historical buildings in the public environment space.
2. A design model that shows the sustainable cultural value of modern buildings through the creation and design methods of public art.

2. Literature Review and Research Process

2.1. Literature Review

Historical streets are composed of residents living construction activities, which are different from the street traffic planning formulated by modern cities. The current development strategies of historic streets include preserving and maintaining historical build-ings, the development of artistic and cultural spaces, and public art combined with public works (such as art streets). Each issue is deeply challenging and developmental because of the difference in each city's historical development and the needs of each area. Still, it is essential to preserve historic streets; the purpose of development and pursuit of a beautiful living environment is consistent. Shennong Street (Figure 2) is a historic street that remains the most complete architectural style and street form in all of Tainan's historical districts since the Qing Dynasty [14]. During the Japanese colonial rule period, the "urban area correction" plan was carried out; most of the buildings on Shennong Street were rebuilt and adapted for residential use. The 1st and 2nd floors of the buildings contain rich facades from different periods that forms one of the main features of this historic district [15].

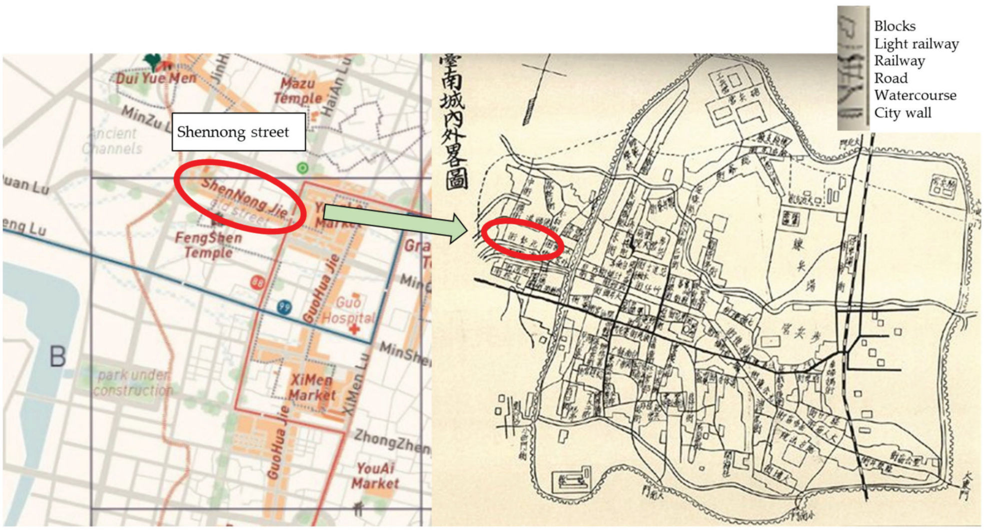


Figure 2. Map comparison of current Shennong Street with an old map drawn by N. Nakagami, *Sketch map of inside and outside Tainan city*, 1900 [16]. Map on left: Tainan City Government [17].

The architectural facade style of a historical street (Figures 3 and 4) contains the life experience and beliefs of the residents and shows the overlapping characteristics of modern life culture and the economic pattern at the time. In this research, a case study was carried out through the design style of the traditional building facade. It used the facade's design style as a reference to propose a design method for the co-construction plan of the historical building space and architectural art engineering.

Figure 3. Landscape of Bei-Shi Street.

Figure 4. Outlook of a historical building, which is the original spot of well-known Yong chuan palanquin workshop.

2.2. Research, Investigation and Process

This research and investigation take the historical streets of Shennong Street as the scope. Through field interviews, document surveys, building facade drawings, and style models, Figure 5 summarizes the definition and classification of facade building types as the basis for the perceptual evaluation of facade building design styles.

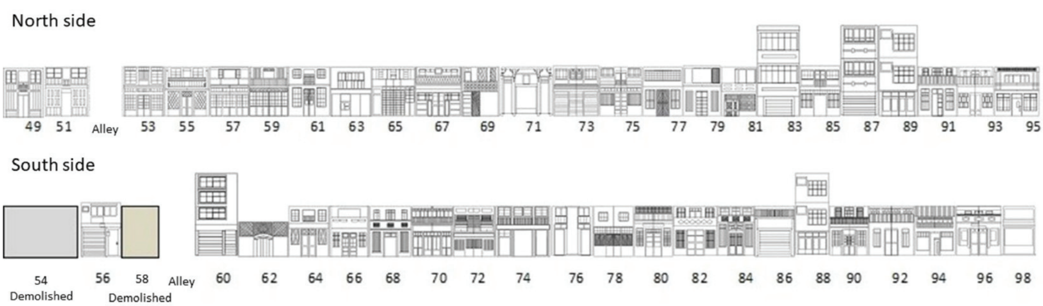


Figure 5. Elevation view of historical buildings on Shennong Street. (Adapted from [18]).

A questionnaire survey was conducted on the facade design styles and components to obtain facade design styles data and historic buildings' spatial planning and public art design styles. The focus of the investigation is as follows:

1. Investigation of main design elements of street building facade:

A total of 47 buildings were on-site, and the field survey time was June 2017. The primary collection of facade styles includes the facade material, window design, and entrance design of the first floor (Floor A), and the facade material, window design, handrail design, and entrance design of the second floor (Floor B), as shown in Figure 6.

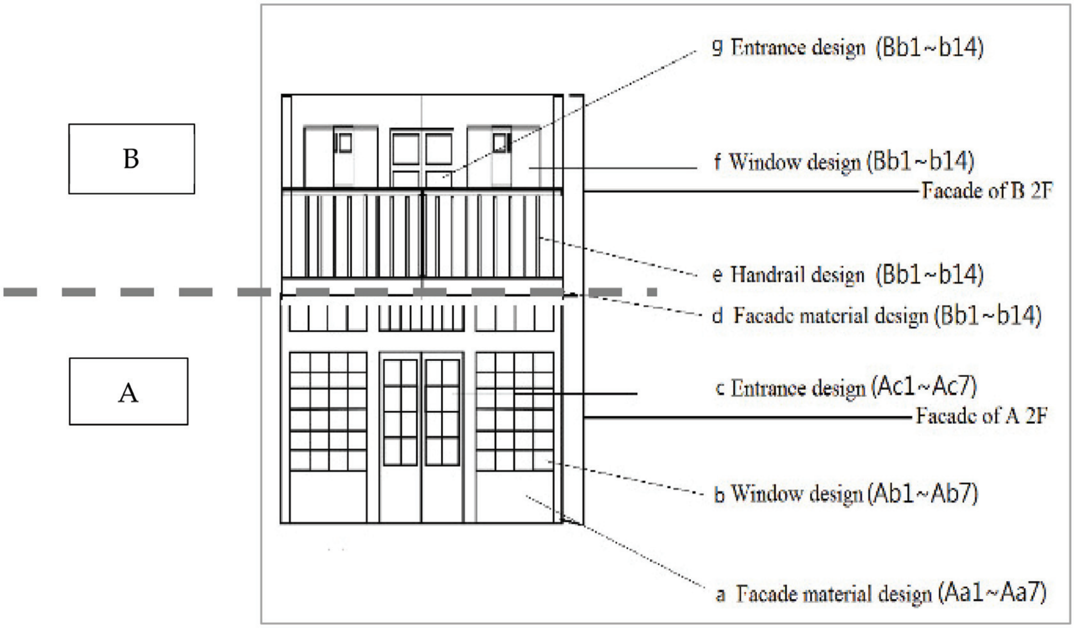


Figure 6. Facade design analysis diagram of historical buildings. (Adapted from [18]).

2. Interview:

Residents were used as the interview objects and conducted in-depth interviews on the current usage of the street, including the problems of community construction, the impact on the usage of the space change, and the historical memory of the buildings. The questions were used to integrate traditional districts' past and present lifestyles and the expectations for current and future use of the space.

3. Questionnaire:

The main evaluation items of the questionnaire were obtained by inviting experts and scholars to conduct interviews and discussions through the aggregated classification and definition data. In this study, experts and scholars screened the items and compared the items of building facades of Floors A and B. The decision-makers selected each paired element with the Likert scale to obtain the pairwise comparison values for each item. The subjects of the questionnaire are experts and scholars with professional backgrounds in architecture and public art to gain the weight value of the design style features of the facade. The research process is shown in Figure 7.

2.3. Classification and Definition of Research Objects

The building facade styles are drawn based on the north and south side buildings (Figure 8). The facade design styles are classified and selected through the Delphic hierarchy process (hereinafter referred to as DHP).

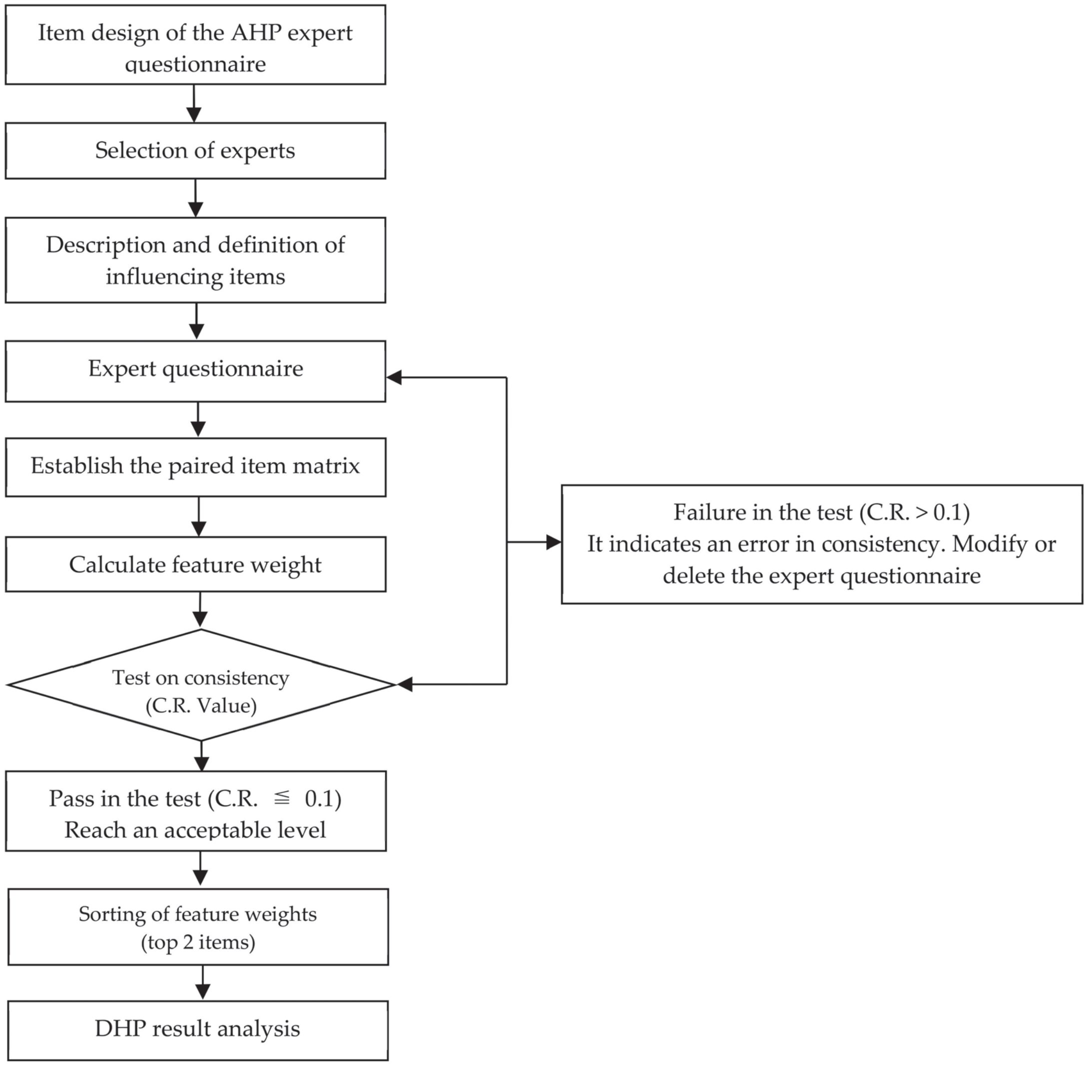


Figure 7. Diagram of the research process. (Adapted from [18]).

In order to distinguish the design styles, techniques, and materials of the facades of historical buildings from Figure 8, they were compared by the DHP method to delete similar design styles. The results concluded that the following building facades are the most important design features, as shown in Figure 9.

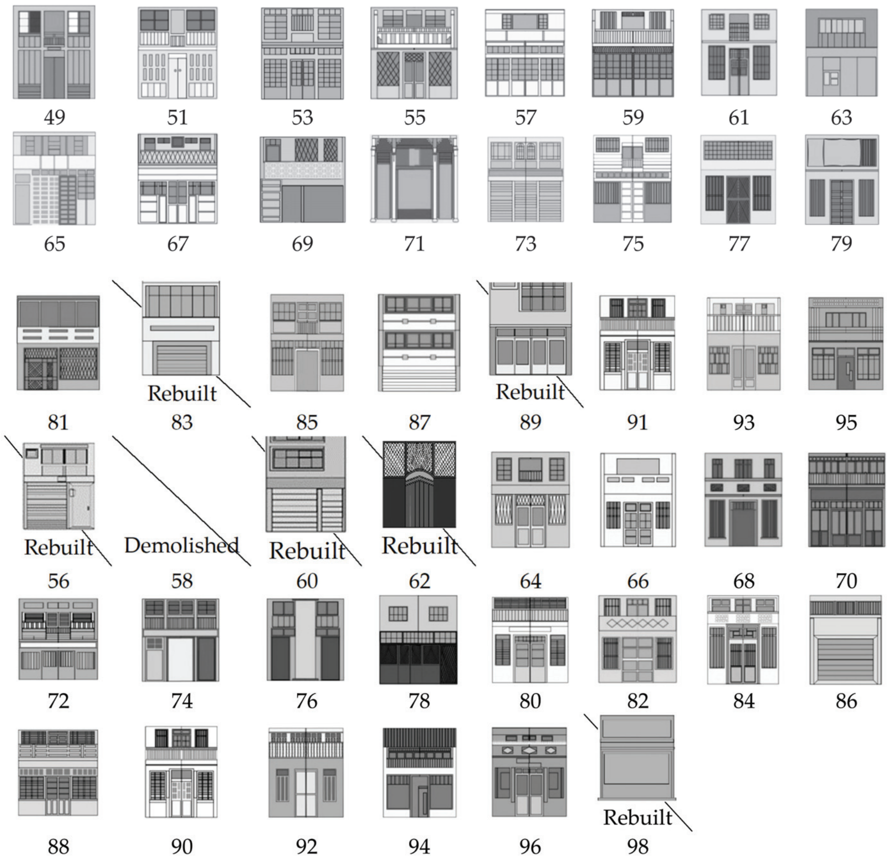


Figure 8. The facade styles of buildings on north and south side. (Adapted from [18]).

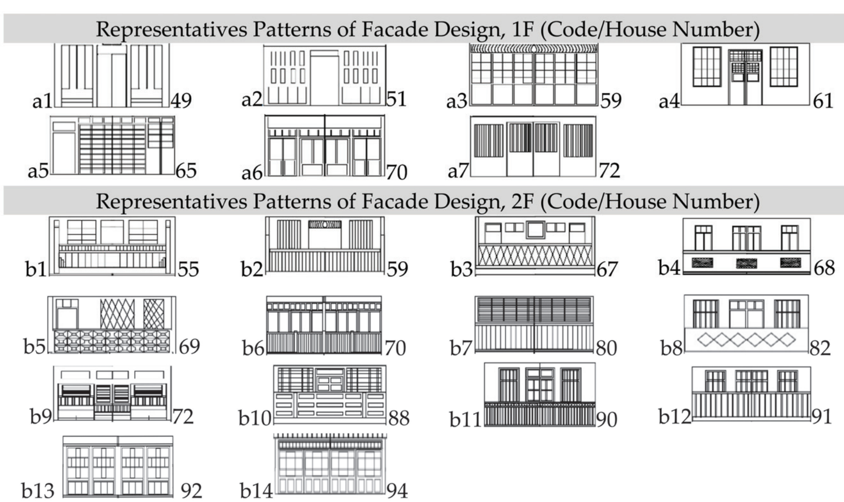


Figure 9. Main design styles of the building facade on Shennong Street. (Adapted from [18]).

A. The Floor As' facade design features:
   1. Multi-format window style (No. 65).
   2. Wooden partition-windowless style (No. 49).
   3. 2:1 multi-grid wooden structure window style. (No. 53, 57, 59).
   4. Open windows on both sides with a middle door and washed stone finish wall style (No. 61, 64, 66, 88, 90).
   5. Long facade wooden door style (No. 70).
   6. Open windows on both sides with wooden facade style (No. 72).

B. The design features of the Floor Bs' facade:
   1. The facade design's axis is divided into three equal parts vertical facade by vertical and horizontal.
   2. 2F's window and door correspond with 1F's design.
   3. The design lines of the balcony are mainly vertical lines, crossing lines, squares, and rhombus.

From Figure 9, the following design rules were concluded:

1. Multi-format window.
2. Open windows on both sides with a middle door.
3. The facade design's axis is divided into three equal parts vertical facade by vertical and horizontal.

These design rules form the overall architectural construction planning of Shennong Street; its unified architectural style suited the living and industrial model at that time. These design rules contain important design elements that can be used in future architectural projects and public art landscape planning.

3. Research Method

3.1. Research Method

Architectural projects and public art landscapes have the characteristics of modern urban space fashion and aesthetics. According to space requirements and shape design, different art forms and design forms are produced, and there is a visual evaluation and functional affordability hidden in the spatial aesthetics. This functional affordability makes the overall construction project have diverse characteristics in the interaction of environmental behavior and forms visual characteristics.

Although the above-mentioned methods have a clear theoretical context and high practicability, they cannot take into account the subjective factors of human qualitative thinking and those factors with high uncertainty; for example, when facing the evaluation of various arts, culture, and creative thinking on the decision-making of public art installations, proposing a simple objective evaluation and decision-making method can provide a result that is in line with the needs of people. Therefore, this article proposes a combination of the DHP and AHP that uses the eigenvalues comparison matrix to analyze and calculate the optimal design features.

This study uses AHP as the primary research method. It provides objective mathematics to address the inevitable subjectivity and personal preferences of individuals or groups of decisions, empowering models with group decision-making capabilities [19]. Furthermore, it can construct a set of pairwise comparison matrices for each element at the upper level to compare elements in the lower level [20].

Conversely, the DHP will be used to centralize and delete opinions to achieve the effectiveness of evaluation indicators. Due to the method contained in AHP, there are three advantages: (a) It will be more effective and simpler to use the DHP with the AHP(EM) to acquire the specific or abstract facade style of the historical building. (b) The analysis of the first and second items in the weight order can concentrate more on the decision-making focus of artworks. (c) Using the DHP for decision-making inspection of art-works can avoid unnecessary pairwise comparisons, which can evaluate the decision-making of setting projects more accurately.

This study examined the extant literature research data and survey analysis, then formed a structured questionnaire. The study then performed a DHP expert evaluation to obtain the classification design characteristics of each facade. AHP(EM) was used to perform a pairwise matrix comparison operation; the weights of each pair of indicators were obtained using MATLAB, a compiling software. A paired matrix comparison of each element was conducted, along with the consistency check and sorting.

The facade design style of historic buildings and public art attributes have a complex design structure, covering the needs of historical culture, urban function, and urban planning. There exist tangible structures, intangible space aesthetics and other factors; therefore, it is essential to evaluate decisions through a method that establishes decision-making principles that can have implications and simplifies the design problem. According to the data obtained from the above evaluation questionnaire, the higher the weight value (ω), the higher the evaluation degree.

Take the matrix diagram in Formula (1) as an example; through a 7×7 matrix, to obtain Lambda max ($\lambda_{\max}$) and the value of CI/CR is ≤ 0.1, which means it is consistent. When the matrix converted into a ω matrix, the weight value of this item can be obtained.

$$CR = \frac{CI}{RI} CI = \frac{\lambda_{\max} - n}{n - 1} \quad (1)$$

3.2. Result of Analysis on Design Evaluation

The building facade is the unity of architecture function, structure, and design aesthetics. It is composed of color, material, scale, proportion, direction, shape, and combination. This study processes perception-level evaluations based on aesthetic elements of the historic building facades, to obtain representative design styles. Through the overall analysis results, the weighted items of artistic features obtained by the weighted eigenvalue method are used to pair with the application method of the existing building facade styles. These can be used as design elements in the current historical street reconstruction, cultural management, and community construction and as an evaluation application method.

The weighted items and the current status of building facades are compared and tested by experts on the analysis and calculation results. After the examination, they all reached the evaluation consistency and obtained the following design evaluation rules for building facades. According to the top two weighted values, the representative styles are as follows (for exact weighted values please refers to Appendices A and B):

1. The window design is mainly based on unity, geometry, order, and balance (Figure 10).

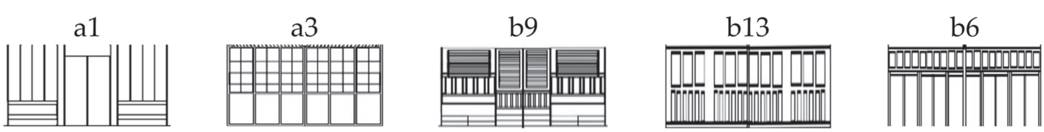


Figure 10. Diagram of representative window designs. (Adapted from [18]).

2. Handrail design styles are the most diverse in patterns and materials. The design styles are mainly based on continuity, rhythm, symbols, proportion, and order (Figure 11).

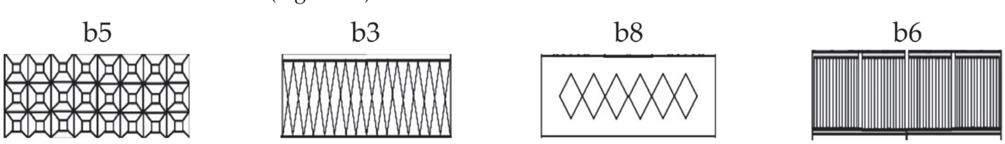


Figure 11. Diagram of representative handrail designs. (Adapted from [18]).

3. The design styles of the entrance are relatively unified, mainly based on proportional order, balance, and stability (Figure 12).

Figure 12. Diagram of representative entrance designs. (Adapted from [18]).

4. Sustainable Design Patterns for Architectural Engineering and Public Art Landscapes

According to the results of traditional architectural design elements (the public space needs, civilian interaction, and the aesthetic engineering concept), an innovative design plan was proposed and won the silver award in a competition of a public art installation project.

The research object in this article is based on the public art proposal: "OPEN—The Folder of Time" for the Tainan Bus Station public art project. Since the Tainan Bus Station public art project is a percent-for-art program and must achieve the requirements for the open competition, it must be related to the architectural design of the Tainan Bus Station itself.

The architects put historical factors and meanings into the architectural design. It carried the function of transportation just like Shennong Street, the most well-preserved historical district in Tainan, which was also used as an important transportation road in the early days (historical and cultural roles overlapped); therefore, by translating Shennong Street during the Qing Dynasty into "Street of Tainan" in buildings, the architects take this as the core concept of the architectural design of the Tainan Bus Station.

The public art proposal "OPEN—The Folder of Time", its design and planning combine with the design concept of the Tainan Bus Station; the representative facade design styles are used as the design elements for public art installations, which deeply describe the geographical connotation, and historical context and continue the historical memory of the "cultural layer" of the installation location.

Tainan Bus Station is located upon the relics of the town office during the Qing Dynasty. In order to avoid deep excavation and damage to the historical relics that were preserved on-site, the design leans toward the shallow foundation and lightweight green building materials, recyclable steel structures and containers as the main structure. As a temporary, non-permanent building, the operation period is expected to be 10 to 15 years. After that, according to the committee of the Tainan Bus Station, it will be demolished for other uses, such as museums.

Therefore, in the public art installation plan, through the steel structure, the building facades are transformed into the structural order of the building space, which is formed by the facade steel structure like a container, performing the concept of a "cultural layer", the time delay, and space division. At the same time, the core concept of this public artwork is consistent with the reuse plan of the Tainan Bus Station, which considered the possible direction of sustainable development in line with the reuse of the structure of the Tainan Bus Station shown as following Figure 13.

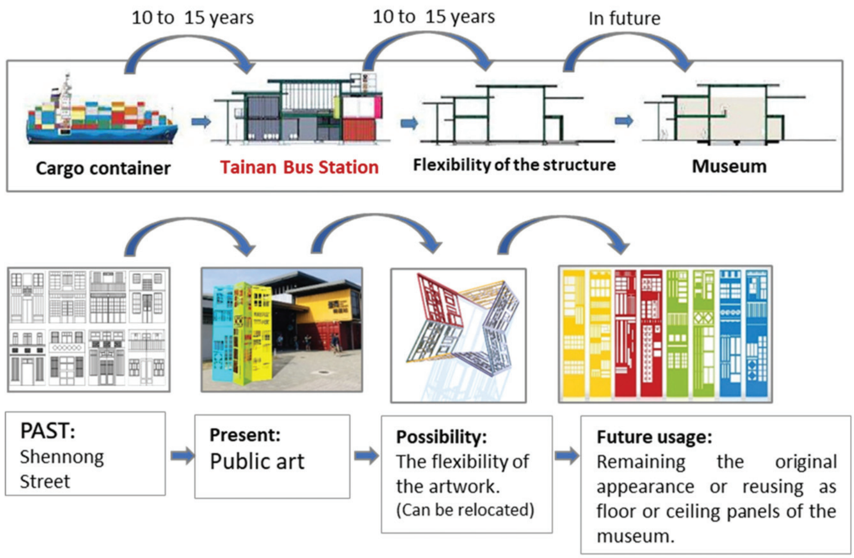


Figure 13. Diagram of the reuse plan. (Upper diagram: Committee of public art installation project on Tainan Bus Station) [21].

4.1. Fusion of Public Art and Architectural Engineering

The fusion of the public art planning and architectural engineering is completed by designing it with the most representative eight groups of facades of historical buildings as a unit (Figure 14). A theme of "OPEN—The Folder of Time" illustrates the significance of the historical architecture, overall cultural atmosphere, and the separated meaning by the cultural layer content of spatial stacking and time deposition on the construction base used.

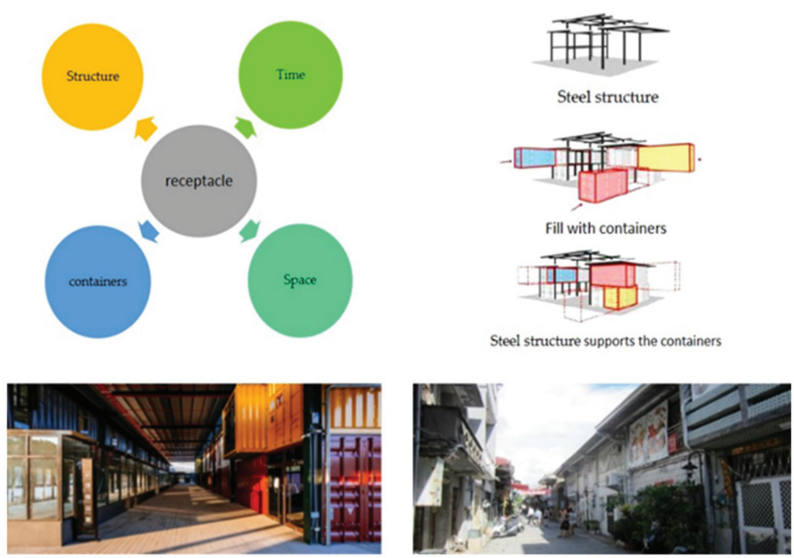


Figure 14. Diagram of the design concept, for fusing public art and architectural engineering. (Upper right structure diagram: Committee of public art installation project on Tainan Bus Station) [21].

"Overall" refers to the "historical building facade" and the corresponding setting location, "Tainan Bus Station" (Figure 15), as an overall of the same cultural layer. The separated overall can refer to the "individuality of different facades of the same historic district", corresponding to "one station after another, each station has integrity; however, different transport vehicles have their individuality".

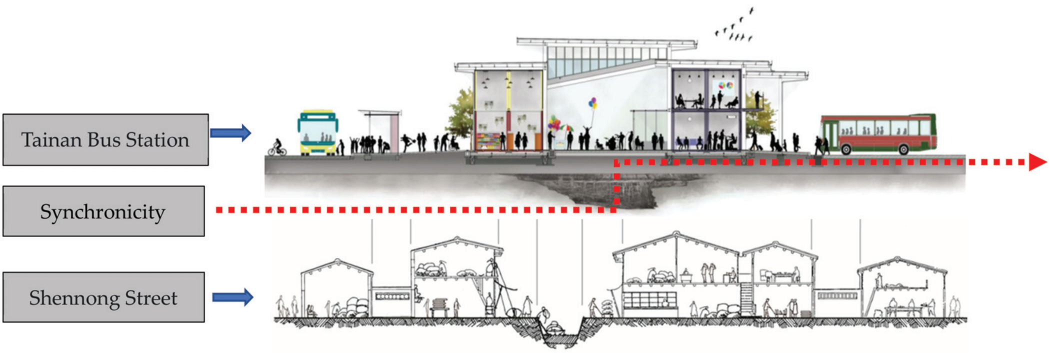


Figure 15. Comparison diagram of the living time stacking between the transit station and the cultural layer. (Picture: Committee of public art installation project on Tainan Bus Station) [21].

4.2. Same Time but Different Individually

Different cultural layers have continuous characteristics in the process of linking history, with both time delay and spatial distinction; history as an event is the "Perfect tense" of the time. Past, present, and future are the three tenses identical in continuous time but different individually from the space point of view. Therefore, this study proposes the public artwork method that expresses the "is form and content" to present the art form in the cultural layer and the multi-layered meaning of diachronic time and synchronic space.

4.3. The Construct of Public Art Landscape and Architectural Engineering

4.3.1. Creation Interpretation

Since the 1990s, the design concept of public art has gone far beyond the simple form of sculpture and a monument sitting alone in the open square [22]. Therefore, this interpretation uses the form of public art to express the unique historical background and location conditions of the "Bus station" and "Street of Tainan" in multiple cultural layers. It also implies the distinguishable characteristics of time, which symbolizes the combination of the three temporal sequences of past, present, and future and the continuous nature of the cultural layer space in the overall architectural space. The location of public art shown as Figure 16.

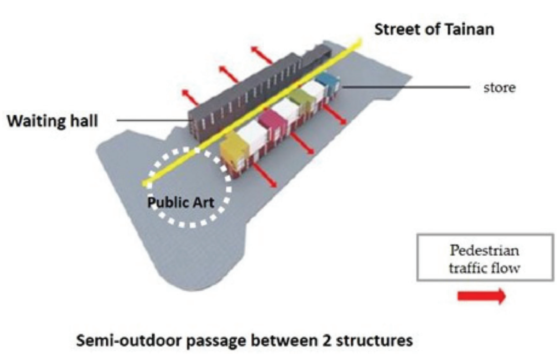


Figure 16. The pedestrian traffic flow of the Tainan Bus Station. (Picture: Committee of public art installation project on Tainan Bus Station) [21].

4.3.2. Design Method

"Public art been increasingly advocated on the basis of contributions to urban regeneration since the 1980s. Most decision-makers argue that public art can help develop a sense of identity, develop the sense of place, promote citizens' identity, address community needs, and social exclusion; has its educational value and the function of foster social change" [23].

Considering the historical background and location conditions of the multiple cultural layers, the representative building facade style (as Figure 17) is present in the way of public art through the following three features: (a) Takes the rhombus patterns that appear in large numbers on the facades of historical buildings as the design elements for the three-dimensional design. (b) With quadrilateral rhombus to interpret the bus station as the heart of urban traffic. (c) The overall meaning of the public art is to present the "ex-tending in all directions" functions of the bus station; this not only transforms the cultural layer design elements of historic buildings but also the historic value of the past is represented in the beautification of modern architectural engineering, which is the fusion of art and architectural engineering that re-deploys meaningful historical documents in the modern urban living space, showing the beneficial result of architectural beauty and cultural experience at the same time.

Figure 17. Elevation view of the public art design with historical building facade.

4.3.3. Color Scheme

One can integrate the color scheme of the building and analyze the cultural layer's time, distance, and space at different nodes to distinguish the difference in hue, saturation, and vibrance. With this color scheme, the public art can also coincide with the architectural design of "Tainan Bus Station", shown as Figures 18 and 19.

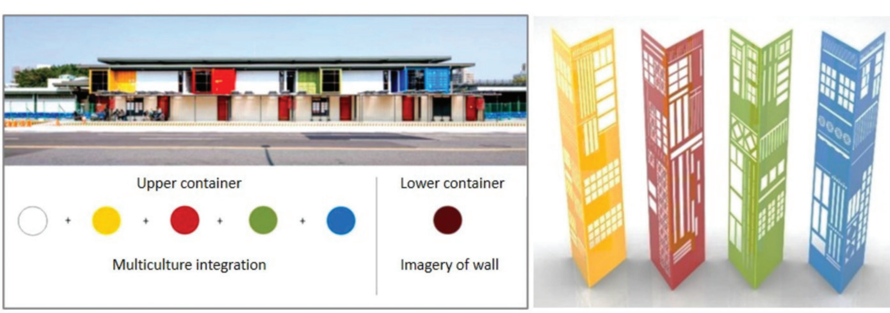


Figure 18. The color scheme of public art and architectural engineering. (Left color scheme: Committee of public art installation project on Tainan Bus Station) [21].

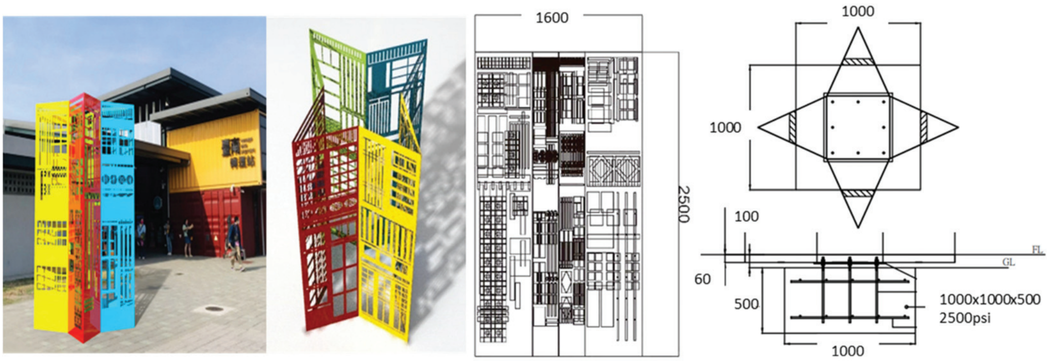


Figure 19. Dimensions of the public artwork (unit: mm) [21].

5. Conclusions

The 19th-century Austrian architect C. Sitte analyzed the spatial characteristics of European cities from the late classical antiquity to the post-industrial revolution in his book "City Planning According to Artistic Principles" (Der Städtebaunach seinen künstlerschen Grundsätzen) (1889). He discovered that the urban space loved by residents was not those large-scale squares or palaces but those well-proportioned, well-interacted, and beautiful urban landscapes; he emphasizes that, with a design sense of free life, the coordination between buildings and the encompassed squares and streets are the elements to achieve the purpose of the aesthetic planning of a city [24]. He believes urban architecture is a comprehensive work of art that must be planned and constructed based on artistic principles. As for urban architecture, he believes that urban architecture is a comprehensive work of art that must be planned and constructed based on artistic principles. D. J. Curtis (2010) also argues that "the arts have an ability to communicate environmental information . . . and to normalize concern for the environment, taking it from the realm of 'problem' to the realm of general conversation or even entertainment" [25]. The public space of Shennong Street has the artistic characteristics of the public space mentioned. The facade of the historical building on Shennong Street is an arrangement of artistic images and the space between the building facades on both sides; the historical street buildings and the artistic features of the facades constitute the historical value of urban development.

Heritage buildings are a cultural concept with evolutionary characteristics, mainly constructed in the category of historic culture and people's living settlements. The construction space of modern projects makes people's living space and the buildings group a certain correlation and produces unique architectural forms and living needs. Public art is an artistic asset with aesthetic attributes in the architectural field and also forms an artistic symbol of urban architectural space. Through describing the boundaries of public artworks, combined artworks, urban architecture, and public spaces are formed into a structure with perceptual entities that residents have a common impression of, which itself becomes an "image" [26]. This means that the public art is a space that creates memory; relatively speaking, the appearance of the cultural layer of a region can be seen from these heritage buildings. In the process of research and practice conducted for this this study, the following discoveries have been made:

1. Applying the design that retains the historical and cultural context of the heritage buildings to the current city is an important method to show the sustainable cultural value of modern buildings.
2. A design model found the balance between the cultural value of historic buildings and public art.

As an implementation case, the purpose of this research is to propose a field of innovation and a direction for sustainable design. Make the preservation of historical buildings not limited to widely discussed issues and methods such as: the maintenance of historical sites, the preservation of cultural relics, spatial activation, reconstruction and reuse. For the public art proposal "OPEN—The Folder of Time", its design and planning combine with the design concept of the Tainan Bus Station to translate history and culture into a sustainable design. By using "public art" as a medium, through the fusion of architectural engineering and art, history and culture are translated into a sustainable design art model. In the face of the rapid development of the city and the current state of continuous renewal and planning of modern urban architecture, through public art combined with sustainable design art solutions, whether it is preservation or construction planning, historical buildings and new construction will form an organic topology line of shaping the urban landscape and urban development.

Therefore, the result and contribution of this article is a practical solution that uses public art combined with cross-domain design, to open up another train of thought for the preservation, activation and reuse of traditional buildings. The authors sincerely hope that the opinions and discoveries in this study can become an innovative design and feasible method that benefit future urban architectural engineering, cultural preservation, and urban renewal projects.

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Appendix A Calculation Result of Questionnaire

A and B layer Aa–Ac items CI/CR verification value ≤ 0.1, expert weight numerical analysis results.

Table A1. Sorting of Floor A, Aa/Ab/Ac in the expert questionnaire. (Adapted from [18]).

ω Sort	Q/Aa	Item	Pairwise Matrices	λ_{max}	CR	ω
1	expert 1	a4	7 × 7	7.0819	0.0103	0.3416
	expert 4	a3	7 × 7	7.0819	0.0103	0.2975
	expert 5	a4	7 × 7	7.3159	0.0398	0.3705
2	expert 1	a1	7 × 7	7.0819	0.0103	0.3215
	expert 4	a4	7 × 7	7.0819	0.0103	0.2469
	expert 5	a1	7 × 7	7.3159	0.0398	0.1898
ω Sort	**Q/Ab**	**Item**	**Pairwise Matrices**	**λ_{max}**	**CR**	**ω**
1	expert 1	a3	7 × 7	7.4891	0.0617	0.3276
	expert 4	a1	7 × 7	7.6825	0.0861	0.3234
	expert 5	a1	7 × 7	7.6163	0.0778	0.2857
2	expert 1	a1	7 × 7	7.4891	0.0617	0.2875
	expert 4	a3	7 × 7	7.6825	0.0861	0.2291
	expert 5	a3	7 × 7	7.6163	0.0778	0.2242
ω Sort	**Q/Ac**	**Item**	**Pairwise Matrices**	**λ_{max}**	**CR**	**ω**
1	expert 2	a3	7 × 7	7.5755	0.0072	0.3679
	expert 4	a3	7 × 7	7.7934	0.1000	0.2976
	expert 5	a4	7 × 7	7.5749	0.0725	0.2212
2	expert 2	a6	7 × 7	7.5755	0.0072	0.2271
	expert 4	a5	7 × 7	7.7934	0.1000	0.1892
	expert 5	a5	7 × 7	7.5749	0.0725	0.2059

Table A2. Sorting of Floor B, Bd/Be/Bf/Bg in the expert questionnaire. (Adapted from [18]).

ω Sort	Q/Bd	Item	Pairwise Matrices	λ_{max}	*CR*	ω
1	expert 1	b9	14 × 14	15.3698	0.0671	0.1815
	expert 2	b12	14 × 14	15.6372	0.0802	0.1316
	expert 4	b12	14 × 14	15.2014	0.0500	0.1433
2	expert 1	b6	14 × 14	15.3698	0.0671	0.1491
	expert 2	b6	14 × 14	15.3698	0.0671	0.1157
	expert 4	b9	14 × 14	15.6372	0.0802	0.1020
ω Sort	Q/Be	Item	Pairwise Matrices	λ_{max}	*CR*	ω
1	expert 1	b5	14 × 14	15.6815	0.0823	0.2714
	expert 2	b5	14 × 14	15.0989	0.0538	0.2650
	expert 4	b3	14 × 14	15.1943	0.0585	0.2547
2	expert 1	b8	14 × 14	15.6815	0.0823	0.1624
	expert 2	b8	14 × 14	15.0989	0.0538	0.1803
	expert 4	b6	14 × 14	15.1943	0.0585	0.1483
ω Sort	Q/Bf	Item	Pairwise Matrices	λ_{max}	*CR*	ω
1	expert 1	b9	14 × 14	15.4979	0.0734	0.2217
	expert 2	b9	14 × 14	15.4636	0.0717	0.1578
	expert 4	b9	14 × 14	15.4070	0.0689	0.1619
2	expert 1	b13	14 × 14	15.4979	0.0734	0.1365
	expert 2	b13	14 × 14	15.4636	0.0717	0.1434
	expert 4	b6	14 × 14	15.4070	0.0689	0.1401
ω Sort	Q/Bg	Item	Pairwise Matrices	λ_{max}	*CR*	ω
1	expert 1	b6	14 × 14	15.4576	0.0714	0.1318
	expert 2	b10	14 × 14	15.5980	0.0782	0.1625
	expert 4	b13	14 × 14	15.2188	0.0597	0.1464
2	expert 1	b13	14 × 14	15.4576	0.0714	0.1213
	expert 2	b13/14	14 × 14	15.5980	0.0782	0.1492
	expert 4	b14	14 × 14	15.2188	0.0597	0.1345

According to the above eigenvalue matrix, to calculate the first and second items' weight value, the following sorting sequence is required:

1. Floor A: Aa-a4, Aa-a3, Aa-a1/Ab-a1, Ab-a3/Ac-a3, Ac-a5, Ac-a6, Ac-a4.
2. Floor B: Bd-b12, Bd-b6, Bd-b9/Be-a5, Be-b3, Be-b8, Be-b6/Bf-b9, Bf-b13, Bf-b6/Bg-b13, Bg-b14, Bg-b10, Bg-b6.

These items are the best representative facade design of Shennong Street. (as the following Table A3).

Table A3. Comparison of the most representative design style on Floor A and Floor B of Shennong Street. (Adapted from [18]).

A		B	
Sort	**ω Project**	**Appraise Project**	**ω Sort**
Aa	a4/a3/a1	Bd	b12/b6/b9
Ab	a1/a4	Be	b5/b3/b8/b6
Ac	a3/a5/a6/a4	Bf	b9/b13/b6
		Bg	b13/b14/b10/b6

Appendix B

Table A4. Floor A Aa-Ac items' *CI*/*CR* verification value ≤ 0.1, expert weighted matrix.

Floor A, item Aa, expert 1, λ_{max} 7.5268, *CR* 0.0665								
Aa	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	5	3	1	7	7	7	0.3215
a2	1/5	1	1/5	1/7	1	1/3	3	0.0444
a3	1/3	5	1	1/5	5	1	5	0.1277
a4	1	7	5	1	7	5	7	0.3416
a5	1/7	1	1/5	1/7	1	1/3	3	0.042
a6	1/7	3	1	1/5	3	1	5	0.0966
a7	1/7	1/3	1/5	1/7	1/3	1/5	1	0.0258

Floor A, item Aa, expert 4, λ_{max} 7.0819, *CR* 0.0103								
Aa	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	5	1/3	1/3	7	7	7	0.2306
a2	1/5	1	1/3	1/5	1	1	3	0.061
a3	3	3	1	3	3	3	3	0.2975
a4	3	5	1/3	1	5	3	5	0.2469
a5	1/7	1	1/3	1/5	1	1/3	1	0.0434
a6	1/7	1	1/3	1/3	3	1	5	0.0834
a7	1/7	1/3	1/3	1/5	1	1/5	1	0.0369

Floor A, item Aa, expert 5, λ_{max} 7.3159, *CR* 0.0398								
Aa	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	5	1/3	1/5	5	5	5	0.1898
a2	1/5	1	1/5	1/5	1/3	1	5	0.0601
a3	3	5	1	1/3	3	1	3	0.1891
a4	5	5	3	1	3	5	7	0.3705
a5	1/5	3	1/3	1/3	1	1/3	1	0.0643
a6	1/5	1	1	1/5	3	1	3	0.0903
a7	1/5	1/5	1/3	1/7	1	1/3	1	0.0355

Floor A, item Ab, expert 1, λ_{max} 7.4891 *CR* 0.0617								
Ab	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	5	1	5	3	3	5	0.2875
a2	1/5	1	1/3	3	1	3	3	0.1157
a3	1	3	1	5	7	3	7	0.3276
a4	1/5	1/3	1/5	1	1/5	1/5	1/3	0.033
a5	1/3	1	1/7	5	1	1	5	0.1111
a6	1/3	1/3	1/3	5	1	1	1/5	0.0814
a7	1/5	1/3	1/7	3	1/5	1/5	1	0.0432

Floor A, item Ab, expert 4, λ_{max} 7.6825 *CR* 0.0861								
Ab	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	5	3	5	1	5	3	0.3234
a2	1/5	1	1	3	1	1/3	1	0.0898
a3	1/3	1	1	5	5	3	3	0.2291
a4	1/5	1/3	1/5	1	1/5	1/5	1/3	0.0307
a5	1	1	1/5	5	1	1	3	0.1339
a6	1/5	3	1/3	5	1	1	3	0.1279
a7	1/3	1	1/3	3	1/3	1/3	1	0.0649

Floor A, item Ab, expert 5, λ_{max} 7.6163, *CR* 0.0778								
Ab	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	5	1	5	1	5	3	0.2857
a2	1/5	1	1	3	1	1/3	1	0.0945
a3	1	1	1	3	5	1	3	0.2242
a4	1/5	1/3	1/3	1	1/5	1/3	1/3	0.0381
a5	1	1	1/5	5	1	1	3	0.1402
a6	1/5	3	1	3	1	1	3	0.1483
a7	1/3	1	1/3	3	1/3	1/3	1	0.0687

Floor A, item Ac, expert 2, λ_{max} 7.5755, *CR* 0.0072								
Ab	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	3	1/7	1/7	1/3	1/5	1	0.0483
a2	1/3	1	1/7	1/5	1/3	1/5	1	0.0357
a3	7	7	1	5	5	1	5	0.3679
a4	7	5	1/5	1	1	1/3	3	0.1432
a5	3	3	1/5	1	1	1	3	0.1283
a6	5	5	1	3	1	1	3	0.2271
a7	1	1	5	3	3	3	1	0.2043

Floor A, item Ac, expert 4, λ_{max} 7.7934, *CR* 0.1000								
Ac	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	5	1/5	1/5	1/3	1/3	1	0.0722
a2	1/5	1	1/3	1/5	1/3	1/4	1	0.045
a3	5	3	1	3	3	1	5	0.2976
a4	5	5	1/3	1	1	1	3	0.1764
a5	3	3	1/3	1	1	3	3	0.1892
a6	3	5	1	1	1/3	1	3	0.1671
a7	1	1	1/5	1/3	1/3	1/3	1	0.0521

Floor A, item Ac, expert 5, λ_{max} 7.5749, *CR* 0.0725								
Ac	a1	a2	a3	a4	a5	a6	a7	ω
a1	1	5	1/3	1/5	1	1/3	1	0.0973
a2	1/5	1	1/5	1/5	1/3	1/5	1	0.0408
a3	3	5	1	1	1	1	3	0.1955
a4	5	5	1	1	1	1	3	0.2212
a5	1	3	1	1	1	3	3	0.2059
a6	3	5	1	1	1/3	1	3	0.1774
a7	1	1	1/3	1/3	1/3	1/3	1	0.0615

Table A5. Floor B Bd-Bg items' *CI/CR* verification value ≤ 0.1, expert weighted matrix.

Floor B, item Bd, expert 1, λ_{max} 15.3698, *CR* 0.0671														
Bd	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1	1	1	1/3	1/3	3	1/3	1/7	3	1/3	1/5	1	1	0.0414
b2	1	1	1	1	1	1/5	3	1/3	1/7	5	1/3	1/3	3	1	0.0535
b3	1/5	1	1	1	1	1/5	5	1/3	1/7	3	1/3	1/3	1	1/5	0.0373

Table A5. *Cont.*

b4	1	1	1	1	1	1/5	3	1	1/5	1/3	1/3	1/5	1	1/5	0.0293
b5	3	1	1	1	1	1/5	3	1	1/7	1/3	1/3	1/5	1	1/5	0.0338
b6	3	5	5	5	5	1	7	3	1	5	3	1	5	1	0.1491
b7	1/3	1/3	1/5	1/3	1/3	1/7	1	1/3	1/7	1/5	1/7	1/7	1/5	1/5	0.0127
b8	3	3	3	1	1	1/3	3	1	1/5	1	1/3	1	3	1/3	0.0591
b9	7	7	7	5	7	1	7	5	1	1	1	1	7	5	0.1815
b10	1/3	1/5	1/3	3	3	1/5	5	1	1	1	3	1/3	3	1/3	0.0645
b11	3	3	3	3	3	1/3	7	3	1	1/3	1	1	5	1	0.0943
b12	5	3	3	5	5	1	7	1	1	3	1	1	7	1	0.1195
b13	1	1/3	1	1	1	1/5	5	1/3	1/7	1/3	1/5	1/7	1	1/3	0.0253
b14	1	1	5	5	5	1	5	3	1/5	3	1	1	3	1	0.098
Floor B, item Bd, expert 2, λ_{max} 15.6372, *CR* 0.0802															
Bd	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1/3	5	1	1	1/5	5	1/7	1/3	5	1	1/5	5	5	0.0751
b2	3	1	5	1	1	1/3	5	1/3	1/5	7	3	1	5	1	0.0992
b3	1/5	1/5	1	1	1	1/5	7	1/3	1/5	1/3	1/5	1/5	1	1/7	0.0236
b4	1	1	1	1	1/3	1/3	5	1	1/5	1/5	1/5	1/3	1	1/3	0.0334
b5	1	1	1	3	1	1	5	1	1/5	1/5	1/3	1/5	1	1/3	0.0422
b6	5	3	5	3	1	1	5	1/3	1	1	1	3	7	3	0.1157
b7	1/5	1/5	1/7	1/5	1/5	1/5	1	1	1/7	1/7	1/3	1/5	1	1/3	0.0174
b8	7	3	3	1	1	3	1	1	3	1	1	1/3	3	1	0.113
b9	3	5	5	5	5	1	7	1/3	1	1	1	1/3	5	3	0.1116
b10	1/5	1/7	3	5	5	1	7	1	1	1	3	3	1	1	0.0917
b11	1	1/3	5	5	3	1	3	1	1	1/3	1	1/3	3	3	0.0689
b12	5	1	5	3	5	1/3	5	3	3	1/3	3	1	5	5	0.1316
b13	1/5	1/5	1	1	1	1/7	1	1/3	1/5	1	1/3	1/5	1	1/3	0.0219
b14	1/5	1	7	3	3	1/3	3	1	1/3	1	1/3	1/5	3	1	0.0541
Floor B, item Bd, expert 4, λ_{max} 15.2014, *CR* 0.0500															
Bd	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1	1	1/3	1	1/3	3	1/5	1/3	3	1/3	1/3	3	1	0.0554
b2	1	1	1	1	1	1	1	1/3	1/3	3	1	1	3	3	0.0757
b3	1/3	1	1	1	1	1/5	3	1	1/3	1/3	1/3	1/3	1	1/5	0.0343
b4	3	1	1	1	1	1/3	3	1	1/5	1/3	1/3	1/3	1	1/3	0.0433
b5	1	1	1	1	1	1	5	1	1/5	1/3	1/3	1/5	1	1/3	0.0423
b6	3	1	5	3	1	1	5	1	1	1	1	1	3	3	0.0964
b7	1/3	1	1/3	1/3	1/5	1/5	1	1	1/7	1/5	1/3	1/5	1	1/3	0.024
b8	5	3	1	1	1	1	1	1	3	1	1/3	1/3	1	1	0.0827
b9	3	3	3	5	5	1	7	1/3	1	1	1	1/3	3	1	0.102
b10	1/3	1/3	3	3	3	1	5	1	1	1	3	3	1	1	0.0993
b11	3	1	3	3	3	1	3	3	1	1/3	1	1/3	3	1	0.0866
b12	3	1	3	3	5	1	5	3	3	1/3	3	1	5	5	0.1433
b13	1/3	1/3	1	1	1	1/3	1	1	1/3	1	1/3	1/5	1	3	0.0435
b14	1	1/3	5	3	3	1/3	3	1	1	1	1	1/5	3	1	0.0706
Floor B, item Be, expert 1, λ_{max} 15.6815, *CR* 0.0823															
Be	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	3	5	1	1/7	5	5	1	1	5	1	5	7	3	0.0954
b2	1/3	1	3	1	1/9	3	5	1/7	1/3	3	1/3	3	5	3	0.0533
b3	1/5	1/3	1	1/3	1/9	1/3	1/3	1/7	1/5	1/3	1/7	1	3	1/3	0.0161
b4	1	1	3	1	1/7	3	5	1/5	3	5	1	5	7	3	0.0815
b5	7	9	9	7	1	7	9	1	5	7	5	7	9	7	0.2714
b6	1/5	1/3	3	1/3	1/7	1	5	1/5	1	3	1/3	5	7	1	0.0441
b7	1/5	1/5	3	1/5	1/9	1/5	1	1/7	1/5	1/3	1/7	1	1	1/3	0.016

Table A5. *Cont.*

b8	1	7	7	5	1	5	7	1	3	5	1	5	7	5	0.1624
b9	1	3	5	1/3	1/5	1	5	1/3	1	3	1	3	7	3	0.0691
b10	1/5	1/3	3	1/5	1/7	1/3	3	1/5	1/3	1	1/5	1	7	1/3	0.0261
b11	1	3	7	1	1/5	3	7	1	1	5	1	7	7	3	0.0973
b12	1/5	1/3	1	1/5	1/7	1/5	1	1/5	1/3	1	1/7	1	3	1/3	0.0185
b13	1/7	1/5	1/3	1/7	1/9	1/7	1	1/7	1/7	1/7	1/7	1/3	1	1/7	0.0106
b14	1/3	1/3	3	1/3	1/7	1	3	1/5	1/3	3	1/3	3	7	1	0.0376
Floor B, item Be, expert 2, λ_{max} 15.0989, *CR* 0.0538															
Be	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	5	1	5	1/7	7	1	1/3	1	5	1	7	7	1	0.0858
b2	1/5	1	1/5	1	1/9	1	3	1/7	1/3	3	1/5	1	5	1	0.0329
b3	1	5	1	3	1/7	1/3	1	1/5	1/3	1	1/5	3	7	1	0.0439
b4	1/5	1	1/3	1	1/7	1	3	1/7	1	1	1/5	3	5	1	0.0326
b5	7	9	7	7	1	9	9	1	9	7	5	9	9	9	0.265
b6	1/7	1	3	1	1/9	1	1	1/7	3	1	1/5	3	5	1	0.0399
b7	1	1/3	1	1/3	1/9	1	1	1/7	1/3	1/3	1/7	1	5	5	0.0361
b8	3	7	5	7	1	7	7	1	7	5	1	7	9	7	0.1803
b9	1	3	3	1	1/9	1/3	3	1/7	1	1/3	1/5	5	7	1	0.0466
b10	1/5	1/3	1	1	1/7	1	3	1/5	3	1	1/3	3	7	1	0.0411
b11	1	5	5	5	1/5	5	7	1	5	3	1	7	9	3	0.1245
b12	1/7	1	1/3	1/3	1/9	1/3	1	1/7	1/5	1/3	1/7	1	5	1/5	0.0165
b13	1/7	1/5	1/7	1/5	1/9	1/5	1/5	1/9	1/7	1/7	1/9	1/5	1	1/7	0.0082
b14	1	1	1	1	1/9	1	5	1/7	1	1	1/3	5	7	1	0.046
Floor B, item Be, expert 4, λ_{max} 15.1943, *CR* 0.0585															
Be	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	3	1	5	1/7	5	1	1	1	1	1	5	5	1	0.044
b2	1/3	1	1/5	1	1/9	1	3	1/7	1/3	3	1/3	1	3	3	0.0357
b3	1	5	1	3	1/7	1/3	1	1/5	1/3	1	1/5	1	3	1	0.2547
b4	1/5	1	1/3	1	1/7	1	3	1/5	1	1	1/5	3	3	1	0.0412
b5	7	9	7	7	1	7	9	1	5	7	5	7	9	7	0.0342
b6	1/5	1	3	1	1/7	1	1	1/5	1	1	1/3	3	5	1	0.1483
b7	1	1/3	1	1/3	1/9	1	1	1/7	1/3	1/3	1/7	1	1	5	0.064
b8	1	7	5	5	1	5	7	1	3	5	1	3	5	5	0.0499
b9	1	3	3	1	1/5	1	3	1/3	1	3	1/5	3	3	3	0.1263
b10	1	1/3	1	1	1/7	1	3	1/5	1/3	1	1/3	3	5	5	0.0239
b11	1	3	5	5	1/5	3	7	1	5	3	1	5	5	5	0.0138
b12	1/5	1	1	1/3	1/7	1/3	1	1/3	1/3	1/3	1/5	1	5	1/5	0.0446
b13	1/5	1/3	1/3	1/3	1/9	1/5	1	1/5	1/3	1/5	1/5	1/5	1	1/7	0.044
b14	1	1/3	1	1	1/7	1	5	1/5	1/3	1/5	1/5	5	7	1	0.0357
Floor B, item Bf, expert 1, λ_{max} 15.4979, *CR* 0.0734															
Bf	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1	3	1	7	1/3	5	3	1/7	1	1/3	1/5	1/5	1	0.0471
b2	1	1	3	1/3	3	1/5	5	1	1/7	1/7	1	1	1/5	1/7	0.0337
b3	1/3	1/3	1	3	5	1/5	3	1	1/7	1/3	1/5	1/3	1/5	1/7	0.0263
b4	1	3	1/3	1	3	1/5	3	1	1/5	1/5	1/5	1/3	1/5	1/5	0.0282
b5	1/7	1/3	1/5	1/3	1	1/7	1	1/3	1/7	1/5	1/7	1/5	1/7	1/5	0.0121
b6	3	5	5	5	7	1	5	5	1/3	3	1	3	1	1/3	0.1072
b7	1/5	1/5	1/3	1/3	1	1/5	1	1/3	1/5	1/3	1/7	1/3	1/5	1/5	0.015
b8	1/3	1	1	1	3	1/5	3	1	1/5	1/3	1	1	1/5	1/5	0.0301
b9	7	7	7	5	7	3	5	5	1	7	3	5	3	3	0.2217
b10	1	7	3	5	5	1/3	3	3	1/7	1	1/3	3	1	3	0.0925

Table A5. *Cont.*

b11	3	1	5	5	7	1	7	1	1/3	3	1	1	1/3	1/3	0.0815
b12	5	1	3	3	5	1/3	3	1	1/5	1/3	1	1	1/5	1/3	0.0533
b13	5	5	5	5	7	1	5	5	1/3	1	3	5	1	3	0.1365
b14	1	7	7	5	5	3	5	5	1/3	1/3	3	3	1/3	1	0.1143
Floor B, item Bf, expert 2, λ_{max} 15.4636, *CR* 0.0717															
Bf	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1/3	5	1	3	1/5	1	1	1/7	1	1/5	1/3	1/5	1	0.0386
b2	3	1	3	1/5	1	1	5	1	1/5	1/7	1/3	1/5	1/7	1/9	0.0349
b3	1/5	1/3	1	5	3	1/7	1	1	1/5	1/5	1/7	1/7	1/7	1/7	0.0242
b4	1	5	1/5	1	1	1/5	1	1	1/5	1/7	1	1	1/7	1/7	0.0313
b5	1/3	1	1/3	1	1	1/7	1	1/3	1/9	1/7	1/7	1/7	1/7	1/5	0.0143
b6	5	1	7	5	7	1	9	7	1	1	1/3	3	1	1	0.109
b7	1	1/5	1	1	1	1/9	1	1	1/7	1/5	1	1	1/7	1/7	0.0221
b8	1	1	1	1	3	1/7	1	1	1/7	1/5	1	1	1/5	1/7	0.026
b9	7	5	5	5	9	1	7	7	1	3	5	5	1	1	0.1578
b10	1	7	5	7	7	1	5	5	1/3	1	7	7	1	1	0.137
b11	5	3	7	1	7	3	1	1	1/5	1/7	1	1	1/5	1/5	0.0689
b12	3	5	7	1	7	1/3	1	1	1/5	1/7	1	1	1/5	1/5	0.0518
b13	5	7	7	7	7	1	7	5	1	1	5	5	1	1	0.1434
b14	1	9	7	7	5	1	7	7	1	1	5	5	1	1	0.1399
Floor B, item Bf, expert 4, λ_{max} 15.4070, *CR* 0.0689															
Bf	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1/3	3	1	3	1/3	1	1	1/7	1	1/3	1/3	1/5	1	0.0386
b2	3	1	3	1/3	1	1/5	5	1	1/5	1/5	1/3	1/5	1/5	1/5	0.0362
b3	1/3	1/3	1	3	3	1/5	1	1	1/5	1/5	1/5	1/3	1/5	1/7	0.0258
b4	1	3	1/3	1	1	1/5	3	1	1/5	1/5	1	1	1/5	1/5	0.0354
b5	1/3	1	1/3	1	1	1/7	1	1/3	1/7	1/7	1/5	1/5	1/7	1/5	0.0167
b6	3	5	5	5	7	1	3	5	1	3	1	3	1	3	0.1401
b7	1	1/5	1	1/3	1	1/3	1	1	1/5	1/3	1	1	1/5	1/5	0.0274
b8	1	1	1	1	3	1/5	1	1	1/5	1/3	1	1	1/5	1/5	0.0315
b9	7	5	5	5	7	1	5	5	1	3	3	3	1	3	0.1619
b10	1	5	5	5	7	1/3	3	3	1/3	1	1/3	3	1	1	0.0893
b11	3	3	5	1	5	1	1	1	1/3	3	1	1	1/3	1/3	0.0738
b12	3	5	3	1	5	1/3	1	1	1/3	1/3	1	1	1/5	1/3	0.0537
b13	5	5	5	5	7	1	5	5	1	1	3	5	1	1	0.1367
b14	1	5	7	5	5	3	5	5	1/3	1	3	3	1	1	0.1323
Floor B, item Bg, expert 1, λ_{max} 15.4576, *CR* 0.0714															
Bg	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1	3	1	3	1/5	5	1	1/3	1	1/3	1/3	1/3	1	0.0494
b2	1	1	3	1	3	1/3	3	1	1/3	1/3	1/3	1/3	1/3	1/3	0.0404
b3	1/3	1/3	1	1/3	1	1/3	3	1/3	1/3	1/3	1/5	1/5	1/5	1/3	0.0236
b4	1	1	3	1	3	1/3	3	1	1/3	1/3	1	1	1/3	1/3	0.0486
b5	1/3	1/3	1	1/3	1	1/5	1	1/3	1/3	1/5	1/5	1/5	1/5	1/5	0.0187
b6	5	3	3	3	5	1	3	3	1	1	3	3	1	1	0.1318
b7	1/5	1/3	1/3	1/3	1	1/3	1	1/3	1/5	1/5	1/5	1/5	1/7	1/5	0.0169
b8	1	1	3	1	3	1/3	3	1	1/3	3	1	1	1/5	1/3	0.0624
b9	3	3	3	3	3	1	5	3	1	1	1	1	1	3	0.113
b10	1	3	3	3	5	1	5	1/3	1	1	1	1	1	1	0.0858
b11	3	3	5	1	5	1/3	5	1	1	1	1	1	3	3	0.1141
b12	3	3	5	1	5	1/3	5	1	1	1	1	1	1/3	1/3	0.0765
b13	3	3	5	3	5	1	7	5	1	1	1/3	3	1	1	0.1213
b14	1	3	3	3	5	1	5	3	1/3	1	1/3	3	1	1	0.0967

Table A5. *Cont.*

Floor B, item Bg, expert 2, λ_{max} 15.5980, *CR* 0.0782															
Bg	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1	5	1	5	1	5	1	1/5	1/5	1/5	1/5	1/5	1/5	0.0397
b2	1	1	5	1	5	1/5	3	1	1/3	1/5	1	1	1/5	1/5	0.0384
b3	1/5	1/5	1	1/5	1	1/5	3	1/5	1/5	1/7	1/5	1/5	1/7	1/7	0.0147
b4	1	1	5	1	5	1/3	3	1	1/3	1/5	1	1	1/5	1/5	0.0395
b5	1/5	1/5	1	1/5	1	1/7	1	1/3	1/5	1/7	1/5	1/5	1/7	1/7	0.0131
b6	1	5	5	3	7	1	7	7	1	1	3	3	1	1	0.1232
b7	1/5	1/3	1/3	1/3	1	1/7	1	1/5	1/7	1/7	1/5	1/5	1/7	1/7	0.0124
b8	1	1	5	1	3	1/7	5	1	1	1/5	1	1	1/5	1/5	0.0423
b9	5	3	5	3	5	1	7	1	1	1/3	3	3	1	1	0.1035
b10	5	5	7	5	7	1	7	5	3	1	5	5	1	1	0.1625
b11	5	1	5	1	5	1/3	5	1	1/3	1/5	1	1/5	1/5	1/5	0.048
b12	5	1	5	1	5	1/3	5	1	1/3	1/5	5	1	1/5	1/5	0.0636
b13	5	5	7	5	7	1	7	5	1	1	5	5	1	1	0.1492
b14	5	5	7	5	7	1	7	5	1	1	5	5	1	1	0.1492
Floor B, item Bg, expert 4, λ_{max} 15.2188, *CR* 0.0597															
Bg	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	ω
b1	1	1	3	1	3	1	5	1	1/3	1	1/5	1/5	1/5	1/5	0.049
b2	1	1	3	1	3	1/3	3	1	1/3	1/5	1/3	1	1/5	1/3	0.0411
b3	1/3	1/3	1	1/3	1	1/3	3	1/3	1/3	1/3	1/5	1/5	1/5	1/5	0.0227
b4	1	1	3	1	3	1/3	3	1	1	1/3	1	1	1/3	1/3	0.0506
b5	1/3	1/3	1	1/3	1	1/5	1	1/3	1/3	1/5	1/5	1/5	1/5	1/5	0.0185
b6	1	3	3	3	5	1	3	3	1	1	3	3	1	1	0.1143
b7	1/5	1/3	1/3	1/3	1	1/3	1	1/3	1/5	1/5	1/5	1/5	1/7	1/7	0.0163
b8	1	1	3	1	3	1/3	3	1	1	1/3	1	1	1/5	1/3	0.0493
b9	3	3	3	1	3	1	5	1	1	1/3	1	1	1	1	0.0819
b10	1	5	3	3	5	1	5	3	3	1	1	3	1	1	0.1219
b11	5	3	5	1	5	1/3	5	1	1	1	1	1	1/3	1/3	0.0818
b12	5	1	5	1	5	1/3	5	1	1	1/3	1	1	1/3	1/3	0.0711
b13	5	5	5	3	5	1	7	5	1	1	3	3	1	1	0.1464
b14	5	3	5	3	5	1	7	3	1	1	3	3	1	1	0.1345

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buildings

Article

Preferences of the Facade Composition in the Context of Its Regularity and Irregularity

Michał Malewczyk *, Antoni Taraszkiewicz and Piotr Czyż

Faculty of Architecture, Gdańsk University of Technology, 80-233 Gdańsk, Poland; antarasz@pg.edu.pl (A.T.); pioczyz@pg.edu.pl (P.C.)
* Correspondence: michal.malewczyk@pg.edu.pl

Abstract: The aim of this study is to determine the preferences of Polish society towards building facades depending on the degree of the composition regularity of the facade elements. The subject matter is inspired by the authors' observations in relation to the current architectural trends. The purposefulness of the conducted research results from several issues. Firstly, the reports of psychology and neurosciences clearly indicate the universality of certain preferences towards visual attributes of objects (e.g., in relation to abstract symmetric patterns), resulting from biological conditions. Secondly, residential, multi-family architecture is by definition designed for a wide group of anonymous users whose expectations must be met. One of the dimensions of the above-mentioned expectations is the visual dimension, partially dependent on the composition of the facade. In the course of the conducted research, it is shown that facades with a regular composition are assessed as more attractive than those with irregular compositions. Moreover, irregular facades evoked a negative effect of a significantly greater force than the positive effect in the case of regular facades. The above-described discoveries shed, in the authors' opinion, a completely new light on the contemporary work of architects. It is extremely important to adapt the visual dimension of architecture to the expectations of its recipients, while taking care of its values and quality as a field of art.

Keywords: composition; aesthetics; multi-family housing; Poland; preferences

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1. Introduction

The main purpose of this study is to determine the aesthetic preferences of Poles depending on the degree of regularity in the composition of building facades. An additional goal is to identify these preferences depending on the type of composition. Aesthetics is naturally a very broad and complex concept, but in relation to this study, it should be considered as a visual dimension of the external part of architecture. The research further narrows the visual dimension of architecture, which is also a broad and complex phenomenon to the composition of window openings (an essential architectural element on most multi-family building facades). Such a limitation allows to limit the conclusions from the study only to the composition of window openings. These should be considered both as a pattern (according to Alexander's theory [1]) and as a component of architecture as a multi-layer composition [2] with an influence on the aesthetics of the whole building.

Therefore, a questionnaire survey was conducted among 109 people. Statistical analyses of the obtained results were used to formulate answers to research questions and conclusions. The significance of the conducted research resulted from the utilitarian nature of residential, multi-family architecture and the resulting universality. Multifamily housing constitutes the main part of the urban fabric and it is extremely important that its aesthetics meet the expectations of modern society. It is impossible to fully meet these expectations without knowing the corresponding statistical data. Although this study refers to the preferences of Poles, and, therefore, its scope is local, it refers to common preferences applicable in the analysed group. It should also be noted that the presented research method is a universal one and is a starting point for global research and for determining the preferences of the general public.

One of the key issues for this study is the concept of aesthetics. Naturally, this is a very broadly understood term [3]. Aesthetics itself is a branch of philosophy; however, aesthetics understood as the visual dimension of an object (e.g., works of art) also depends on other philosophical trends and concepts. Nowadays, we can observe the emergence of voices suggesting the need to redefine the directions in which the aesthetics of architecture should follow. In the opinion of the authors, special attention should be paid to trends relating to the aesthetics of the everyday [4], an example of which may be the Super Normal [5] initiative. Roger Scrouton [6], among others, draws attention to the importance of creating the aesthetics of architecture in the context of its impact on everyday life. Everyday architecture is also treated as a counterpoint to a world engulfed in consumerism and the necessity to follow fashion [7], a counterpoint to architecture defined by Tom Dyckhoff as "wowhaus" architecture [8]. The need to direct the way of creating architecture to its user is also indicated by Jeremy Till, who called architecture a frame for life [9]. It is very important to fill the gap between architectural monuments and people, as Till also states [9], but in the authors opinion it is not possible without obtaining the knowledge of the real expectations and preferences of ordinary users of architecture.

Another important issue for these considerations is the growing interest in irregularity in the context of shaping the visual dimension of architecture. This tendency is evidenced by many international projects, but the most important for these considerations are objects from Poland. It is worth paying attention to the Polish multi-family architecture, realized in 2011–2021 and, at the same time, nominated for the Mies van der Rohe award. During this period, seven multi-family projects were created (Figure 1) which were nominated for this prestigious award and, therefore, are examples of architecture of above-average quality. These projects inspire other architects and, above all, set trends in design and also reflect the current trends in this segment of architecture. The analysis of the facades of these objects shows that in the case of four (out of seven) implementations, we deal with irregular compositions and with irregular (in terms of texture or colour) facade materials. The two embodiments also operate in an irregular form. It should also be noted that there is a certain irregularity (formal, compositional or material) in each of the realizations. The results of the above analyses are presented in Table 1. In the opinion of the authors, it can, therefore, be concluded that we are dealing with a clear tendency related to the shaping of the contemporary aesthetics of Polish multi-family architecture.

Figure 1. Polish residential, multi-family projects nominated for the Mies van der Rohe for 2011–2021: (**a**) Atmosfera real estate; (**b**) Riverview real estate; (**c**) Nowy Werdon building; (**d**) Nowy Nikiszowiec real estate; (**e**) Unikato building; (**f**) Sprzeczna 4 building; (**g**) 19 Dzielnica real estate.

Table 1. List of irregularities in relation to the analysed housing developments.

Project Name	Designer	a	b	c
Atmosfera	arch_it		X	
Riverview	APA Wojciechowski		X	X
Nowy Werdon	Biuro Projektowe Maleccy		X	X
Nowy Nikiszowiec	22ARCHITEKCI			X
Unikato	KWK PROMES	X		X
Sprzeczna 4	BBGK	X		X
19 Dzielnica	JEMS Architekci		X	

(a) Irregularity of form. (b) Irregularity of composition. (c) Irregularity of material.

At the same time, due to the utility nature of multi-family housing, a question should be asked whether this direction is in line with the users' expectations. Doubts about the purposefulness of this aesthetic tendency arise from the results of research carried out in many different fields. Firstly, there are many studies which, based on quantitative research, indicate a clear difference between the aesthetic judgments determined by architects and non-architects [10]. Secondly, research clearly shows people's preference for objects and systems with regular features. One should pay attention to the discoveries determined in 2014 by a group of scientists—Pecchinenda, Bertamini, Makin and Ruta [11]. The results of four experiments clearly indicated a tendency to choose patterns or symbols that are symmetrical to asymmetrical. Equally important are the discoveries related to the preferences for fractal-based patterns, which are highly ordered and regular structures. Such patterns are considered to be much more aesthetic than those not based on such structures [12–14]. The same regularity was observed in relation to abstract regular patterns, which, in the research of the Bertamini, Makin and Rampone team, were associated with positively marked words. The associations with irregular patterns were opposite [15]. Thirdly, too much visual variety in the built environment can simply result in spatial chaos.

On the other hand, there are many reasons to move away from extremely repetitive facades. Reports of videoecology clearly indicate the problem of the disappearance of gray brain cells caused by exposure to environments composed of the same, repeatable elements [16,17]. Visually diverse environments also evoke much more positive reactions in recipients [18]. Therefore, it can be assumed that the clear regularity and repeatability in the case of architecture does not reflect the aesthetic needs of a human being, as the results of research by psychologists and neuropsychologists suggest. This could also suggest that we should design irregular compositions that break the monotony and predictability of regular ones. However, in the opinion of the authors, it is not possible to resolve the aesthetic dispute between regularity and irregularity without examining the actual preferences.

An extremely important issue for these considerations is also the issue of universal, biological determinants that govern the processes of perception, determining aesthetic judgments and experiencing beauty [19]. Despite the relatively short tradition of experimental aesthetics or neuroscience, attention should be paid to three publications from 2004 by Vartanian and Goel [20], Kawabata and Zeki [21] and Cela-Conde et al. [22]. All the above-mentioned teams of researchers, thanks to the technology enabling neuroimaging (fMRI or MRI), clearly indicated that when the recipient contacted an object generally considered as beautiful, the reward system was activated in the brain. The results of these studies also highlight the lack of a single structure in the brain responsible for making aesthetic judgments, which are rather the result of more complex processes. Naturally, neurosciences clearly flatten the character of aesthetic experience and may also only provide empirical confirmation of intuitive judgments about beauty [23]. Nevertheless, this approach proves the possibility of describing universal determinants of beauty, common to the general public and independent of the individual's particular characteristics.

Determining the aesthetic preferences regarding the composition of building facades in the context of the degree of their regularity is important as long as they strengthen the designers' awareness of how to shape the space. They can primarily help to determine the directions in which aesthetics should follow in order to meet the expectations of its recipients. They can also help in determining the directions in which architecture should go in order to simultaneously meet the needs and expectations of its users and, at the same time, to not cease being art. The implementation of this task, however, is the role of architects, whose knowledge should be as broad as possible. The results and conclusions of this study can also be a very powerful planning tool. The use of a specific type of composition in a given area could help with building spatial order, but also with breaking the aesthetic monotony or be an architectural reinforcement of an urban dominant.

2. Materials and Method

The aim of the study was to determine the preferences of Poles towards building facades in the context of their regularity. The study was conducted in three stages. The first step was to prepare the research material; then, an internet survey was conducted. The last stage was to carry out statistical analyses of the collected results and to formulate conclusions.

Naturally, each architectural object is a complex being, but each of its components influences the perception of the whole. This approach to the multi-element nature of architecture is reflected in the pattern language proposed by Christopher Alexander [1]. According to the authors, one of the most important patterns is the composition of architectural elements, such as window openings, balconies or elevation panels, because the way the same elements are arranged on the same facade causes its perception to be completely different. The composition also determines the complexity of the facade and the degree of its order [24]. These two determinants were reflected in the parametric method of assessing the aesthetics of an object, proposed by Birkhoff [25] and refined by Eysenck [26]. The composition, therefore, has a significant impact on the perception of the aesthetics of the entire building. A key aspect of the study was to isolate the composition as the test item so as to discover pure preferences for themselves.

2.1. Research Questions

1. Is there a relationship between the degree of regularity in facade compositions and aesthetic preferences?
2. Are regular compositions considered more aesthetic than those with a greater degree of irregularity?
3. Is there a relationship between the type of composition and aesthetic preferences?
4. What kind of composition is preferred the most or the least?

2.2. Research Material

Five visualizations of the building's facades were prepared for the study. The limitation of the number of stimuli presented during the study resulted from the processing capacity of the human brain. The maximum number of items stored in working memory is between five and nine [27]. Comparing stimuli (which was the task of the respondents during the study) requires storing them in working memory. Therefore, limiting number of stimuli to five minimized the impact of limited human cognitive abilities on the final test result.

The stimuli were digitally generated to maximize control over their final image. The only variable between the stimuli was the composition of the window openings. The window openings were presented as the simplest and no other elements were placed on the facade, so that, according to the theory of multilayer composition [2], the compositions of many layers doid not overlap and did not affect the perception of the whole. The basis for each of the compositions was the elevation (Figure 2) with dimensions of 16 × 10 m placed on a uniform background, showing a meadow and greenery in the distance. Reducing the building to a flat facade drawing made it possible to eliminate the influence of perspective on the respondents' perception process. Compositions no. 1–5 (Figure 3) were designed as systems of decreasing degree of regularity, with composition no. 1 having the highest and composition no. 5 having the lowest degree of regularity. This effect was achieved through the use of compositions that differed in terms of type of composition elements (one, two or three types of composition elements) and the method of building vertical composition lines. The composition type indicated tentatively with the letter "X" (Figure 4) meant compositions composed of elements stacked on top of each other at equal horizontal distances (the highest degree of regularity). Compositions tentatively marked with the letter "Y" (Figure 5) were compositions consisting of clearly marked compositional verticals (the same elements one above the other), but the distances between the vertical lines were different (average degree of regularity). The composition type, initially marked with the letter "Z" (Figure 6), also had different distances between the compositional verticals; however, additionally, these lines were not built by the elements arranged in accordance with the axis of symmetry one above the other, but by the side edges of these elements (the lowest level of regularity).

Figure 2. The basis for the stimuli for research.

Figure 3. The incentives presented in the study: (**a**) composition no. 1; (**b**) composition no. 2; (**c**) composition no. 3; (**d**) composition no. 4; (**e**) composition no. 5.

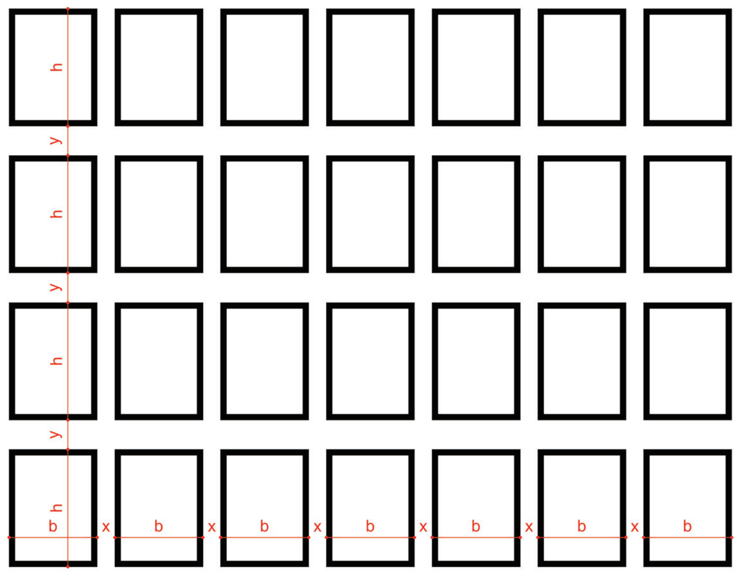

Figure 4. Diagram showing the assumptions of an "X" composition.

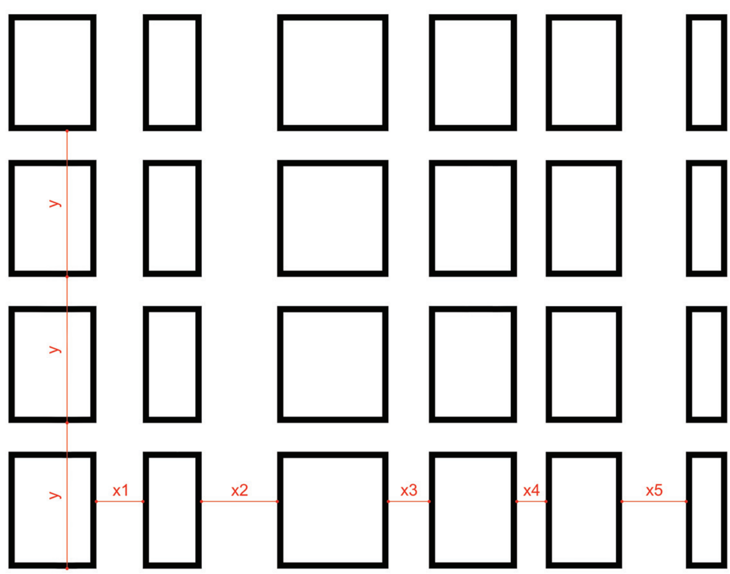

Figure 5. Diagram showing the assumptions of a "Y" composition.

Composition no. 1 (Figure 3a) is the composition of type X with the highest degree of regularity. Composition no. 2 (Figure 3b) is an example of a Y-type composition which differed from the first composition only by the horizontal distances between the window openings and used the same compositional elements. Composition no. 3 (Figure 3c) is also an example of a Y-type composition; however, in this case, different widths of the elements were added, which reduced the degree of regularity of the arrangement with respect to composition no. 2. Composition no. 4 (Figure 3d) is a Z-type composition, based on elements with two different horizontal dimensions. Composition no. 5 (Figure 3e) is also an example of a Z-type composition; however, in this case, elements of three different horizontal dimensions were used. All compositions had 15 elements of equal height arranged in three horizontal lines.

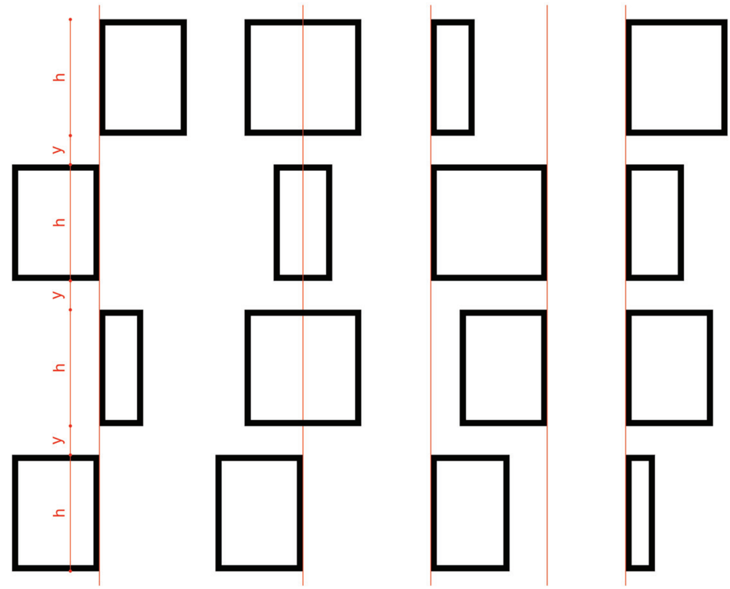

Figure 6. Diagram showing the assumptions of a "Z" composition.

The graphics were prepared on the basis of the original 3D model created in Blender, rendered with the Cycles rendering engine and then processed in Affinity Photo.

2.3. Variables

The following independent variables were introduced into the study: the degree of regularity, defined by a number from 1 to 5, where 1 is the most regular, and 5 the least regular, and the composition type, marked with the letters X, Y and Z (in accordance with the previously described types of compositions). The dependent variable was the degree of aesthetic preference, indicated by a number from 1 to 5, with 1 being the most preferred and 5 being the least preferred.

2.4. Procedure

The performed procedure was based on previous studies [10,28]; however, it used different stimuli, and the rating scale was also limited from 1 to 10 to 1 to 5. On the basis of the prepared research material, an online questionnaire was developed, consisting of two parts. The first part consisted of one task aimed at arranging randomly displayed graphics (described in Section 2.2) from the prettiest (value 1) to the ugliest (value 5). The second part of the questionnaire was not the main element of the study, but it allowed to characterize the research group. This part contained three questions concerning gender, age and education of the respondents, respectively. The survey was conducted from 23 May 2020 to 1 June 2020 and took the form of an online survey. The link to the survey was placed on one of the social networks (Facebook) and shared using a post promotion tool. The message was addressed to people aged 18 to 65 declaring living in Poland.

2.5. Characteristics of the Study Participants

The study involved 109 people (N = 109) and met the statistical guidelines for the minimum survey sample for populations larger than 5000 [29]. Margin of error of the research was at the level of 9%, with a confidence level of 95%. Respondents were aged 18 to 62 (M = 31.18, SD = 11.25), of which 75 were women and 34 were men. In total, 73 people had higher education (66.97%), 28 people secondary (25.68%) and 4 people (3.67%) each had primary and vocational education.

3. Results

3.1. Research Questions 1 and 2

In order to answer research question one, a one-way ANOVA was performed in an intergroup scheme. The dependent variable in these calculations was the degree of regularity (on a scale from one, the most regular, to five, the least regular) to which the presented stimuli belonged. The dependent variable valued the determining aesthetic preferences in relation to stimuli (on a scale from one, the most attractive, to five, the least attractive). A summary of the results obtained during the above-described operation is presented in Table 2.

Table 2. ANOVA summary of the variable "degree of aesthetic preference" depending on the degree of regularity of the composition.

Source	SS	df	MS	F
Between groups	167.76	4	41.94	22.83 **
Inside groups	890.86	485	1.84	
Overall	1058.62	489		

** $p < 0.001$.

The analysis of variance turned out to be statistically significant—F (4.489) = 22.833, $p < 0.001$—, which proved the relationship between the degree of regularity of the composition and aesthetic preferences.

Post hoc tests were performed to see if there were differences in aesthetic preferences depending on the particular composition. The result of Levene's test for the variable "aesthetic preferences" turned out to be statistically significant ($p < 0.001$); hence, the assumption of the equality of variance was rejected and Dunnett's T3 test was used. The analyses showed that there was a statistically significant difference in aesthetic preferences between compositions no. 1 and no. 4 and 5, between compositions no. 2 and no. 4 and 5, and between compositions no. 3 and no. 4 and 5.

The above results, together with the results of the descriptive statistics (Table 3), indicated the existence of two groups of compositions and provided answers to research question two. The first group consisted of compositions with a higher degree of regularity, i.e., no. 1 (M = 2.34; SD = 1.428) , no. 2 (M = 2.45; SD = 1.202) and no. 3 (M = 2.64; SD = 1.270), which did not differ statistically significantly in terms of the degree of aesthetic preferences. The second group consisted of compositions with a lower degree of regularity, i.e., no. 4 (M = 3.62; SD = 1.240) and no. 5 (M = 3.68; SD = 1.596), which also did not differ statistically significantly from each other in terms of the degree of aesthetic preferences. In contrast, the compositions of the first group (i.e., no. 1, 2 and 3) were statistically significantly more preferred than the compositions of the second group (i.e., no. 4 and 5).

The data collected during the survey were also subjected to a statistical correlation analysis. A statistically significant, weak, positive correlation was found between the degree of regularity and the degree of aesthetic preference: r = 0.372; $p = 0.01$. Therefore, the higher the degree of regularity in the composition, the higher the degree of aesthetic preference, which was consistent with the analyses carried out earlier on research question two.

However, attention should be paid to the graph (Figure 7) of the distribution of the frequency of assessments of the degree of aesthetic preference depending on the degree of the regularity of the composition. Although the mean values of the degree of aesthetic preference for the compositions with the degree of regularity 1, 2 and 3 were similar (which was confirmed by the post hoc tests carried out), the response frequency distribution graphs for these compositions clearly differed from each other. Composition no. 1 was significantly more frequently rated as the most aesthetic (37.76% of the response) than compositions no. 2 (21.35% of the response) and no. 3 (16.33% of the response). On the other hand, composition no. 5 was rated as the least visually attractive by 49.49% of the respondents, i.e., 11.73 percentage points more than the most positive grades for composition no. 1. In view of the above, it could be assumed that the irregular compositions elicited negative reactions more strongly than the regular compositions elicited the positive reactions.

Table 3. Descriptive statistics for the dependent variable "Degree of Aesthetic Preference" for composition.

Function	No. 1	No. 2	No. 3	No. 4	No. 5
Standard deviation	1.428	1.202	1.270	1.240	1.596
Standard error	0.144	0.121	0.128	0.125	0.161
The minimum value	2.05	2.21	2.39	3.37	3.36
Mean *	2.34	2.45	2.64	3.62	3.68
The maximum value	2.62	2.69	2.90	3.87	4.00

* Lower value means greater aesthetic preference for a given composition.

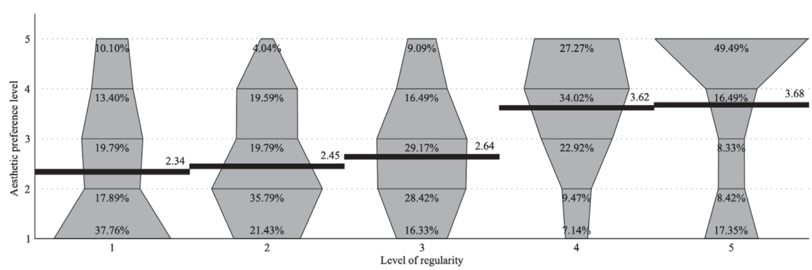

Figure 7. Distribution of aesthetic preferences in relation to the degree of regularity of the facade.

It is also interesting to note that 55.65% of the aesthetic preference score for composition no. 1 was above the average, and for composition no. 2 this was 57.22%. Compositions no. 3, 4 and 5 had more than half of the scores below average, and composition no. 5 had 65.85% of these scores. The above results (presented in Figure 8) meant that regular compositions were more often assessed as the most attractive, while irregular compositions had the opposite effect.

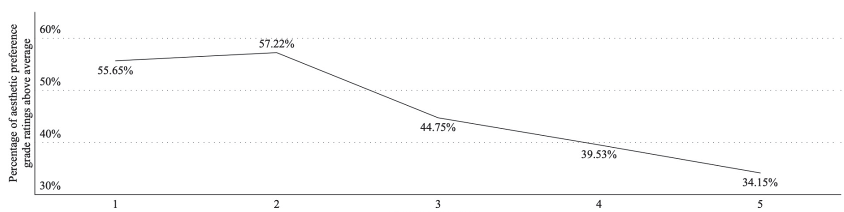

Figure 8. Percentage of aesthetic preference grade above avarage.

The conducted analyses indicated a clear relationship between the degree of regularity in the composition and the degree of aesthetic preference. Although the analyses based on the comparison of means did not prove a linear gradation of correlating variables with each other, the frequency plots showed a different effect. More regular compositions were judged to be more aesthetic than less regular compositions. Equally important is the fact that irregular compositions were assessed as visually unattractive, much more than regular compositions were assessed as attractive. In other words, irregular stimuli elicited a more pronounced effect than regular stimuli.

3.2. Research Questions 3 and 4

In order to answer research question three, a one-way ANOVA was performed in an intergroup design. The dependent variable in these calculations was, the type of composition (marked with the letters X, Y and Z), to which the presented stimuli belonged. Dependent variables valued the determining aesthetic preferences in relation to stimuli (on a scale from one, the most attractive, to five, the least attractive). A summary of the results obtained during the above-described operation is presented in Table 4.

Table 4. ANOVA summary for the variable "degree of aesthetic preference" depending on the type of composition.

Source	SS	df	MS	F
Between groups	165.74	2	82.87	45.199 **
Inside groups	892.88	487	1.83	
Overall	1058.62	489		

** $p < 0.001$.

The analysis of variance turned out to be statistically significant—F (2.489) = 45.199, $p < 0.001$—, which proved the relationship between the type of composition and aesthetic preferences.

Post hoc tests were performed to see if there were differences in aesthetic preferences depending on the particular type of composition. The result of Levene's test for the variable "aesthetic preferences" turned out to be statistically significant ($p < 0.001$); hence, the assumption of the equality of variance was rejected and Dunnett's T3 test was used. The analyses showed that there was a statistically significant difference ($p = 0.05$) in terms of the aesthetic preferences between composition type X and Z, and also between type B and E. The above results combined with the results of descriptive statistics meant that compositions of type X (M = 2.34; SD = 1.428) and Y (M = 2.55; SD = 1.237) were preferred at a similar level. At the same time, these compositions were more preferred than the Z type compositions (M = 3.65; SD = 1.426). Descriptive statistics are presented in Table 5.

Table 5. Descriptive statistics for the dependent variable "Degree of Aesthetic Preference" for composition.

Function	Type X	Type Y	Type Z
Standard deviation	1.428	1.237	1.426
Standard error	0.144	0.088	0.102
The minimum value	2.05	2.37	3.45
Mean *	2.34	2.55	3.65
The maximum value	2.62	2.72	3.85

* Lower value means greater aesthetic preference for a given composition.

One should also pay attention to the data contained in Figures 9 and 10. The distribution of the frequency of the assessments of the degree of aesthetic preference depending on the type of composition showed that although the means for type X and Y were similar (which resulted from the post hoc tests), the compositions of type X were almost twice as likely to be rated most attractive (37.76% of responses) than compositions of type Y (18.88% of responses). Equally important is the fact that only 36.85% of the respondents assessed

Z-type compositions above average and, what is even more important, only 21.18% of the respondents assessed such compositions as positive (value one or two). The above results clearly indicate that X-type compositions were perceived as more attractive compared to Y-type compositions, and the compositions of both types clearly dominated (in terms of aesthetic preferences) over Z-type compositions.

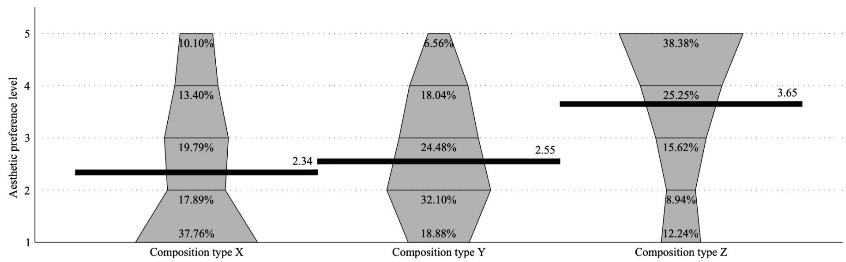

Figure 9. Distribution of aesthetic preferences in relation to the composition type of the facade.

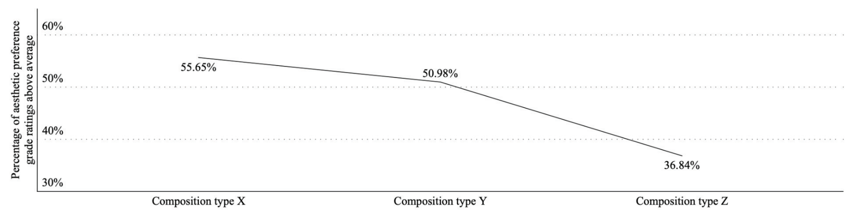

Figure 10. Percentage of aesthetic preference grade above average.

The conducted analyses indicated a clear relationship between the type of composition and the degree of aesthetic preference. Statistics based on averages showed that both the X and Y-type compositions were stated to be more attractive than the Z compositions; however, the differences between X and Y types were statistically insignificant. The analysis of the frequency charts showed, however, that also between types X and Y there were clear differences in the degree of aesthetic preference, where X-type compositions were twice as likely to be the most attractive compared to Y-type compositions.

4. Discussion

The aim of this study was to determine the relationship between the degree of regularity of the composition and the type of composition of the building facade and aesthetic preferences. Therefore, a questionnaire survey was conducted. Statistical analyses of the collected results created the possibly to answer research questions and formulate conclusions.

The results of statistical analyses clearly indicated the relationship between the degree of the regularity of the composition and the aesthetic preferences for these compositions. Although the correlation index indicated a weak relationship between these two variables, further analyses clearly showed that, generally, compositions with a higher degree of regularity were preferred over the less regular ones. Thus, the compositions of the type X and Y were considered more visually attractive than the compositions of the type Z. It could, therefore, be assumed that the key element for the perception of a given facade composition is the legibility of the vertical composition axes. The compositional axes in the case of Z-type compositions were marked less clearly than the arrangement of elements one above the other according to their axis of symmetry, as in the case of X and Y compositions. It also resulted from the Gestalt principles closeness and continuity [30], according to which we perceive compositional elements one above the other as one vertical line. The grouping of elements vertically and not horizontally results from the vertical nature of architecture [31].

This direction is also suggested by the window openings themselves, which usually have the proportions of a vertically arranged rectangle.

However, a question may be raised as to whether the compositional axes themselves or the clarity of the rule according to which a given composition was created were important in this aspect. Naturally, compositions of type X were subject to the greatest number of constraints and were the most ordered; therefore, the readability of these rules was the greatest in this case. Furthermore, the arrangement of elements one above the other according to the axis of symmetry of each of them was the most natural arrangement, and the compositional axes built by the side edges of the elements (as in the case of Z-type compositions) were not so clear and required a longer analysis. The application of compositional rules, however, was closely related to building compositional axes, although not necessarily in the vertical direction. Therefore, it may not be possible to investigate the correlation between the clarity of a compositional rule and aesthetic preferences in isolating the compositional axes from readability. The results of such analyses would certainly be very interesting and would broaden the knowledge of the perception of composition.

5. Conclusions

The results of the study are in line with previous reports on abstract patterns [11–15]. Facades with a regular composition were found more aesthetic than those with an irregular composition. However, the most important for shaping architecture is the effect associated with the negative impact of irregularity, which was clearly stronger than the positive impact of regularity. Such results suggest the need to explore the subject of composition, especially in the context of the perception of irregular compositions (e.g., "Z" type), as it may turn out that they are definitely considered visually unattractive. On the other hand, the conscious use of compositional irregularity may be a desirable visual reinforcement for a dominant or other significant object.

Nevertheless, in the opinion of the authors, formulating general guidelines for designers and architects on the basis of this study would be too hasty. The conducted research should be treated as a starting point for further analyses, deepening the subject of the perception of compositions. First of all, attention should be paid to the problem of the scale of the building. It may turn out that, in the case of larger buildings, regular compositions would not be the most frequently chosen, which would be consistent with the reports of videoecology [16,17]. Relating the research to larger facades would also involve the analysis of compositions consisting of a greater number of elements and would also allow the creation of systems with more subtle differences in the degree of regularity.

Subsequent research should also take into account the influence of other architectural elements on composition preferences. It may turn out that different surroundings, a different colour or material of the façade, different shapes of windows or forms of roofs or the shape of the façade itself would result in a change in preferences regarding the composition.

Another important issue is the multilayer composition theory [2] and the influence of the composition of individual layers on the preference for the composition of the whole. Certainly, the way the stimulus is presented is also important. It would be interesting to see the results of research carried out on the basis of visualizations of buildings from the human perspective. Furthermore, the use of technologies, such as VR, could provide interesting results and would make it possible to arrange a virtual walk; thus, bringing the perception processes occurring during the study closer to those that appear under normal conditions.

This study, in the opinion of the authors, also indicated a very important feature of the composition, which is the degree of regularity. Not only preferences, but also the perception of the degree of regularity in the composition should be the subject of separate research. The results of such analyses could allow for a more conscious design, as they would give designers an understanding of what reactions and perceptions are generated by specific aesthetic treatments.

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Conflicts of Interest: The authors declare no conflict of interest.

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The Interior Experience of Architecture: An Emotional Connection between Space and the Body

Keunhye Lee

Department of Interior Architecture, Gachon University, Seongnam-si 13120, Korea; narykh.lee@gmail.com; Tel.: +82-(0)10-8769-9387

Abstract: This paper provides a phenomenological understanding of interior space to explore the emotional connection between space and experience. It focuses on the significant aspects of interior space, considering how people experience interior space and which aspects improve the quality of spatial and emotional experience. I have argued that the interior experience offers effective ways of stimulating emotional experience to create spatial perception as a way of understanding architecture. Interior experience can be developed through: (a) stimulating a lived body; (b) emphasizing materiality; and (c) generating emotional connection. This allows people to develop an awareness of the sensual aspects of the interior space and improve the quality of their emotional experiences. I have drawn upon representative case studies about spatial experience to explore how they use materiality to stimulate sensory effects and how the multi-sensory space connects with emotional experience, which is one of the fundamental aspects of this paper. I found that an integrated body and materiality are fundamental elements that are needed to enrich the spatial experience, even in an abstract dimension of the work without architectural form. Thus, this paper contributes to the understanding and knowledge of the relationship between interior space and experience with respect to improving the quality of the emotional experience in order to develop spatial experience and considering how experience intervenes in interior space to create a multi-sensory space.

Keywords: interior experience; multi-sensory experience; movement; sensory body; emotion; materiality

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1. Introduction

This paper provides a phenomenological understanding of interior space to explore the emotional connection between space and experience. It emphasizes the importance of interior experience as a way of understanding architecture. It considers how people experience interior space, what elements, forms, and techniques can be used to improve the quality of spatial experience in architecture, and which aspects of interior space stimulate multiple senses, which help to create a better experience through emotional connection in the realm of architecture.

Over the last century, the field of architecture has focused on the functional and morphological aspects rather than on its relationship to people and its environment of interior space [1–4]. In addition, the visual-oriented representation of architecture has led to the predominance of the visual experience over other sensory effects [5].

In recent decades, however, there has been much discussion on the phenomenological understanding of architectural space, as it has become more critical to focus on how people experience the space rather than on the current visual-oriented architectural form; this has been raised as a fundamental issue in both an academic and practical context [4,6–10]. Although there are already many studies on the phenomenological understanding of architecture, these rarely discuss the importance of the interior experience of architecture and its connection to the emotional aspects that enrich the quality of architecture. An interior experience that emphasizes the body and environmental stimuli represents an immersive experience, affecting emotion [11]. The body here means bodily movements and senses as a subject to interact with interior space, while environmental stimuli are understood as interior environments that directly respond to the body. In this sense, this paper argues that the interactive connections between the body and environmental stimuli are substantial elements for generating the emotional experience that improves the quality of interior experience, understood as "the origins of architecture" [12]. Thus, it is worth looking at the interior experience of architecture for an emotional connection between space and experience, engaging the body and various aspects of interior environments.

An architectural experience cannot be perceived merely through the visual sense. Instead, as has been emphasized by many theorists and architects, such as Juhani Pallasmaa, Peter Zumthor, Kengo Kuma, and Yi-Fu Tuan, it is understood through the eyes and experienced through the entire range of bodily senses and the physical movements of the body "as one moves through it and actively interacts with it" [13] (p. 168). This idea was initially developed by philosophers such as Kant and Hegel and later by Martin Heidegger, Gaston Bachelard, and Maurice Merleau-Ponty. These phenomena and how we experience space through our body are emphasized [14] (p. 6). In this sense, Finnish architect Juhani Pallasmaa (2005) states that "[e]xperiencing architecture is multi-sensory; qualities of space, matter and scale are measured together by the eye, ear, nose, skin, tongue, skeleton and muscle. Architecture strengthens one's sense of being in the world, and this is basically an enforced experience of self. Instead of mere vision, or the five classical senses, architecture involves several realms of sensory experience which interact and fuse into each other" [10] (p. 41).

In this respect, some contemporary architects, designers, and artists highlight the importance of spatial experience in their projects by engaging with several issues, such as materiality, the body, senses, emotion, and environments. Their projects are presented using various methods, including architectural space, pavilion, and installation. For example, Peter Zumthor's Thermal Vals provides a phenomenological experience in which various sensory elements are transmitted to the body; it allows people to touch water and stones, see the light and darkness, hear the sounds of flowing water, and smell the mist of the water [7,15]. The Blur Building by Diller + Scofidio concentrated on the awareness of bodily experiences and sensations to generate an emotional connection. This pavilion provided an immersive experience that stimulated all of the senses due to the sight being blocked by mist [16] (pp. 48–49). Responding to Peter Zumthor's architecture, Olafur Eliasson's the Mediated Motion provided sequential spaces filled with natural materials, including water, steam, fog, earth, wood, fungus, and duckweed [17]. Eliasson allowed visitors to be a part of the exhibition, engaging "their senses, memory, and reflections to make his projects more profound" [18]. Some works create a physical architectural space, stimulating spatial experience through bodily movements and senses, while some other projects present abstract space using ephemeral yet experiential material, engaging emotional experience or feelings. They have the power to provide a spatial experience through bodily engagement and to stimulate users' emotions. While visual-oriented spatial experience focuses on the physical forms of architecture, interior experiences that are felt through engaging the body and environmental stimuli provide multi-sensory space and generate various types of emotional experience [13] (p. 169). These projects trigger me to consider: (a) the meaning of experience in the realm of architecture; (b) how people can obtain a sensory experience from interior space; and (c) which aspects of interior space can improve the quality of spatial and emotional experiences. This paper investigates various elements to find a way of improving the emotional experience and therefore developing the interior space, rather than measuring the emotional levels numerically. Thus, the hypothesis of this paper relies on the qualitative-analytical and bibliographical research methods. To explore these research questions, I formulated two hypotheses.

1. An interactive connection between the body and various elements of interior space improves the interior experience, providing a personal connection to culture and emotion.

2. Sensory effects that enhance the emotional connection with the interior space can potentially enrich the spatial experience and improve its quality to greater effect than functional or form-oriented factors.

This is an opportunity to develop the idea of the body and interior space, which may lead to theoretical and practical aspects with contemporary significance. Methodologically, this paper demonstrates the value of the phenomenological understanding of the interior experience for emotional connection. For this, I investigate:

1. The meaning and essential aspects of interior space;
2. The meaning of the body and experience in architectural space;
3. Case studies, through analyzing the selected architectural space; and
4. Various effective ways of improving the qualities of interior experience and its emotional connection, which I then go on to discuss.

Thus, this paper attempts to analyze various characteristics of the environmental stimuli of interior space as a way of showing how experiencing space can create a connection with personal emotion. This is done through the use of selected case studies of architectural representation that are presented in various ways. This paper presents ways in which the interior experience can contribute to a phenomenological understanding of the architectural realm, engaging several key issues, such as the body, senses, emotional experience, and culture, which solidify spatial perception.

2. Interior Experience as the Origin of Architecture

2.1. Interior Space

This section investigates the meanings and essential aspects of interior space in understanding architecture. It focuses on the body and materiality, understood as a subject and object, respectively, considering how interior space engages the body and provides a sensual experience.

Many architects and researchers focus on the primacy of interior space in architectural experience because "the inside is always more important than the outside" [19] (p. 274). This is because most people spend more than 90 percent of their lives indoors [20] (p. 4). In this sense, Bart Verschaffel states that the significant aspect of architecture is "the creation of an interior, [which] separates a circumscribed space from its environment and turns it into an inside" [21]. In addition, interior space can impact the people who occupy and use those spaces; it is strongly related to our body and is understood as a communicative form. In this sense, Frank Lloyd Wright states, "[t]he space within becomes the reality of the building" [22] (p. 217), because interior space allows people to dwell, live, move, and enact the rituals of their everyday life. It demonstrates that the "reality of the building does not consist in the four walls and the roof but in the space within to be lived in" [22] (p. 80). Concerning this, John Dewey defines architecture as "the formation of interior space", as it provides "opportunity for movement and action" [23]. These ideas emphasize the important connection between interior space and the body. The interior space, engaging the body, provides spatial experience, which generates an emotional connection. Many architects, such as Louis Kahn, Wright, and Zumthor, agree that the most important function of architecture is "to enrich experience and enhance the life that takes place within it" [12] (p. 9). Paul Goldberger also highlights the importance of interior experience, "by staying in one place and taking it all in" [24], in order to feel the space. This emphasizes that interior experience is emotional and communicative because it engages the body.

People continuously interact with various elements of interior space. The environment of interior space provides material worlds. Material worlds here not only means physical aspects, such as wood, brick, and concrete, but also substances, including proportion, form, texture, light, shapes, color, temperature, smell, and even sound. This is understood as environmental stimuli. It can be divided into two aspects: the morphological factor, which is a visual composition of architectural space, and the sensual factor, which relates to arousal of people's sensory perceptions [25]. For example, people primarily experience the various features of environmental materials within an interior space. Beyond the immediate visual qualities of a space, the sensual factor can be felt through our body; for example, people can smell various odors, touch the texture of surfaces, and reflect sound while walking inside. This means that interior space can be "defined not only by occupation but also by materiality" [26] (p. 1). The materiality of the interior space can reflect the spatial usages, revealing traces made by our body, as Walter Benjamin states [27]. This shows that materiality, as an environmental stimulus, can enhance the spatial experience by engaging the body. In relation to this, Peter Zumthor states that "[t]he material presence of things in a piece of architecture, its frame. That kind of things has a sensual effect on me" [28] (p. 23). This shows that materials provide interior environments and directly stimulate sensory experience. In other words, materiality can be understood as a medium to connect with the body and the interior space. It shows how people relate to the interior space and engage with materiality; a method of communication between the body and the space. The environmental stimuli can also evoke our memory and cause us to "feel" [14]. Moreover, social and cultural environments are also a substantial factor affecting what people experience, because the built environment is an integral part of the social and cultural order [29] (p. 457). In relation to this, Kahn refers to the interior space as "a society of space", which generates social and cultural relations [12].

The interior space becomes the manifestation of what people perceive, experience, and feel. It also reflects how people use, occupy, transform, and adapt to space. This spatial experience can transform the space into place, emphasizing the sense of insideness within the dwelling [30] (p. 20). It shows that the interior space is strongly related to a lived body [31] within the material world, reflecting spatial identity and culture. The interior space contains various elements, comprising physical factors, space, and the body. In other words, the interior space can be defined by the body and becomes the reflection of the identity, subjective experience, and personal responses [26] (p. 2). Thus, interior spaces can be understood and explained not only by architectural forms, but also by their relation to the body, environmental stimuli, and culture, which forms the meaning of space through experience. This idea provides a framework for exploring how the multi-sensory atmosphere of interior space can be formed and how this stimulates spatial experience and emotional connection. Table 1 shows the key aspects of interior space.

Table 1. Characteristics of interior space. Source: author's drawing.

	Contents	
Environmental Stimuli	Morphological Factor (Form and pattern)	volume, scale, rhythm, order, proportion, contrast
	Sensual Factor (Material connection)	texture, light, shadow, color, temperature, sound, smell
	Influential Factor	cultural symbolism, local/social issue
Container	• Interior space is a container where various elements, such as the body, objects, and materials, are involved. • Interior space engages the body as a form to interact with. • Interior space can be transformed into a place through bodily experience.	

2.2. The Body and Experience

The body is significant in the understanding of architecture and its history. Historically, architecture has mainly been experienced through the visual sense. The body can be understood as an element of nature and ingredient of form, and in the past it was described as the most fundamental measurement of self [16]. It has long been the medium through which Western culture and society has represented the architectural environment [7]. Although the body was a fundamental representation of architecture and has been used as a system of proportion throughout history, the experiential and emotional roles played by the body in the subject's thinking were ignored entirely, a situation that lasted until the 20th century [6,16]. This shows that the physical representation of the body emphasizes the visual aspects rather than the spatial experiences. However, contemporary theorists and architects, such as Maurice Merleau-Ponty, Juhani Pallasmaa, and Peter Zumthor, highlight the significant aspects of the bodily experience for emotional connection within the interior space of architecture. They consider how a lived body can "effectively create a more emotionally charged space and consequently [cause] an emotional connection within architecture" [16] (p. 12). The physical body and its emotional connection can stimulate the sensory experience of architecture.

The body can be a form that is used to interact with space, allowing us to experience the interior environment that generates spatial perception. The bodily experience in architectural space can be interpreted through phenomenological understanding. Phenomenology is the most effective and applicable approach to architecture in response to the body, emphasizing experience through continuous interaction with various elements [32] (p. 565). For example, people experience space through the body as soon as they enter an inside area. In this sense, Merleau-Ponty concentrates on perception, body, and the sensible dimension of human experience, providing "an important perspective on more practical, applied architectural issues" [5] (p. 13). Pallasmaa is indebted to Merleau-Ponty, particularly to themes such as the lived body, perception, and mobility. In this regard, Steen Eiler Rasmussen underlines the experience of architectural space, stating that "it is not enough to see architecture; you must experience it" [33]. In this sense, Zumthor uses emotion as a measuring tool for experience [28]. This means that architecture is not just experienced visually, but through the entire body, such as through movements and the senses, stimulating spatial experience [34]. In other words, the phenomenological approach is used to explore the relationship between space and the body through experiences. This idea can be seen as parallel to the Asian philosophy of traditional architecture, which emphasizes the interrelationships between body, mind, environment, and cultural identity in order to understand architectural space [35–39]. However, these ideas have rarely been discussed in the realm of architecture, either in Asia or in the West [38,40]. Furthermore, bodily movement is also an important method of experiencing space. Bodily movement can be divided into two aspects: physical movement and visual movement. It provides dynamic experiences through changes that occur due to spatial sequences [41,42]. It shows that bodily senses and movements provide constant dialogue with interior space due to spatial experience.

Spatial experience can be physical, sensory, and mental. The term "experience" itself emphasizes the body as a medium for interacting with objects and space, generating emotional aspects. According to the *Cambridge Dictionary* (2022), experience means "something that happens to you that affects how you feel" [43]. This shows that the word includes both physical and emotional qualities through doing and feeling. In this sense, to experience space is to interact with space through the body and mind; people can recognize, act on, and perceive the space through their entire body. This means that the physical, sensory, and emotional aspects of the body cannot be separated. For example, people can perceive the surface of the concrete with their eyes, feel the surface by touching it with their skin, smell the air of an interior space, and listen to the sound of footsteps while walking inside. Therefore, an entire body can be viewed as a sensing apparatus that gauges a space, other people, and surrounding objects in order to produce a spatial experience [44]. This method of sensory experience can generate an emotional experience; it is specific to place, time, and materials. In this respect, Yi-Fu Tuan states that "place is a center of meaning constructed by experience [. . .] through not only the eyes and mind but also through the more passive and direct modes of experience" [45], which evokes feelings. This shows that place can be understood as a space where a particular spatial experience and its emotional connection are embedded. John Dewey defines experience as the whole process of human adaptation to the environment through interaction with the environment. He also emphasizes that human activities are incorporated from rational and emotional thoughts and acts [46] (p. 41).

People perceive the world through a lens generated by the emotions they experience [12,47]. Emotions are an expression of our feelings that appear according to certain situations and experiences. Emotions are related to both personal experiences of interior space and social experiences, affecting spatial perception and definition. This can be embedded within the body as memories, which form a spatial identity. For example, each person has different spatial memories, as they have experienced space differently [48]. This shows that interior space can evoke a socially memorized spatial experience that affects one's emotions. In other words, we can all experience space differently, even if we are in the same space. In this sense, Pallasmaa states that "all experience implies the acts of recollecting, remembering and comparing" [10] (p. 72). This allows us to experience interior space in various ways, stimulated by overlapping our present experiences and the memories formed by past experiences [46] (p. 38) within the culture.

Thus, to experience space is to understand space phenomenologically, engaging the body, environmental stimuli, and culture to provide an emotional connection (see Figure 1). This provides some of the varying approaches for understanding the distinct ways of conceptualizing how interior space is experienced through the meanings of the body, which could provide theoretical and practical approaches to exploring the cultural context. Experiencing space in this way has been described in phenomenology as "multi-sensory", a way of interacting with space through a sensing apparatus of the body. In relation to this, Tuan (1977) explores the relationship between people and space, examining the sensory and affective experience. Tuan writes, "[t]he given cannot be known in itself, what can be known is a reality that is a construct of experience, a creation of feeling and thought" [49] (p. 9). Tuan's idea addresses how people feel and think about space and how they form a sense of attachment to space, based upon memories or intimate experiences.

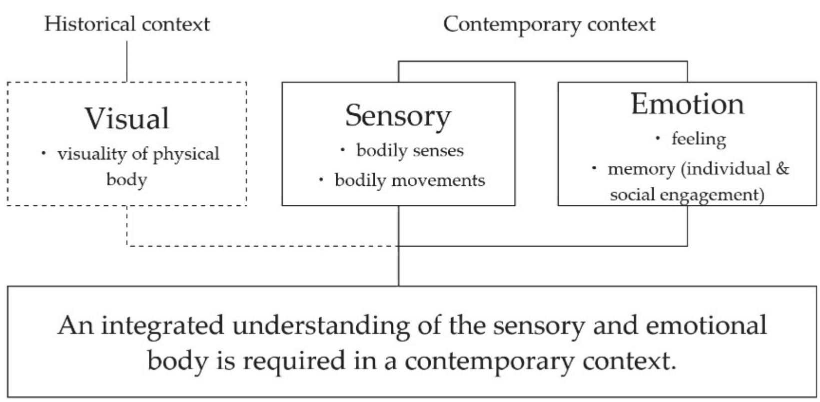


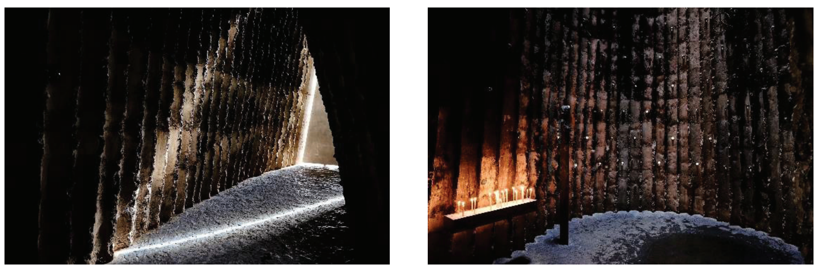
Figure 1. Phenomenological understanding of the body. Source: author's drawing.

3. Multi-Sensory Experience and Emotional Connection: A Review

The interior experience is likely to be significant in the phenomenological understanding of architecture, but discussions regarding the issues concerning the emotional connection are still at an early stage. Therefore, due to the limited amount of research regarding the connection between interior experience and emotion, it is worth looking at several architectural projects. The review of these projects not only covers existing architecture, but also pavilions and conceptual installations. This is because such projects provide both the symbolic meaning of architectural space and various ways of understanding spatial experience. For the case study, I have therefore selected two prominent phenomenological architects, Peter Zumthor and Kengo Kuma, and analyzed how they created architectural space in order to improve the quality of interior experiences and emotional connections.

3.1. Bruder Klaus Field Chapel, Peter Zumthor

In 2007, the Bruder Klaus Field Chapel was built by Peter Zumthor in Mechernich in Germany (see Figure 2). The most significant aspects of the Chapel are found in the construction methods [50,51]. Twenty-four layers of concrete were poured into a wooden frame surrounding the tree trunks, which were stacked in a curved conical form. Once the concrete had set, the wooden frame was set on fire. When the blaze subsided, only the concrete was left, containing a blackened void where the logs' shape and bark were imprinted, and emitting a particular smell. After removing the frame, many small holes were left behind in the walls and crystal shafts were inserted into the holes, which created an effect reminiscent of the night sky [50–53]. These refracted lights from the crystal shafts contrasted to the rough, blackened concrete surfaces surrounding them [51,52]. These elements were used to create a structure, but the effects are far more evident in the interior space; "the process of construction is integrated with the experience of space" [53] (p. 290).



(**a**) (**b**)

Figure 2. Peter Zumthor, Bruder Klaus Field Chapel, 2007. (**a**) entrance area (**b**) interior space (Photos: August Fischer).

The environments of the interior space are a stark contrast to the smooth, angular façade. During the short journey from entering the structure to the inner space, "the horizontal movement through space is slowly shifted to a vertical movement with the eyes" [53] (p. 290). "[The] gaze is pulled up by obvious directionality to the point where the roof is open to the sky and the night stars" [50]. Sunlight, air, and rain all penetrate the opening and create a particular environment and experience based on the time of day and the season.

3.2. Serpentine Pavilion, Peter Zumthor

The Serpentine Pavilion 2011 was created by Peter Zumthor for meditation that evoked a spiritual experience (see Figure 3). At the center of the pavilion was an inner garden, which was conceived by Dutch designer Piet Oudolf [54]. Zumthor highlighted the role of the senses and emotions in our architectural experience. The pavilion provided a hallway with multiple paths and staggered doorways for visitors, which gently guided them to a central, hidden inner garden. The covered pathways and seating areas surrounding the central space created a calm and meditative environment from which visitors looked out onto the richly planted sunlit garden, which was the center of the pavilion [55].

While traveling through a dark hallway with intermittent natural light streams, visitors were directed "away from the bustling city and toward the secluded, intimate interior" [56]. Through blackness and shadow, "visitors entered the pavilion from the lawn and began the transition into the central garden, a place abstracted from the world of noise, traffic, and the smells of London—an interior space that allowed people to sit, to walk, and to observe the flowers" [54] for meditation. The carefully chosen flora produced various colors, fragrances, and textures that stimulated the individuals' bodily senses [56].

(**a**) Sitting areas (**b**) A floral garden (**c**) Corridor

Figure 3. Peter Zumthor, Serpentine Pavilion, 2011. (Photos (**a**,**b**): author. Photo (**c**): John Offenbach).

3.3. Sensing Space, Kengo Kuma (2014)

The Sensing Space was a new type of architecture exhibition presented at the Royal Academy in 2014, emphasizing the experiential aspects rather than the functional aspects of architecture. Seven prominent architects were invited to focus on the sensory qualities of architecture [57]. The exhibition encouraged visitors to consider how architecture makes people feel. As a part of the Sensing Space exhibition, Kuma introduced certain scents into two darkened rooms to provoke memories of a particular space: the smell associated with architectural aspects of Japanese culture (see Figure 4). He interpreted the aroma of architecture as a full bodily sensation "inspired by a *Ko-Do*, Japanese smell ceremony, which has similarities to a *chado*, the traditional Japanese tea ceremony" [58].

(**a**) (**b**)

Figure 4. Kengo Kuma, Sensing Space, 2014. (**a**) Kuma's installation (**b**) Kuma's installation (Photos: James Harris).

In these darkened rooms, he created the woven bamboo structures as a traditional Japanese architectural material, with spotlights infused with the aroma of *tatami* mats and *hinoki*. Kuma referred to darkness as being "very important in traditional Japanese architecture [...] Darkness also emphasizes the distinctive scent in each installation" [59]. A review in the *New Statesman* stated that this particular scent evoked the childhood home that comforted him and sent him "to the sleep of the innocents" [59]. This is a personal experience shared not only with visitors who have similar memories, but also those who are not familiar with the smell.

3.4. GC Prostho Museum Research Center, Kengo Kuma (2010)

Designed by Kengo Kuma, the wooden structure of the GC Prostho Museum Research Center was built in Aichi Prefecture, Japan, in 2010 (see Figure 5). The GC Prostho was inspired by a traditional Japanese toy called a Chidori. Chidori is a three-dimensional puzzle composed of interlocking timber sticks that feature joints that can be assembled by twisting the sticks without the aid of fittings, such as nails [60–62]. The Chidori system provides a flexible structure and anti-object where space is delineated by light, structure, and materiality. People first encounter the wooden structure and experience glimpses of the interior space according to light conditions [60]. When entering inside, people experience "a cave-like space carved out of the lattice that is concurrently experienced as connected to the exterior while distanced from it due to the viewing angle densities of the Chidori system" [60]. The quality of spatial experience is provided by integrating light and shadow from the east-facing structure; "sunlight filters through the lattice structure, creating an ever-changing pattern of shadows" [53]. Kuma refers to these patterns created by light and shadow as "a forest of deciduous trees, where you can enjoy sunshine filtering through" [62]. This filtering of light through lattice provides constantly changing patterns and volumes throughout the day and allows people to experience the spiritual nature of the space in various ways.

(**a**) (**b**) (**c**)

Figure 5. Kengo Kuma, GC Prostho Museum Research Center, 2010. (**a**) Façade (**b**) The lattice structure (**c**) Interior space (Photos: Daici Ano).

4. Analysis and Discussion

The case studies discussed above present the important connection between the sensory body and materiality (environmental stimuli) and show that the interior experience affects the emotional experience. Three key aspects have been raised as significant in order to improve the qualities of interior experiences, which are: (a) the stimulation of the body through movements and senses; (b) the use of materiality, which allows people to develop an awareness of the sensual aspects of interior space; and (c) emotional connection, which can be shaped both individually and socially. However, throughout the research, I found that: (a) these three aspects cannot be separated, but rather an integrated understanding is required, providing multi-sensory experience; (b) a particular factor provides cultural experience by stimulating socially shared memory; and (c) an abstract dimension of a work without architectural form also provides spatial experience through stimulating bodily senses and evoking personal memory. It allows people to smell, hear, and touch the materials of the interior space while walking inside, which evokes a particular memory of one's past experiences through emotional connection. This means that interior experience is physical, sensory, cultural, and mental. The characteristics of the architectural projects found through analyzing the case studies are as follows (see Tables 2 and 3).

As shown above, the case studies concentrate on particular environmental materials and stimulate bodily senses in order to provide a spatial experience and its emotional connection. For example, Bruder Klaus Field Chapel and Serpentine Pavilion focus on the integrated ways of using various environmental elements, providing a multi-sensory space. On the other hand, Kuma's Sensing Space and Prostho Museum concentrate on a particular element, stimulating a socially shared memory. The materials help people to experience, feel, and perceive the space in a particular way. In this sense, Zumthor states that "materials react with one another and have their radiance, so that the material composition gives rise to something unique" [28] (p. 24). The materiality stimulates bodily senses, which are not independent, but interactive with each other, to provide a multi-sensory experience of a place in time.

Table 2. Characteristics of architectural projects. Source: author's drawing.

	Peter Zumthor's Bruder Klaus Chapel	Peter Zumthor's Serpentine Pavilion	Kengo Kuma's Sensing Space	Kengo Kuma's GC Prostho Museum
Type	Chapel	Pavilion	Installation	Museum
Location	Mechernich, Germany	Hyde Park, UK	Royal Academy, UK	Aichi, Japan
The Body	• Movements • Senses: smell, tactility	• Movements • Senses: smell, hearing, tactility	• Senses: smell	• Movements • Senses: tactility
Materiality	Light, water, concrete, woods, and fire.	Plants, flowers, black wall, light	Aromas, wood strips	Light, shadow, woods, glass
Emotion	• Spiritual inspiration • Meditation	• Meditation • Relaxation	• Socially shared memory	• Sense of space • Cultural connection
Spatial Experience	To emphasize material experience, particularly smell and tactility, through multi-sensory space for spiritual experience. To use native materials for a strong connection to a particular place in Germany.	To emphasize visitors' sensory experiences and provide space for meditation. To provide various emotional experiences through the interaction of gardens, light, and darkness.	To provide a culturally specific spatial experience, providing a socially shared smell of a Japanese home. To emphasize materiality and senses rather than architectural form.	To provide a sense of space with formlessness, providing a cultural idea of a lattice structure. To use light and shadow for various spatial experiences in changing spatial atmospheres.
↓ Various aspects, such as the physical and sensory body, materiality, and emotional connection, were combined to improve the quality of the interior experience.				

Table 3. Analysis of various aspects of spatial experience for emotional connection. Source: author's drawing.

	Morphological Factor					Sensual Factor								Influential Factor		The Body	
	Volume	**Scale**	**Rhythm**	**Order**	**Proportion**	**Contrast**	**Texture**	**Light**	**Shadow**	**Color**	**Temperature**	**Sound**	**Smell**	**Culture**	**Local**	**Senses**	**Movements**
BKC	○	○				○	○	○	○		○	○	○		○	○	○
SP	○	○			○	○		○	○	○	○	○				○	○
SS			○	○	○				○				○	○		○	
PM	○	○	○	○	○		○							○		○	○

BKC: Bruder Klaus Chapel, SP: Serpentine Pavilion, SS: Sensing Space, PM: Prostho Museum.

An integrated understanding of environmental stimuli and the body can improve the multi-sensory experience. Thus, experiencing architecture provides a multi-sensory space; "qualities of space, matter and scale are measured together by the eye, ear, nose, skin, tongue, skeleton and muscle" [10] (p. 41) within the material worlds. This means that interior space provides a sensory experience that combines all of the senses. The interior space reinforces one's sense of identity and enriches the experience. For example, when visiting an architectural space, what most strikes people is not the physical function for which it was created, but the feelings it transmits through materials, stimulating their bodily senses. In this sense, the case studies demonstrate that the stimulation of bodily senses and their connection to environmental stimuli can improve the quality of spatial experiences, generating emotion.

Peter Zumthor focused on the tactile sense in order to provide spatial experiences when engaging with materiality in the Chapel. In particular, he focused on the sense of touch, which is directly related to the use of materials, and deals with several key issues, such as the body, surroundings, and spatial continuity in time [63]; it connects with particular aspects, such as environments and the culture of a specific place. In relation to this, many architects and theorists concentrate on significant aspects of tactility as a source of a visual sense that exceeds "two-dimensional surface texture" [64]. This introduces a sense of how "touch performances propose qualities of feeling that impact powerfully and ideologically" [65] (p. 167). This means that differentiated sensory organs in the skin can understand space by "touching", which is related to the sense of touch. Jennifer Fisher, Assistant Professor of Contemporary Art and Curatorial Studies at York University, highlights that "tactilism is strikingly performative" [65] (p. 166). It means that tactilism stimulates one's entire body, engaging various elements within space. The tactile experience that integrates space and one's own experience is perceived through the skin. The skin is a sensory organ and acts as a canvas for tactile sensation within the cultural context. In this regard, the tactile sense provides two key attributes: texture and temperature [20,66,67]. For example, our skin can measure the temperature of the surroundings in an interior space and can experience the texture of an interior space through the tactile experience of stroking the surface. Moreover, the sense of touch can be considered the visual unconscious. In relation to this, Merleau-Ponty focuses on the significance of "visual tactilism". He argues that people can see the depth, smoothness, softness, and hardness of matter with their eyes [68]. This shows that the visual-tactile sense observes both materials that are far away and things that are close with the same intensity, combining them into a coherent and intimate experience. Zumthor also writes about material, stating that "people interact with objects. As an architect, that is what I deal with all the time" [28] (p. 17). He argues that touch is a synergetic sensory link that amplifies our bodily experience of the architectural form [69]. For this, he concentrates on the interrelationship between space, time, sounds, smell, light, and shadow, emphasizing the importance of materiality. Sense of smell is also an important idea that enables both the Chapel (smoke smell) and Serpentine Pavilion (floral scent) to improve the quality of the interior experience in relation to materiality. For example, a particular smell, which was left behind in Bruder Klaus Field Chapel, can directly link that place with something that was burned in the past. Moreover, the sense of sound is also a significant aspect of environmental stimuli in the Chapel; it is never absent, and relates strongly to materials in the interior space. According to Pallasmaa, the sense of sound creates an experience of interiority, compared to the sense of sight, which implies exteriority [10]. Hearing allows one to perceive the environment in cooperation with sight and imagination. Sound measures space and its scale. The sound is provided depending on the pattern and scale of the space and materials [10] (p. 75). These sensory experiences are again integrated through the body and constantly interact with materials and the surrounding environment. Spatial experience through the sensory body resonates in our consciousness and highlights material experience in interior architecture.

Culture is also a significant aspect of interior experience. A particular environmental element evokes personal memory, which then connects to spatial experience within a culture. In particular, the sense of smell is strongly linked to cultural aspects, evoking a particular memory. In this respect, it is worth looking at Kuma's Sensing Space, as it underlines materiality rather than architectural form. Kuma's abstract wooden structure containing a particular smell evoked a socially shared memory of a Japanese home for those visitors who had experience of living there and gave information about the cultural smell of the architecture to others who do not have this shared memory. These culturally specific sensory experiences and memories stimulate our emotions and feelings in particular situations related to the cultural space. Kuma's installation also highlighted the experiential rather than the functional aspects of architecture. It simply provided a sense of smell in a dark room without an architectural form, but stimulated spatial experiences and emotional connections. It demonstrated a significant aspect, which is that spatial experience can be developed not only in an architectural form, but also in material worlds with regard to the cultural context. Thus, the spatial experience can be developed not through the reality of architectural representation, but rather through "the awakening of the imagination" [17], based on the predominant experience. Kuma's Sensing Space also emphasized darkness in order to provide the aesthetic value of Japanese architecture. Shadow and darkness are considered to be a silent space in Japanese culture. The Japanese are familiar with living in darkness and discover beauty in shadows. According to Jun'ichirō Tanizaki, this is because the Japanese spend much of their daily lives in the heavy darkness that hangs beneath the eaves [70]. Thus, the darkened room in Sensing Space provided a familiar sensation of Japanese home culture. In relation to this, light and shadow, as environmental elements, provide various ways of experiencing space. Light and shadow are significant and enable us to experience and feel a particular spatial environment [14,71]. Together, they enrich the quality of materiality, providing volume, smoothness, temperature, and patterns; they provide a particular atmosphere of interior space [14,71]. This can also be found in other case studies. The Prostho Museum, for example, emphasized the integration of light and shadow, engaging the wooden lattice structure. It provided various ways of experiencing space through observing the changes in spatial volume and atmosphere created by the changing levels of light and shadow throughout the day. This aspect can also be linked to the Japanese cultural context by engaging particular elements, such as shadow, lattice structure, and timber. In the Chapel, however, light and shadow were used for spirituality as they have a mystifying quality. In ancient Greece, the light was respected for its spirituality and was considered to create a sacred place for holding ceremonies, creating an ecstatic mood and an atmosphere of divinity [14,72]. Light also provides a comfortable environment. As I mentioned in the previous section, the Serpentine Pavilion provided both dark corridors and a garden filled with light, allowing people to experience different ways of meditation, both through walking and through remaining separated from the world of noise and the smells of London. This shows that an interior experience of architecture can be transformed into an emotional level of experience of architecture.

Through this interior experience combining the body and materiality, a particular emotion, such as spiritual, meditative, cultural, or enjoyable, can be evoked. This means that the body, materiality, and emotional connection offer a fundamental idea for enriching the interior experience. Emotions generated through sensory experience within space also recall memories of past space, which embodies interior experiences. Thus, people can experience, perceive, and feel the space, which creates spatial imagination; this can be developed both individually and socially. Thus, interior experience represents several key issues, such as the body, materiality, culture, emotion, and memory (see Figure 6).

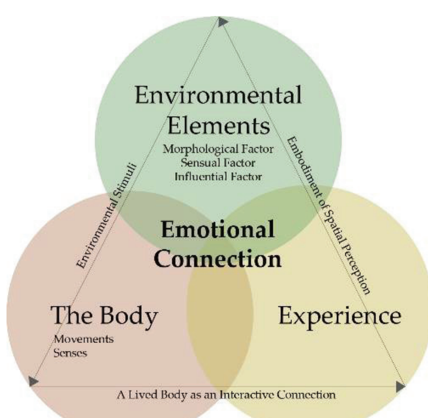


Figure 6. Embodiment of spatial experience for emotional connection. Source: author's drawing.

5. Conclusions

This paper provides a phenomenological understanding of interior space in order to explore the emotional connection between space and experience. This paper incorporates a literature review and gathers together theoretical research based on issues of interior space, experience, and emotion. I have explored the important role of the interior experience within the field of architecture, engaging the bodily sense, materials, culture, and identity. The interior space here refers not only to physical aspects, such as materiality, but also to a container where bodily activity and movements are embedded within the culture. In this paper, I have argued that interior space offers effective ways of developing spatial and emotional experiences. Throughout this research paper, I found that the body and materiality are essential in order to improve the quality of experiences in the realm of interior space, which is understood as the origins of architecture. The spatial experience of architecture is developed by: (a) the body, which includes bodily movements and senses; (b) materiality, which represents the interior environment, stimulating the body; and (c) emotional connection, which evokes both individual and socially shared memories.

Although a phenomenological understanding of architecture is becoming a more important social issue in contemporary society, it seldom considers interior experience but instead focuses on a visual sense of architectural representation. In this paper, I try to trace what effect the spatial experience has on improving the quality of interior design through examining the body and materiality in a contemporary architectural context, considering the roles of interior space and the effects of experience. This paper also concentrates on phenomenological and emotional experience in understanding architecture, which affects the users' perceptions and experiences through phenomenological engagement. Interior space provides a personal connection to communication to offer an individual experience and social engagement through predominant memories. The important aspects of interior space are to provide bodily participation and emotional experience in engaging the body, and allowing them to interact, communicate with, and recognize previous experience to embody spatial perception. Thus, interior space can be transformed into a place where the body is involved, allowing people to discover the interior environment that stimulates users' emotions and improves interior design to give users a better experience. In this paper, I have drawn upon the representative case studies regarding the interior experience to explore how they provide sensory effects and materials and engage people, providing an emotional experience to improve the quality of the interior space, which is one of the fundamental aspects of this paper. I found three significant aspects: (a) an integrated understanding of the body, materiality (environmental stimuli), and how emotion plays a substantial role in improving the quality of the interior experience; (b) a particular factor provides cultural experience by stimulating socially shared memory; and (c) material worlds that engage the body can enrich both spatial and emotional experience, even in an abstract structure. This highlights the idea that spatial experience is not only a functional but also a sensory and material experience. From this perspective, the emotional experience can substantially improve the quality of interior space to enable a better understanding of architecture. It is difficult to generalize the findings of this paper with regard to the architectural environments as only four case studies were explored. Moreover, the data were interpreted and analyzed by reflecting the researcher's perspectives, which could provide a subjective view in some respects. Nevertheless, this approach is still substantial and widely used in the qualitative analysis of spatial experience. More discussions will be necessary to develop ideas on how sensory stimulation and materiality affect emotional experience and to look at what qualities need to be developed to allow the interior experience to become more powerful, which could be examined in future studies.

A phenomenological understanding of interior space can bring about the stimulation of emotional feelings and memories, leading to new ways of thinking about architecture, which helps us to develop interior or architectural design. Therefore, I expect that this paper will contribute to the understanding and knowledge of the relationship between interior space, the body, environmental stimuli, and materiality, considering how experience interacts with architecture to create a multi-sensory space.

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buildings

MDPI

Communication

Apparent Destruction Architectural Design for the Sustainability of Building Skins

Magdalena Celadyn [1,*] and Waclaw Celadyn [2]

[1] Faculty of Interior Design, Academy of Fine Arts in Krakow, 31-157 Kraków, Poland
[2] Faculty of Architecture, Cracow Technical University, 30-155 Kraków, Poland
* Correspondence: mceladyn@asp.krakow.pl

Abstract: Technical durability and aesthetical longevity of building skins are among the fundamental demands of sustainable architecture in terms of building fabric's physical changes due to deterioration. This concept paper presents a design concept intended to fill the existing gap related to the limited durability of buildings and non-existing design methods for its effective extension. The study concentrates on the anticipation and assimilation of disintegration processes occurring in time into the architectural design methodology to promote the design techniques focused on the visual expression of the coexistence of nature and the artificial in the function of time. This study investigates the building's enclosure as an active boundary through which the building's interaction with the natural environment occurs, as well as a regulator of the building's energy performance and a factor conditioning their durability. The consideration of formal and esthetical deconstruction in architectural design is followed by the analyses of some relevant examples of completed buildings and cultural determinants underlying this issue. The proposed Apparent Destruction Architectural Design (ADAD) concept addresses the time-dependency of the building skins' physical properties manifested by the deterioration, destruction and re-figuration of the building's fabric. This design concept offers a solution to the disturbing problem of architecture's impermanence enhances the issue of sustainability of the building's fabric in time, becomes a means to search for the unconventional comprehension and vision of architecture, as well as to reframe the architectural design toward its compliance with sustainability postulates through the aesthetic concept.

Keywords: architectural design; apparent destruction; entropy; technical durability; aesthetical longevity

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1. Introduction

The issue of buildings' longevity remains one of the fundamental requirements of sustainable architecture due to the constant transformations as a function of time. These changes are related to the characteristics of the destruction process that are recognised as unrecommended for technical reasons, as well as for aesthetical intentions. The obvious response is to slow down these changes by undertaking preservation efforts that cause elevated financial costs, which include, among others, additional expenses due to increased energy consumption. The buildings' rising energy absorbency throughout their life cycle, therefore, becomes a factor contrary to the sustainability paradigm. The occupants' acceptance of visible signs of weathering or effects of the systematic deterioration of material substance, as well as a positive perception of a building's destruction-related aesthetics, can be indicated as essential factors in overcoming these negative consequences.

Buildings, or "composite structures" enabling different human activities and having "both an internal space and an external form" ([1], p. 6), render a built environment component essential. The question of forming a building's envelope refers partially to the technical pillar that, along with social, economic and biophysical postulates constituting the principles of sustainability [2], assures the construction of durable and functional structures of high environmental performance and quality.

The self-modification of the initial phase of architectonic objects, disclosed after the completion of a spatial concept of the aesthetics being specifically defined as well as purposely developed by architects, remains unavoidable. The kind of this correction, the intensiveness or the ultimate results, are difficult to anticipate since they depend on the multifaceted factors that influence this process independently or synergistically. This development has a destructive character mainly in terms of its materiality and formality, as well as functionality or semanticity.

This article examines the durability-oriented design methods to shape the building skin that goes beyond the direct application of the developed building techniques to focus on the eco-aesthetic measures within the design process. The study investigates the building enclosure as the active boundary through which the building's interaction with the environment occurs, as well as a "component in the integration" ([3], p. 1) of human-made structures with natural ecosystems, and which does so in terms of the anticipation and assimilation of disintegration processes occurring over time. It considers an architectural design methodology that promotes the coexistence of architecture and nature. The article analyses the character, scale and range of the relationship between the deterioration of the technical conditions of buildings associated with their limited durability within their life cycle and the aesthetical effects of this phenomenon.

This paper presents a conceptual framework aimed at implementing the Apparent Destruction Architectural Design (ADAD) concept into the design methodology, supplementing the strategy for effective resources management that fulfils the environmental sustainability issue. Specifically, its technical pillar [2] is accomplished with lean design and construction, as is done as well with the introduction of recycled materials and durable structures. The main objectives of the study are as follows: (1) formulate an apparent destruction architectural design framework in view of the building enclosure's sustainability; (2) determine the range of possible formal and technical interventions within the building skin to employ the design scheme and then examine the character of their contribution to sustainability; (3) recognise the apparent destruction as a means to reframe the architectural design toward its compliance with sustainability postulates.

All those postulates are intended to respond to the apparent necessity to launch a serious discussion about further methods to increase the sustainability of buildings by way of unconventional solutions. The presented concept is designed to fill the existing gap related to the limited durability of buildings and non-existing methods of its effective extension. Written published materials have not indicated this way of dealing with the analysed issue so far.

The structure of this article is as follows: the first part addresses the building skins and emphasizes their substantial role in the buildings designed in accordance with sustainability postulates and in view of their function as a separator between the exterior and interior of buildings, as well as a regulator of their energy performance. This section also deals with the issue of the durability of buildings conditioned by building envelopes. The next chapter considers formal and aesthetical deconstruction in architectural design, analysing some relevant examples of completed buildings. It also discusses the cultural determinants underlying this issue. Crucial is the section dealing with the introduced term "apparent destruction design", which explains the meaning and essence of the idea by analysing it in larger, energy-related and biophilic contexts. The application modes of this concept in executed buildings, presented in the next fragment of the paper, give the idea of the results of the implementation of the destruction concept. The Discussion chapter attempts to justify the investigation of the realm of the interrelationship between the human-made and natural environments that is the inspiration of the presented idea.

2. Building Skin and Sustainability Postulates

As Lee noted, the "building envelope occupies a special position within the strategies of sustainable design" ([4], p. 120). These strategies respond to the functional, technical and energy-related questions in a cohesive manner and assure the "symbiotic relationship with natural environment" ([5], p. 260). The building skin, also referred to as the building envelope, shell, fabric or enclosure, establishes a physical boundary between the interior of a building and the outdoors. The structure and technically advanced components of this "environmental separator" generally situated between the inside and outside of a building ([6], p. 2) are expected primarily to respond to external circumstances, providing users with psycho-physical comfort.

For the purposes of this study, the term building skin is applied to analyse the apparent destruction of a building's external surface in the context of its environmental sustainability. The term building skin designates the active position of this building component and its ability to "selectively admit and reject" ([7], p. 247) the natural environment's influence in time, as well as to overcome its position as a boundary to physical and psychological control of the environment [8]. This interrelationship results in visible signs of progressive physical deterioration of building materials and products over time. The building skin, providing the "transition between inside and outside" ([9], p. 9), becomes a responsive building component in view of the following sustainable postulates: (1) low level of energy consumption; (2) effective management of resources with emphasis on the materials' durability; (3) enhancement of indoor environment quality parameters; (4) articulation of interconnectedness and interdependency of human-made and natural environments to provide the building's functional and aesthetical cohesion. This serves to modulate the occupants' multisensorial emotional and cognitive experience of a building and intensify the topophilia [10], understood as individually developed and emotionally based reception of the space.

2.1. Energy Efficiency

Building skin responds to the sustainability requirements in a way to contribute to the object's high environmental performance, mainly through the control over effective energy consumption within the object's life cycle, as mentioned earlier, meaning both operational and embodied energy.

The supplementing design techniques to accomplish the energy-efficiency-related demand through the building skins outline, in large measure, comprise the following: (1) spatial disposition respecting functional demands as well as building orientation and exposure to meteorological conditions; (2) modularity of enclosure construction; (3) simplicity of surface treatment of the enclosure's finishing layer and limited processing (e.g., mechanical working, plastic forming, abrasive machining); (4) application of reclaimed, recycled or recyclable building materials and products; (5) assembly technique allowing for the sporadically executed partial demounting of the damaged parts and their replacement.

These above-mentioned procedures, having a direct or indirect impact on the appearance of the enclosure, are decisive in this regard and should override aesthetical concerns in a genuinely sustainable design. However, this seems to be a challenge to the ingrained methods of aesthetical perceptions. This paper proposes a new approach to the issue of energy-related features of building skins that brings them closer to the natural aspects of the environment.

2.2. Effective Resources Management

In searching for notions relevant to the analysis of the connection between architecture and the sustainability paradigm, Lee highlights concepts addressing the relationship between the sensory perception that enables the qualitative evaluation of an object and the quantifiable measures applied to its assessment [4]. These notions denote the "role of architectonics in informing the relationship between the expression of material culture and the environment" ([4], p. 10).

Given that sustainable architecture is to address and stimulate the users' senses [11] and considering the external wall as a compound functionally and technically developed to enclose and dress the built structure, retaining superiority over the construction in terms of form and the content of architecture [12], the study focuses on the questions of building skin materiality, identified as an essential factor of aesthetical distinctiveness. In addressing the pro-environmental postulates, the building skin design is to simultaneously provide the occupants with the high values of formal qualities that affect users' perception on the cognitive, behavioural, and emotional levels. Limited to the buildings' enclosure, the study area denotes perception as the "subjective assessment of individuals" [11], influencing the users' qualitative evaluation of the building's performance.

To achieve this, the effective management of resources is necessary, namely the suitable choice of building technology related to the skin and emphasising its low embodied energy as well as durable materials and their fixing techniques.

2.3. Durability of Building Fabric

Durability is the most frequently mentioned and considered part of the sustainability paradigm [13,14]. However, the difference between durability and longevity should be elaborated on, given that they have a similar meaning. Some sources define durability as "the quality of being able to last a long time without becoming damaged" [15], "the power of uninterrupted or long continuance in any condition; the power of resisting agents or influences which tend to cause changes, decay, or dissolution" [16]. Another definition relates to the characteristics of a concept, meaning its ability "to exist for a long time without significant deterioration in quality or value" [17]. Longevity is defined as the "long duration of individual life" or "long continuance" [18]. It seems evident that the term durability rather than longevity applies most closely to the problems related to architecture and construction, as well as to the analysis in this paper. However, the term longevity will be used in relation to aesthetical issues.

Another concept used in relation to sustainability and close in meaning is resilience, understood as the "ability of a system to absorb disturbances and still retain its basic function and structure" ([19], p. 1). This concept, allowing small re-arrangements irrelevant to the object's identity and integrity, is aimed to "build capacity to work with change" ([19], p. 14). The durability of any component, regarded as the quality of maintaining the object's satisfactory performance, is correlated with the environmental and operation-related factors that cause deteriorating or degrading effects upon the object's properties and its functioning. Durability is the "product of a large number of factors" [20], including the type and quality of materials chosen or the degree of exposure to which a building is subjected. As noted by Legget, it is justified to analyse this term separately within each major building components category, including the group "exterior finishes" [20].

Technical durability in the case of buildings, addressed through design and construction, remains the factor enabling the amortisation of environmental and economic costs [21] and assessments of the ability of a building and its parts to "perform required functions in its service environment over a period of time without unforeseen cost for maintenance or repair" ([6], p. 2). Durability informs the extent to which a material maintains its original requirements over time [22]. It refers to the state of the conceived material object, defining its ability to fulfil the assigned functional requirements within the anticipated lifespan "without breaking down irreparably" ([4], p. 12), whereas sustainability is understood as a process that means continuity reached through the presence of necessary structures and relations. The term durability, considered sustainability's complementary component [4], addresses the appropriate building methods that are to maximise the value of the object in terms of its utility duration. This approach to the question of the object's usefulness implicates the evaluation of the introduced building materials, as well as the applied building techniques, based on the postulates derived from the sustainability strategy of effective resources management corresponding to the object's lifetime performance.

The degree of sustainability of buildings and their components in the design strategy is defined by the materials' durability-related features that correspond to the objects' life cycle performance [23]. These comprise the following factors that are meant to function- and technique-related solutions: (1) functional effectiveness defined by low-cost and simple building technologies; (2) adaptability, meaning easy change in function and potential for relocation in the future; (3) ease of demounting process and separation of combined materials or components for further reuse; (4) susceptibility of selected products and materials to recycling; (5) transparency and simplicity, understood as the clarity of applied technical solutions complemented by easy inspection; (6) dynamism of systems allowing for ecological risks instead of their stability.

Among the issues essential for the aesthetical longevity of objects manifested through the physical condition of the object's surface are the following:

- Amenability for and ease of maintenance [24,25], as well as its low frequency;
- Evolutive capacity, meaning the possibility of future improvements in the building's technical life cycle;
- Ability of materials to withstand time-related malformations or those provoked by users, supplemented with the introduction of envelope patterns to absorb possible buckling "without detracting from the appearance" ([25], p. 87) of the object's finishing layer and that of the object as a whole.

These factors influence the perception of a building as a subject of continuing physical degradation and disfigurements and have an impact on its durability. To assure the steady performance of a building shell in a lifespan, the applied construction techniques, treatments and selected building materials usually improve its technical durability and formal soundness, as well as its aesthetical approval. As a concept, the apparent destruction architectural design refers to the interconnectedness of human-made and natural environments in view of the building's lifespan. The concept employs technical durability accompanied by aesthetical longevity as the criteria of sustainability-oriented architectural design. The above-mentioned building skin sustainability features and the indoor-outdoor relationship, unlike indoor environment parameters irrelevant for this study, are considered in the following sections.

3. Destruction in Architectural Design

The deterioration over time of building facades is a common occurrence and is a noticeable phenomenon. The main three environmental conditions that have the greatest effect on the built fabric are temperature (ambient and surface), humidity (absolute and relative) and sunlight (ultraviolet), along with atmospheric pollution [26], while additional human-induced degradation features, related to the object's operation and users' behaviour, are littering, graffiti and vandalism [26].

These transformations concerning the building's envelope usually do not cause any direct inconveniences in terms of the real objects' functionality and to a certain point, have technically harmless effects. Their negative connotations usually decrease the overall aesthetical value and thus can have, in some cases, an indirect impact on functional features. Destruction, for the purpose of this specifically oriented analysis, is to be defined as pursuing the disintegration of the above-mentioned characteristics and parameters of the building over time. They differ significantly from the initial stage, expressing the originally developed form. There are different indirect levels of destruction to be recognised within the temporal range before the final stage and the extremal form assigned to this process.

It is reasonable to recognise other notions to describe the process of multilayered changes in the building fabric, including deformation, disfigurement, degeneration and disintegration. Destruction, as it embraces the above-mentioned, seems to be the most appropriate term and thus is referred to in the following sections of this paper.

3.1. Formal and Aesthetical Destruction

The SITE group dramatised the disposable and substandard qualities of selected buildings in the projects realised from the 1970's [27]. That, as Wines admitted, made them appear as "arrested somewhere between construction and demolition" ([28], p. 98). Their objects, frequently realised in the form of artificial ruins, remained "simultaneously unfinished and decaying" [27], witnessing the unsettling process of completion, anticipating the inevitable future destruction of buildings that were created in a way to emphasise their material "fragility and ephemerality" [27] in view of the progressing physical decomposition over time, and the final disappearance as a result of nature's dominance. Artists and architects from SITE recognised in the creation of the buildings as "monuments of entropy" ([29], p. 428), being a partial response to the whole spectrum of social concerns that arose in the 1970's, and to the criticism about the expansion of the consumption model. Their buildings' formal appearance as artificial ruins, as well as the exposure of nature's role in the process of specific consumption of building fabric, were the most often explored SITE design method. This was possibly associated with the investigation of the destruction, decay and incompletion constituting fundamentals of the architectural design concept.

The Maison Zalotay by Elemer Zalotay, representing the architectural design exploring the destruction of material substance that expanded in time remains one of the most extravagant examples of the architectural "design of the concrete" [30] based on considering the acquisition of available artefacts and projecting possible effects of their reassembly in a new context. This redesign concept, being a response to problems caused by the accumulation of solid post-construction and post-consumption waste, vastly introduced the materials acquired by scavenging as valuable resources. This building, exploding out of its natural surroundings, resembled "a collage choreography that fills the site with a cacophony of anarchic movement" ([31], p. 109). It constituted the specific spatial composition of used parts that had undergone degradation. They were reclaimed and then purposely assembled together to shape an unconventional form of housing construction.

Although this object was not erected on the strictly defined destruction aesthetic concept, the final effect referred to its main postulates, including the exposure of the lapse of time and limited material durability. It accomplished the sustainability paradigm requirements, proving its low energy consumption level, ease of accessibility of local resources featuring building components, as well as formal cohesiveness to enable adaptability. The Maison Zalotay, constructed entirely with different reclaimed solid waste, including aluminium, plastics and glass, exemplified a model of spontaneous architecture or garbage architecture, which, along with Reynold's "radically sustainable architecture" [32], featuring the tentative and largely autonomous "earthship biotecture" [33], was the ultimate example of experimental handmade structures. The Maison Zalotay constructed with reclaimed materials and repurposed solid post-consumption waste was conceived with the consideration of sustainability issues to decrease the impact of materials' lifecycle on the environment and increase their durability. The upcycling of reclaimed objects and products, based on their introduction in a new formal and functional context, remains a proposal for the effective management of waste.

3.2. Cultural Determinants

Culture unquestionably has important influences on multidimensional aspects of individuals' relationships with the physical environment [34]. The coexistence of symbolic durability and physical impermanence, being the distinguishing feature of the Japanese architectural culture, concentrates on acceptance and demonstration of transience, imperfection, change in various ways, the effects of weathering [35] and the incompleteness of things together with a contribution to resource efficiency. The aesthetics based on these determinants and derived from the wabi-sabi concept refers to the beauty that is deficient, impermanent and incomplete and still remains "the most conspicuous and characteristic feature of what we think of as traditional Japanese beauty" [36]. As Powell indicates, wabi-sabi nurtures all kinds of material objects that remain authentic by acknowledging some certainties. These can be summarised as follows: nothing lasts, nothing is finished, nothing is perfect [37].

This approach, being opposite to the European concept, acknowledges the temporality of material objects and their lack of precision caused by the changing usage methods implying fallibility and limited lifespan. The analytical valorisation of the damage to material substances, including architectural objects, provides them with contemplation-oriented values. The process of the growing old of the introduced building materials, according to the wabi-aesthetics, adds to their attractiveness caused by the demonstration of physical changes occurring over time. Thus, objects gain a positive perception by observers and occupants.

The wabi-aesthetics, celebrating irregularity, rough surfaces or defects [35], seems to expose the value of the destruction concept in architecture in the function of the flow of time and to accept its occurrence in buildings. Although the philosophy of constant renewal of building substance, being the essence of cyclic reconstruction of architectural objects present in Japanese architectural tradition, stands in contradiction to the mentioned wabi-aesthetics, the practice of systematic rebuilding can be explained as a need for providing objects with stable identity through the impermanent consecutive embodiments. The analogical inconsequence is present in some European philosophy concepts that maintain the inexistence of identity in view of constant evolutions of material substance. The variability in architecture presently frequently analysed is the postulate of sustainable design guidelines concerning functional solutions.

4. Apparent Destruction Design

The apparent destruction scheme, in terms of the extension of building materials and products technical life, supplements the related sustainable design strategies already well recognised and analysed in the literature as follows: (1) design for repair; (2) design for remake and replacement; (3) design for reclamation, allowing the avoidance of reprocessing or decrease in repairing processes; (4) design for disassembly; (5) design for deconstruction, understood as the process being "construction in reverse" [38], and conceived to avoid the costly and environmentally harmful final demolition phase.

Related architectural interventions to enhance the environmentally responsible architectural design are:

- Architectural design for adaptive reuse, defined as the reintroduction of salvaged building components or products into the structure of a newly conceived or refurbished building, executed in distinct functional, formal or spatial contexts [39], introduced to complete the building envelope;
- The dematerialisation scheme, a basic strategy in sustainable design, considered through: (1) reduction in the quantity of materials used in construction and finishing works; (2) design cost-effectiveness in terms of maintenance, replacement or alteration of building components; (3) sporadic substitution of originally installed building components, leading to economical and environmentally responsible use of materials throughout the buildings' life cycle [24].

The dematerialisation scheme, which precedes the discussed apparent destruction design concept, emphasises the dynamics of changes in artificial forms with the passage of time, with ongoing exposure of signs of wear and tear on the enclosures due to environmental conditions occurring in the natural surroundings.

The following subsections discuss the most important aspects of the concept: (1) "passage of time" ([40], p. 17); (2) entropy in terms of acceleration of building skin's visual maturity; (3) technical durability; (4) aesthetical longevity; (5) biophilic design patterns.

4.1. Apparent Destruction and Time Passage

Considering that no physical structure remains "immune to the passing of time" ([41], p. 10), the apparent destruction concept raises an issue of *temporal framework* [35] as relevant to the architectural design methodology. This design scheme anticipates architectural technical decay or the ultimate dismantling processes due to the deterioration of the material's value from the passage of time. These processes are responsible for the building's premature and multidimensional obsolescence, stimulation of users' negative aesthetical experience, and generating additional financial and environmental costs caused by partial replacement, deconstruction and/or ultimate demolition.

The apparent destruction scheme mediates the architecture–nature relationship with emphasis on the dimension of time, acknowledging that time is an inevitable, continuous and ongoing process of change [41], as well as "a material to be used in architecture" ([42], p. 192). ADAD provides the alternative proposition in the discussion on the relationship between matter and time to overcome the building skins' specific vulnerability to the effects of time and the visible revenge of time [43]. It does accommodate while shaping building skins, the compound and unavoidable processes of ageing and weathering that feature the "breakdown and alteration of materials by mechanical and chemical processes" ([26], p. 109); processes that are not usually considered as "conscious and positive elements in design" ([43], p. 79). ADAD provides a solution to the change of position of architectural objects being in "a deep defense against the terror of time"([8], p. 59).

The decay and deterioration of material substance become a relevant element of the character of the architecture itself due to their creative transformation of the assimilation of possible changes in a building's quality prior to its real appearance after the passage of time. The exposure of building fabric to climatic factors causes physical changes that alter the performance and physical characteristics of the affected building materials.

4.2. Apparent Destruction and Entropy

Destruction of the building's envelope material, in its natural, spontaneous, purposeful or accidental form, generates an increase in the entropy of a system, such as building fabric. In consequence, there is an intensification of the formal complexity since the formally and aesthetically consistent building elements become less organised. The lack of tidiness follows the spontaneous and unintended appearance of additional elements of spatial layouts or surface arrangements caused by deterioration. The latter provokes the dissonance within the originally developed structure and finally implies the negative perception of an architectural object, and thence of its disapproval.

Considering the issue of destruction in architecture, we have in mind a different degree of this process. The same relates to facades. We analyse the problem of the natural degeneration of the technical and aesthetical state of external surfaces of buildings, aside from the potential mechanical human-related damages. Natural destructive processes are the result of entropy, which in the changing environmental conditions are unavoidable. Therefore, in its life cycle, every building is subject to gradual destruction. Entropy is defined as the "quantitative measure of the degree of disorder in a system"; furthermore, it maintains that "physical systems move towards a state of maximum disorder "([44], p. 8). As Arnheim underlines, "the more remote the arrangement is from a random distribution, the lower will be its entropy and the higher its level of order"([44], p. 16). During the operation of a building, we undertake corrective actions to rectify its degradation, and finally complete destruction as a result of the action of the Second Law of Thermodynamics, and "the degradation of the matter and energy in the universe to an ultimate state of inert uniformity" [45]. The exterior facades of buildings are subject to this law as they are in constant movement from a state of order to disorder.

Destruction or disappearance can become inspirational as a design process. Entropy provides buildings with dynamics in the function of time, with the gradual vanishing of the elements that originally made up the spatial-material composition toward the development of new ones of usually negative connotations. Since this process frequently intensifies beyond the author's control, it is difficult to predict intermediate phases of the change within the object's multidimensional disposition originally developed by designers.

The apparent destruction design concept takes from some point of entropy development of a facade material and uses it at a point of installation. The dynamic entropic process proceeds in a highly randomised sequence, so its effects are usually unpredictable. In architecture, entropy can be considered from a physical and technical viewpoint or from the artist's perspective. The image of a façade changes in line with the entropy of the façade material turning into a natural pattern. This process can be illustrated by the curve presented in Figure 1.

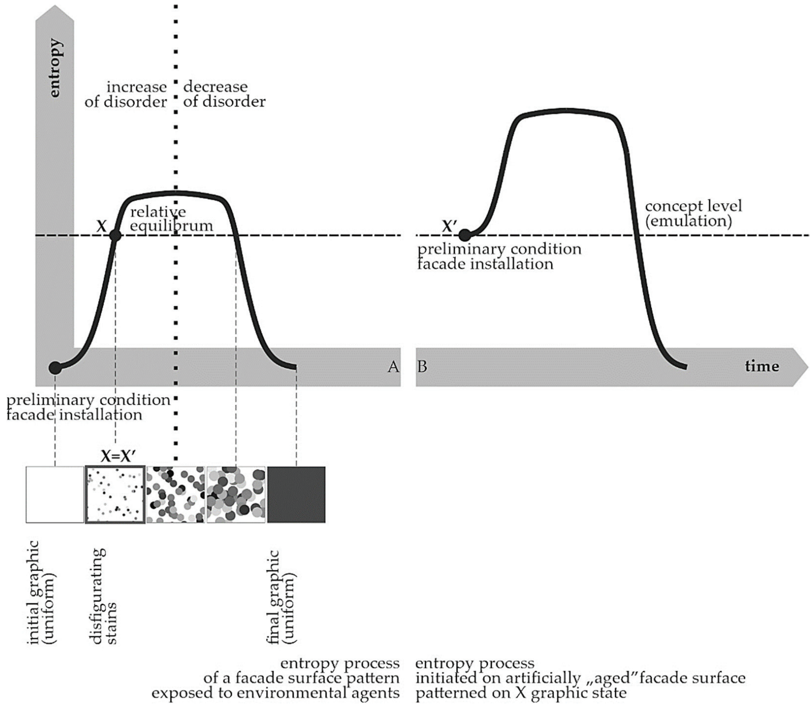


Figure 1. The mechanism of building skin graphic entropy plotted as a function of time (**A**) and its emulation in the ADAD concept (**B**) is considered from an art perspective.

The increasing disorder continues theoretically to the point of total destruction in the physical and technical senses, as this is considered an irreversible process. However, in the art aspect, it stops at some apex and then continues toward a greater order. The initial image turns gradually to its negative as a result of the increased complexity of degradation spots, as illustrated in curve A. This can seem similar to the entropy in reversible processes in physics; however, the final result is different from the initial state in terms of the colour, texture or integrity of the material. The intensity and/or uniformity can be equal, as indicated in Figure 1.

The advanced state of entropy is seen as a certain disorder in its visual composition that can be imitated in a new façade material at the moment of its installation in accordance with the ADAD concept. The process of entropy then begins and proceeds in a way similar to that of the original material; however, its range of relative equilibrium (apex) is achieved by the higher degree of entropy (curve B), which is due to the initiation of entropy at a later stage of its theoretical development and in new environmental conditions.

The ADAD is to create an effect of accelerated and purposely induced visual maturity of an enclosure that accommodates the signs of weathering and materials' malformations occurring over time. It is to "resist the inauthentic and unreliable feeling of the artificial environment" ([46], p. 129).

4.3. Technical Durability

Durability is enhanced with the more rational maintenance of building components, where maintenance could be defined as "routine work necessary to keep the fabric of a place in good order. In other words, the main objective of maintenance is to limit deterioration" [47]. Nevertheless, the area and frequency of these works should be substantially limited. The low frequency of maintenance operations, as well as the rarity of replacement of the components installed in a building with new elements, depend, among other things, on the avoidance of technologies and building materials vulnerable to deformations due to accelerated unfavourable weathering process or intentional or accidental mechanical damages. The priority of high durability is crucial when drawing up the specifications for the building materials and products that are to be introduced [24].

The technical durability, conditioned by the physio-chemical characteristics of building materials, techniques of assembly, methods of finishing and climatic factors, remain in tight relation to the formal aspects of architectural design, emphasised mainly in a developed aesthetical concept. Because it features aesthetical longevity, the ADAD concept provides the enhancement of design for the sustainable durability strategy.

The concept of Apparent Destruction Architectural Design (ADAD) allows the durability aim to be achieved and, therefore, underlies the sustainable strategy of efficient resource management. This model of controlled and deliberately employed deterioration, in order to support the durability scheme and, in consequence, the sustainability goals, comprises the following:

- Adequate shape of a building volume enabling undemanding fixing of the cladding;
- Application of construction techniques and manufacturing technologies to diminish or ignore the presence of factors that harmfully affect the physical parameters of the finishing layers of the built structures (e.g., disadvantageous location of objects in places exposed to intentional or accidental mechanical damages, exposure to intensive and destructive effect of adverse climatic conditions);
- Selection of recommendable building materials, possibly recycled and recyclable;
- Selection of materials of which physical properties allow stable performance to be applied, including multiple tool cutting, chemical treatment or profiling.

The consideration of the environmental responsiveness of buildings remains unseparated from the analysis of the aesthetic-related issues [48]. It does require the simultaneous recognition of physical and functional aspects, as well as an aesthetic concept. The latter component, while revealing "mediation between culture and nature" ([4], p. 10) and remaining the "site for the development and display of a new cooperative contract between built culture and nature" ([48], p. xiv), proves its significant role in building up occupants' understanding and acceptance of the architects' environmental-oriented approach.

The controlled destruction of a building's structure is associated with the assimilation of signs of the flow of time in which they emerge. The negative and disqualifying perception of the buildings' fabric that shows gradual dissonance between initial perfection of manufacturing and continuing signs of weathering or deterioration due to intensive or careless use is to be partially tempered by the introduction of inventive design methods and techniques. These are to evoke a positive perception with the purposely introduced apparent destruction scheme, where the carefully displayed visible and tactile attributes of forms and finishes, sometimes completed with purposefully exposed imperfections, serve the assimilation of the signs of ageing within the component's composition. Imperfections and visible signs of physical deterioration initially considered in the component's configuration, although apparently omitting the phase of contemplation of the original state or observed through the cause of transformation, still allow the observer to experience the object's impermanence as representing the reflected aesthetics over and against natural processes.

4.4. Aesthetical Longevity

The design methods and techniques to decrease the separation of the occupants from the natural environment realised through physical boundaries materialised in the appearance of the building's enclosure are to limit the negative effects, such as "inadequate contact with natural light, ventilation, materials, vegetation, views" ([40], p. 5). They are to correct the forms of artificial structures toward their formal unobtrusiveness within the surroundings, through the effectiveness in resources management, as well as the lean design and construction scheme that imposes significant limitations on the usage of building materials and the production of solid waste. The implementation of building technologies and techniques is to define the aesthetic framework of the formal environment's homogeneity-oriented architectural design.

The ADAD addresses the methods to demonstrate the continuity of the phenomenon of a building's ageing, being "always time-specific" ([49], p. 209). Apparent destruction as an aesthetic concept draws on examples of the degradation of building substances arising over time, mainly due to unfavourable climate-related conditions and factors, such as rainwater, winds, sun or radiation. The range of material losses occurring on the surface of a building's envelope as a result of these processes combines irregular stains or dye penetrations visible on the cladding material. The spatial or structural destruction refers to the building's single elements or to their composition-forming building parts. The extreme situations cause its visual degradation, structural damages, loss of physical qualities or other failures, suggesting progressive devastation of the object.

These above-mentioned visible indicators of a building's continually occurring physical changes can be analysed as stimulating factors for the search for new aesthetic concepts, as well as to become instruments to build "consonance of nature and artificially created work" ([50], p. 75). Apparent destruction is a design device valued in a formal as well as in an aesthetical aspect. It does assist to "capture a true sense of connectedness and bio-integration" ([51], p. 415).

ADAD extends the simple introduction of building materials for finishes simulating malformations or physical symptoms of time-related material destruction toward its systematic consideration in the context of the sustainability paradigm in architectural design. The concept discussed is situated near the whole-systems model in its formal and aesthetic aspects. It does echo the reconciliatory approach in design that acknowledges the integral aspects of humans and natural systems acknowledged in the Trajectory of Environmentally Responsible Design by Reed [52].

4.5. Biophilic Design Attributes

Inclusion of the selected patterns of biophilic design into the environment-oriented design methodology allows the avoidance of the dominant approach to modern architectural and landscape design, where nature is treated mainly as a "trivial and irrelevant consideration" ([40], p. 5), to "connect human occupants and passersby with the experience of nature" ([53], p. 110) and to get compound proficiency of the nature in the human-made environment through the developed solutions concerning formal and technical aspects. The development of these, in particular, "encourages an emotional attachment to particular settings and places" ([40], p. 7).

The apparent destruction refers to the changed approach to the understanding and appreciation of nature in its origin, structure and function. This is realised even with the exposure of conceived artificial elements inspired by natural structures initially regarded as "aesthetically negative" [54] and thus bringing detrimental connotations. The creative transformation of these attributes allows the observers' acceptance and positive perception to be gained. The apparent destruction design concept is a proposal to complement the discussion on the aesthetics of sustainability with regard to the formal expression of building envelopes, with the inclusion of attributes of biophilic design viewed as the "largely missing link in prevailing approaches to sustainable design" ([55]. p. 5).

The proposed design concept is aimed at the conjunction of the postulates of a sustainability design framework concerning efficiency in the resource management discussed in the context of building materials' longevity with design methods and techniques addressing the aesthetics model of "visual ecology" [56]. This model addresses the inclusion of the concept of biophilia into the sustainable design methodology, as well as various forms of biomimicry applied, in particular, in terms of an architectural object's formal appearance, as inspired by nature in terms of the functional concepts of an organism [57], and mimicking its selected features in a search for unconventional solutions in compliance with sustainability postulates [58]. These proposals should combine the developed construction techniques with the selection of building materials of specific physical characteristics and attributes, enabling their permanent integration with the environment within the structure's lifecycle. This study is an attempt to supplement an "aesthetics of ecology" ([59], p. 28), considering the principles and mechanics that prove the object design as environmentally responsive and responsible alike. Through the apparent destruction concept, as a sustainable architectural design scheme applied to define the enclosure, the building is to "express its qualities in the intelligent economy of reduced means" ([11], p. 49) as a support of the strategy of effective resources management.

The possibility of the coexistence of the built environment with the natural environment "depends to a great extent on the designer's ability to understand and creatively integrate various technologies in an appropriate manner" ([60], p. 66). This harmonised interrelationship comprises the abilities of human-made objects, being temporary structures placed in the surrounding natural environment ([60], p. 69), to overcome the changes caused by various factors related to climatic conditions. The capabilities of artificial structures to accommodate these changes are to be recognised by designers in an aesthetical context as well. Purposefully exposed imperfections or unfinished elements of external surfaces, giving an insight into the methods of processing and assembling, as indicated by Walker while discussing product design methods, might "absorb wear and tear" ([25], p. 87), allowing effective assimilation of the damaging results of weathering or physical damages caused intentionally in time, and thus remaining conformed to the overall appearance of the building designed in conformity with the apparent destruction scheme.

The apparent destruction concept, derived from the symbiotic design and endorsed with selected attributes within biophilic design patterns, responds to the demand for the *visual congruency* of human-made structures with natural settings [34]. This interrelationship of artificial and natural environments is achieved with the effect of mingling, blurring and ultimately dissolving the physical boundaries separating inner spaces from natural surroundings. The quality of this design scheme is achieved through the display of similarities in spatial configurations, textures and colours, as well as the application of "broken symmetries" ([61], p. 78) to obtain a coherent visual effect and patterns that mimic natural objects. It is to form buildings as objects that are the "self-evident part of their surrounding" ([50], p. 17). ADAD provides a design methodology with the biophilic design postulates of complexity and order, characterised by the presence of rich sensory information that is configured with a coherent spatial hierarchy, similar to the occurrence of design in nature [62].

The following section relates to the architectural discipline's aesthetics while discussing the environmental sustainability-related questions, with emphasis on architectural design methods to align the surface of external enclosures. The discussion over architectural design methods and techniques addresses the layout of envelope surfaces and materials specification with regard to sustainability issues.

5. Apparent Destruction—Application Modes

As Carlson indicates, every natural object demonstrates an integral relationship to its own environment [63]. The interventions undertaken by architects should be, then, focused on creating the similarly stable interconnectedness between artificial objects and their natural surroundings, in the formal as well as aesthetic aspects, understood as relating to the ways in which people respond to a place (e.g., local building materials, designed and natural landscapes) through its multi-sensorial and intellectual experience ([26], p. 269).

An aesthetics-oriented appreciation of the natural environment as a source of inspiration for buildings tends mostly to be the exposed component of the built environment. It does require original measures for analysis, interpretation and creative use of natural processes. Within the design process, including the building being treated as a complex construction product, addressing sustainability issues and proving to possess an environmental consciousness, there is a need to generate design solutions that, as Walker indicates, challenge conventions and well-established notions of aesthetics, as well as inspire new studies [25].

The apparent destruction model applied to a building skin addresses this postulate with the consideration of the physical characteristics and processing of materials. Design methods, comprising the core of the apparent destruction model in the search for formal continuity and the relationship between an architectural object and its natural surroundings, include the following:

- Selection of durable materials to assure their long-lasting appearance and performance to eliminate the need for excessive conservation and maintenance;
- Consideration of building materials as aesthetically appealing in their natural state;
- Reproduction, put in effect by the application of patterns, rhythm, tectonics and textures borrowed from abiotic forms;
- Imitation of destructive processes occurring in the appearance of natural structures from weathering;
- Assimilation of possible negative effects caused by the weathering assured by a surface layout;
- Accidental arrangement of openings that remain in accordance with functional requirements and effectiveness in terms of spatial layout;
- Employment of different processing of materials forming the cladding to achieve the effect of accelerated ageing;
- Broad exposure of signs of apparent destruction in finishes throughout the building skin inherent in the envelope's composition;
- Employment of techniques to emphasise the signs of a building's visual maturity as opposed to its aesthetic obsolescence;
- Reduction of a building's geometry to a minimalist form to vastly expose the envelope's texture.

Coexistence and continuity of artificial and natural environments is articulated with design techniques to observe constant and inevitable physical changes in a building's envelope influenced by environmental conditions over time. The appearance of potential conspicuous defects of the building cladding, caused mainly by changing weather conditions, ageing, wear and tear or destruction, as well as naturally developed changes, constitute a valuable factor in defining the formal identity of the structure and its connection to the natural context. The apparent destruction concept incorporates biological references into the design of the enclosure in terms of their composition, realised through a formal configuration of surfaces, placement of nature-inspired patterns and textures in the enclosure layout and the arrangement and shaping of openings. The ultimate objective of this concept is to avoid a building's premature aesthetic obsolescence [25] that might be caused by the aesthetic perfection of design, provoking the exposure of parts demanding replacement due to their defective appearance. The ADAD scheme, accommodating the ongoing physical changes in building fabric caused by weathering or operation, denotes the "symbiotic interrelationship between building and the site" ([64], p. 249) and thus complies with the complex sustainability issues.

The emerging new building techniques and technologies based on software along with computer-controlled machining tools allow the graphic design to be made full use of in the production of building materials to apply the apparent destruction design concept, mimicking the physical changes that develop naturally on a building fabric with the passage of time. These mainly concern decolourisation, texture irregularities appearing on the finishing layer or perforation of material in the case of the long-lasting influence of specific aggressive external factors. The following subsections examine the apparent destruction concept through the discussion of the exemplary types of surface compositions. They are developed in anticipation of the impact of meteorological factors on the deterioration of the materials' physical parameters and mimicking them to build a cohesive aesthetical scheme. The selection of the composition and its critical analysis is made with an emphasis on attributes of selected patterns and processing techniques applied to imitate the naturally occurring decay or deterioration of matter, building materials and characteristics of surfaces.

5.1. Flat Compositions

The apparent destruction concept exercises the defining of surfaces through their irregularities as a result of the process of the ageing of building materials. This mainly concerns experiments with the shaping of building facades. The colour and graphic scheme of the building materials used to realise this concept imitate materials undergoing an intensive and advanced process of degradation appearing over time. This approach, anticipating future physical changes, can be described as deceptive and anachronistic since it falsely suggests the flow of time and its destructive consequences on the building fabric. However, the value inhering in the objective of this ADAD concept is its own justification and thus withstands the criticism.

In order to intensify the destruction-related changes that naturally develop over time and to avoid repeatable arrangements, individually developed building and processing techniques are exercised to achieve the effect of apparent randomness in the configuration of components, repetition of patterns, rhythmic variations and contrasting juxtaposition of textures. Still, the composition and assigned technical measures enable recognition of the "organized complexity" ([40], p. 19) of the enclosure's layout, allowing observers to experience it in an orderly and organised way.

The design techniques to realise the plane apparent destruction scheme in flat compositions, preconditioned by the selection of durable building materials to withstand the applied physical or chemical treatments (e.g., stainless steel, Corten, concrete, brick, stone), comprise the following:

- Visual patterns featuring irregular stains occurring on the finishing layer executed with Corten caused by chemical reactions triggered by ongoing meteorological phenomena;
- Shading applied to the adjacent modules to control the sharpness of surface boundaries and to facilitate its formal blending with the surrounding;
- Seemingly uncontrolled configuration of the openings being disposed accordingly to functional demands;
- Individually developed building treatment techniques for the finishing layer (e.g., embossment, brushing, sheet-metal forming, perforation);
- Mixture of processing techniques to obtain apparent malformations in the surface layer that are deliberately introduced and to anticipate possible damages occurring in the span of time due to intensive usage (e.g., brushing and perforation, fading out and colour saturation);
- Spontaneous yet carefully controlled juxtaposition of adjacent modules differing in finish (e.g., bright and matte, satin and rough, plain and perforated).

Possible effects of building material selection, graphic layout and employment of processing techniques to execute the apparent destruction concept in the flat compositions of enclosures are presented in Figure 2.

The apparent destruction design concept is investigated in the context of selected sustainability considerations focused on buildings within an architectural design framework. Among them is conservation, understood as a measure of the object's physical durability and effectiveness in terms of formal quality, aesthetical identity and sensorial stimulation, all influencing the social perception of a human-made object. In the search for design techniques that comply with these sustainable approaches, the apparent destruction concept examines the formal and technical means to figure out the objects relationship with the natural surroundings. This approach remains in tune with Venturi's opinion that buildings have been made to communicate the ideas hidden behind the architectural concept through their enclosures [65]. The design concept is defined jointly by the composition, the applied building techniques and the used building materials, which all together enable this expression. These main categories were used to create the typology of unconventional design interventions to affect the building envelope. The inclusion of selected attributes into the building components' design framework assigned to the category of biophilic design based on natural patterns and processes [55,66] adds to the meaning of the physical presence of nature and awareness of natural processes, especially seasonal and temporal changes.

(**a**) (**b**) (**c**) (**d**)

Figure 2. Applicationf ADAD concept in the flat composition of an enclosure; (**a**) Façade cladding in Corten steel sheeting, Centro de Convenciones de Barcelona, Barcelona, Spain, arch. Josep Lluis Mateo-MAP Arquitectos, 2004 (Photo by M. Celadyn, 2014); (**b**) Inner courtyard walls' cladding with plane and perforated Corten sheeting, Teaching Center Vienna University of Economics and Business, Wien, BUSarchitektur ZT GmbH, 2013 (Photo by M. Celadyn); (**c**) Façade cladding in partially perforated and stamped stainless steel sheeting, Museu Blau, Barcelona, arch. Herzog and de Meuron, 2011 (Photo by M. Celadyn); (**d**) "The wings" sculptures fabricated with panels of brushed aluminium, EXPO Mediolan, arch. D. Libeskind, 2015 (Photo by M. Celadyn).

Table 1 identifies the main attributes of the flat composition scheme with applied techniques to realise the ADAD conceptual framework, as well as the possible impact of these variables on the formal appearance of the building enclosure.

Table 1. Typology of flat composition in ADAD concept.

Plane Composition Attributes	Processing	Material	Surface Appearance
Accidentality	Manufacturing process to obtain the effect of premature ageing due to corrosion	Corten plain sheets	Random configuration of openings contrasted with rigid arrangement of cladding
Shading	Manufacturing process to obtain the effect of premature ageing due to corrosion	Corten plain or perforated sheets	Discolourations, softening of colours, rupture, irregularity in displacement of stains, dissolving
Seriality	Mechanical working based on embossment	Stainless steel, aluminium	Unconstrained placement, repetitive forms, monochromatic collage of polished, shiny, brushed and matte modules, clustering of perforations
Complementary Contrasts	Perforation, brushing, grooving	Stainless steel	Scratches arranged randomly, malformations of cladding, scratches, cuts

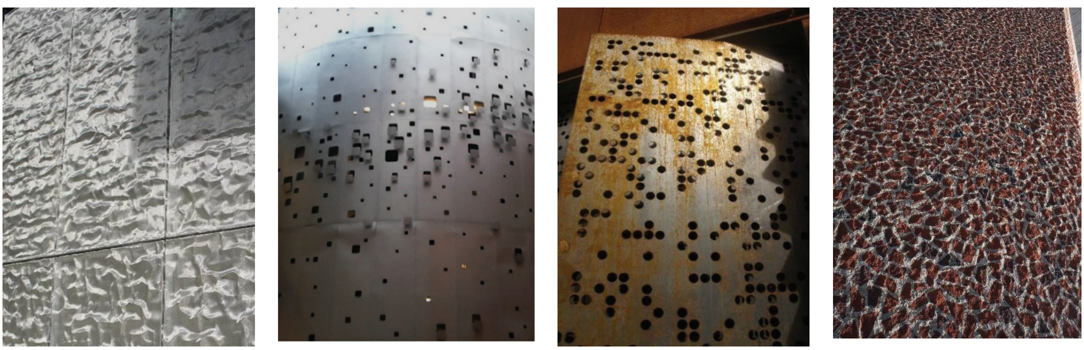
5.2. Relief Compositions

Similar to flat compositions, the application of design techniques to realise relief compositions is preconditioned by the selection of durable building materials to withstand the chosen physical processing or chemical treatment. The relief compositions of building skin introduced traditionally used building materials (e.g., wood, copper, concrete, brick), as well as these recently vastly employed, especially in public buildings, such as aluminium, stainless steel, Corten or titan.

The design techniques to realise the apparent destruction scheme in relief compositions comprise the following:

- Layout featuring embossed or press-formed metal modules with visible deep gaps between;
- Random arrangement of repeated forms;
- Tectonic articulation;
- Broken rhythms of adjacent modules;
- Graded porosity of segments.

Distinct modes of application of the apparent destruction concept to relief compositions employing tactile patterns illustrate the dependence of aesthetic effects on the material's physical parameters and applied specific processing methods, as well as the spectrum of possible results influencing the dynamics, colour saturation and tectonics of the enclosing surface. The possible modes of application of relief compositions to building enclosures are presented in Figure 3.



(**a**) (**b**) (**c**) (**d**)

Figure 3. Application of ADAD concept in relief composition of building enclosure; (**a**) Façade cladding in wrinkled steel mesh, pavilion, EXPO Milan, 2015 (Photo by M. Celadyn); (**b**) Inner courtyard walls' cladding with perforated stainless steel sheeting, Stary Browar (Old Brewery) Commercial Center, Poznan, Poland, arch. ADS Studio, R. Kaja, 2007 (Photo by W. Celadyn, 2014); (**c**) The external pivoting doors with perforated steel and stains from the Corten-finished walls' cladding, British pavilion, EXPO Milan, 2015, (Photo by M. Celadyn); (**d**) External wall cladding with *picado* technique, CKK Jordanki Congress and Culture Centre, Torun, Poland, arch. Menis Arquitectos, 2015 (Photo by M. Celadyn).

The typology presented in Table 2 combines the selected relief compositions that emphasise the range of examination of the appearance of finishing layers on the façade. The various processing techniques applied were examined as means to modify the building's volume, to transform its surface and moderate its interference in the setting.

An exemplary list of processing methods contributing to the surface effects comprises these commonly used techniques that are based on modern technologies as well as innovative ones that explore mixed techniques to reinterpret traditional building techniques. One of them, named *picado*, offers the concrete-clinker brick conglomerate made with crushed red brick [67] reclaimed from a local factory and then embedded into the thick reinforced concrete to shape three-dimensional building cladding [68]. This technique represents an unconventional way toward the reduction of the negative impact on the natural environment and addresses an efficient resource management sustainability strategy. It merges the design for reuse with the aesthetic concept of apparent destruction.

Table 2. Typology of relief composition in the ADAD concept.

Relief Composition Attribute	Processing	Material	Surface Appearance
Crease	Embossment, stretching, folding	Stainless steel	Wrinkled mesh, undulating, folds, bulges of metal sheets causing deceptive illusion of building volume or slight movement, slots, irregular texture
Abrasion	Mechanical treatment of building materials	Stainless steel	Irregular openings, porous, rough, robust layer of the cladding, clustering, random disposition of repeated projecting pieces
Puncture	Grooving	Stainless steel	Perforation on an irregular grid, breaking, cutting, collapse
Chipping	*Picado* conglomerate of reclaimed building materials, crushing, adaptive reuse of recovered building products of high durability	Reused brick, concrete	Roughness, robustness, hardness, brutality

6. Discussion

The apparent destruction of architectural design concept is to add to the discussion about potential methods for making contemporary architecture more sustainable. As mentioned earlier, much has already been said and written about operational energy saving in buildings and also about the reduction of embodied energy in buildings through a suitable choice of building materials and components. Relatively lower attention is assigned to the issue of the longer technical durability of building systems. The ADAD concept indicates ways to prolong the life cycle of conventional building materials in both the technical and aesthetical and symbolic meaning. This component of the scheme partially refers to architecture that is resistant to the pressure of changing styles and traditional perception of building aesthetics that are a restrictive factor for the implementation of "aged" materials. It can introduce new aesthetic and technical values to contemporary architecture, as well as contribute to its interconnectedness with nature through the exposure of creatively transformed nature-produced signs of decay of the building fabric. External surfaces' accommodation of the effects of environmental factors results in the gradual mingling and dissolving of the object's outlines. The softening of the building edges' sharpness and strength evolves with the application of processing techniques along with graphic patterns introduced to provoke the blurring of lines limiting the façade material in the process of transition between the artificial and natural.

Apparent destruction architectural design aiming at the increase in technical durability of building skins introduces a sort of camouflage of the actual age of buildings, which could be contested as a means of purely aesthetic treatment. However, there are some features that stand behind such an approach to the issue of architectural design and sustainability; these comprise the following:

- Extension of the life cycle of materials and building components due to the acceptance of their time-responding aesthetics;
- Decrease in embodied energy of buildings due to less frequent maintenance procedures executed in view of expected aesthetical corrections;
- Reduction of new building materials used in renovation works or as replacements;
- Aesthetic and formal integration of buildings with their natural surroundings.

All these features are directly or indirectly part of the sustainability paradigm for architecture. The building envelope concept faces changing climatic conditions as well as the consequences of the occupants' conduct while showing its eco-aesthetical aspect that reflects the object's resilience and longevity alike.

ADAD considers anticipation, accommodation and creative adaptation as well as the progressive transformation of the signs of matter's decay caused by environmental factors related to time passage. As a result of the assimilation of possible changes in a building's quality prior to its real appearance and their creative altering with selected building techniques, the decay of the surface itself becomes a relevant element of the character of the artificial. Therefore, the discussed design concept is to transcend the distractive evidence of time passage and to substantially weaken the phenomenon defined as buildings' captivity to transformations in the function of time.

Furthermore, ADAD recognises the similarity of morphologies of building skins and those observed in components of the natural environment as complementarities derived, in part, from the biophilic design. This component of the scheme partially refers to architecture that is resistant to the pressure of changing styles and traditional perceptions of building aesthetics that are a restrictive factor for the implementation of "aged" materials.

The environment-responsible postulate of the formal integration of artificial and natural forms proceeds within ADAD in two interconnected areas. These comprise the following:

- Alteration of signs of physical decomposition of building fabric denoting the passage of time to underline the physical transition between the artificial and natural, remaining as the leading design principle;
- Bio-mimicking of the enclosure's composition to enhance the human-made object's formal integration with the natural surrounding and their aesthetical interdependence.

The increase in the durability of buildings and their envelopes goes against the current trend in architecture characterised by frequent exchange of facades and exterior finishes, technical services and "interior constitutive components" [39]. This tendency is to be stopped with the introduction of unconventional design methods and techniques. Apparent destruction addresses the time-dependency of the building skins' physical properties manifested by the destruction and re-figuration of building fabric. This design concept offers a solution to the disturbing problem of architecture's impermanence and enhances the issue of sustainability of building fabric over time.

The paper attempts to investigate the realm of the interrelationship between the human-made and natural environments through the examination of the building's envelope while underscoring the interconnectedness of these environments and continuity of space. The concept is designed not only to indicate a novel idea for architecture and the building industry but also to spark discussion on some unconventional ways to perceive architecture through the lens of the extended view of sustainability in the built environment and some new challenges for the public in the perception of our buildings.

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Article

Creative Thinking in the Architecture Design Studio: Bibliometric Analysis and Literature Review

Eun Joo Park [1] and Sanghee Lee [2,*]

[1] Department of Architecture, Sejong University, Seoul 05006, Korea; ej_park@sejong.ac.kr
[2] Department of Architecture, Dongyang Mirae University, Seoul 08221, Korea
* Correspondence: iris79@dongyang.ac.kr

Abstract: It is increasingly important for researchers and educators to find effective ways to stimulate students' creativity. In design education, the specificity of design, defined as open-ended problems and ill-defined problems, provides a special opportunity to improve creativity. Nevertheless, design education itself encounters other issues concerning creativity, such as not specifying in detail what creative design pedagogy should be. Thus, a comprehensive review of existing studies is needed to guide research in this field better. We used bibliometric analysis to provide information on literature statistics of the 658 articles published in design research–related journals between 1982 and 2022. An in-depth review of the 36 selected articles revealed the existing research on the design studio to investigate creativity from three perspectives: (1) creativity criteria and evaluation, (2) idea generation and development, and (3) pedagogy in the design studio. This study provides a roadmap for global educators and researchers focusing on pedagogy that enhances students' creativity in the design studio.

Keywords: creative thinking; design studio; design education; design research; bibliometric

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1. Introduction

Creativity is characterized by the ability to deal with ideas of expression and produce unique and useful results [1]. It is often qualified by its outcome but can be associated with a specific process that is likely to produce creative artifacts in design [2,3]. A creative design process is a special type of design that generates innovative ideas [2,4]. Guilford pointed out that creativity is closely related to the ability to reconstruct problems and reinterpret thinking, which leads to freedom from fixation when developing logical solutions [5]. New ideas emerge from a new combination of existing knowledge and ideas found in experiments. Designers can find solutions based on processes such as problem interpretation, memory exploration, and adoption of relevant knowledge [6]. Cross argued for a design way of knowing that was distinct from scientific and academic ways of knowing [7].

Creative design thinking can be a powerful way to motivate various design ideas by allowing an interactive understanding of ill-defined design issues [7–11]. Accordingly, many researchers and educators have attempted to find effective ways to stimulate students' creative thinking, and they emphasize the importance of design education [7–10,12–15]. Transitions between divergence and convergence thinking often occur throughout creative design idea generation [16]. Dorst studied the core of design thinking to generate ideas, defined reasoning patterns derived from design, and emphasized abduction as a basic reasoning pattern for creative thinking [12]. Enhancing creativity is crucial in design fields and helps students discover their visions, acquire core expertise and knowledge, and understand the professional philosophy and foundation of the design process [11]. Students can intensively demonstrate their creative skills while learning during the design process and engaging in communication, discussion, and knowledge acquisition methods [17]. Design thinking has become a way to lead students' creativity and innovation, teach creative problem solving, and improve or rediscover creative confidence [18,19].

In the university education environment, each field has its own basic characteristics. The architectural department is an active area where research, design, and implementation processes are based on interaction, sharing, and production at the forefront rather than on theoretical processes [20]. Creativity and spatial ability are representative cognitive abilities that are considered important in architectural and spatial design [21–24]. The architecture design studio is a unique educational area in which students require creative abilities and communication skills [25]. The design studios are the most fundamental course of architectural education where students acquire practical and theoretical knowledge and creatively transform that knowledge into a representation of design models [26,27]. Design education has a complex and contradictory structure based on comprehensive and abstract concepts. Nevertheless, it can be a powerful way to allow interactive understanding of ill-defined design issues and motivate additional design ideas [9]. The design studio approach consists of repetitive reflections and representations in the design process [28]. In terms of the education aspect, how new operative techniques change the role of creative thinking in the design studio needs to be identified rather than just experimenting with techniques [29].

One of the problems with architectural design education is the gap between knowledge acquisition and knowledge application in design studios [30–32]. Design is related to subjective creativity, but the empirical university paradigm emphasizes objective rationality in education [17,33]. Design education has generally been delivered to students through the subjective teaching method of teachers rather than through a systematic academic approach [34]. Design education tends to be ignored as an academic category from a general educational perspective that values logical and empirical education. Thus, design education should have an educational model with more academic methods to improve creativity because promoting creativity is an important issue, and interdisciplinary integration should be emphasized [35]. Against this background, in the area of design education, many studies related to education to enhance creativity are currently being actively conducted. To improve students' creativity in design education and develop a more rigorous and academic approach to design education, it is necessary to form an educational platform that can take potential thinking to the next level within a new educational paradigm based on creative experience according to university standards.

Based on the research content analyzed, we aimed to extract research trends that could be important in future design education by identifying keywords related to creativity that have been actively explored in design research. Therefore, this study sought to understand creativity in relation to the design studio, along with the integral relationships between (1) creativity, (2) design strategy, and (3) design education. The composition of this paper is as follows. Section 2 describes the applied methodology, while Section 3 addresses the results of the bibliometric analysis. Section 4 discusses the findings and Section 5 presents the conclusions.

2. Materials and Methods

The use of traditional review methods depends on the objectives of the review and the size and nature of the literature under review. Since bibliographic analysis and meta-analysis are both inherently quantitative, the differences can confuse some scholars. To clarify this distinction, quantitative methods can handle large quantities of literature but are relatively different in terms of usage. In particular, meta-analysis focuses on summarizing empirical evidence by analyzing the direction, intensity, and relationship between the effects. It is useful for solving open research questions with data closer to conclusive than reported in any single primary study [36]. In contrast, the bibliometric analysis summarizes bibliographic and intellectual structures in the field by analyzing social and structural relationships between different research components such as authors, countries, institutions, and topics [37]. Thus, this study employed a bibliometric methodology summarizing quantitative techniques on bibliometric data to facilitate an approach to scientific databases via the Web of Science (WoS) to obtain large amounts of bibliometric data using software such as VOSviewer. The WoS is one of the world's largest bibliometric databases for peer-reviewed studies, and it delivers the results of various analyses and forms linked to VOSviewer. Therefore, it was considered an appropriate method for identifying evolving research trends in creative thinking in design research across disciplines. To achieve this, the bibliometric study was conducted over the following five steps [37]: (1) define the aim and scope of the study, (2) choose the techniques for the bibliometric approach, (3) collect the data for bibliometric analysis, (4) run the bibliometric analysis comprising performance analysis and science mapping, and (5) deliver the findings and discuss their implications for future research.

2.1. The Aim and Scope of the Study

This study aimed to contribute to future research directions on researchers' creativity in design-related areas by presenting and reviewing research trends to improve students' creativity in design studios. In addition, the bibliometric study delivers theoretical and methodological references to creativity in the design studio. Researchers can obtain an understanding of the gaps between different disciplines and obtain a variety of ideas about design education that enhances students' creativity. Thus, we conducted a literature review to capture the developing topics and emerging concepts in design education that were relevant to our research questions on creative thinking in design research. This study addresses the following main research questions:

RQ1. How can creativity in the design process be evaluated in students' work?
RQ2. What are some effective educational tools in the design studio to support the creativity of design concepts?
RQ3. What educational practices are found in design studios to enhance creativity?

2.2. Framework for the Study

Table 1 shows the selection process adopted and analysis of the study at each phase. In the first study-selection phase, a preliminary study was conducted based on the title, abstract, and keyword. In the second bibliometric approach phase, a descriptive and quantitative methodology analysis of traditional literature reviews from the WoS databases was conducted based on publication year, the number of total citations, the most productive authors and countries, and the co-occurrence network of author keywords.

Table 1. Flowchart summarizing study procedure.

Phase 1:	2.3. Study selection	(1) Selection of databases with bibliometric data: The WoS		
		(2) Selection of software tools for analysis: VOSviewer		
		(3) Selection of query wording and Boolean operators: ("creativity" or "creative thinking") and ("design studio" or "education") and ("architecture" or "urban design" or "built environment")	⇨	n = 709
		(4) Selection of timespan: 1982–2022	⇨	n = 708
		(5) Selection of document types: Journal articles and proceedings articles, excluding review articles	⇨	n = 685
		(6) Selection of language: English	⇨	n = 661
		(7) Screening	⇨	n = 658

Table 1. *Cont.*

Phase 2: Bibliometric approach	2.4. Bibliometric approach	(1) Descriptive bibliometric analysis of WoS research: Number of publication year		
		(2) Descriptive bibliometric analysis of WoS research: Total citations		
		(3) Descriptive bibliometric analysis of WoS research: The most productive authors and countries		
		(4) Descriptive bibliometric analysis of WoS research: Co-occurrence network of author keywords		
Phase 3: Bibliometric Analysis	3.1. Performance analysis	3.1.1. Converting data from WoS to appropriate format for bibliometric analysis: Publication years of relevant citations		
		3.1.2. Most cited publications in WoS search result		
		3.1.3. Most prolific authors in WoS database		
	3.2. Science mapping	3.2.1. Co-authorship analysis of authors: Mapping the scientific collaboration of authors, countries, and organizations		
		3.2.2. Co-occurrence—Keywords in WoS: Most frequently used words, author keywords, co-occurrence, network of authors' keywords	⇨	105 keywords out of 502
	3.3. Intervention methods of the studies	3.3.1. Creativity in design studio: Creativity criteria Creativity evaluation	⇨	n = 36
		3.3.2. Idea generation and development: Reasoning patterns Representation tools		
		3.3.3. Pedagogy in design studio: Design studio set-up Enhancing creativity		
	3.4. Overall review			
Phase 4:	Discussion			
Phase 5:	Conclusions and directions for future research			

The VOSviewer software is used for visualizing the bibliometric networks employing the data imported from the WoS data source. Figure 1 shows the process of the bibliometric analysis of the data extracted from the WoS using the VOSviewer software.

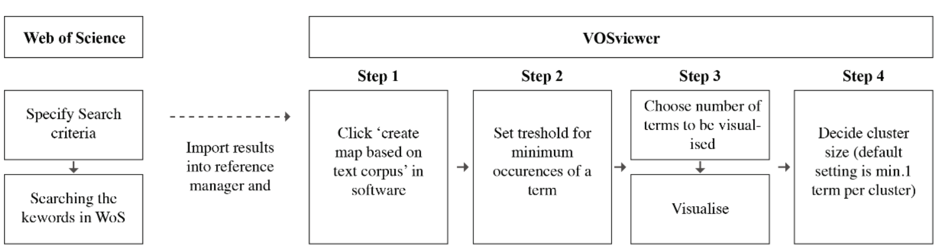


Figure 1. The process of the bibliometric analysis using the VOSviewer.

2.3. Study Selection: Phase 1

To ascertain the scope and ensure eligibility of existing studies on design research for creativity, we selected related articles from the WoS from 1982 to 2022 for further analysis using the keywords ("creativity" or "creative thinking") and ("design studio" or "education") and ("architecture" or "urban design" or "built environment"). The file contained key information for literature analysis, such as author, subject, source, abstract, citation, document type, number of citations, keywords, and publisher information. We limited the results to articles and proceedings published in English. Intervention studies in peer-reviewed journals were included, whereas conference papers, essays, reports, and dissertations were excluded. These articles were judged based on their relevance and results. After several iterations, the keyword group consisting of terms to be excluded was applied to the databases. This search produced 658 articles. The selection criteria were as follows:

1. document types: journal articles and proceedings articles excluding review articles;
2. use of language: English;
3. publication year: from 1982 to 2022.

2.4. Bibliometric Approach: Phase 2

This study employed a quantitative bibliometric approach and was largely classified into qualitative and quantitative methodologies. In addition, from the traditional literature reviews available, this study focused on a narrow range of domain, method, and theory-based reviews using qualitative techniques [37–39]. The technical bibliometric approach from the WoS was categorized into four analysis techniques, as follows:

1. number of publications in a year;
2. total citations;
3. most productive authors and countries;
4. co-occurrence network of author keywords.

3. Results: Bibliometric Analysis

Bibliometric analysis is a common and rigorous method for exploring or analyzing large volumes of scientific data to discover new trends and examine the intellectual structure of specific areas in the existing literature [37]. First, performance analysis condenses the productive research components of the number of publications and citations per year, analysis of publications by journals, research area, authors, affiliations, and countries. Next, science mapping explores the relationships between research components categorized into five analysis techniques, as follows:

1. Citation analysis classifies the relationships between the most significant publications in the field of creativity in the design studio;
2. Co-citation analysis reveals the intellectual structure through publications, assuming publications that are cited together frequently are similar thematically;
3. Bibliographic coupling exposes periodical or current development of topics through the relationships between cited publications;
4. Co-word analysis discovers existing and future relationships between topics in the research area of creativity in the design studio;
5. Co-authorship observes the research network among authors and the equivalent impacts on the development of creativity in the design studio.

3.1. Performance Analysis: Phase 3 (1)

3.1.1. Publication Years of Relevant Citations

The 658 published research articles were analyzed, and the results are presented. Figure 1 reveals increased research in "creative thinking in the design studio" and presents indicators of publication activity based on records included in the WoS databases. It covers the number of publications (i.e., annual and cumulative) for the period of 1982–2022 and the number of citations that these items received. The data indicated that from 2010 to 2019, the number of publications of relevant citations increased considerably. However, the sharp decline in publications in 2021 and 2022 was due to unfinished bibliographic data records (see Figure 2). This trend will continue to demonstrate a rise in any future studies conducted. Therefore, further analysis is needed to gain more insight into the direction of research in this area.

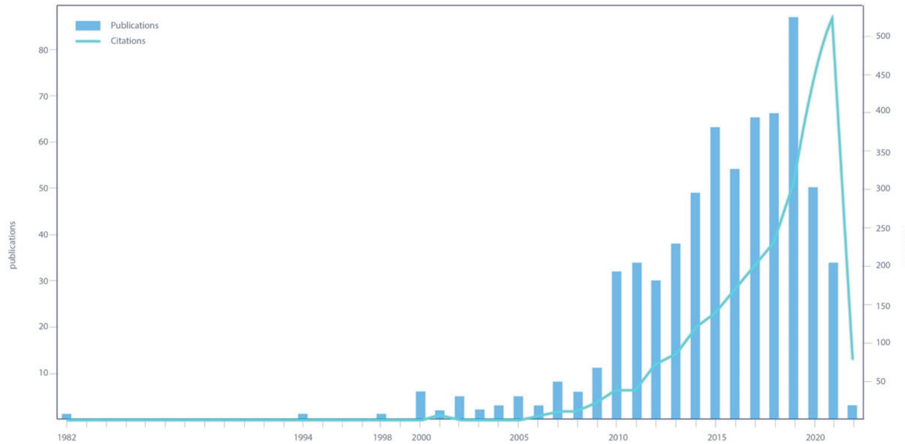


Figure 2. Times cited and publications over time.

3.1.2. Most Cited Publications

Table 2 shows the top 10 most cited papers in the WoS search results over the whole period from 1982 to 2022. The purpose of this analysis was to identify the main sources of ideas and determine which paper has had the most influence in shaping the content and the design research field. Moreover, we also present the research areas and number of the journals cited over the whole period, which indicates the change in the cited journals' influence on the design research. The most cited paper in the WoS databases, with 93 citations, was "How good are good ideas? Correlates of design creativity", written by Goldschmidt and Tatsa [40]. It should be noted that most studies on the lists with the highest number of citations were published in the journal *Design Studies*.

Table 2. The top 10 most cited papers in WoS search results for "Creative thinking for sustainable education in the design studio".

No.	Author(s)	Year Published	Paper Title	Journal	Discipline	Citation Count
1	Goldschmidt and Tatsa [40]	2005	How good are good ideas? Correlates of design creativity	*Design Studies*	Engineering	93
2	Goldschmidt and Sever [41]	2011	Inspiring design ideas with texts	*Design Studies*	Engineering	89
3	Ozkan and Dogan [42]	2013	Cognitive strategies of analogical reasoning in design: Differences between expert and novice designers	*Design Studies*	Engineering	66
4	Rahimian and Ibrahim [43]	2011	Impacts of VR 3D sketching on novice designers' spatial cognition in collaborative conceptual architectural design	*Design Studies*	Engineering	58
5	Kokotovich [44]	2008	Problem analysis and thinking tools: an empirical study of non-hierarchical mind mapping	*Design Studies*	Engineering	58

Table 2. *Cont.*

No.	Author(s)	Year Published	Paper Title	Journal	Discipline	Citation Count
6	Ibrahim and Rahimian [45]	2010	Comparison of CAD and manual sketching tools for teaching architectural design	*Automation in Construction*	Construction and Building Technology Engineering	57
7	Srinivasan et al. [46]	2016	Genetic markers of human evolution are enriched in schizophrenia	*Biological Psychiatry*	Neurosciences and Neurology Psychiatry	50
8	Demirkan and Afacan [47]	2012	Assessing creativity in design education: Analysis of creativity factors in the first-year design studio	*Design Studies*	Engineering	46
9	Cai et al. [48]	2010	Extended linkography and distance graph in design evaluation: An empirical study of the dual effects of inspiration sources in creative design	*Design Studies*	Engineering	46
10	Kowaltowski et al. [49]	2010	Methods that may stimulate creativity and their use in architectural design education	*International Journal of Technology and Design Education Psychology*	Education and Educational Research Engineering	45

3.1.3. Most Prolific Authors

The most productive authors with the most frequent contributions to the creativity in the design field in the WoS databases were Kim D.S. and Kim M.H., each with seven publications. Interestingly, South Korea was the most productive country in all periods (See Table 3).

Table 3. Most productive authors, organizations, and countries in the WoS database.

	Author	Institution	Country	Documents	Citations
1	Kim, D.S.	Kumoh National University Technology	South Korea	7	41
2	Kim, M.H.	Kyung Hee University	South Korea	7	25
3	Casakin, H.	Ariel University	Israel	6	53
4	Hua, C.H.	Kyung Hee University	South Korea	6	39
5	Cho, J.Y.	Kyung Hee University	South Korea	5	45
6	Hasirci, D.	İzmir University of Economics	Turkey	5	31
7	Lee, J.M.	Pusan National University	South Korea	5	21
8	Chen, Y.	University of South China	China	4	27
9	Dorado, M.I.A.	Universidad de Málaga	Spain	4	0
10	Huynh-the, T.	Kumoh National University Technology	South Korea	4	40

3.2. Science Mapping: Phase 3 (2)

3.2.1. Co-Authorship Analysis of Authors

Co-authorship analysis identified the intellectual collaborative structure of authors, countries, and organizations. The relationships between authors, countries, and organizations are displayed on the network map in Figure 2, and the links connecting the nodes represent the relationships. The size of the node characterizes the number of citations, while the thickness of the connection between the nodes establishes the strength of collaboration. Individual collaborative groups are assigned different colored circles.

(1) Authors

The threshold for bibliometric data was set as one for the minimum number of documents per author. Of the 1528 authors, only 33 met the threshold to create the collaboration network map shown in Figure 3. Nevertheless, co-authorship demonstrated that noticeable names from productive authors such as Goldschmidt, G., Kowaltowski, D., Demirkan, H., and Wang, T. had established firm research cooperative relationships.

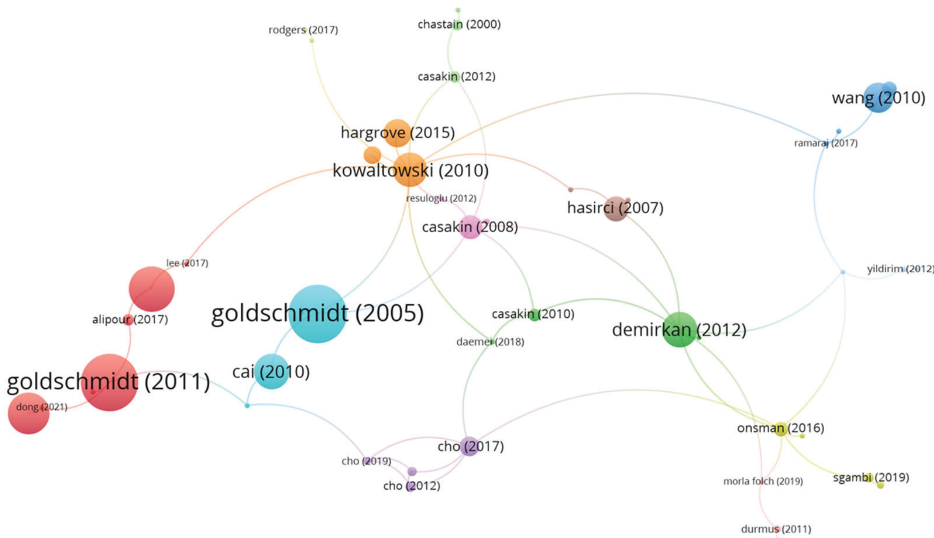


Figure 3. Mapping of authors' collaboration network.

(2) Countries

Regional collaboration and research hotspots were obtained with the visualization of co-authorship occurrences of countries. The distribution of studies across geographic regions appears in Figure 4. The size of the circles represents the number of occurrences of papers. Collaboration strength is demonstrated by the distance between circles in individual pairs. All studies were distributed internationally, with publications from all global regions. This suggests that the themes identified through the qualitative grounded theory analysis were likely to be general characteristics of studio pedagogy rather than specific to one nation's pedagogical tradition, thereby indicating an increasing trend of international collaboration among the authors. Analysis revealed 69 countries represented by collaborating authors in the WoS databases:

- Turkey and the United States had the greatest total link strength in relation to the international collaboration of authors;
- China, Spain, India, and South Korea had a high number of publications, but their international collaboration strength was relatively low.

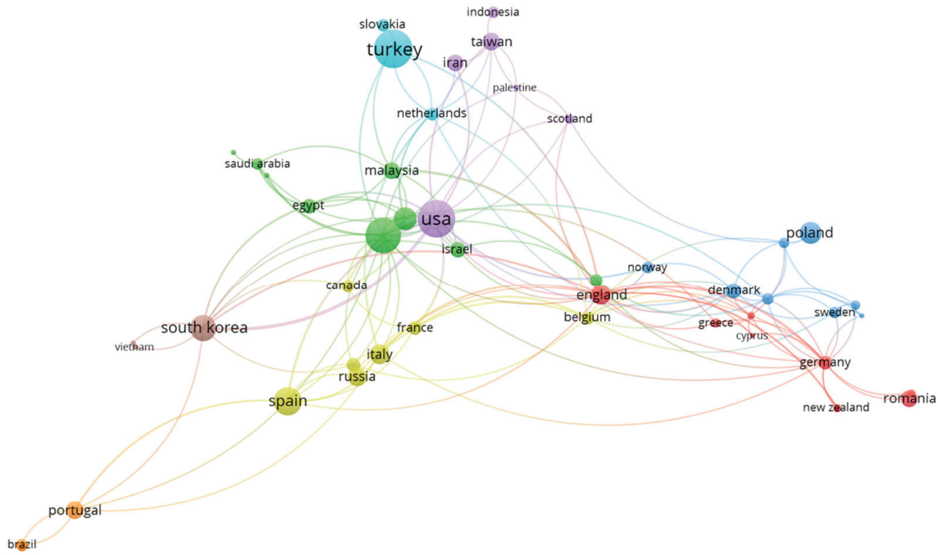


Figure 4. Co-authorship network of countries.

(3) Organization

To examine its international influence, we grouped the countries of the authors' affiliations into seven groups, displayed below in Figure 5. University Lisbon Ozyegin University, Mimar Sinan Fine Arts University, and Kyung Hee University appeared to have a relatively close network of relationships with other universities. However, the strongest relationship between Kyung Hee University and Pusan National University stood out.

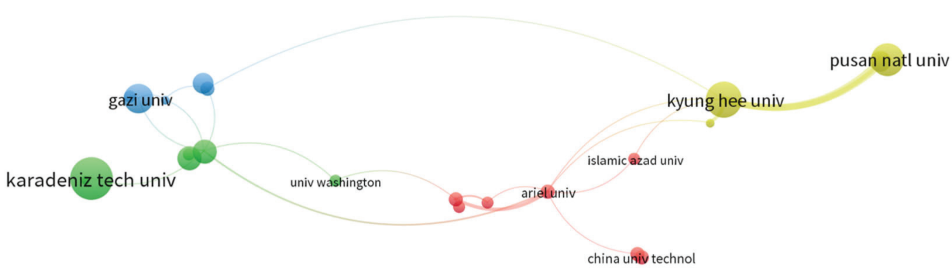


Figure 5. Co-authorship organization networks.

3.2.2. Co-Occurrence—Keywords Plus

The threshold for the co-occurrence of keywords was set to twice, and 105 out of 502 keywords were classified as visualization items. The keyword co-occurrence network is provided in Figure 6. The size of the circle corresponds to the number of occurrences of the illustrated keyword. The larger the circle, the more the author keyword was selected in the WoS databases. The subject similarity and its relative strength are demonstrated by the distance between the elements of an individual pair. Different colors of the circle are assigned to individual keyword clusters. The network in Figure 6 shows 12 individual clusters representing the individual subfields of the research fields identified in the WoS databases. The links between particular keywords indicate the number of papers in which the keywords co-occurred.

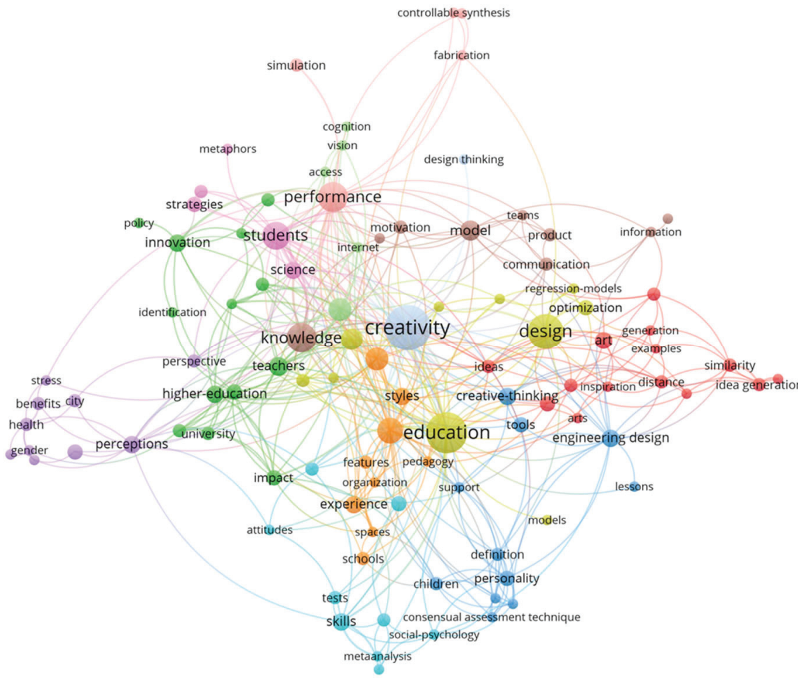


Figure 6. Co-occurrence network of author keywords (min. number of occurrences: two) in WoS.

Analyzing Figure 6, it may be concluded that the core topics with the highest total link strength were “creativity,” “education,” and “students.” Twelve subfields (clusters of author keywords) were identified in the research fields, and the three main subfields were as follows:

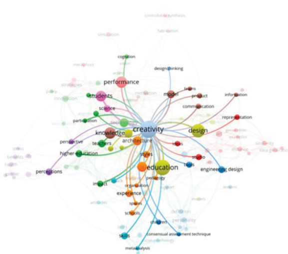
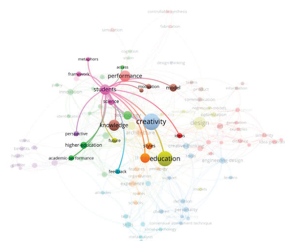
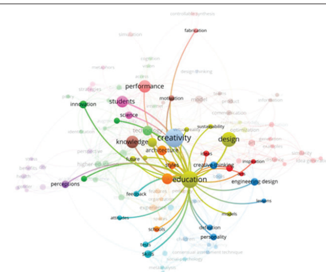
- Yellow cluster: Groups keywords such as creativity, design thinking, and experience;
- Pink cluster: Groups keywords such as design, tool, and sustainability;
- Brown cluster: Groups keywords such as education, knowledge, and challenges.

The results demonstrate a considerable diversity of the co-occurrence of author keywords in individual publications in the WoS, proving the multi-faceted and multi-dimensional character of this particular scientific field.

3.3. Intervention Methods of the Studies

In this section, the findings are discussed, focusing on the latest technology in creativity in the context of architectural design studios. The findings provide an overall explanation of the main topics identified primarily as important in the early stages of the design process, also known as the most creative conceptual stage of the entire design process. Before the establishment of creative design thinking as a term in the research field of interdisciplinary study, discussions focused on three aspects of research findings: (1) creativity criteria and evaluation, (2) idea generation and development, and (3) pedagogy in the design studio (See Table 4).

Table 4. Defining aspects of creativity, design strategy, and design studio.

Creativity	Design Strategy	Design Studio
		
Creativity criteria, Creativity evaluation	Idea generation, Idea development	Pedagogy

3.3.1. Creativity in the Design Studio

(1) Creativity criteria

Creativity is an individual's core ability to create original, useful, and unexpected tasks [1,50,51]. Therefore, rather than attempt to reach an agreement on how to define creativity, it may be more advantageous to review topics or characteristics related to how to understand creativity in a variety of contexts.

- Guilford emphasized divergent thinking and that creativity is closely related to reconstructing problems and defined fluency, flexibility, and originality [5];
- Goldschmidt argued that convergent thinking also plays a role in creativity, and design literature, which views design as a priori creative activity, mostly accepts this view [16];
- Doston argued that interest in design thinking was sparked in organizations that had difficulty dealing with complex problem situations, which could be particularly useful in the context of abductive reasoning in how design practices handled themes and frames [12];
- Taylor proposed five typologies of creativity: expressive, productive, inventive, innovative, and emergent [52];
- Jackson and Shaw reported specific topics of definition, including creativity, innovation, transfer, and application of ideas [53];
- Using qualitative analysis, Kleiman observed five categories of creative experience: constraint-oriented, process-oriented, product-oriented, transformation-oriented, and implementation-oriented [54];
- Cropley defined engineers as problem solvers, explained that the core activity of engineering is design, and suggested that creativity is inherent in the design process [55].

(2) Creativity evaluation

Many studies consider assessing creative outputs to discuss critical issues related to the measurement of students' activity. While efforts have been made to identify approaches to improving student creativity [56,57], there is no way to claim to be effective in student growth. The level of creativity in higher education is again related to the idea that the creativity practiced in higher education is deeply entrenched.

- Casakin and Kreitler emphasized the relationship between the evaluation of creativity in design problem solving and the level of expertise of evaluators [58];
- Hargrove and Nietfeld noted that evaluation played an important role in tracking students' conceptual understanding of the metacognitive process [59];

- Acikgoz evaluated the quality of learning achieved during the design team collaboration based on a rubric that included defining problems, idea generation, linking and integrating ideas, and adapting to the task at hand. He has shown that structured architectural processes significantly affect the overall consistency between design thinking, idea generation, and finding solutions [60];
- Choi and Kim enhanced novelty and familiarity measurement by using "third elements" that address ambiguous aspects such as clarity, communication, and observation to capture the behavioral aspects related to creative activities. The development of this triangular approach is worth considering in a very social and dynamic space [61];
- Grover et al. evaluated the support provided by typology in three key stages of the design process. Exploring the framing stage of a design project has shown that searching for relevant functions and identifying metaphorical typologies based on cultural, contextual, or empirical phenomena is challenging for most students [62].

3.3.2. Idea Generation and Development

Idea generation and development is the development of ideas and strategies that support various reasoning methods to influence students' design thinking in the design process and the expression of various techniques [7].

(1) Reasoning patterns

Analogical reasoning may be viewed as a critical aid in problem-solving, especially in solving architectural design problems. Metaphors can help designers understand unfamiliar problems and expand the scope of potential design solutions, especially in the early stages of the design process. Moreover, by examining the relationship between creativity and metaphor, it is evident that metaphor plays an important role in design creativity.

- Hofstadter revealed that analogy is a cognitive process that can support the acquisition of new knowledge [63,64];
- Dorst described abduction as a basic inference pattern for design strategies that define creative thinking. He studied the core of design thinking for idea generation, defined design-derived reasoning patterns, and emphasized abduction as the fundamental reasoning pattern for creative thinking [12];
- Casakin and van Timmeren revealed that analogical reasoning supports architectural education by employing visual and verbal analogies in the early stages of the design process [65];
- Schön argued that metaphor can help one reflect on the nature of a situation when solving unusual design problems. Without metaphor, it would be difficult to obtain solutions [27];
- Orthony emphasized that metaphor allows us to understand unknown situations in relation to familiar situations [66].

(2) Representation tools

Expressing creativity and visual experience is an essential part of architectural design. Design representations are used for a variety of purposes, including as a means of supporting reflective activities [67] and communicating design intentions to others [7]. Creativity can be developed through training, such as intentionally capturing new ideas [68–70].

- De Bono explained that brainstorming is a method for improving creativity and is a good example of enhancing and maximizing idea generation [71,72];
- Choi and Kim described how stimuli can generate thought extensions. Their work focused on the level of abstraction provided during brainstorming and troubleshooting, and the authors suggest that this can be particularly effective in digital contexts [73];
- Juhani emphasized that drawing refers to the essential meaning of revealing and embodying inner thoughts and emotions as much as recording the external world [74];

- Clear described that architectural drawings are traditionally considered to have two main functions: communicating practical information about design and constructing architectural projects, or communicating aesthetic information about building materials or stylistic aspirations [75];
- Park revealed that drawings represent a good medium for design and communication, and text could stimulate students' creativity as a thinking transition in architectural studios [29].

3.3.3. Pedagogy in the Design Studio

In the context of architectural design pedagogy, creativity-related education was emphasized as essential to producing self-sufficient and innovative future architects [76]. To this end, we identified (1) design studio set-up and (2) enhancing creativity to support creative education.

(1) Design studio set-up

- Goldschmidt and Tatsa analyzed student ideas generated during the development of a design studio project with additional ideas organized by fellow students and instructors. Their approach led to deep insights into how ideas are structured along the design process in terms of quality as well as quantity [40];
- Casakin and Kreitler compared the way students and teachers explored the design creativity process and outcomes. They found that while students focused on operational aspects, teachers paid more attention to innovative aspects of student processes and outcomes. They concluded that design studio intervention programs could consider these differences to facilitate the acquisition of design procedures and provide deeper insights into how students perceive design creativity compared to teachers [58];
- Asefi and Imani considered more broadly the "mode transitions" required to accommodate different types of thinking employed in different stages of the design process by using comparative studies of student outcomes. They advocated an active strategic education model and assigned various tools and methods for use in design studio work [76];
- Kowaltowski et al., from the perspective of an instructor, reviewed the creativity method and its use in a design studio. They interviewed 28 design instructors on how to apply it to design studios, reporting that the method is typically applied in an unstructured manner and that a more structured approach would help [49];
- Grover et al., used the historical theory of typology as a structured framework for the knowledge search contained in architectural building precedents to guide students through various stages of the design process. The design phase included frame definition, conceptual design, and detailed project development [62];
- Suh and Cho explored the relationship between an individual's cognitive style and creative performance by structuring the design process according to the different design stages. Their study found that intuitive students were more creative in the early stages, whereas adaptive and more analytical students improved their creativity at the end of the process [77];
- Kavousi et al., proposed a conceptual model that focuses on the impact of metacognitive processing in design education on student design thinking and making. Their research demonstrated how super-cognitive components interact and how they support training programs to improve the design process and creative outcomes generated [78];
- Avsec revealed that design thinking is closely related to self-directed learning and emphasized that creative design thinking can provide metacognitive insights that include interpersonal skills, creativity, and digital skills that are strongly explained by design thinking variables [79].

(2) Enhancing creativity

- Alterio and McDrury revealed that reflection on experience creates meaningful learning to improve creativity, interprets learning as behavior, and evaluates the results of these behaviors through self-reflection learning. This learning method shows that reflective practice trains students' creativity during studio projects [80];
- Hargrove and Nietfeld explored the effectiveness of creativity education in the form of associated thinking strategies. The pedagogical approach aimed at supporting creative problem solving consisted of integrating activities related to creative thinking strategies to encourage super-cognitive development. Creative thinking reflects the ability to be trained and developed over time [59];
- Bhattacharya et al., argued that active exposure to unusual experiences and/or situations can have useful creativity-enhancing applications in design studios. Their pedagogical approach was based on the idea that a conceptual mix of virtual scenarios can be used to enhance and train divergent thinking while dealing with a variety of unfamiliar and unexpected design situations [81].

(3) Problem-solving

- Kruger and Cross described that designers using problem-driven design strategies manage to produce the best results in terms of a balance between overall solution quality and creativity [82];
- Wrigley verified that design thinking creates a highly reflective creative process that allows students to review and critically think about their design process to create a deeper understanding of the evolution of design thinking as a problem-solving activity [83];
- Lee et al., revealed that the design process sometimes begins with solutions that are not problems through the empirical study of engineering designers with experience in successfully searching for problems that fit new technology solutions [84].

3.4. Overall Review

The characteristics of creativity in the design studio were considered, and three major themes and six subcategories were identified above in Section 3.3. The major themes included creativity, idea generation and development, and pedagogy in the design studio. The themes cover practical considerations that help architectural design studios' creative activities, as well as theoretical models and frameworks that underlie creativity interpretation in this context. The themes related to each category and directly addressed in the articles are shown in Table 5. Further, 36 selected articles are sorted by year and the remainder are organized by themes, and each sub-category sorts the description of each category.

Table 5. Overall review of the 36 selected articles.

Themes	Categories	Subcategories		Description	Articles
Creativity	Creative criteria	Divergent thinking	(1)	Emphasized fluency, flexibility, and originality	[5]
		Convergent thinking	(2)	Argued that convergent thinking also plays a role in creativity, and design literature, which views design as a priori creative activity, mostly accepts this view	[16]
		Abductive reasoning	(3)	Argued that abductive reasoning could be useful in dealing with open and complex problem situations, especially in the way themes and frames are handled	[12]
			(4)	Covered expressive, productive, inventive, innovative, and emergent typologies	[52]

Table 5. *Cont.*

Themes	Categories	Subcategories	Description	Articles
Creativity	Creative criteria	Typologies	(5) Provided specific topics of definition, including creativity, innovation, transfer, and application of ideas	[53]
			(6) Defined five categories of creative experience: constraint-oriented, process-oriented, product-oriented, transformation-oriented, and implementation-oriented by using qualitative analysis	[54]
		Engineering activity	(7) Defined engineers as problem solvers, explained that the core activities of engineering are design, and suggested that creativity is inherent in the design process	[55]
	Creativity evaluation	Self-evaluation	(8) Explored the relationship between the creativity assessment of design problem solving and the level of expertise of evaluators	[58]
		Metacognitive process	(9) Constructed a mental model for a creative approach to design problem solving and evaluation of students' creative and metacognitive thinking through a final design project	[59]
		Structuring architectural processes	(10) Evaluated the quality of learning achieved during the design team collaboration based on a rubric that included defining problems, idea generation, linking and integrating ideas, and adapting to the task at hand	[60]
		Third elements	(11) Measured novelty and familiarity and addressed ambiguous elements such as clarity, communication, and observation	[61]
		Metaphorical typologies	(12) Evaluated the support provided by typology in three key stages of the design process based on cultural, contextual, and empirical phenomena	[62]
Idea generation and development	Reasoning pattern	Analogical reasoning	(13) Detailed a cognitive process that can support the acquisition of new knowledge	[63,64]
			(14) Provided a basic inference pattern for design strategies that define inference patterns and provide creative thinking	[12]
			(15) Used visual and verbal analogies in the early stages of the design process to support architectural education	[65]
		Metaphorical reasoning	(16) Reflected on the nature of a situation when solving unusual design problems	[27]
			(17) Focused on understanding unknown situations in relation to familiar situations	[66]
		Brainstorming	(18) Discussed how this enhances and maximizes idea generation	[71,72]
			(19) Covered how stimuli can generate thought extensions particularly effective in digital contexts	[73]
			(20) Explored how this reveals and embodies inner thoughts and emotions	[74]

Table 5. *Cont.*

Themes	Categories	Subcategories	Description	Articles
	Representation tools	Drawings	(21) Studied communication of practical information and construction of architectural projects, or communication of aesthetic information or stylistic aspirations	[75]
			(22) Examined how text is used as a thinking transition in architectural studios—A good medium for design and communication	[29]
Pedagogy	Design studio set-up	Demonstrate	(23) Analyzed students' idea generations during the development of projects using additional ideas organized by students and instructors to demonstrate deep insights into how ideas are structured during the design process	[40]
		Comparativity	(24) Compared the design creativity process of students and teachers, finding that students focus on operational aspects, while teachers pay more attention to student processes and outcomes	[58]
			(25) Considered more broadly the "mode transitions" required to accommodate different types of thinking at different stages of the design process by using comparative studies of student outcomes	[76]
		Interview	(26) Interviewed 28 design instructors to examine the method of creativity and its use in the design studio, and suggested a more structured approach needed for the design studios	[49]
		Historical theory	(27) Used the historical theory of typology as a structured framework, including frame definition, conceptual design, and detailed project development	[62]
		Structuring the design process	(28) Explored the relationship between individual cognitive styles and creative performance	[77]
		Metacognitive process	(29) Proposed a conceptual model focusing on the role of metacognitive processing in design training programs to improve the generated design process and creative outcomes	[78]
			(30) Emphasized that creative design thinking can provide metacognitive insights that include interpersonal skills, creativity, and digital skills that are strongly explained by design thinking variables	[79]
	Enhancing creativity	Self-reflection	(31) Explored reflections on experience that create meaningful learning to enhance creativity, interpreted learning as behavior, and revealed that reflective practice trains students' creativity	[80]
		Super-cognitive development	(32) Explored an educational approach to supporting creative problem solving consisting of integrating activities related to creative thinking strategies to encourage super-cognitive development	[59]
		Active exposure	(33) Examined how a conceptual mix of virtual scenarios can be used to enhance and train divergent thinking while dealing with a variety of unfamiliar and unexpected design situations	[81]

Table 5. *Cont.*

Themes	Categories	Subcategories	Description	Articles
			(34) Designers using problem-driven design strategies manage to produce the best results in terms of a balance between overall solution quality and creativity	[82]
	Problem-solving		(35) Design thinking creates a highly reflective creative process that allows students to review and critically think about their design process to create a deeper understanding of the evolution of design thinking as a problem-solving activity	[83]
			(36) The design process sometimes begins with solutions that are not problems	[84]

4. Discussion

This study focused on the latest trends in creativity conducted in the context of architectural design studios. Architectural design studios are employed in the most practical courses in architectural education in which students acquire practical and theoretical knowledge and learn how to transform that knowledge creatively into their own spatial designs [27,85]. This study demonstrates that architectural design studios develop an understanding of the entire design process, which stimulates students' creative thinking. Teaching methods for creative design provide a holistic explanation of the key education related to teaching creativity in the context of architectural design studios. Creativity in design studios emerged from well-studied research themes that included Creativity, Idea generation and development, and Pedagogy in design studios. Each theme included categories which included Creative criteria and Creativity evaluation, Reasoning pattern and Representation tools, Design studio set-up, and Enhancing creativity and Problem-solving. The overall themes and their categories are presented in Figure 7.

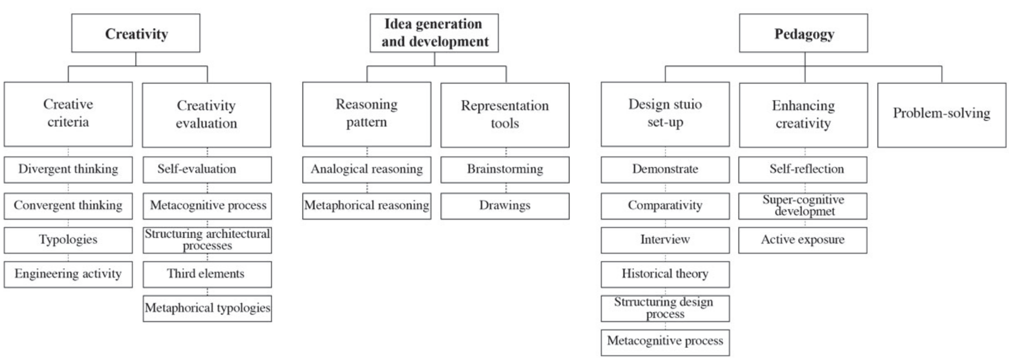


Figure 7. The overall themes and categories of the 36 selected articles.

In this study, How can creativity be evaluated in students' work in the design process? What are some effective educational tools in the design studio that support the creative design concepts? and What educational practices are found in design studios to enhance creativity? founded for answers to the initial research questions. Based on the answers to the research questions, some issues to be considered for enhancing creativity are identified.

First, according to recent studies, some interesting issues were found regarding the definition of creative criteria, including divergent thinking and typologies in design studios. In the context of the evaluation of creativity, we confirm a wide range of uses that stimulate students' creativity, such as self-evaluation, metacognitive processes, structuring architectural processes, third elements, and metaphorical typologies. The approach to enhancing students' creative thinking consists of integrated activities related to creative thinking strategies. It emphasizes that creative thinking is the ability to be trained and developed over time [68–70].

Second, creative design strategies are a special type of design process that generate innovative ideas and creative artifacts in design [3,4]. Idea generation is possible because of the identification of new visual cues supported by interactive conversations established by designers between available external sources and internal representations of analogy and metaphorical reasoning patterns. It is suitable for use with advanced representation techniques. However, it is also recommended that the structure that supports activities be increased, despite individual reflection and perception of students. This may include the types of stimuli used to improve ideation, the background knowledge needed to support ideation, or the representation of ideas and concepts. Information can relate to users and contexts as well as stimulation and background technical information. How the tools and information used to manage them are manipulated afterwards is a key concern identified in this category. For a successful path through creative processes, students are required to reflect on their processes and explain them clearly in the work.

Last, design studios are highly constructivist, and instructors use a learner-centered approach rather than a teacher-centered approach. This constructive and open-ended approach is consistent with recent studies, and the teaching methods are more effective in enhancing higher-level learning outcomes [86]. Particularly, architectural education is a unique area that requires creativity, drives innovative ideas, and constructs cognitive receptive procedural perceptions that enrich creativity. Teaching methods for creative design deal with issues related to teaching creativity in the context of architectural design studios.

These issues stem from the nature of the creative process and lead to a loss of potential for students to learn creativity. In such cases, transforming the teaching methods of other subjects to promote creative learning outcomes is likely to cause similar problems for both instructors and students. These findings reveal problems that can arise when teaching methods lead to creative learning outcomes. Nevertheless, participation in conferences and educator networks and partnerships with certification bodies can facilitate the sharing of best practices and innovations for curriculum development and help implement these more broadly in the future.

5. Conclusions

The study examined the scientific flow of publications and citations over time and revealed prominent publications, prolific journals, research areas, authors, countries, and organizations related to creative thinking in the architecture design studios. Several bibliometric techniques, such as performance analysis and science mapping, were identified to investigate academic production, collaboration, and research topics. The review from an initial pool of 658 articles resulted in the analysis of 36 articles according to the main themes of creativity in design studios, which broadly reflected the issues of enhancing creativity in design education.

This study explored the characteristics of publications to contribute to the literature on creativity in design studios and to understand the developing research trends in this area. This study provides a solid foundation and contributes to related fields so that researchers may gain a comprehensive perspective, identify knowledge gaps, and derive fresh ideas for future study. We have specified examples of research in areas of immersion, presence, and social presence. However, many other areas, including architecture, will benefit from creativity in design studios. As our consideration of creativity continues to evolve, results from academic disciplines such as neuroscience, psychology, and sociology will inform future cognitive models and tools that support collaborative creative design activities. In terms of pedagogy, these new concepts and approaches could be constructed and developed in a way that is practical, feasible, and beneficial to the application of architectural design studios. The topics and issues presented in this study are intended to provide the foundation for these surveys and to support the next generation of creative educators and architects.

As with other types of study, literature reviews have limitations, and many are related to the quality and quantity of original research and the quality of systematic consideration procedures. This type of review aims to provide an objective view of the literature, but there are areas where subjective decisions may be affected by bias, such as source selection and thesis review. In this study, the nature of many studies on the subject of creativity in architectural design studios meant that thorough examination and review were needed to reach full agreement on strictly relevant paper pools. While many studies have explored creativity, the literature related to the role of creativity in architectural design studios is relatively limited. This required additional searches for sources based on the researchers' experience, as well as reinforcement of the optimized search string used in WoS databases. This was a resource-intensive and time-consuming task that required high levels of motivation and persistence.

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Article

Application of Advanced Building Techniques to Enhance the Environmental Performance of Interior Components

Magdalena Celadyn [1,*] and Waclaw Celadyn [2]

[1] Faculty of Interior Design, Academy of Fine Arts in Krakow, 31-157 Krakow, Poland
[2] Faculty of Architecture, Cracow Technical University, 31-155 Krakow, Poland; wceladyn@pk.edu.pl
* Correspondence: mceladyn@asp.krakow.pl

Abstract: This paper discusses the impact of advanced building techniques, in tune with selected building materials and their physical attributes, applied to complete constitutive interiors components on these components' environmental performance and aesthetics. There is an understanding of technological practices as essential for the effective management of the design process; still, the creative introduction of advanced building techniques is not commonly recognized by interior architects. The objective of the research is to indicate the possible multidimensional consequences of the analysis of materials' physical attributes and the consistent application of advanced building techniques to complete interior components. The basis for this study formed the design concepts of aesthetic functionalism, place attachment, and a content-context model of the association between interior components and the building fabric. Some theoretical frameworks were used for a qualitative evaluation of interior components of selected cultural facilities completed in the last decade in Poland. The performance of these components was measured in the function of applied innovative building techniques and specified building materials. Research findings have proved the impact of building techniques on the performance of interior components as instruments to increase interior functional use, formal uniformity, and aesthetic cohesion of buildings and their inner spaces, as well as the scale of multisensorial effectiveness.

Keywords: architecture; interior design; advanced building techniques; interior components; aesthetic functionalism; sensorial experiences

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1. Introduction

The process of designing the built environment, and specifically buildings as the most substantial part, has become "more technically challenging" ([1], p. 70). The understanding of technological practices is essential to the development of a quality design in the built environment, and the design itself requires a creative integration of technology based on both aesthetic and scientific judgments, being equally important factors assuring its successful application [1]. While the new technologies extended the range of building materials, "new manufacturing techniques enhanced the performance characteristics and broadened the spectrum of unique aesthetic properties" ([2], p. 2) of building materials and products.

Buildings remain primarily physical artifacts [3] identified by the materials, allowing designers to explore the geometric patterns of space, as well as making associations and stories which communicate to the end users of inner space ([4], p. 186). The built environment, including buildings and their interior spaces, can be conceptualized as being made up of *substances* (e.g., steel, wood, glass) and *surfaces* (e.g., floors, ceilings, walls) [5]. In this framework, the multifaceted arrangements of substances and surfaces are named layouts that provide occupants with affordances as the function-associated perceived properties of inner spaces. Therefore, the designers' efforts should be focused on broader analyses continued throughout the design process, and combine studies on forms and shapes, as well as research on two interrelated elements-substances and surfaces [6]. The creative application of building materials to these *surfaces*, specified as "constitutive interior components" [7], encompassing suspended or integrated ceilings, raised floors, partition walls, space dividers, multifunctional structures and cladding, assures the fulfilment of the bottom functional requirements, and conditions multifaceted experiences of users on the cognitive, aesthetic, as well as emotional level. Innovative and justified introduction of materials into the structure of components should express a "new technical and cultural atmosphere, within which the transformation of matter is taking place" instead of being exclusively focused on the designing and manufacturing of "limited number of sophisticated materials developed in a few advanced applicative areas" ([8], p. 18).

Architects and interior designers frequently anchor their attention exclusively to the visual quality of designed objects [3,9,10]. Meanwhile, the anticipation of the users' multisensorial experience and its stimulation through careful selection of building materials are a valuable and inspirational part of the design process; therefore, they should be encompassed by architects and designers [11]. The built environment and the atmosphere of a space are nothing if not multisensory [10], offering the users' complex experiences including visual, sound, olfactory, as well as palpable to building materials' texture and temperature remaining "two of the key attributes of tactile sensation" [3]. The building materials, complemented with advanced building technologies and related manufacturing techniques to complete interior components, contribute to the complex delivery of emotional and cognitive experiences to perceivers. This issue imposes on architects and interior architects the necessity for constant improvement of the knowledge on technical aspects of the architectural design process, exploring aesthetic dimensions, and experimenting with physical attributes of materials, building technologies and techniques. Regarding the environmental impact of selected construction methods, the selected building technologies and materials should respond to functional, and formal demands, as well as environmental requirements, as they "condition technical durability" ([12], p. 24) of buildings. The adaptation of durable building materials and construction techniques to the intended use of the object, as well as the introduction of separable structural segments are becoming, therefore, a means to assure the optimisation of the design process in relation to the building life cycle assessment [13]. The compliance with the demands for environmental sustainability of design requires rational choices from architects, including technologies and techniques that remain "compatible with natural processes and living systems" [1].

The study on the relationship between functional requirements, high environmental performance of interiors, formal concept on the one hand, and building techniques to accomplish the objectives on the other, proves that technical solutions remain essential for building interiors' "aesthetic functionalism" ([14], p. x). The quality of spatial functional proposals, therefore, depends on the creative exploration of the possibilities of building techniques and the analysis of materials' physical parameters. Given that materials possess "inherent poetry that is interconnected with human experience" ([2], p. 10), they are to "assume a poetic *imaginative* quality in the context of an architectural object", if they occur in a meaningful situation [15]. Materials strengthen the design concept while offering opportunities for users to interpret it and to express meaning. The users' perception of objects' materiality is influenced by a variety of materials' distinctive physical attributes, including texture, and finishing methods. Place-perception "experienced through all senses in a four-dimensional manner" ([16], p. 517), although subjective and associated with individually inherited cultural behavioural patterns, is intensely stimulated by "spatial juxtapositions and material treatments" [17] being aligned with abstract design concepts.

The combined consideration of structural achievements, technical details, spatial effects, as well as formal composition, usually discussed separately by architecture critics [14], conditions the modification of interior architectural design to accomplish formal and functional cohesion, enhancing the functional use of interior spaces while providing users with multisensory experience to build up the topophilia [18], understood as individually developed and emotionally-based reception of the space.

The above mentioned issues have not been sufficiently analyzed, and a multifaceted approach to them is absent in the current literature; especially relative to interior architectural design. This situation motivates an examination these problems from a lens of practicing architects and researchers trying to entrance this issue within the framework of the created method of systematization.

The paper examines the interior components' performance, with emphasis on functional use, formal uniformity, and aesthetic cohesion, in the function of building materials jointly analyzed physical and sensorial attributes, as well as applied advanced building techniques. The main objective is to investigate the connection between the creative integration of innovative building techniques, associated with structural engineering, acoustical engineering, or material sciences, demonstrated within inner space planning and design of multifunctional constitutive interior components, and the validation of design decisions exploring the area of aesthetic expression of inner spaces.

2. Materials and Methods

The bases for this study were the following selected design theories and schemes:

1. Model of the relationship between interior components considered as *content*, and its *context* shaped by a building's envelope and structure. It is based on the framework within the urban scale [19], modified and aimed to assess objects' interconnection in architectural scale;
2. Aesthetic functionalism concept [14] analyzed through the paradigm of purposefulness (identified by the authors with timeliness and materiality as complementing ideas) defined by the balanced presence of distant requirements of environmental efficiency and symbolic expression; this model was adapted to the scale of inner spaces and their components as appropriate to accomplish jointly these demands, with emphasis on the advanced individually developed building techniques;
3. Place attachment model [20,21] aimed at the description of the interconnectedness of individuals and their immediate environment organized by interior spaces and their components, and discussed in relation to the impact of space user's multisensorial experiences on their acceptance of space.

The theoretical framework built around these above-mentioned concepts was then verified with comparative case studies of interior spaces of cultural complexes completed in the last decade in Poland. The exemplary objects chosen for the analysis presented an innovative approach to the application of advanced building techniques in the shaping of interior spaces and their components. Inspections made on site along with the visual qualitative data, complemented with technical information shared by the designers and consultants involved, served to prepare diagrams to assess the multifaceted influence of the techniques applied and physical properties of building materials on interiors and their components' performance.

2.1. Building Technique—Means of Defining the Formal Coherence of Interiors and Building Fabric

The scheme by Tschumi, originally made to define the relationship between the architectural form, influenced by its *content*, and its multidimensional *context* [19], identified indifference, cooperation, and conflict. For this study, the initial model was adapted to verify the quality and type of multifaceted dependence between interior spaces and their components on one side, and the building structural elements and shell on the other. The selected constitutive interior components expressed their form derived from the content, whereas the building structural elements and building envelopes formed contexts. Interior components that were questioned in the study combined the structurally developed and multifunctional inner walls, as well as suspended ceilings.

The framework developed to assess the associations between these two objects respected the following criteria:

1. Functional, referring to the possibilities of endorsement of the building's and its interiors' performance;
2. Formal with the focus on the accomplishment of aesthetic use;
3. Socio-cultural, making connotations to local building practices, material traditions, and behavioral patterns.

The possible levels of these interactions between interior components and building fabric becoming the context regarding advanced building technologies, materials' characteristics, and technical solutions to complete objects—all being factors that stimulate the quality of design, which were categorized as follows:

- Coherence, understood as endorsement of the level of building functional use, as well as an exposure of formal uniformity, to influence the multisensorial experience of the built environment and thus intensify the sense of topophilia [18];
- Irrelevance, demonstrating the autonomy of design concepts applied to inner spaces and their spatial context defined by the building shell, its structural solutions, formal appearance, as well as reduced mutual interactions on the formal and aesthetic planes;
- Contrast, present in a juxtaposition of form and material, evoking disturbing emotional, cognitive, or aesthetic dissonance;
- Inconsistency, provoking malfunctioning of the object or misunderstanding of the overall design concept.

2.2. Building Techniques—Means of Assuring the Cohesion of Spaces' Functional Use and Aesthetics

The purpose of an interior space and its components can be identified by the presence of two supplementing and mutually strengthening characteristics situated at the opposite sides. These were assigned by Grabow and Spreckelmeyer originally to the purpose of a building, considered as a spatial-functional entity [14]. Environmental efficiency, interpreted as an aesthetic and technical response and achieved with the leading concept of the building understood as an "extension of the technologies they contain" ([14], p. 15), is to be balanced with the symbolic appearance of objects. Transcending practical concerns offers the occupants a spectrum of existential, emotional, and mental meanings.

It is justified to discuss this question of cohesion between the functional and aesthetical aspects of designed objects, environmental efficiency, and symbolic expression, respectively, in regard to the shaping of inner spaces and their components, and in particular the techniques applied in view of their completion. Creative introduction of advanced technique methods to shape inner spaces and their constitutive components affects these components' functional use in its complexity. The material concept should be developed alongside the overall design since materials remain an integral part of the creative concept [13]. The well-considered use of building technologies, building products, as well as materials support the materialization of the design idea [13]. Building materials can be revitalized and transformed with the implementation of modern construction technologies, and therefore they can be offered a "new lease of life simply through introducing new manufacturing and production methods" ([4], p. 193).

The main criteria of evaluation of the quality of relations between interior components and building fabric, in function of the introduced technical solutions, combine the following:

1. Responsiveness/awareness in terms of the building's and inner spaces' environmental performance, in accordance with prior assumptions;
2. Physical comfort of the users gained through the optimization of parameters of the indoor environment quality, particularly acoustical characteristics;
3. Symbolic content demonstrated through selected building materials and techniques to shape the components of inner space, chosen to intensify an overall building's formal and aesthetical statements.

The possible levels of interaction existing within each of the proposed criteria groups include the following:

- Endorsement, meaning the practice of environmentally oriented activation of interior components obtained through the modification of their structure or surface with building techniques;
- Moderation, observed in balance within the treatment of components as multifunctional interior architectural design instruments, as well as a means for multidimensional formal interpretation;
- Insignificance, proving the designers' insufficient efforts in considering environmental contextualization of designed components as an integral design criterion, or lack of a consistent vision of the formal and aesthetical appearance of the building fabric;
- Contradiction, providing the observer with conflicting information provoking cognitive confusion or emotional dissonance as to the object's functionality.

2.3. Building Techniques—Means of Expansion of Users' Experience and Support of Place Attachment

The creative exploration of technology and technic solutions in interiors provide the replacement of the immediate persuasion of "tiresome and soporific uniformity of experience" ([22], p. 76) with a long-lasting and simultaneously stimulating experience, as well as multisensory interactions, that leads to enhancement of user's self-experience. Moreover, the introduction of innovative building techniques and the exploration of material physical attributes fulfill the functional and formal requirements, while representing the necessary "supportive background for human activities and perceptions" [22]. The critical opinion by Spence [23] that echoed Williams' [24] statement that "aside from meeting common standards of performance, architects do little creatively with acoustical, thermal, olfactory, and tactile sensory responses" ([24], p. 5) remains still relevant, even regarding the design of public buildings' inner spaces.

Introduction of advanced building technologies and techniques allows to extend the strictly technical interpretation of applied solutions to create a physical setting. The creative exploration of the possibilities of building techniques and their introduction to complete interior components is an approach to make significant changes to visitors' perception. Design concept endorsed with creatively implemented building technology and selection of building materials offers the inner spaces end-users' multi-sensorial experiences, while forming emotional bonds with their immediate physical environment. While "the interface of interior space is composed of building materials" the texture of these wall finishing materials is becoming "an essential aspect of the building environment perception and quality evaluation" [25]. The innovative implementation of manufacturing processes to shape components is a potential driver to influence the multisensorial experience of the built environment and thus intensify the topophilia [18]. The end users of inner spaces develop meanings, which being attached to objects or environments and aroused through the developed modes of communication, affect occupants' perceptions and subsequently established interactions [26].

The exploration of technical aspects by designers throughout the interior architectural design contributes to the built up of this specific meaning-making process, which is essential for the acceptance of architectural objects. This practice is supportive for the forming of a relationship of visitors with a specific setting, and sets the foundation for place attachment, defined as the cognitive and emotional connection of an individual to a particular scenario or environment [20]. The place attachment scheme involves "positively experienced bonds" [21] developed from the behavioral, affective, as well as cognitive connections occurring between individuals and their social-physical environment. These relations, identified by Riley as primarily associated with the meanings of and experiences in a place [27], and involving both functional and meaningful aspects of space [28], should be examined through the interior architectural design process.

We assume that the exploration of materials' physical properties and the range of application of advanced building techniques to complete objects contributes to the support of the design theory of place attachment. In particular, this can be applied to the "third place theory" [29,30] that originally considered the concept of community buildings as social places, meeting places, or public space. Cultural facilities, apart from their primary functions and great scale events, offer unlimited access and provide visitors with adjacent spaces (e.g., libraries, galleries, bookstores, conference spaces, and reading rooms) suitable to conduct different forms of culture-related activities. They allow participation in various occurrences (e.g., exhibitions, soirees, courses, lectures, presentations), and active engagement in other forms of social-cultural communication. They all can be treated to some extent as informal space for public gathering or public meeting centers for participants sharing some common ground, relative to how people experience interactions and sensations within the space. The appearance of culture center interiors, when thoroughly characterized using innovative building technologies, is to strengthen the place attachment model based on people's emotions and feelings, positive and negative experiences or effects, and satisfaction.

The persuasive role of building techniques in the built-up of associations of interior components, as well as buildings, can be analysed regarding the following factors:

1. Provision of sensorial stimuli understood as introduction of technical measures to deliver and strengthen interior occupants' sensorial experiences, including visual, light, tactile, as well as sound;
2. Formal soundness, to establish objects' identity through the exploration of technical aspects of design proposals, differing in scale, range, as well as modes of application;
3. Materiality, based on the intensive and deliberate exposure of manufacturing techniques and building materials' physical characteristics, being interior components' technical attributes, as well as the means of their formal expression.

The levels of possible interactions between identified elements within this group of criteria combine the following:

- Intensiveness, describing the high concentration of applied building techniques to exploit their physical appearance as a means to fulfill function-related requirements;
- Multiplicity, meaning the application of different technical solutions appealing to objects' emotional as well as cognitive perception;
- Ambiguousness, revealing the weakness of chosen design and manufacturing techniques that result in the absence of observers' emotional or cognitive response, as well as weakness of a design concept;
- Confusion, providing observers with mixed reactions that result in their psycho-physical dissatisfaction, misunderstanding, or final rejection of the overall design concept.

2.4. Building Techniques in the Evaluation of Interior Components' Performance

The emphasis on the technical aspects of the building interior environment, in particular the experimental approach to building materials' usage in the shaping of interior components, demonstrates the architects and designer's ability to incorporate both architecture art and architecture science into the design process. The application of advanced building techniques to complete interior components is becoming a measure of recognition of these components' multifunctionality. This is demonstrated through their active role in an enhancement of interiors' performance, or in an encouragement of the occupants' multisensorial experience and denotation of inner spaces, when interior architectural design instruments are structurally integrated with the main building's elements.

Table 1 illustrates a theoretical framework for further qualitative evaluation of the impact of building techniques on the environmental and aesthetical performances of inner spaces. The questions proposed for further examination comprise the following: (1) areas of relation including the patterns of multifaceted *content-context* dependence between interior components, defined through technical solutions, and the building as a spatial-functional-formal-socio-cultural entity, use functions and aesthetics functions, as well as users' perception complemented with development of sense of place attachment; (2) criteria assigned to the evaluation of interaction between selected factors; (3) possible levels of interaction within each criterial group.

Table 1. Interior components' performance in function of building materials' attributes and applied advanced building techniques. The selected area of relation, criteria and levels of qualitative evaluation.

Area of Relation	Criteria	Levels of Interaction
Multifaceted *content-context* dependence	Functional Formal Socio-cultural	Coherence Irrelevance Contrast Inconsistency
Functional use Aesthetics	Responsiveness Physical comfort Symbolic meaning	Endorsement Moderation Insignificance Contradiction
Users' perception Place attachment	Provision of sensorial stimuli Formal soundness Materialism	Intensiveness Multiplicity Ambiguousness Confusion

3. Building Techniques as a Means to Improve Interior Components' Performance and Aesthetics—Case Studies

The issues considered can be further elucidated by appropriate analyses of a set of exemplary significant buildings epitomizing the impact of various technologies on multifaceted performance of their interior components. We selected four cases to be studied in this regard. Their selection was based on the principle of public buildings of great importance for the local community in terms of their exclusive function, symbolic aspects, local architectural features, and aesthetic values. Their most important features in view of the problems analyzed in this paper seem to be acoustic characteristics, sensorial issues, place attachment attributes and some other related parameters. Each of the cases addresses these issues in a similar way, but with various technical means.

The following subsections include analyses of the relationship between the exercised building technology, building techniques, materials' characteristics, formal composition of interior spaces, and their aesthetic integrity, as well as interiors' perception by the occupants.

Critical review of inner spaces and their components was based on case studies of the selected cultural facilities and comprised the following issues:

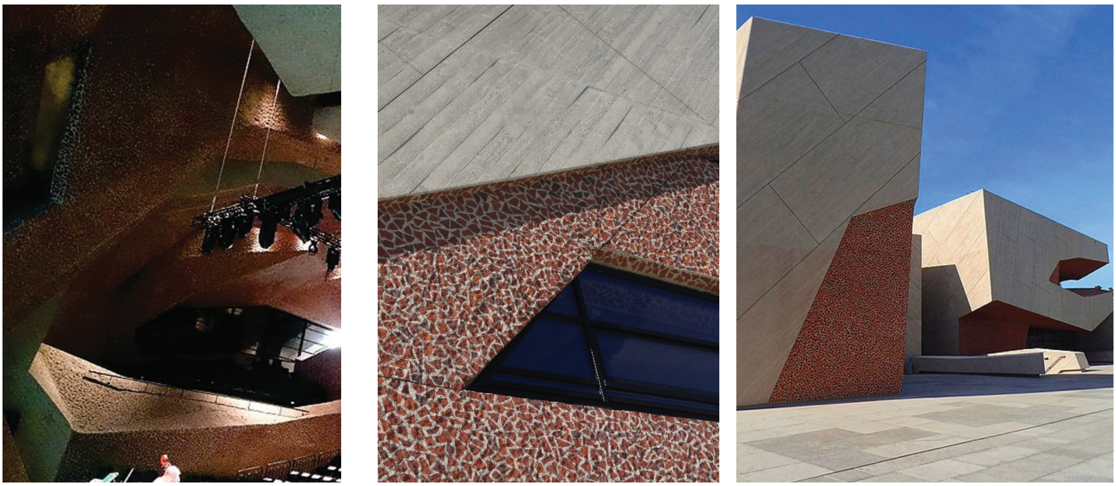
1. Category of the introduced building technology comprising building product characteristics, materials' physical features;
2. Range of application of particular building technologies and technical solutions to form the components of interiors;
3. Area of support of the functional use of a building and endorsement of interiors' performance, understood as the capacity to fulfil primary and secondary functional requirements, achieved through structural and material solutions;
4. Multitude of sensorial and cognitive experiences of the users of interior spaces;
5. Implication of the applied technique on the interiors' formal and aesthetic definitions.

These detailed issues were then interpreted and summarized in tables supporting the conclusive assessment of the associations between building technologies and interior components in terms of interconnectedness between interior components and the building's structure, cohesion of inner spaces' functional use and aesthetics, as well as the range of users' experience stimulating the growth of place attachment. The buildings selected for the research contain a multitude of different spaces due to their size and special functions. This study analysed only these which are principal in terms of dominant functions.

3.1. Case 1: CKK Jordanki Congress and Culture Centre, Toruń

Innovative technique named *picado* ("chopped"), was conceived by Fernando Menis and initially introduced in the Magma Arte and Congresos in Tenerife completed in 2005.

This novel building technique is based on mixing thick reinforced concrete with other building materials (e.g., brick, volcanic tuff) and following process of hacking off the outer surface of the product used as a finishing layer (Figure 1). As the architects had indicated, the *picado* construction technology exercised in this project presented an attempt to search for a contemporary reinterpretation of the traditional brick [31].



(**a**) (**b**) (**c**)

Figure 1. CKK Jordanki Congress and Culture Centre, Toruń, 2015, arch. Menis Arquitectos. (**a**) Interior cladding with concrete-brick conglomerate panels. Source: https://pl.m.wikipedia.org/wiki/Plik:Auditorium_of_Conference_and_Cultural_Centre_%22Jordanki%22,_Toru%C5%84,_Poland.jpg (accessed on 31 May 2021) , photo by M. Sulik. (**b**) Exterior wall cladding with *picado* technique, (photo by M. Celadyn). (**c**) Exterior view. Source: https://commons.wikimedia.org/wiki/File:Centrum_Kulturalno-Kongresowe_Jordanki_w_Toruniu92.jpg,photo (accessed on 31 May 2021) by Mateuszgdynia.

In CKK Jordanki Congress and Culture Centre in Toruń, an architectural competition winning project completed in 2015, the architects proposed two types of picado techniques contributing to the advantageous acoustic parameters of selected interior spaces, including concert hall, lobby. The first type of picado consisted of prefabricated panels made with rushed red brick, reclaimed from a local factory, and then reused to shape the three-dimensional interior cladding, melted into the thick reinforced concrete. This conglomerate was to improve the sound diffusion inside the building. The conglomerate of volcanic reddish stone from China and reinforced concrete introduced by the architects to form the second type of panes, was supposed to assure the appropriate level of sound absorption and control of reverberation time in the concert hall. To control efficiently the parameters of reverberation time and sound intelligibility within the main concert hall, the architects developed a system of mobile suspended panels (measuring from 80 to 140 sq. m, weighting from 11 up to 20 tonne, and changing their position above the stage from 3 to 5 m in height). These modules, accomplished similarly to the *picado* technique, were to adjust the space geometry and volume according to the actual functional needs.

Therefore, different acoustic requirements were fulfilled in this space to cater to concerts of symphonic or chamber orchestras, operas, and theatre performances. The studies on the hall's acoustic parameters, conducted throughout the design interactive process, influenced the formal and aesthetic appearance. The plastic properties of concrete allowed control of the geometry of the concert hall volume and sound reflections reaching the listeners. According to the architects, the optimization of acoustic parameters was accomplished due to the specific quality of the construction technology of "chopping the surface of the brick with concrete mix" [32].

The building technology defined the cohesiveness of building interiors and multilayered sculptural envelope of the building, where precast concrete along with the concrete-clinker brick conglomerate were vastly exposed. The porous, robust surface of the cladding layer provided occupants, especially those gathered inside the building, with an intensive haptic experience. The rough surface of concrete panels exposed through the interiors, along with the modules of conglomerates, due to their monolithic representation fulfilled the sense of topophilia [33], understood as the correlation of an individual's subjective and emotional perception of the territory and its material character [18]. Introverted inner spaces intensified the visitors' experience of a void surrounded and dominated by massive enclosures. The architects underlined "the isotropic properties of concrete and stone: carving, hollowing, grooving, forging, shifting figures–decomposing in order to highlight the labyrinth properties" [34] while shaping interiors of the building.

This complex confirmed the value of Menis' work as a sensorial and tactile architectural intervention that was strongly based on materials and their textures [35]. The innovative construction technique exploring brick as a structural and cladding material became itself a creative commentary on the architecture of the past. The construction technology, with reference to the local building practice and cultural heritage of Toruń, became a means to decode the local traditional architecture. Moreover, traditional building materials and construction techniques were reinterpreted by the architect in an unconventional way oriented toward the reduction of the negative impact on the natural environment [35] achieved by an efficient resource management strategy in the architectural design process.

The qualitative evaluation of the area relation determined in function of the application of building techniques to shape interiors of CKK Jordanki Congress and Culture Centre in Toruń illustrates Figure 2.

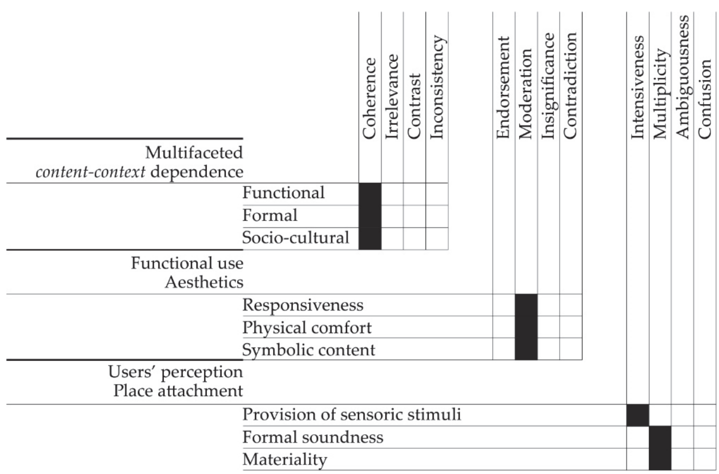
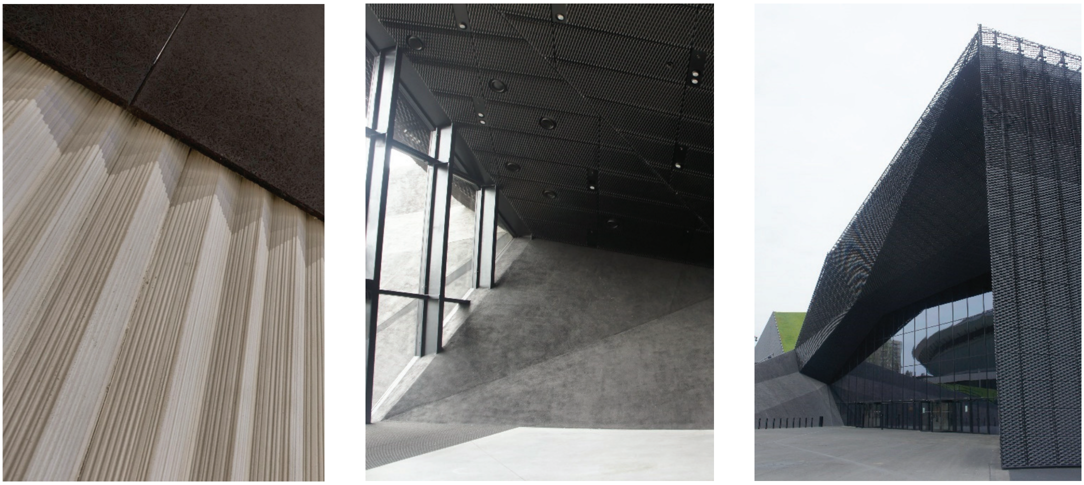


Figure 2. The qualitative evaluation of the area relation determined in function of the application of building techniques within the main criteria group. Case study: CKK Jordanki Congress and Culture Centre, Toruń.

3.2. Case 2: International Congress Centre, Katowice

International Congress Centre in Katowice, completed in 2015, was another commercial building realized as part of the Sphere of Culture, the project of revitalization of a postindustrial area previously occupied by the mining facility named Katowice (Figure 3).



(a) (b) (c)

Figure 3. International Congress Centre, Katowice 2015, JEMS Architects. (**a**) The sound absorbing wall cladding in the multifunctional space, (photo by A.K. Kłosak); (**b**) fragment of the main hallway, (photo by M. Celadyn); (**c**) main entrance, (photo by M. Celadyn).

The architects described their project as the "rectangular structure that is intersected by a *canyon*" [36]. The main role of this artificially formed trench was to link the main entrance courtyard with a historical route leading to the settlement of the historic district of Katowice. This architectural concept is noticeable in a negative cave-like volume of the ground floor main lobby. From this circulation area, an access to the multifunctional space, speech auditorium, meeting rooms, and auxiliary spaces is allowed.

One of the most characteristic features of the multifunctional space, which is intended to host fairs, congresses, concerts, and meetings, are finishing concrete panels with the sole use of sound amplification (Figure 3). These were developed as concrete structural wall inner cladding, as well as sound diffusion elements covering the lower part of the walls. They were part of the acoustic concept of this space aimed at the control of reverberation time at low frequencies and elimination of audible echoes. Prefabricated concrete diffusers, proposed and analyzed by the leading acoustic consultants archAKUSTIK, finally took the form of vertical *zigzag*-shaped precast concrete panels measuring 250 cm height, 4.75 cm depth and 50 cm width [37,38].

The concrete wall cladding elements were supplemented with sound-absorbing composite modular panels. These were made with a 25 mm finishing layer of wood-wool (Heradesign) painted in black and 50 mm thick mineral wool, mounted on a supporting steel structure. Additionally, a void of 60 cm wide was left behind the panels to enhance the performance of the absorbing modules. These sound absorbing panels were installed above the concrete wall cladding, as well as beneath the ceiling, leaving a void of approximately 400 cm where, along with the HVAC installations, additional acoustical baffles (Rockfon) were placed to prevent the occurrence of possible excessive reverberation in this closed area.

The technical proposals made by acoustic engineers relative to technical solutions to optimize acoustic performance, confirmed the high absorption capacity and substantial contribution to the indoor environment quality of these technical proposals. The support of acoustic consultants was crucial to fulfil the functional requirements and assure high performance, while confirming formal and technical consistency. The building techniques and products made their appearance as interior architectural design instruments to demonstrate the complex tectonic of interior spaces. Moreover, the design solutions concerning interior constitutive components through their uniform structure and finishes, allowed maintenance of the stylistic homogeneity of the building inner spaces of different volume and functions.

This formal and aesthetical uniformity was accomplished with modular panels made with a mesh as a coating material and means to control the acoustics parameters of the space. These panels were vastly introduced in the speech auditorium and the main hallway to cover the ceilings and parts of the walls, becoming the most distinctive interior spaces' attributes. In multi-layered aluminium mesh the finished panels introduced into the interiors is a reminiscence of the transparent building envelope. A steel mesh painted in black was mounted on a supportive structure in front of the south facing glazed facade to avoid overheating of the interiors caused by solar thermal radiation. Therefore, the metal mesh along with the rough surfaces of concrete cladding became the most exposed building material to fulfil the multifunctional demands and to outline the formal appearance and aesthetic identity of the building envelope, as well as interior components.

The qualitative evaluation of the area relation determined in function of the application of building techniques to shape interior of multifunctional space in International Congress Centre in Katowice illustrates Figure 4.

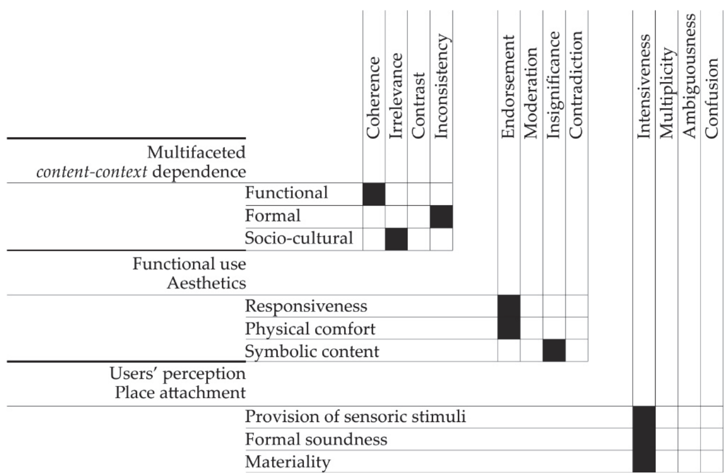


Figure 4. The qualitative evaluation of the area relation, determined in function to the application of building techniques, within main criteria group. Case study: International Congress Centre, Katowice.

3.3. Case 3: Polish National Radio Symphony Orchestra House, Katowice

The seat of the Polish National Radio Symphony Orchestra in Katowice, completed in 2014, was the first building that had been realized within the program of revitalization of the post-industrial area in the city center, becoming part of the Axis of Culture (Figure 5).

(**a**) (**b**) (**c**)

Figure 5. Polish National Radio Symphony Orchestra House, Katowice, 2014, arch. Konior Studio. (**a**) The inner precast concrete cladding of the main concert hall. Source: M. Charciarek [33]; (**b**): The inner cast concrete layered wall of the main lobby, (photo by M. Celadyn); (**c**): Main entrance. Source: https://commons.wikimedia.org/wiki/File:Katowice_05.15_NOSPR_2.JPG (accessed on 31 May 2021), photo by M. Mróz.

The multilayered shell of the main concert hall volume, being a separate structure set in a multifunctional atrium, introduced innovative building technologies to respond to the functional requirements of the main music hall, providing the audience with a high quality experience [39]. The main concert hall's acoustic parameters met all the highest standards that were applied by the world-renowned acoustic consulting firm Nagata Acoustics. The design of the main concert hall exercised initially the traditional *shoebox* spatial configuration, then transformed into an adapted *vineyard* type. This was executed by increasing the width of the hall beyond a typical shoebox shape and adding audience seating around all sides of the stage. The latter assured reduction of the distance between the audience and the stage, "thus increasing the sense of intimacy from visual and acoustical perspectives" [40]. The multilayered enclosure of the main concert hall consisted of the following parts: (1) spherical, dyed-in -mass, monolithic cast concrete on the shell adjoining the atrium with a visible timber-like relief of the formwork; (2) acoustic insulation with mineral wool; (3) cladding with precast undulated concrete panels on the inner side of the concert hall, to assure appropriate acoustic parameters (i.e., reverberation time, sound absorption, diffusion, audibility, intelligibility sensed in every part of the space).

The first proposals, as to the shaping and finishing of the enclosures, were based on the results of computer-aided simulations. Software applications Rhinoceros and Grasshopper allowed the control and shape of the space geometry, convert abstract figures to form separate segments to be obtained on CNC machines. The technology of microshaping was introduced to shape the structural concrete assuring appropriate reflection of high and medium frequency sounds. Negative reusable formliners were developed to pour in-situ mortar and form modular panels of 3 m height and 1.5 m width [41]. The necessary continuation of a wave-like 5 cm deep relief pattern present on each module, was achieved due to the precision of the elastic elastomer formliners. The final recommendations, concerning technical solutions to optimize acoustic parameters were prepared by Nagata Acoustic collaborating with the acoustic engineering office Pracownia Akustyczna Kozłowski responsible for the overall acoustic concept [42]. These advices were based on the results of investigations conducted with the use of a physical realistic model of the main concert hall, that was realized on the scale of 1:10. This model combined the building products and materials specified to structure and finish the walls, miniatures of chairs, statuettes of the audience, as well as mobile acoustic panels mounted above the stage. Physical tests carried out with specialist equipment allowed empirical verification of the initial proposals (i.e., geometry of the hall, building technology, specification of materials) that were based on the parametric modelling software indications. The expressive *curtain-like* inner cladding made with self-compacting pigmented concrete panels played an essential role in the acoustic design, assuring desirable sound reflection and diffusion. Technical and physical aspects of the project did not dominate the interior architectural design. Fluidity and apparent softness of the *concrete drapery* provided guests with ambiguous impressions concerning the interior components materiality. Solid curtains, with their strong vertical articulation, allowed the visitors to explore visual as well as tactile qualities of this interior component. The concrete panels, meticulously developed and irregularly folded, complemented the listeners' aural sensations with multi-sensorial experiences, featuring timeless structures resounding with music. Concrete, being the commonly introduced high-quality finishing material, proved its versatility, adding to the interior components an expressive touch. The roughness of the outer layer of the concrete enclosure of the concert hall, as well as its anthracite color were purposely applied by the architects. These were to connotate the local tradition of mining industry and building techniques of timber formworks, and thus to put the building into a wide social-cultural context.

The qualitative evaluation of the area relation determined in function of the application of building techniques to shape interior of the main concert hall of the Polish National Radio Symphony Orchestra House in Katowice illustrates Figure 6.

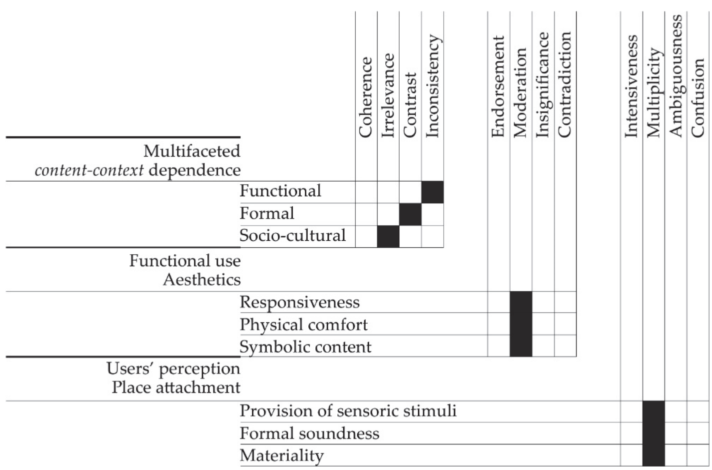


Figure 6. The qualitative evaluation of the area relation, determined in function to the application of building techniques, within main criteria group. Case study: Polish National Radio Symphony Orchestra House, Katowice.

3.4. Case 4: Museum of the History of Polish Jews, Polin, Warsaw

The most spectacular space of the Museum of the History of Polish Jews, POLIN, Warsaw, conceived by Lahdelma and Mahlamäki Architects and completed in 2013, is the main lobby area, where advanced building technology, as well as architectural design methods act in a coherent manner. The shape of the passage was finally defined by the architect only when the project was almost finished with a perfectly organized floor plan [43]. The rigid building volume of a rectangular prism was interrupted by a freely drawn inner passage (Figure 7), where the whole dramatism of the building interior was hidden [44].

(**a**) (**b**) (**c**)

Figure 7. Museum of the History of Polish Jews, POLIN, Warsaw, 2013, Lahdelma and Mahlamäki Architects + Kurylowicz and Associates. (**a**) Enclosure of the main entrance hall made with shotcrete, (photo by M. Celadyn); (**b**) main entrance hall, photo by M. Celadyn); (**c**) main entrance (photo by M. Celadyn).

The noticeable contrast in geometry of the building volume and lobby space is even more spectacular in terms of technology applied to conceive the passage. The concrete spraying application technique was chosen to form double-curved and full height inner walls that were to surround the main entrance area. Three-dimensional walls surfaces followed the principle of "combining the load-bearing structure and the skin into one tectonic self-supporting element" [45]. Dividers were to enclose the entrance hall and span two main parts of the building that was assigned a role of a city multifunctional center for research, exhibition, education, and culture. As Mahlamäki indicated, the main entrance enclosure presumably was "the biggest uniform, geometrically double-curving surface that has ever been realized" [46].

The engineers actively participated in the process of developing the most appropriate technology allowing to conceive this curvilinear 26 m heigh wall proposed by the architects. Construction work was preceded by defining the geometry of the wall panels with AutoCAD and Rhinoceros application software that followed the scanning of the initial freehand sketches prepared by Mahlamäki himself. Design team efforts were oriented to replace the conventional wall construction made entirely of reinforced concrete, with a unique solution based on a three-layer concept, as more suitable to reproduce the desirable organic shape of the wall [47]. The primary steel structure was made with vertical pipes (dia. 273 mm), horizontally braced, and formed into a grid by means of secondary steel pipe profiles (dia. 100 mm) [48]. This skeleton construction was then complemented with the layers consisting of double-breasted steel supportive components and flexible beaver-boards with fixed reinforcing mesh on top of them to copy the undulating surface of the enclosures of the hall. The first layer was based on rounded quartz aggregates and Portland cement, and the second layer with white cement supplemented with closely matched coloring sprayed repeatedly on the formwork formed the 50 mm thick final coating of the two structurally developed dividers. The plastic expansion joint strips were removed and replaced with a fireproof silicone material, whereas the control joint strips left in the concrete structure reflected the grid wall pattern [45], becoming a naturally conceived yet sophisticated architectural detail.

The innovative and technically supported shaping of the building main entrance confirmed concrete's versatility and strength. The building technology based on structural dry-mix shotcrete and architectural through dyed shotcrete, exercised to form a high passage enclosed with irregularly folded walls, allowed realization of the primary architectural concept. This idea was to accomplish a metaphoric visualization of the Red Sea parting for the Jewish exodus from Egypt, as well as to symbolically refer to the drama of the Holocaust.

The qualitative evaluation of the area relation determined in function of the application of building techniques to shape main entrance hall of Museum of the History of Polish Jews, POLIN, in Warsaw illustrates Figure 8.

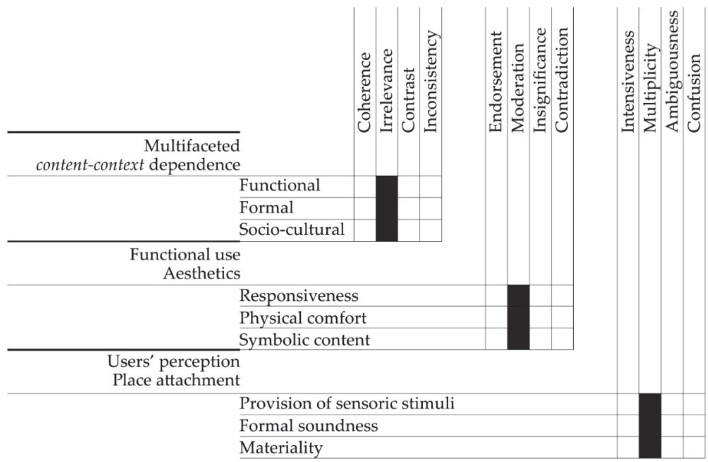


Figure 8. The qualitative evaluation of the area relation, determined in function to the application of building techniques, within main criteria group. Case study: Main entrance area, Museum of the History of Polish Jews, POLIN, Warsaw.

4. Discussion

The analyses of the three areas considered extensively in this research and referring to the four selected buildings have been visualized in the form of relevant graphical presentations in Figures 2, 4, 6 and 8. The comparison between them and the summary results indicate that in the area of relation named as Multifaceted *content-context* dependence, outcomes are very diversified. The biggest coherence in functional, formal, and socio-cultural assessment criteria was found in case 1, and the highest discrepancies in this area are characteristic of case 3. The traits of cases 2 and 4 are less identifiable and less coherent.

Within the second area relation recognized as Functional use, Aesthetics, the results are better identifiable. Very consistent moderation was found in the case of three buildings: 1, 3, and 4. Case 4 shows some discrepancies in its characteristics.

The third area relation was identified as user's perception, place attachment features multiplicity in cases 3 and 4, and the highest intensiveness is in case 2. The most valued is the result relative to case 1, which represents the highest intensiveness within multiplicity. This building should be considered as the best implementation of contemporary technical means to obtain an appropriate multi-faceted response to the issue of the most valued characteristics of contemporary interiors.

The qualitative evaluation diagrams relative to every single case of the presented buildings can be superimposed to finally indicate the actual state of mutual relations of the analyzed issues. To do so, it is useful to apply the same adopted scheme in which to introduce the relevant characteristics of every studied building.

The resulting Figure 9 shows the summary of the prevailing traits for the whole set of cases. The analysis of all data in the diagram revealed that in the first area no cases fall within the traits: contrast or inconsistency. The second area comprises only one insignificance and no contradiction. Within the third area, there is no ambiguousness and no confusion.

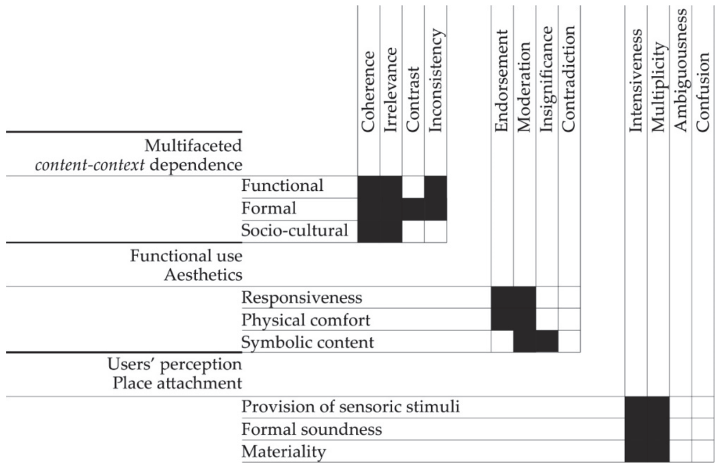


Figure 9. Summary of singular characteristics of four selected cases in the three examined areas of relation.

The research indicates a very diversified impact of implemented technical means on the technical, environmental, esthetic, social and symbolic features of the analyzed significant buildings. This statement encompasses an extensive set of features, but other more concise related characteristics contained in Table 2 are also supportive and useful in deducing and confirming the final results of this research, which is the confirmed impact of the basic technical means, including implemented building material and its texture characteristics on the technical performance and place attachment characteristics of the analyzed buildings and their internal spaces.

Table 2. Comparison of the influence of building techniques on the environmetal performance of public building interiors in terms of their technical, aesthetic, and symbolic features.

Case Study Public Building	Material	Texture Characteristics	Technical Function of Textured Surface	Place Attachment Symbolic Source
CKK Jordanki Congress and Culture Centre, Toruń	concrete and brick	irregular, broken line of section profile	sound diffusion	reference to local historical brick material
International Congress Centre, Katowice	concrete panels	zigzag-shaped repetitive vertical strips	sound amplification and diffusion	indirect reference to façade striped, black steel meshed panels reminiscent of coal-mine walls
Polish National Radio Symphony Orchestra House, Katowice	concrete	irregular arrangement of repetitive triangular strips	sound diffusion	reference to coal mine black scraped walls
Museum of the History of Polish Jews, Polin, Warsaw	concrete-shotcrete	undulating rough surface with fine exposed grains	sound diffusion	historic tale of Jewish dramatic events

5. Conclusions

The study was intended to be meaningful for the theory and practice of interior architectural design, which is presently very modestly representative of valuable contributions in terms of the design methodology based on a scientific approach to solving related problems. This research paper has provided an inquiry on the interior components' performance in function of building materials' attributes and applied advanced building techniques. The analysis combined physical appearance, as well as multifunctionality of these components in relation to the innovative methods and techniques introduced to implement advanced building technologies. It proved that technical solutions remain essential for building interiors' aesthetic functionalism. The paper indicates that the creative development and following introduction of innovative building techniques, demonstrated within the inner space planning and the design of multifunctional constitutive interior components, supports and validates design decisions in many aspects. The proposals recognizing building materials characteristics and acknowledging the potentials of building techniques, enable fulfilment of fundamental functional demands, while exploring the area of aesthetic expression of inner spaces to influence the users' perception, encourage their multisensorial experiences and to form the sense of place attachment. Research findings have proved the impact of building techniques on the performance of interior components as instruments to increase interior functional use, formal uniformity, and aesthetic cohesion of buildings and their inner spaces.

The results of this research study indicate that the progress in the integration of architectural and engineering disciplines with the art of creation of inner spaces can be achieved through extensive exploration and innovative implementation of building techniques. In particular, the designers' experimental approach to building materials' usage in the shaping of interior components is to demonstrate the architects and interior architects ability to incorporate both architecture art and architecture science into the design process.

The outcomes of the conducted study indicate the necessity for the further corrections in interior architectural design methodology, both in the currently executed educational framework and professional practice. These improvements should evolve toward a consistent employment of advanced building techniques, to accomplish interior architectural design requirements, examined as means to assure: (1) formal coherence of interiors and building fabric; (2) cohesion of internal spaces' functional use and aesthetics; (3) expansion of users' experience and support of place attachment. The enlisted design determinants are significant factors of the interior components' high environmental performance concerning the optimisation of indoor quality parameters. The efficient management of building materials, as well as implementation of unconventional building techniques, proving the multifaceted approach to the creation of the indoor environment, remain substantial factors to strengthen the position of interior architectural design discipline within the integrative design process.

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Article

Evaluating the Color Preferences for Elderly Depression in the United Arab Emirates

Chuloh Jung [1,*], Naglaa Sami Abdelaziz Mahmoud [2], Gamal El Samanoudy [2] and Nahla Al Qassimi [1]

[1] Department of Architecture, College of Architecture, Art and Design, Healthy & Sustainable Built Environment Research Center, Ajman University, Ajman 346, United Arab Emirates; n.alqassimi@ajman.ac.ae
[2] Department of Interior Design, College of Architecture, Art and Design, Healthy & Sustainable Built Environment Research Center, Ajman University, Ajman 346, United Arab Emirates; n.abdelaziz@ajman.ac.ae (N.S.A.M.); g.elsamanoudy@ajman.ac.ae (G.E.S.)
* Correspondence: c.jung@ajman.ac.ae

Abstract: The elderly are more prone to develop depression from physical, psychological, and economic changes, and 25.7% of the United Arab Emirates' (UAE) elderly population suffer from depression. Color therapy is a widely accepted treatment to solve the depressive symptoms of the elderly. The color preference of the Seniors' Happiness Centre—in Ajman UAE—a residential space for the elderly, could improve the quality of life, including depression symptoms. This paper explored the relationship between the color preference of the resident bedroom space and the depressive symptoms. As a methodology, using color images as stimuli, the physiological and psychological responses of the 86 elderly participants to the proposed color preference of the resident bedroom interiors—observed through a viewing box to simulate 3D space perception—were compared and analyzed to investigate the relationship between the color preference and depression by a survey with the Geriatric Depression Scale (GDS) and Electroencephalogram (EEG) measurement. The results showed that the elderly's preference for warm colors is higher than that of cold colors, and each room needs a different color scheme because the elderly, 65 and above, have different visual characteristics. There was no significant difference between the left and right alpha wave values of the prefrontal cortex of the participant group. The main reason is that the brain waves are minute electrical signals and appear different from person to person. The color scheme on one side of the wall with increased saturation seemed to improve depressive symptoms effectively. It was found that psychologically, healthy elderly reacted positively to the single-color scheme of the Blue cool color, but elderly with depression reacted well to the contrast color scheme of the Blue-Yellow/Red cool color. This study will serve as critical data to propose more color preferences for the Seniors' Happiness Center suitable for the elderly by studying the response to more diverse colors in the UAE.

Keywords: color scheme; elderly with depression; color preference; interior design; residential space

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1. Introduction

According to the United Nations, all the countries in the world are experiencing a dramatic change in the age structure of their population, driven by longer life expectancy and decreased fertility [1]. On a global scale, there were 727 million persons over 65 years in 2020. By 2050, the projected global number of older persons will be over 1.5 billion. This means that those 65 years or over will increase from 9.3% in 2020 to 16.0% by 2050 [2]. In the United Arab Emirates, the percentage of elderly persons, 60 years and above, in 2000 was 5.1% and is expected to reach 23.6% by 2025 [3]. The United Arab Emirates has a population structure in which UAE nationals make up 11.6% while expatriates make up 88.4%, and many expatriates were born in the UAE or lived for many decades [4].

As human become old, their physical functions deteriorate, and they suffer from various age-related chronic diseases and exhibit anxiety and depressive symptoms [5].

Older people are more likely to develop depressive symptoms due to stress from physical, psychological, and economic changes [6]. Even those who previously suffered from depression are more likely to recur [7]. Compared to epidemiological studies in the MENA regions, which demonstrate depression rates ranging from 13% to 18% [8], 25.7% of the UAE elderly population suffer from depression (20.2%) and anxiety (5.6%) [9]. Depressive symptoms are one of the most common mental disorders in old age. Hence, studies should prevent and manage depressive symptoms in old age [10]. Early detection in the United Arab Emirates is difficult because the elderly feel uncomfortable going to the hospital independently and feel reluctant about mental health problems [11]. Negligence of the depressive symptoms will delay recovery and lead to suicide [12]. It has been reported that it is beneficial to combine non-drug therapy with antidepressants to improve depressive symptoms [13]. Different color routines could be partially a factor that affects the body and the psychology of a person, and it might be used to solve psychological characteristics such as depression, but not from direct physical exposure to it [14]. For the mental health of the elderly, the color might make them feel secure and willing to live if it is selected based on their individual preferences [15]. When creating elderly residents, designers should consider that the color preference should have characteristics different from ordinary adults. The elderly prefer colors associated with their cultural backgrounds, while the young select colors with different perspectives, trends, or moods [16]. The color cognition and cultural aspects affect the color selection. In that case, it is possible to create an interior environment that improves the quality of life and recovers depression symptoms [17].

This study aimed to find out the difference in response to the color preference of the residential space concerning the depressive symptoms of the elderly inhabitants. For this purpose, according to the degree of depression in elderly residents 65 years or older, the physiological and psychological responses to the Seniors' Happiness Centre's color preference were compared and analyzed to investigate the relationship between color preference and depression using prepared colored image stimuli, representing their own resident room's picture.

2. Materials and Methods

2.1. Elderly Depression and Color Therapy

The elderly face various problems that they have not experienced before with aging. In old age, adverse events such as the decline in physical function, loss of social status, anxiety about death, and demise of a spouse affect depressed emotions [18]. In the elderly, hopelessness leads to depressive, negative psychology, including low self-esteem, social atrophy, pessimistic despair about the future, death, and suicidal thoughts [19]. Aged people usually have some symptoms of sadness, and depression is a common mental health-related problem in the elderly. Unfortunately, the level of knowledge held by healthcare professions in its diagnosis and treatment is now significantly below that which would be ideal [20]. Physical aging induces miserable symptoms in the elderly and causes depression, a negative psychological state accompanied by psychological problems, and decreased physical function. Depression in old age makes the daily life of the elderly difficult due to the feeling of helplessness [21]. Unlike other age groups, depressive symptoms in the elderly are more pronounced than atypical symptoms and complaints of depressed emotions, with physical symptoms and cognitive decline. Anxiety and depression individuals are more inclined to choose a hue of gray to describe their feelings. Therefore, it is difficult to diagnose, and it is often mistaken for another disease and receives inappropriate treatment [22].

Recently, active color therapy research was conducted in psychology and medicine. Art therapy has been reported to help people with various illnesses, including depression. Chromotherapy, or colors to heal, was practiced by several ancient cultures, including the Egyptians and the Chinese. Chromotherapy is also known as light therapy or colorology [23]. Therefore, color therapy, derived from the same principle, has been proven to advance depression treatments positively. Color therapy can provide psychological balance by stimulating the five senses with color to obtain a psychological therapeutic effect and affect metabolism [24]. In particular, colors treat depressive symptoms as effectively in the psychological stability of depressed people. Psychopathological processes are thought to be a significant component in color preferences, in addition to the impacts, as mentioned above, of colors on mood [25]. Depressed humans have a significantly lower retinal response and sensitivity than healthy humans, leading to the same result as removing color vibrations, which is the cause of continuing depressed emotions, which aggravates depression [26]. As such, colors are closely linked to depressive symptoms, so it is essential to control the color of the interior bedroom environment for residents to avoid depressive symptoms [27].

2.2. Aging and Color Scheme for Residential Space

As people age, they experience several changes caused by aging. Visual acuity generally weakens after the age of 60, and vision yellowing occurs [28]. Due to vision yellowing, the recognition ability of short-wavelength-series colors is significantly lowered compared to long-wavelength-series colors [29]. Due to the deterioration of the color recognition ability, it is necessary to create an environment that considers the characteristics of the elderly residents, such as giving a difference in brightness or increasing the brightness [30]. Color is an environmental stimulus that humans perceive and stimulate more strongly than form [31]. For the elderly, color can complement the deteriorated sensory function and give a sense of psychological stability when constructing information about the environment [32]. Therefore, the color plan of the elderly resident's interior bedroom must consider the preferred colors and physical changes due to aging. In general, low-saturation colors, often used in Seniors' Happiness Centre in the United Arab Emirates, are a risk factor for the elderly who have a weakened ability to perceive colors [33]. When people become old, their color vision deteriorates. A process known as 'brunescence' occurs when the crystalline lens ages, allowing the hue to become yellowish and saturated.

There is also a study finding stating that the elderly prefer vivid and colorful colors and that as one of the precautions for the color planning of the elderly's interior bedroom, a friendly and soft atmosphere should be created by using warm colors as a whole [34]. Perception and preferences for hue, chroma, and lightness are influenced by age, and color vision disparities caused by inherited color deficits have directly impacted color preferences. Similarly, color vision restrictions caused by lens brunescence should directly impact color choices. Although some researchers have indicated that color selection differs between older and younger individuals as the young follow trends, more recent investigations have discovered that color preference, psychologically, varies between older and younger persons [35]. Therefore, it is necessary to give changes and diversity in consideration of visual characteristics a stable and comfortable atmosphere in the color plan of the Seniors' Happiness Centre for the elderly.

2.3. The Depression Symptoms and Color Reactions by Electroencephalogram

In recent years, the investigation of emotional and mental processes and relationships using brainwave characteristics has increased in various fields [36]. An electroencephalogram (EEG) is a way to measure a human's various biological signals and is used as an index to judge psychological reactions and emotions [37]. The measurement of brain waves occurs in all areas of the brain and depend on the frequency band standards: delta waves (δ, 0–4 Hz), theta waves (Θ, 4–8 Hz), alpha waves (α, 8–13 Hz), beta waves (β, 13–30 Hz), and gamma waves (γ, 30–50 Hz) [38]. Alpha waves are fundamental neurophysiological waves that reflect the brain's stable state (conscious, creative, relaxed, and light meditation). As it is less affected by brain waves in other areas, the alpha wave has been used to measure emotional stability for a long time [39]. An EEG is used to diagnose and treat depressive symptoms, and it is possible to discriminate the depressed state through the resting EEG [40]. It is an objective measurement method for depressive symptoms, not differences due to subjective depressive symptoms or simple mood changes [41]. The brain waves' simple mood changes—for example, depression—are usually accompanied by the asymmetry of the frontal cortex alpha waves. The activation of the left frontal cortex is associated with pleasant and positive emotions, and the activation of the right frontal cortex is associated with depressive and negative emotions [42]. The left/right activation of the frontal cortex grasp feelings of pleasure, discomfort, and depression. Neuroscience, the difference in EEG asymmetry between the depressive and regular groups, can be used for clinical diagnosis.

Brain waves help analyze and judge reactions and emotions to colors through objective numbers. For instance, in previous studies regarding depressive symptoms, the red color symbolized vitality and had a therapeutic effect [43]. Therefore, psychological therapy effectively treated depressed patients in red interiors and excited patients in blue interiors [44]. The color's uses, in this case, with high brightness, saturation, and warm colors, bring excitement, and low brightness, saturation, and cold colors bring a sense of calm. As such, color and human physiological reactions rely upon psychological reactions, and both reactions and emotions can be measured through brain waves [45].

2.4. Research Method

As shown in Figure 1, the conducted literature review and research contribute to understanding the physiological reactions of the elderly to the color of their interior bedroom. In the literature review, previous compared studies on the psychological characteristics of the elderly, their reaction to color, and the color planning of similar centers for the elderly have led to concrete discussion [46]. The authors established the survey research plan and the survey targets based on the literature review results. In addition, they determined the measurement variable and the survey tools for the progress of the research. The selection of the study participants focused on the elderly aged 65 years or older who had no color perception and brain disease problems. The participants recruited were 86 voluntary elderly residents with the cooperation of two Seniors' Happiness Centers, Mushairaf Area and Al Jurf Area, in the Ajman region of the United Arab Emirates. Each of them signed a consent form requesting their names' privacy and refused to take pictures while proceeding in the experiments. The survey participants were classified into two groups, an ordinary range group (group A) and a group showing depressive symptoms (group B) using the Geriatric Depression Scale (GDS) test. A psychological evaluation of the color image of the interior bedroom was conducted through a questionnaire survey using a color image-emotion evaluation tool and an EEG measurement experiment. The survey research was conducted from January to December 2020 while maintaining social distancing, and a total of 80 responses were used for analysis (Table 1).

Table 1. Classification of investigation targets.

Participants		Level of Depression		Total
		Group A	**Group B**	
Age Group	60s	10 (17.5%)	3 (10.0%)	13 (14.9%)
	70s	34 (59.6%)	19 (63.3%)	53 (60.9%)
	80s and Above	13 (22.8%)	8 (26.7%)	21 (24.1%)
Gender	Male	28 (60.9%)	18 (39.1%)	46 (52.8%)
	Female	29 (70.75%)	12 (29.3%)	41 (47.1%)
Total		57 (65.5%)	30 (34.5%)	87 (100.0%)

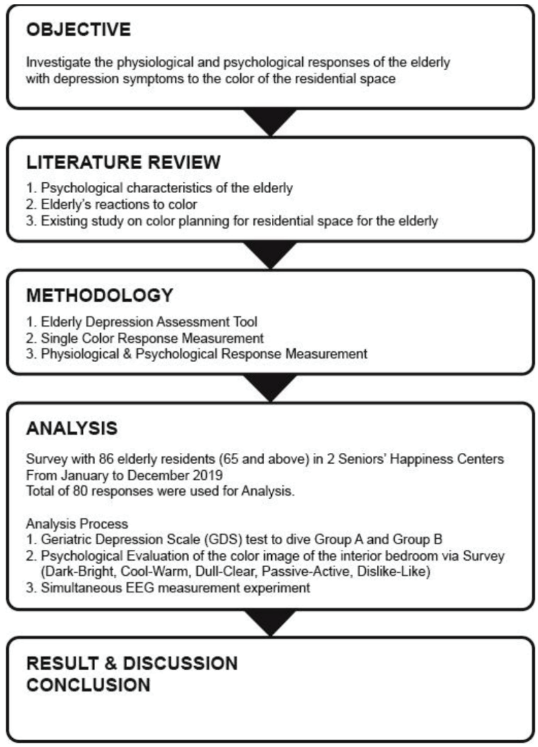


Figure 1. Research process: objective, literature review, methodology, analysis, result, discussion, and conclusion.

2.5. Investigation Tool

2.5.1. Elderly Depression Assessment Tool

The degree of depression or simple mood change of the residents was evaluated using Yesavage, Brink, and Rose's Geriatric Depression Scale (GDS) [47]. There were 30 evaluation entries used in this study, and each statement can be answered simply by using 'Yes/No'. The total score ranged from 0 to 30, where the higher the score, the more serious the depressed state. In this study, the collected answers that range between 0 and 14 points were group 'A', and the answers that range between (15–30) points were group 'B'.

2.5.2. Single-Color Response Measurement

A color chart is indispensable to understand and investigate the participants' preferences for level of color (Preferred, Non-Preferred, and Self-Representation Colors). Thus, based on the Munsell system, the authors created a palette of 10 essential colors (Red (R), Yellow (Y), Green (G), Blue (B), Purple (P), Yellow/Red (Y/R), Green/Yellow (G/Y), Blue/Green (B/G), Purple/Blue (P/B), and Red/Purple (R/P)), in addition to three achromatic colors (White (W), Black (B), and Neutral Gray (nG)) to make a 60 cm × 90 cm hardboard, as shown in Figure 2.

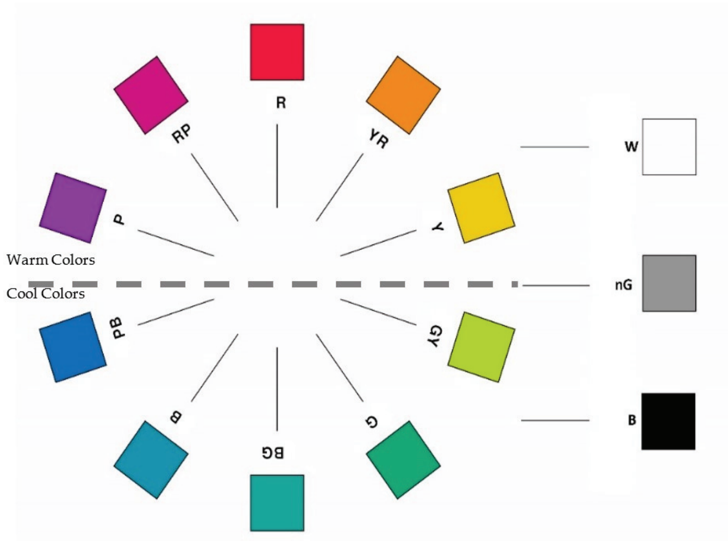


Figure 2. Palette of ten essential and three achromatic colors (source: authors, based on the Munsell system-licensed file under the Creative Commons Attribution 3.0 Unported license, 2021).

2.5.3. Color Scheme of Resident Interior Bedroom

The suggested color scheme for the resident interior bedroom was the warm colors and their contrast as cool colors, based on the psychological and emotional response standards related to the cultural background [48]. The decisive warm hues selection was R, Y, Y/R, and G/Y, while the cool hues selection was complementary of the warm selections, B/G, P/B, B, and P. The range of choices considered the significance of the warm and cold colors to verify their effects on depression or mood change in previous studies [49]. In addition, the elderly had a lower short-wavelength transmittance due to their visual characteristics [50]. Consequently, using a single-color scheme as a concept aimed to reach psychological stability and contrast colors to create change and diversity [51]. Therefore, the study used a single color (as a front wall: Yellow, Yellow/Red, Green/Yellow, Red, and Blue.

Additionally, the study used a contrast color (as side wall) for the specific single colors, as follows: Yellow-Purple/Blue, Yellow/Red-Blue, Green/Yellow-Purple, Red-Blue/Green, and Blue-Yellow/Red (Figure 3). The achromatic color used was single Grey. The range of brightness and saturation was customized as Vivid (V) tone, which is the range of medium and high saturation, and very pale (Vp) tone, which is the range of high brightness and low saturation (Value 5, Chroma 5), considering the characteristics of interior color and the effect on the EEG. The color application range considered the focal color for the front wall of the interior bedroom, which is visually recognized most, and the secondary color for the sidewall, in the very pale state to blend with the elderly visual conditions (Figure 3). The target residential space was a resident interior bedroom (40 m^2) of the Seniors' Happiness Centre, and the samples were produced with the Photoshop program (Color Picker to simulate the Munsell Colors) based on an actual picture from their interior's rooms. It is worth mentioning that the color mode used was CMYK for calibration so that the color values of the selected Munsell were the same on the screen display and when printed in reality.

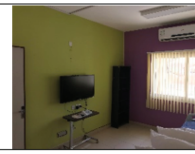
Color scheme	5 Y (Vp)	5 YR (Vp)	5 GY (Vp)
Single Color			
	5 Y 11/2	5 YR 11/2	5 GY 11/2
Contrast Color			
	5 Y-P/B 11/2	5 Y/R-B 11/2	5 G/Y-P 11/2
Color scheme	5 R (Vp)	5 B (Vp)	5 nG
Single Color			
	5 R 11/2	5 B 11/2	5 11/1
Contrast Color			
	5 R-B/G 11/2	5 B-Y/R 11/2	

Figure 3. The 11 samples of the stimuli of indoor space color scheme each has two versions except Neutral Gray (source: authors, based on an actual elderly room, 2021).

2.5.4. Physiological and Psychological Response Measurement

The physiological response to color was measured using two channels of Neuro harmony S. Two gold-plated dry electrodes were used to measure the EEG in the left and right frontal cortex. Fp1 (left) and Fp2 (right) of the frontal cortex were set as the active electrode, Fpz as the ground electrode, and the ear cortex as the reference electrode [52].

The occipital cortex is the area that primarily acquires visual information in the cerebrum, and the prefrontal cortex is the cortex that understands the acquired color information and is involved in decision-making.

In this study, the EEG value of the prefrontal cortex was used for analysis. The EEG test focused on the experimenter; for accurate data, the first and last stimuli were designated in gray, and stimuli were given for 10 s each. Each color image was stimulated for 20 s, and a gray sheet was displayed for 10 s between color images to reduce the influence of each other (Figure 4). It was calibrated using (Figure 5) Spyder4 Express [53]. According to a particular sequence, the experiment was conducted by maintaining a stable state in the same interior environment where natural light and external noise were blocked. Six pairs of adjectives were placed at the ends of both directions, and a 5-point Likert scale was constructed and evaluated to respond to the participant's thoughts. Three was 'neutral', 2 and 4 were 'slightly', and 1 and 5 were 'extremely'.

Figure 4. The EEG measurement procedure sequence shows the experimental duration.

Figure 5. The EEG measurement tools, by authors.

3. Results

The classification of the 86 participants—where 48 were from Mushairaf Area and 38 were from Aljurf Area—was group A (53 (male = 25, female = 28)) and group B (33 (male = 19, female = 14)). The elderly aged 70 and above were very high, with 63.75% (51 residents), 15% (12 residents) in their 60s, and 21.25% (17 residents) in their 80s or older. The distribution of gender was 52.5% (44 residents) for males and 47.5% (42 residents) for females.

3.1. Color Preferencing

The response between residents with depressive symptoms and healthy residents was evident with the single-color preference showing no difference. In this study, the difference between the color preferences of group A and group B was identified, using 10 chromatic basic colors of the Munsell system and 3 achromatic (Figure 1), to *Preferred* and *Non-Preferred* colors, and the *Color which Represents them*.

As a result of analyzing *Preferred* colors in (Table 2) and the statistical analysis of the results in Figure 6, group A showed a somewhat higher preference for cool colors to warm colors in the order of 'Blue' with 13 (26%) and 'Yellow pale' with 7 (14%). The result is consistent with previous studies showing that the preference for colors is related to the country's environment and the cognitive responses of the elderly [54]. For the reason of their preference, participants answered the following for 'Yellow': 'passive' and 'makes the heart happy'; 'Blue': 'bright color' and 'is always my favorite color'. Nine people (30%) had 'Blue' and four people (13.3%) had 'Yellow' as their preferred color in group B (Figure 6). For the reasons of their preference, they answered the following for 'Blue': 'sea color' and 'it feels good'; 'Yellow': 'the color is deep' and 'it is the sand color'.

Table 2. Participants' preferred color, non-preferred color, and representative color.

Selection/Participants		R	Y/R	Y	G/Y	G	B/G	B	P/B	P	R/P	W	nG	Black	Total
Preferred Color	Group A	2 4	5 10	7 14	5 10	4 8	3 6	13 26	4 8	3 6	2 4	2 4	0 0	0 0	50 100%
	Group B	2 6.7	3 10	4 13.3	1 3.3	3 10	2 6.7	9 30	3 10	1 3.3	2 6.7	0 0	0 0	0 0	30 100%
	All	4 5	8 10	6 7.5	6 7.5	11 13.75	5 6.25	20 25	7 8.75	7 8.75	4 5	2 2.5	0 0	0 0	80 100%
Non-Preferred Color	Group A	2 4	2 4	3 6	2 4	2 4	3 6	2 4	2 4	2 4	3 6	2 4	11 22	14 28	50 100%
	Group B	5 16.6	0 0	2 6.7	0 0	0 0	2 6.7	0 0	1 3.3	2 6.7	2 6.7	2 6.7	6 20	8 26.6	30 100
	All	1 1.25	0 0	5 6.25	0 0	0 0	3 3.75	2 2.5	3 3.75	6 7.5	5 6.25	4 5	17 21.25	28 35	80 100
Color which represent them	Group A	2 4	2 4	10 20	9 18	6 12	3 6	14 28	1 2	1 2	1 2	1 2	0 0	0 0	50 100%
	Group B	2 6.7	0 0	4 13.3	2 6.7	3 10	0 0	6 20	4 13.3	3 10	1 3.3	2 6.7	1 3.3	2 6.7	30 100%
	All	4 5	2 2.5	14 17.5	11 13.75	9 11.25	3 3.75	20 25	5 6.25	4 5	2 2.5	3 3.75	1 1.25	2 2.5	80 100%

As a result of the analysis of Non-Preferred colors, the ratio of achromatic colors such as 'White', 'Black', and 'Neutral Grey' was high in both groups. The result is consistent with previous studies that showed that the Non-Preferred for 'Black' is high. Group A had 14 people (28%) in 'Black' and 11 people (22%) in 'Grey'. For Non-Preferred reasons, 'Black' responded with 'despair rises', 'hopeless', and 'dark and gloomy'; and 'Neutral Grey' responded with 'be ambiguous', 'dull', and 'not clear'. Group B had 8 'Black' (26.6%) and 6 'Neutral Grey' (20%). For Non-Preferred reasons, 'Black' had 'dark', and 'Grey' had 'ambiguous' and 'sneaky'.

As a result of the analysis of the colors representing themselves (Table 2) (Figure 6), group A was in the order of 14 'Blue' (28%), 10 'Yellow' (20%), and 9 'Green-Yellow' (18%). For selection reasons, 'Blue' had 'clear and calm', 'clear', and 'unconditionally good'; 'Yellow' had 'bright color' and 'looks good'; 'Green-Yellow' had 'stable color', 'positive', and 'fresh'. Group B had 6 'Blue' (20%), 4 'Yellow' (13.3%), and 4 'Purple-Blue' (13.3%). In the case of 'Blue' as a reason for the selection, they answered, 'to be blue', 'to be seen well', and 'to be bright'. Group A showed a high proportion of cool colors representing themselves compared to the preferred color. Group B showed various preferences and choices for the preferred color and the color representing themselves, regardless of the distinction between gender.

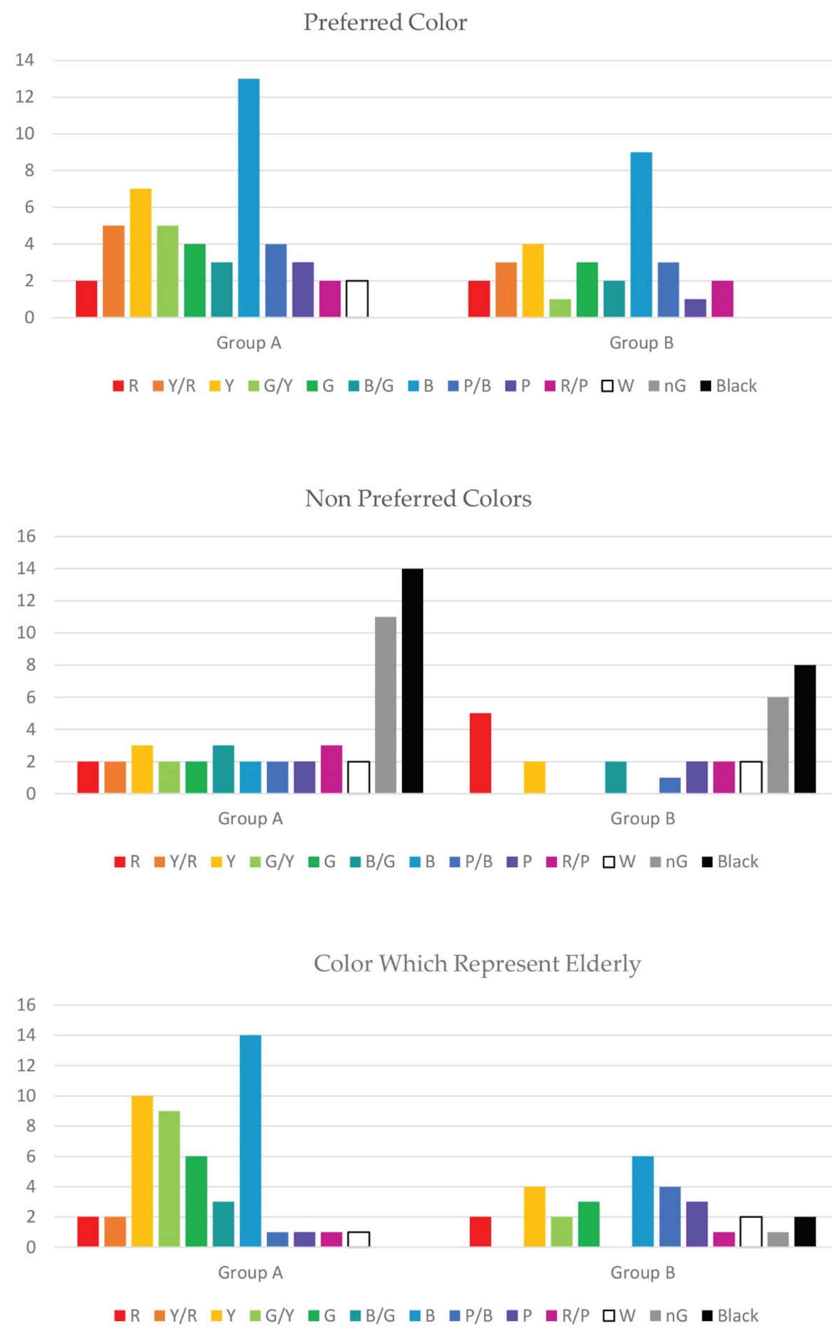


Figure 6. Statistical analysis showing the number of 'Preferred', 'Non-Preferred', and the 'Color Which Represents Them' participants, as provided in Table 2.

3.2. Psychological Response

Figure 7 shows the evaluation results—using the Likert Scale—of the psychological response to the stimuli of the eleven residents' interior bedroom color scheme images. As a single cool color, the evaluation results for the color Blue were generally similar between group A and group B. For the color Yellow, the average of group A came in the second selection as it was 'bright', 'warm', 'clear', and 'active'. The color Green/Yellow in group A had a lower average of 'clear' than group B. For the color Yellow/Red, the average of group A for 'clear' and 'active' was higher than that of group B. For the color Neutral Grey, the average of group A's 'cloudy' and 'static' was somewhat higher. The color Red, in Group A, had 'dark' and 'dull', while the color Yellow/Red had 'warm' and 'dull'.

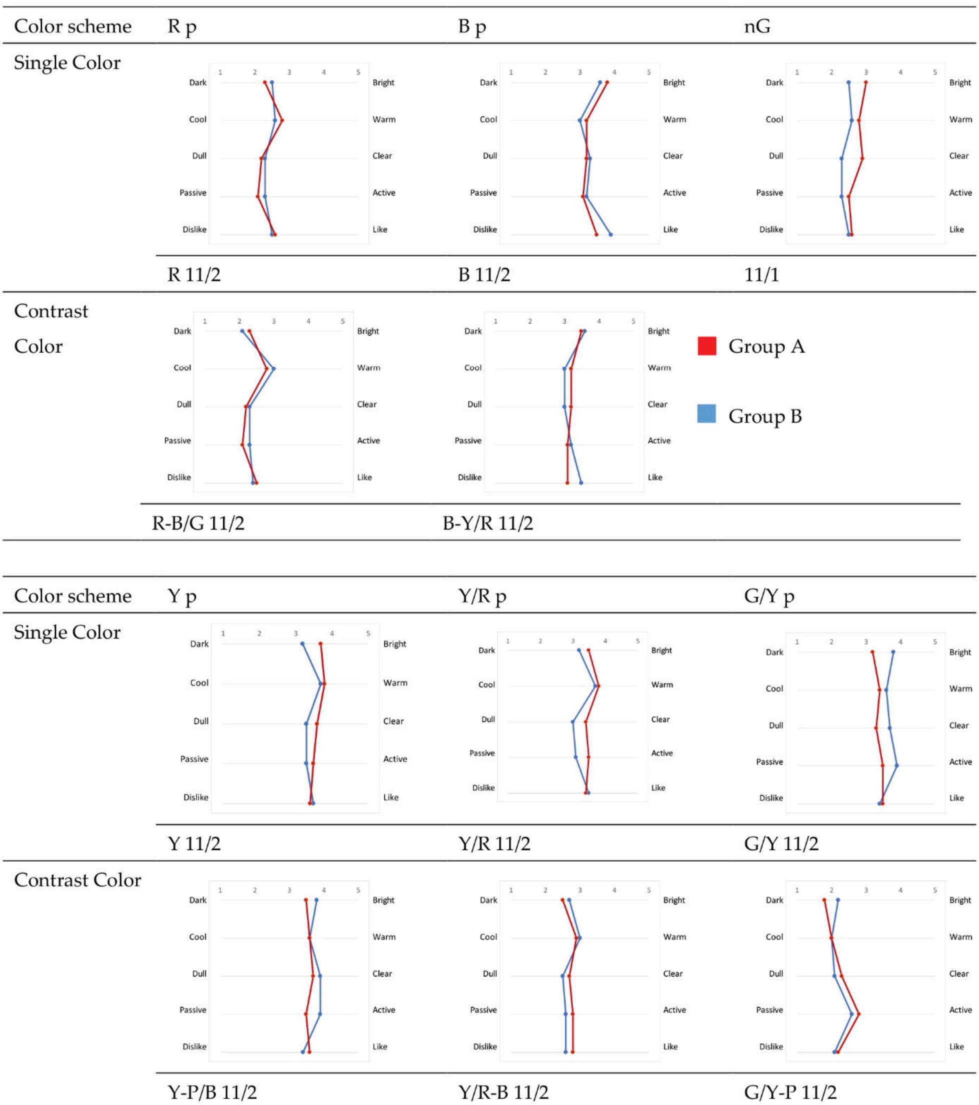


Figure 7. Psychological response to interior space colors based on 1–5 Likert scale.

For the contrasting color scheme, the averages of group A and group B for all emotional adjectives were generally similar, and it was found that the average of 'static' in the group was high. In the case of Yellow/Red-Blue and Green/Yellow-Purple, the average of 'dark' and 'cool' was high for cool colors, and the average of 'dark' and 'warm' was high for warm colors. In the contrasting colors, Yellow-Purple/Blue, Red-Blue/Green, and Blue-Yellow/Red, group B's average 'dull' and 'static' were somewhat high.

As for the achromatic color-matching image, the average of 'bright', 'warm', and 'clear' of group B was somewhat higher, and there was no difference between groups for the other 'static-active and 'dislike—like'. The achromatic color-matching image found that, overall, all adjective vocabulary was evaluated close to 'selection 3'.

An independent sample *t*-test was conducted to analyze the difference in the response of 'pleasure' to the color-matching image concerning depression symptoms (Table 3). There was no significant difference between groups except for the achromatic color-matching image in the response score of 'pleasure' for the 11 color-matching stimuli images. In both groups, the score of the cool-color B (M = 3.39, SD = 1.19) was highest, whereas the warm color R (M = 2.62, SD = 1.23) had the lowest score. Looking at each group, the averages of B (M = 3.50, SD = 1.15) for group A and Y/R (M = 3.31, SD = 1.28) for group B were slightly higher. On the other hand, the averages of achromatic color (M = 2.78, SD = 1.22) in group A and (M = 2.60, SD = 1.23) in group B were slightly lower. However, a graph representing the mean response and SD of 'Pleasure' for stimuli color images resulted in a *t*-test of 0.96% (there was no significant (n.s) difference between the groups ($p < 5\%$)) (Figure 8).

Table 3. The score of 'Pleasure' for stimuli color images.

Color Type	Group A M (SD)	Group B M (SD)	Total M (SD)	*t*-Test Result
Yellow	3.40 (1.20)	3.21 (1.23)	3.33 (1.21)	−1.642 (n.s)
Yellow/Red	3.38 (1.13)	3.31 (1.28)	3.36 (1.18)	−0.947 (n.s)
Green/Yellow	3.34 (1.15)	3.17 (1.23)	3.29 (1.21)	−0.454 (n.s)
Red	2.86 (1.21)	2.55 (1.18)	2.76 (1.22)	−0.921 (n.s)
Blue	3.50 (1.15)	3.17 (1.25)	3.39 (1.19)	−1.068 (n.s)
Yellow-Blue	3.14 (1.20)	2.52 (1.35)	2.93 (1.28)	−1.029 (n.s)
Yellow/Red-Blue	2.85 (1.21)	2.55 (1.18)	2.76 (1.22)	−0.929 (n.s)
Green/Yellow-Purple	3.00 (1.15)	3.00 (1.22)	3.00 (1.17)	−0.973 (n.s)
Red-Blue/Green	2.80 (1.22)	2.42 (1.17)	2.62 (1.23)	−0.878 (n.s)
Blue-Yellow/Red	3.14 (1.17)	2.62 (1.32)	2.83 (1.20)	−0.929 (n.s)
neutralGrey	2.78 (1.22)	2.60 (1.23)	2.82 (1.22)	−0.858 (n.s)

M: mean, SD: standard deviation.

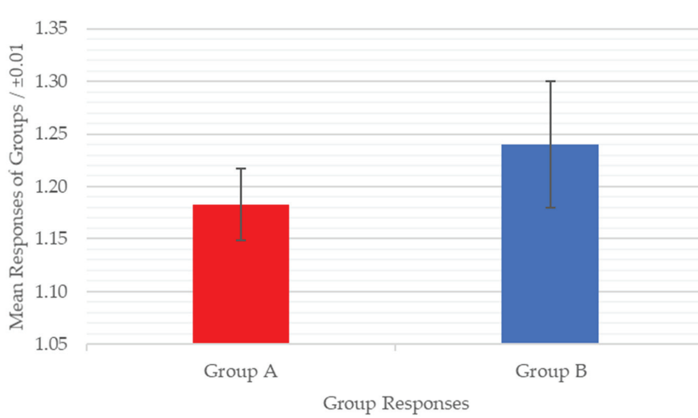


Figure 8. Graph of the mean response and standard deviation of 'Pleasure' for stimuli color images.

3.3. Physiological Response

An EEG measurement is a precise test, so out of a total of 80 survey residents who participated in psychological characteristics analysis, ten residents in group A (male = 6 people, female = 4 people) and ten residents in group B (male = 4 residents, female = 6 people), a total of twenty residents were selected, and the analysis used the measured results. As a result, the 'male and female' ratio was 50.0%, while the 'age' ratio was 50.0% (10 residents) in their 70s, 35.0% (7 residents) in their 80s and over, and 15.0% (3 residents) in their 60s (Table 4).

Table 4. Classification of investigation targets for EEG.

Participants		Level of Depression		Total
		Group A	Group B	
Age Group	60s	2 (20.0%)	1 (10.0%)	3 (15.0%)
	70s	4 (40.0%)	6 (60.0%)	10 (50.0%)
	80s and Above	4 (40.0%)	3 (30.0%)	7 (35.0%)
Gender	Male	6 (60.0%)	4 (40.0%)	10 (50.0%)
	Female	4 (40.0%)	6 (60.0%)	10 (50.0%)
Total		10 (100.0%)	10 (100.0%)	20 (100.0%)

According to the color samples, the observation and the measurement showed a change in alpha wave of 8~13 Hz. Alpha wave (α) signals of the left (Fp1) and right (Fp2) prefrontal cortexes were collected to analyze the EEG signal for the degree of depression and color-matching images. Alpha waves are brain waves that represent positive and negative emotions in human emotions. As an EEG is a fine electrical signal, it may not be statistically significant, but the difference can effectively identify the emotions. The formula for analyzing the alpha wave asymmetry value (valence value) is as follows: prefrontal alpha wave asymmetry = Fp1(a) − Fp2(a) (Fp1(a): left frontal cortex, Fp2(a): right frontal cortex, a: alpha wave). The Mann–Whitney test compared the alpha wave asymmetry values of group A and group B, a nonparametric test [55]. Table 5 shows the alpha wave asymmetry values for each group's eleven color-matching images.

Table 5. The score of 'Pleasure' for color images stimuli.

Experimental Colors	Group A M (SD)	Group B M (SD)	Total M (SD)	*z*-Value
Closed Eye	0.66 (0.49)	−0.41 (0.35)	0.38 (0.96)	−3.782
neutralGrey	0.63 (1.28)	−0.41 (0.35)	0.95 (1.93)	−2.268
Yellow	0.81 (1.33)	−0.20 (1.90)	1.10 (1.51)	−3.326
Yellow/Red	0.79 (1.20)	−0.07 (1.14)	0.38 (0.96)	−3.326
Green/Yellow	0.70 (1.17)	−0.51 (1.20)	0.98 (1.80)	−2.297
Red	0.61 (1.07)	−0.08 (0.54)	0.82 (1.49)	−3.628
Blue	0.90 (1.24)	−0.14 (1.39)	0.60 (0.93)	−3.024
Yellow-Blue	0.86 (1.32)	−0.53 (1.22)	0.52 (0.86)	−3.232
Yellow/Red-Blue	0.84 (1.19)	−0.13 (1.20)	0.38 (0.96)	−2.797
Green/Yellow-Purple	0.60 (1.25)	−0.54 (1.53)	0.31 (1.43)	−3.366
Red-Blue/Green	0.59 (1.25)	−0.41 (1.28)	0.76 (1.10)	−2.177
Blue-Yellow/Red	0.89 (2.10)	−0.05 (0.64)	0.76 (1.11)	−3.781

Valence = Fp1(a) − Fp2(a) (Fp1(a): left frontal cortex, Fp2(a): right frontal cortex, a: alpha wave).

There was a significant difference in the valence's average values for Group A and Group B; Group A had a positive response, and Group B had the majority of negative responses (Table 5). When the eyes were closed, the valence value was 0.66 (SD = 0.49) in group A, and −0.41 (SD = 0.35) in group B. In group A, the valence values of Neutral Gray (M = 0.63), B (M = 0.90), Y/R (M = 0.79), and R-B/G (M = 0.59) were lower than or similar to the closed eyes values. In addition, the valence values of all other color-matching images were higher than those of the closed eyes. In group B, the values for all color-matching images except G/Y-P ($M = -0.54$) and achromatic ($M = -0.41$) were higher than when the eyes were closed.

Group A had the highest valence value for B cool similar color ($M = 0.90$, $SD = 1.24$), and the valence value for the similar cold color of B-Y/R ($M = 0.89$, $SD = 2.10$) was high. In group B, the valence value of the R-B/G warm contrast color ($M = 0.41$, $SD = 1.28$) was highest, and B and Y/R-B (100) were in order. Overall, group A had a high valence value for warm and similar color images, whereas group B had a high valence value for cold and contrast color images, indicating a significant difference in emotional response for each color image. SD was high, representing an increase in alpha brain wave amplitude in the occipital area in the depressed group, which means increasing the functional level and the ability to reduce symptoms of depression.

The analysis target was to detect the positive and negative emotional responses through the asymmetry values of the frontal cortex's left/right alpha wave to the cool color-matching image. The frequencies of single and contrast images showed preference to the single color in both groups. In general, participants of group A experienced positive emotions even when viewing color-matching images compared to group B. The single cool color Blue showed better acceptance where Group A accepted it entire-ly, but in Group B, only eight experienced positive emotions. Unlike cool colors, warm colors showed significant differences. Group A negatively evaluated Red and its con-trast Red-Blue Green with nine and eight participants, respectively. Group B evaluated six and ten negatively for the red color and its contrast, contrary to the Yellow color (Figure 6), respectively.

4. Discussion

This study aimed to find the significant differences in psychological and physiological responses to the color image of the resident's interior bedroom according to the degree of preference response in the elderly population. However, there is a limit in proposing as authentic an interior as possible of the Seniors' Happiness Centre color scheme by applying a simple color scheme and expression technique so that the elderly over 65 in the UAE do not have difficulty in evaluating the color scheme of a three-dimensional residential space. In response to the UAE social change, which is gradually becoming older in the future, it proposed reducing and avoiding depression, a severe elderly disease, by preparing an interior bedroom in the Seniors' Happiness Centre color scheme that considers the psychological characteristics of the elderly.

First, as a result of investigating group A and B's preferred colors (Figure 9), it was discovered that group A had a strong preference for cold colors, while group B had a modest choice for bright colors based on their eyesight. The results of group A are not consistent with the results of the previous studies that the elderly's preference, in the far eastern country, for warm colors is higher than that of cool colors—such a result is associated with the cultural color cognition [56]. The UAE elderly spent their lives primarily on the seaside (blue) and the desert (yellow). In addition, the sea represents the expansion of life as it produces their essential food source [57]. The results of both groups are different to the results of the previous studies that college students of different age groups prefer achromatic colors as the degree of depression increases. Such a result can be interpreted as a characteristic of the elderly who prefer bright colors compared to other age groups. In other words, it can be seen that the elderly have different characteristics from ordinary adults in terms of vision, and a differentiated color plan is needed in the elderly space [58]. As a result of examining the non-preferred colors of groups A and B, both groups A and B showed high dislike rates for achromatic colors such as black and neutral grey. It can be seen that both the regular group and the depressed group have a low preference for neutral colors such as grey and negative perceptions of black [59]. Among the achromatic colors, black and neutral grey are highly unfavorable, and black and neutral grey require attention when planning the color of residential spaces. As a result of examining the colors representing group A and group B, the ratio of cool color was high, and group B showed a low difference according to the color temperature.

Cool Color Scheme Frequency Analysis

Warm Color Scheme Frequency Analysis

Figure 9. Single color vs. contrast color scheme—positive vs. negative emotions frequency's analysis.

Second, it was found that there was little difference in the vocabulary of psychological adjectives for color-matching images according to the degree of depression except for a few items. Such an outcome can be interpreted as having similar psychological reactions to the spatial color image in the case of the elderly regardless of the degree of depression or simple mood change and representing emotions. The mean value of the SD scale for 'pleasure' for the color-matching images of group A and group B differed in the achromatic color-matching image. The single-color score of the cool colors of both groups was high (blue), and the score of the warm color single color was lower (yellow). Looking at each group, the average of the cool color contrast B-Y/R in the B group and the warm color similar color Y-P/B in the A group was high. Both groups had high psychological reactions to cool colors, so it can be seen that a color plan taking this into account is necessary.

Third, there was no significant difference between the left and right alpha wave values of the prefrontal cortex of group A and group B. This is considered because the brain waves are minute electrical signals and appear different from person to person. However, measuring the valence value for the color-matching image showed significant differences depending on the group. Group A responded positively to the single-color scheme of the B cool color, and group B responded positively to the contrast color of the B-Y/R cool color. Thus, there was no difference in the prefrontal alpha waves of the two groups, but there was a difference in the asymmetry of the alpha waves representing emotions, so it is possible to grasp the subjects' preference for color-matching.

The cultural background and the cognitive responses were found to significantly impact the colors' selection, where single is better than the contrasting [58]. Contrary to the studies performed in Western countries, the cool colors were the preferred colors, especially the sea color, for 26% for standard group A and 30% for depressed group B. The sand color in the warm colors came next in their preferred colors and self-representation by 20% for group A and 13% for group B.

Furthermore, the positive and negative emotions matched the color selection. The correspondence of results proves and accentuates the results of this research.

5. Conclusions

This paper investigated the relationship between the color preference of the resident bedroom space, using color images as stimuli, and the depression symptoms using physiological and psychological responses. Understanding the difference in response to the color image of interior resident experimental rooms for color planning of the Seniors' Happiness Centre considering the psychological and physiological reactions of the elderly aged 65 or older in the UAE was a key target. The participants were classified into group A and group B according to the results of the Geriatric Depression Scale and representing the emotional or mood change (GDS) test. Psychological and physiological responses to the single color and twelve color-matching images of the two groups were measured using stimuli images and then analyzed. As for the color-matching image, twelve models were produced from one achromatic color (Neutral Grey), single and contrast colors of warm colors (Yellow, Red, and Yellow/Red), and cool colors (Blue and Green/Yellow). The psychological response to the color image was the average value of the semantic. Furthermore, different method scales composed of adjectives of the color image and the physiological response were measured and analyzed for the prefrontal cortex's EEG alpha wave asymmetry value using a five-point Likert scale.

As mentioned above, psychologically, group A responded positively to the single-color scheme of the Blue cool color, and group B responded positively to the contrast color of the Blue-Yellow/Red cool color. Physiologically, group A responded positively to the single-color scheme of Yellow as a warm color, and group B responded positively to the contrast color scheme of the B-Y/R cool color. Thus, group A showed a common reaction, psychologically and physiologically, favoring a similar color scheme of (Blue) cool colors. However, it can be seen that group B, psychologically, showed a positive response to the contrasting color through their preference for (Yellow/Blue), a warm hue-contrasting color, and they selected the cool hue-contrasting color (Blue-Yellow/Red), physiologically. Following this result, it will be possible to develop an alternative color scheme for residents' interior bedrooms that can be applied in practice. The color scheme on one side of the wall with increased saturation seemed to avoid depressive symptoms or represent emotions effectively.

Future research will propose a more varied color scheme suitable for the characteristics of the elderly by studying the response to more diverse colors. Furthermore, the physiological data of such an investigation need to increase in scope and study to obtain appropriate and reliable conclusions. Such a section enables future research linking the color physiological effects on the elderly within a greater variety of interior spaces.

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buildings

Article

Optimal Design and Verification of Informal Learning Spaces (ILS) in Chinese Universities Based on Visual Perception Analysis

Yuzhen Chen [1,2], Jinxiu Wu [1,*], Yamei Zou [1], Wei Dong [1] and Xin Zhou [1]

[1] School of Architecture, Southeast University, Nanjing 210096, China
[2] School of Architecture, Xiamen University Tan Kah Kee College, Zhangzhou 363105, China
* Correspondence: wu_jinxiu@seu.edu.cn; Tel.: +86-138-5167-3898

Abstract: As the focus on higher education in China gradually shifts from rapid development to an emphasis on quality, the need for campus environments to become facilitators of education has gained increasing attention. The accelerated development of information technology has also led to tremendous changes in both teaching and learning methods, with informal learning taking on an increasingly important role. Furthermore, the development of human sensing technology, especially visual perception technology, has brought in new opportunities for the research and optimization of informal learning spaces (ILSs) in universities. This paper focuses on the ILS in Chinese universities by exploring optimal design approaches based on visual perception analysis. Through research and field investigation, this paper proposes revised theoretical research of classifications and spatial elements of ILS in universities more applicable to the architectural study of space. This paper also explores practical optimal design methods with two case studies and makes experiments with wearable eye trackers to study the users' perception in these spaces before and after optimization. The optimal design is made from the aspects of physical space, facilities, and environment. Visual perception experiments and quantitative analysis were used to obtain a higher level of experimental accuracy than the previous studies and thus to study the real feeling of users in spaces. By these means, the effect of the optimized design was verified and the relation between users' perceptions and the spatial environments was explored for further improvements to optimal design methods. This article can provide theoretical and practical references for campus space optimization research and design, especially for ILS on university campuses.

Keywords: informal learning space (ILS); visual perception analysis; wearable eye tracker; optimal design and verification

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1. Introduction

The accelerated development of China's economy after the reform has provided unprecedented opportunities for the development of universities. In 2019, the number of enrolled students in China's universities reached 38.33 million, which ranked it first in the world [1]. The number of universities was 2824, ranking second in the world. The development of Chinese higher education has entered a new stage with the development model shifting from incremental development to stock optimization [2]. In the new stage, informal learning space (ILS) becomes as crucial as the teaching space since Chinese universities are paying more attention to the cultivation of students' comprehensive ability. While the way of cultivation is no longer limited to teaching in classrooms; dialogue, seminars, communication, contemplation, and even rest have become significant ways to enhance students' abilities. However, research shows that both the quantity and quality of ILS in Chinese universities need to be improved [3–8].

Research on ILS began with a qualitative discussion at a theoretical level, covering the influencing factors, student behaviors, and their satisfaction with the space. For example, Ahamd A. Alhusban assessed students' needs for ILS through questionnaires and studied ways to meet these needs through corresponding guidelines [9]. Descriptive statistics and Pearson correlation coefficient was applied to analyze the data, and the results revealed that interrelationships among all campus urban design principles have a strong positive linear relationship. Moreover, Xianfeng Wu studied the relationship between ILS design points and behavior patterns through field research and questionnaires [3]. Six significant design characteristics influencing the use of ILS was identified in this study, including comfort, flexibility, functionality, spatial hierarchy, openness, and other support facilities. Shirley Dugdale [10] proposed an "informal learning landscape" for campus planning by integrating both formal and informal learning spaces. He highlighted the criticality of learning activities and human interaction and suggested that campuses need to create a participatory architecture to support these communities of learners. Maheran et al. [11] investigated how ILS on university campus outdoor spaces can enhance students' academic performance. This study suggested that it is important to take the outdoor classroom into consideration during the campus landscape design, as it affects students' activities such as learning, educating, meeting, exploring, as well as relaxing. Ran Ranjin et al. [12] investigated the relevance of informal learning behaviors to campus open spaces through field behavioral observations and provided recommendations for space regeneration design, highlighting the importance of informal learning behaviors in the design of spatial regeneration. Tian Yang [13] explored the relationship among "Information, space, and people" in research on three types of ILS in college libraries in the United States. This study emphasized the construction of diverse learner-centered spaces. Among them, the most famous research is Lennie Scott-Webber's research theoretical framework of ILS and its design guidelines [14]. She stressed that as higher education undergoes dramatic changes due to changes in pedagogy and technology, which are reshaping the needs of learners, the planning, design, and use of learning spaces must change. Therefore, previous studies have carried out some theoretical research on the optimal design of ILS, and several research have concluded that it is important to strengthen the interaction between ILS and learners, emphasizing the importance of the human experience created by ILS to the design effect. However, there is a lack of ILS classification methods applicable to architecture space research, and few studies have focused in-depth research on the relationship between the spatial elements of ILS and users' feelings on it in a quantitative way. This affects the application of the theories and methods in the practice design of ILS.

On the other hand, the rapid development of new technologies has contributed significantly to the depth of human perception research [15–18]. Among them, visual perception, as an essential part of human perception, is one of the most important ways in which humans perceive space. For example, ETH Zurich optimized the signage design and space organization in Frankfurt Airport with help of data collected from subjects wearing eye-tracking devices [19]. Dr. Nikhil Naik et al. at MIT used "Streetchange", a machine learning technology that provides a visual approach to urban space design and street image research to assess and analyze the elements in urban space that affect perception [20]. Dr. Alexander Erath et al. from the Future Cities Lab at ETH Zurich built a highly realistic virtual reality environment by combining 3D modeling and traffic simulation techniques. Although most of the previous literature presents the use of new technologies of visual perception in urban public spaces and streets, the study by Lebrun, C. points out that people's visual perception of architectural space is not related to the type of building, but depends mainly on landscape elements [21]. In addition, Małgorzata Lisi' nska-Ku´snierz's research shows the applicability of eye-tracking in assessing the visual perception of architectural works and points to its potential for the disciplines of architecture and urban planning [22]. The eye-tracking technology helps to accurately establish the relationship between the user's visual perception in space and the spatial elements so that the spatial components of ILS can be studied and optimized accordingly to promote its use. Therefore, it is necessary to introduce human perception technologies into the campus ILS research.

Different from traditional theoretical studies of ILS, the above-mentioned research has brought new opportunities for the design of ILS, especially for the interaction between users. Some researchers have tried to apply new technological tools (visual perception) in urban public areas and streets [23,24]; however, little research has been applied to the optimal design of ILS. Therefore, based on the problems found in the extensive investigation and literature review, this paper proposes revised theoretical research for classifications and spatial elements of campus ILS more applicable to architecture space study. This paper also explores practical optimal design methods for campus ILS and verifies the effect of optimal design with the help of new technologies. The visual perception technology represented by the wearable eye-tracking device is introduced to collect data on users' feelings in ILS at a much higher level of accuracy than in previous studies and thus improve the quality and efficiency of optimal design. The methodology in this paper can provide theoretical and practical references also for other campus space research.

This study aims to investigate the optimal design and verification of ILS in Chinese universities using visual perception analysis to solve existing problems and promote usage by both faculty and staff.

The objectives of this study are as follows:

- To verify the effect of optimal design of ILS on visual perception experiment and quantitative analysis.
- To study the relationship between users' visual perception and spatial elements for further optimal design methods.
- To propose practical recommendations to enhance the use of ILS in Chinese universities.

2. Methodology

Based on the above objectives, the framework of this research is as follows: Firstly, a theoretical analysis of classifications and spatial elements of ILS was presented through research and investigation. Secondly, two case studies are made to illustrate the research and optimal design methods. Eye-tracking data before and after the optimal design were obtained through visual perception experiments [25], and quantitative analyses were conducted to study the relationship between users' visual perception and spatial elements and thus verify the design effect. Finally, the optimal design method for ILS in Chinese universities is summarized and enhanced.

The research framework of this study is shown in Figure 1.

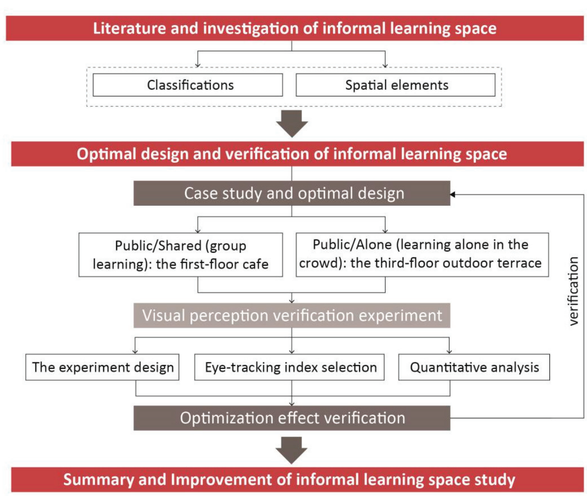
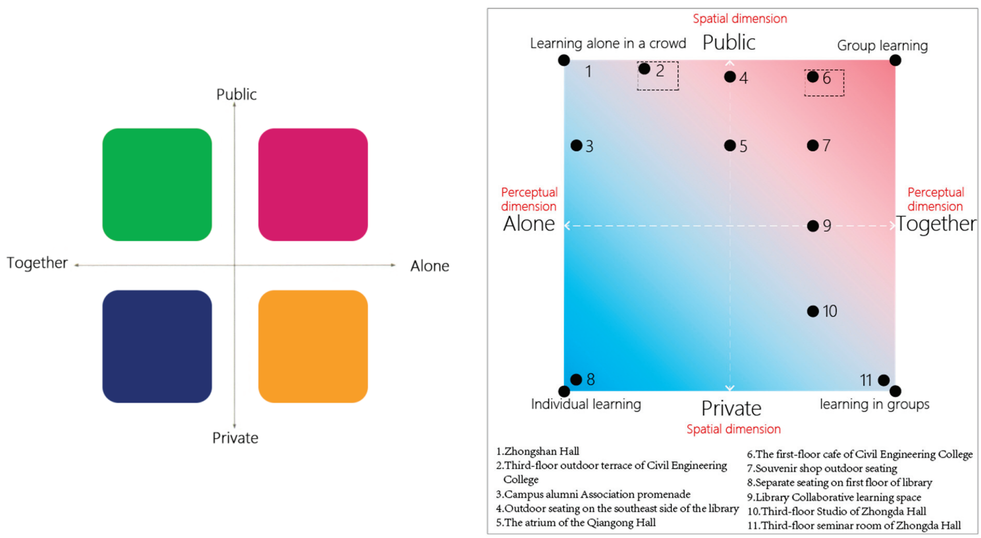


Figure 1. Framework of the research.

2.1. Litterateurs and Investigation

2.1.1. Litterateurs and Classification

While U.S. higher education had impressive success in its nearly 400-year history, the planning and design of learning spaces on U.S. campuses also reflect a more programmatic approach to formal learning and learning. As today's teaching methods and campus spaces are changing, variation in learning spaces is inevitable. For this reason, Weber proposed a four-quadrant theoretical framework to support those learning behaviors in informal learning environments. The quadrant theory framework consists of four quadrants, Private/Alone, Private/Together, Public/Alone, and Public/Together, as shown in Figure 2a [8]. The advantage of this theory is that it covers all types of behaviors and spaces that occur in ILS. Nevertheless, the drawback of this theory is that it does not reflect the ambiguous and transitional ILS. Based on the problems that emerged from this theory and preliminary study, this paper further broadens and optimizes the theoretical study to make it more applicable to the study of architectural space.



(**a**) (**b**)

Figure 2. Classification of ILS in universities. (**a**) Weber's four-quadrant theoretical framework.; (**b**) The framework for classifying ILS in this paper and the 11 ILS investigated in Southeast University.

This paper suggests a revised theoretical framework to support engaged learning behaviors by dividing ILS into four categories from the spatial and perceptual dimensions as the vertical and horizontal coordinates of the four-quadrant framework, which are Private/Alone (Individual learning), Private/Shared (Group learning), Public/Alone (Learning in the crowd), Public/Shared (Group learning), and Public/Alone (Open group learning).

(1) Private/Alone (Individual learning): closed and smaller private spaces with defined boundaries, usually found in the library, with students' static behaviors.

(2) Private/ Shared (Learning in groups): private spaces with defined boundaries and moderate scale, usually located inside academic buildings or libraries, with student groups' relatively dynamic learning behaviors.

(3) Public/Alone (Learning alone in the crowd): open spaces usually located in public areas, such as study rooms in libraries, gray spaces, etc., with students learning behaviors changing according to the atmosphere of the surroundings.

(4) Public/Shared (Group learning): open and more functionally complex spaces usually located in cafes, normally with student groups' dynamic learning behaviors, and some of them also connect with outdoor spaces.

2.1.2. Field Investigation

An extensive study of ILS in universities was conducted in Nanjing, with a total of 61 cases of field investigation on 11 campuses. Considering the representativeness of the case study and the convenience of subsequent experiments, this paper focuses on the Sipailou Campus of Southeast University for an in-depth study. The reasons were as follows:

Firstly, Southeast University was established in 1902 and is one of the earliest and most prestigious universities in China, and Sipailou Campus is the oldest campus of Southeast University. During its 120 years of development, it has formed a campus space and architecture with both a long history and contemporary development and has a strong representation of almost the entire process of the construction and development of university campuses in modern China.

Secondly, the School of Architecture of Southeast University, which is located on this campus, is one of the top three architecture schools in China and has the top experimental facilities in the field of architecture, and the advanced experimental conditions are conducive to the subsequent experiments and research.

A total of 11 cases of ILS in Sipailou Campus, Southeast University were studied and classified in Figure 2b. Then, case studies and optimal design were made for two spaces: the first-floor cafe (Public/Shared) and the third-floor terrace (Public/Alone) in the building of the School of Civil Engineering of Southeast University. These studies aim to cover the most frequent types of public ILS in the investigation and contain both indoor and outdoor ILS.

2.1.3. Spatial Elements Study

In field investigation, it is shown that ILSs in universities are composed of three elements: physical space, facilities, and environment. The former two can be directly perceived through visuals, while the latter can be mainly perceived by visuals and/or feelings.

(1) Physical Space: the material elements of space, including the location, size, enclosure, material, color, etc.
(2) Facilities: the elements to help with space functions, often in the form of furniture and equipment, and linked with users' behavior.
(3) Environment: Including landscape and the physical environment. The landscape environment emphasizes the natural and artificial environments both indoor and outdoor. The physical environment refers to the thermal, optical, and acoustic environment, etc., influenced by material elements. Environment analysis based on visual perception in this study involves only the landscape environment.

2.2. Case Studies and Optimal Design

2.2.1. Case Studies

Two spaces were chosen in this paper to make case studies in the practice project of optimal design of the College of Civil Engineering building of Southeast University. They were the first-floor cafe as the typical case for the "Public/Shared" type and the third-floor outdoor terrace for the "Public/Alone" type. The reasons were as follows: First, it was discovered in former investigations that the number of public ILS in the universities was much more than that of private ones and was used much more frequently. Second, both interior and exterior ILS should be covered.

(1) The first-floor cafe (Public/Shared):

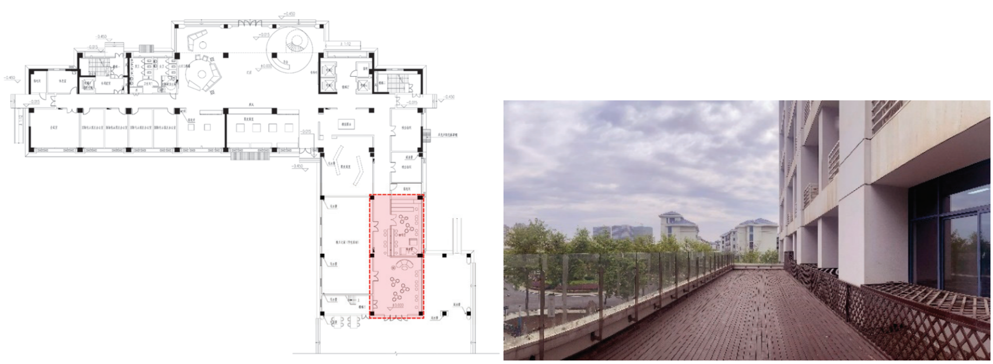
The cafe on the first floor was optimized from the original activity center and the adjacent sub-foyer, as shown in the red area in Figure 3. Before optimization, the original activity center was separated from the sub-foyer by a wall. Investigation showed that the activity center activity was used frequently, yet the sub-foyer was always empty. The main problem with this space is the lack of facilities for people to stay in.

(**a**) (**b**)

Figure 3. The first-floor cafe before optimization of t. (**a**) Original plan. (**b**) Photo.

(2) The third-floor terrace (Public/Alone):

As shown in Figure 4, The third-floor terrace is located adjacent to the public rest space and is one of the few spaces in the building where faculty and students can have access to the landscape. However, it was shown in the investigation that there are many problems with this space, such as no facilities for people to rest, and not being open enough to the adjacent spaces. So, students seldom stay there.



(**a**) (**b**)

Figure 4. The third-floor terrace before optimization. (**a**) Original plan. (**b**) Photo.

2.2.2. Optimal Design

Based on the research on the elements of ILS and the problems found in the field research, optimal designs in two case studies were made from the following three aspects: physical space, facilities, and environment. The aim of optimal design was to solve the existing problems and promote the usage by faculty and students.

2.3. Visual Perception Experiment

Aim for exploring a much more efficient optimal design method, eye-tracking data from images of the space before and after the optimal design were obtained by visual perception experiment. Being able to capture the visual dynamics of the subjects, the eye-tracking device was used as the main tool for data collection in the experiment. Then the quantified data were analyzed to reflect the real feelings of the subjects in space and thus to check the effectiveness of the optimal design.

2.3.1. Data Collection and Processing

(1) Collecting the typical images before and after optimal design in the case studies.
(2) Making visual perception experiments by utilizing Tobii Pro Lab for quantitative analysis of the perception data of subjects before and after optimal design. Enough valid visual perception data are collected with a wearable eye-tracker and various indexes are selected.
(3) Comparing the visualization results before and after the optimal design by the processing and analysis of eye-tracking data.

2.3.2. Visual Perception Experiment

(1) Subject setting: refer to previous relevant experiment procedures, this experiment was performed a total of 18 times. According to the criteria with a sampling rate greater than or equal to 80% [24], finally 11 sets of valid data were obtained from six subjects.
(2) Stimulus material: images of ILS before and after optimization.
(3) Experiment procedure:

Step 1: once the subject entered the digital laboratory and took their seat, they put on Tobii Glasses 2 (Figure 5a) and performed the first eye-tracking device calibration under the experimenter's instruction.


(a)

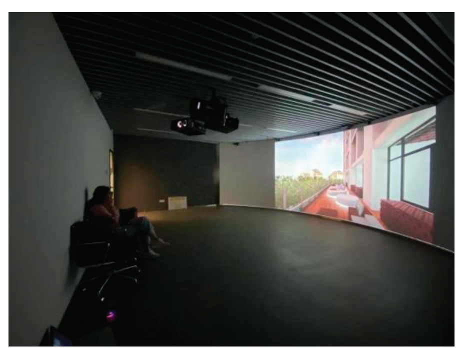

(b)

Figure 5. Visual perception experiment. (**a**) Wearable eye-tracker Tobii Glasses 2. (**b**) Experiment in the digital laboratory.

Step 2: after successful calibration, the experimenter provided the subject a cue and started playing the stimulus material, which the subject watched for one minute.

Step 3: after the first viewing, the experimenter ended the data recording. The subject then proceeded to the second and third viewing under the experimenter's instructions.

Step 4: after the third viewing, the subject removed the oculomotor and left the laboratory.

2.3.3. Eye-Tracking Index Selection

Researchers used the Tobii Pro Lab to make quantitative analysis according to eye-tracking distribution maps, the heat maps and gaze plots, in which the following eye-tracking index was chosen, are shown in Figure 6. In addition, various spatial areas were defined in both photos and perspectives before and after optimal design, which contributed to creating the areas of interest (AOI). Then, after drawing the target area of interest when analyzing the stimulus material, the following eye-tracking indexes were selected for visual observation: total fixation duration (TFD), the average fixation duration (AFD), the time to first fixation (TFF), the total glance duration (TGD), the average glance duration (AGD), and the glance count (GC) as shown in Table 1. With reference to the study of human visual perception when reading, the six indexes were classified into "visual observation "(TFD/AFD/TFF) and "visual search" (TGD/AGD/GC).

Table 1. Eye-tracking indicators and meanings [1].

Eye-Tracking Concepts and Indicators		Indicator Abbreviations	Definition	Meaning
Visual observation	The total fixation duration	TFD	Total time spent gazing within a given AOI	The longer the time, the more attractive the AOI is
	The average fixation duration	AFD	The average duration of all gazes within a given AOI	The longer the time, the more informative or difficult the AOI is to understand, or the more attractive the AOI is
	The time to the first fixation	TFF	The time from the beginning of a time interval to a fixation on the first AOI	The shorter the time, the easier the AOI is to engage the subject at the beginning
Visual search	The total glance duration	TGD	The duration between the end of the last fixation before entering an AOI (including the entry saccade [2]) and the end of the last fixation within that AOI (before the exit saccade [3])	The longer the time, the richer the information in the AOI is, the more difficult it is to be understood, or the higher the relevance of all parts in the AOI is
	The average Glance Duration	AGD	The average duration of all sweeps within a given AOI	The longer the time, the more invalid the search of the AOI is
	The glance count	GC	Number of sweeps for an AOI occurring in a time interval	The higher the number, the longer the subject's search process on that AOI

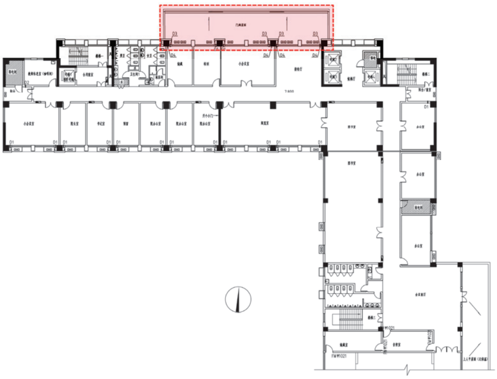
[1] Tobii Pro Glasses 2 Product Description (WWW Document), n.d. URL https://nbtltd.com/wp-content/uploads/2018/05/tobiiproproductdescription.pdf, accessed on 1 April 2022; [2] Saccade: central concave vision moves rapidly from one point to another in the oculomotor area. [3] Entry Saccade: the eye movement before the first gaze point in the target AOI. Exit saccade: the eye movement after the last gaze point in the target AOI.

3. Results and Discussion

3.1. Optimal Design

3.1.1. Case 1: The First-Floor Cafe (Public/Shared)

The optimal design was made according to the three spatial elements. As shown in Figure 6. Firstly, for the physical space, the solid wall of the student activity center was changed to transparent glass to make the space brighter and create multi-level visual communications. While the sub-foyer took utmost advantage of the original windows, the materials used in this space were mainly wood to make people feel much warmer. Second, in terms of facilities, furniture such as chairs, seats, and drinking fountains were added to meet faculty and students' needs for seating and communication and thus attracted them to stay for group learning. Third, for environment, artificial light was added at the top to ensure the quality of the light environment.



(**a**)

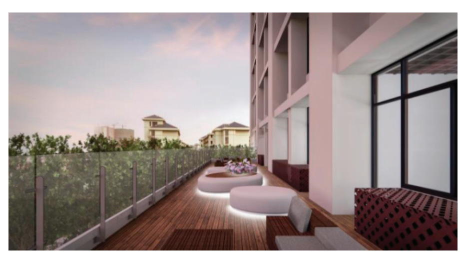
(**b**)

Figure 6. The first-floor cafe after optimal design. (**a**) Optimized plan. (**b**) Rendering of the space after optimal design.

3.1.2. Case 2: The Third-Floor Outdoor Terrace (Public/Alone)

The optimal design was also made according to the three spatial elements. In terms of the physical space, as shown in the red area in Figure 7, the addition of the door ensured direct access from the rest area to the terrace. As for the facilities, various types of seats were added, and the materials of which were chosen according to the exterior environment. As for the environment, some seats were integrated with artificial light and greenery, which not only enhanced the comfort of users but also offered nighttime lighting.

(**a**)



(**b**)

Figure 7. The third-floor terrace after optimal design. (**a**) Optimized plan. (**b**) Rendering of the space after optimal design.

3.2. Visual Perception Analysis and Verification

3.2.1. Case 1: The First-Floor Cafe (Public/Shared) for Open Group Learning

A comparison of the eye-tracking heat maps before and after optimization in Figure 8a,b showed that the size and number of red and yellow parts were much larger and more numerous than before. The green parts were dispersed over the entire picture, even in the black area outside the image before optimization; shifting to be more convergent, it was mainly concentrated in the horizontal direction after optimal design. This means that the number of viewers' visual attention points in the first-floor cafe increased after optimization, the visual order was no longer aimless, which demonstrated the space became more attractive after optimal design.

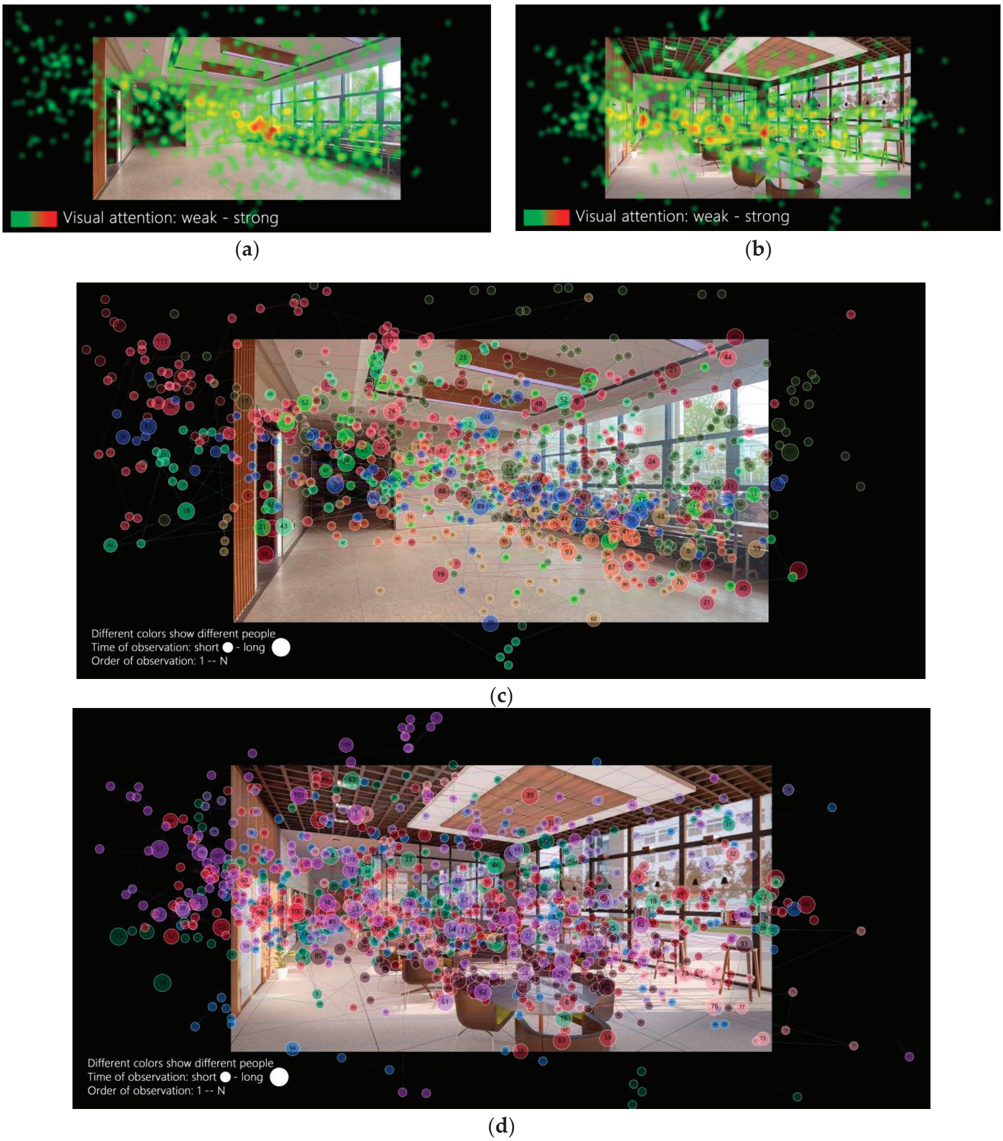
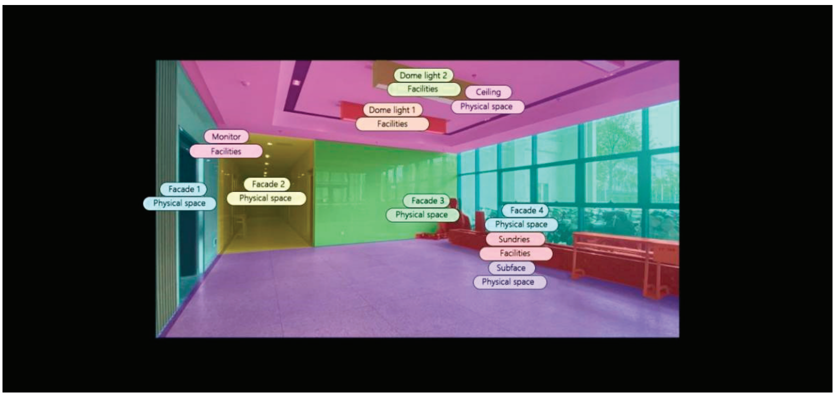


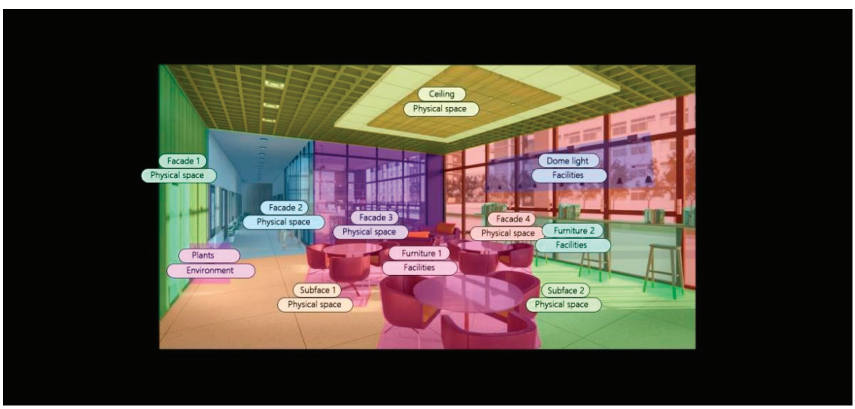
Figure 8. Distribution of eye-tracking data of the first-floor cafe. (**a**) The heat map before optimization. (**b**) The heat map after optimization. (**c**) The gaze plots before optimization. (**d**) The gaze plots after optimization.

A comparison of the gaze plots in Figure 8c,d indicated the viewers' visual order. For instance, most of the dots were concentrated on furniture after optimization rather than scattered on every object. Before optimization, the eyesight initially started from the objects in the space, and facade 3, then moved to other spatial elements, and finally returned to the objects. After optimization, people's eyesight mostly started from furniture 1 and continued to stay on the various facilities. Larger and more widely distributed dots indicate that the optimized space had more ability in attracting people.

The classification of the AOI was shown in Figure 9. The corresponding eye-tracking data were then derived, and a comparison between the spatial elements before and after optimization can be obtained in Table 2.



(**a**)



(**b**)

Figure 9. AOI division before and after optimization of the first-floor cafe. (**a**) Before optimization. (**b**) After optimization.

(1) Visual observation (TFD, AFD, and TFF)

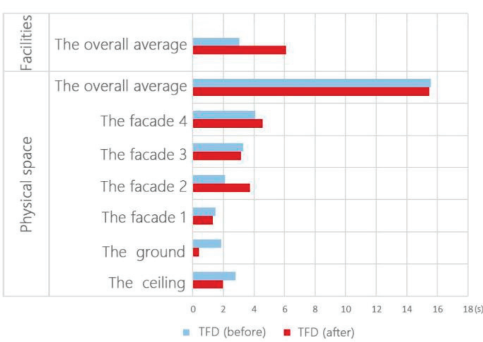
In terms of the total index, the TFD of facilities after optimization was higher than before. It was proved that increasing the number of furniture (tables and chairs) can provide people a clear understanding of the spatial function and thus strengthen the recognition of the optimized space.

As for the average index, the AFD of facade 2 and facade 3, which were the main elements of the space, was higher after the optimal design. It meant that variation in the transparency of the facade by changing materials can contribute to building a more attractive space. Moreover, the AFD of the facilities was lower after the optimal design, which meant that the optimized facilities can efficiently convey the functional information of the space.

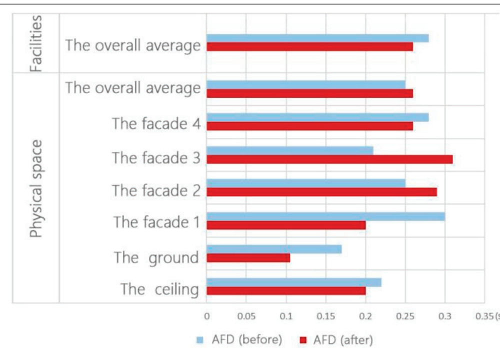
When it came to the observation sequence, the TFF of facade 1, the top, and the bottom of the physical space increased after the optimal design while the TFF of the facilities decreased. This proved that after the optimal design of the materials of the spatial facade, users paid less attention to the spatial elements that were not directly related to their activities.

Table 2. Comparison of eye-tracking data of the first-floor cafe before and after optimization.

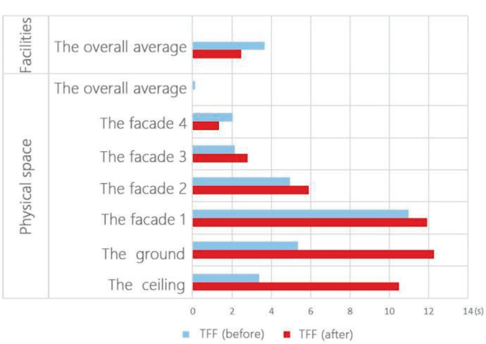
TFD



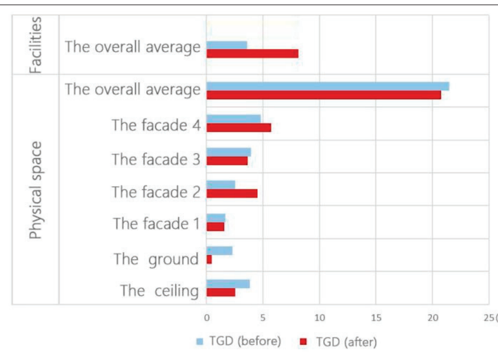
AFD



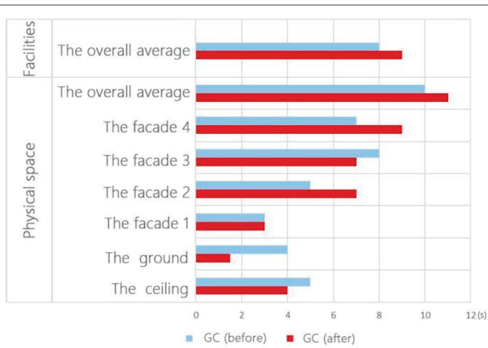
TFF



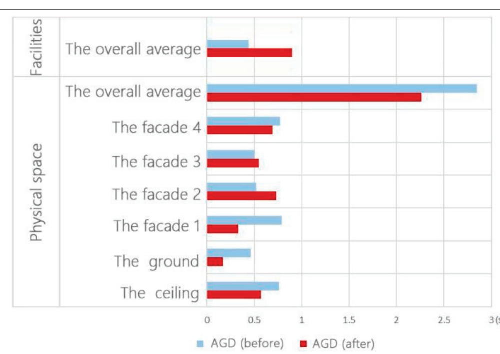
TGD



GC



AGD



(2) Visual search (TGD, GC, and AGD)

After optimization, it appeared that the TGD and the GC staying on facilities were more than those before optimization, with less difference between the TGD of physical space and facilities. This showed that the visual attention and level of each component of the space were almost the same, leading to the unity of the space.

As for the average index, the result indicated the difference between the AGD of the physical space and the space facilities shrank after optimization. Thus, it demonstrated that increasing the furniture types can enrich the space hierarchy, helping with the understanding of the space, and reducing the abruptness and discordance in the space. A comparison of eye-tracking data of the first-floor cafe before and after optimization is shown in Table 2.

3.2.2. Case 2: Public/Alone: Learning Alone in the Crowd: The Third-Floor Terrace

As seen in the comparison of the eye-tracking heat maps in Figure 10a,b, the area and amount of red and yellow parts of the diagram showed an obvious increase after the optimization. Whereas visual attention which was previously concentrated in the center of the image now distributed horizontally after optimization. Overall, the amount of visual focus attention points on heat maps for the terrace increased after the optimal design.

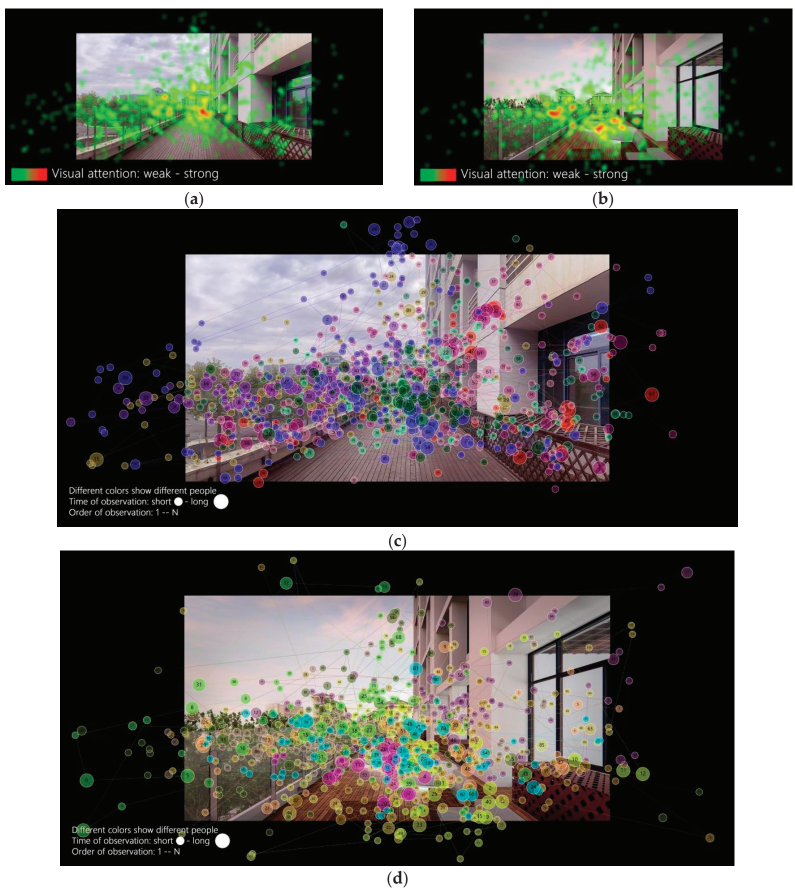
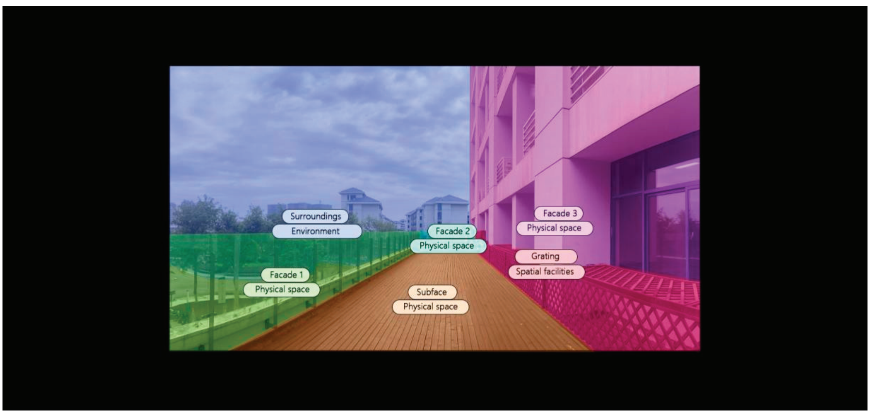


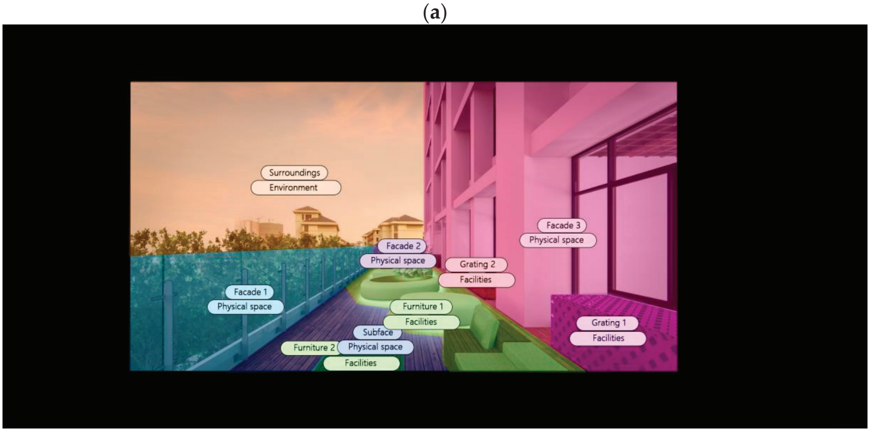
Figure 10. Distribution of eye-tracking data of the third-floor terrace. (**a**) The heat map before optimization. (**b**) The heat map after optimization. (**c**) The gaze plots before optimization. (**d**) The gaze plots after optimization.

A comparison of the gaze maps in Figure 10c,d showed that most of the origin points were focused on objects, which represented the users' visual position mostly in the center of the space. The dots were mostly concentrated on the landscape and facilities after optimization, with order of dots indicating the subjects' visual order. As for gaze order, it started from the sky and then shifted to other spatial elements, and finally returned to the facilities repeatedly. The results indicated that the size of the dots is related to the duration of the gaze time. So, it was shown that the optimized exterior space with natural landscape and facilities was more attractive.

The classification of the AOI according to spatial elements is shown in Figure 11. Eye-tracking data were then derived, and a comparison between the spatial elements before and after optimization can be seen in Table 3.



(**a**)



(**b**)

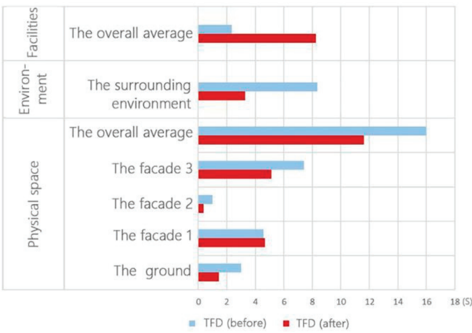
Figure 11. AOI division diagram before and after optimization of the third-floor outdoor terrace. (**a**) Before optimization. (**b**) After optimization.

(1) Visual observation (TFD, AFD, and TFF)

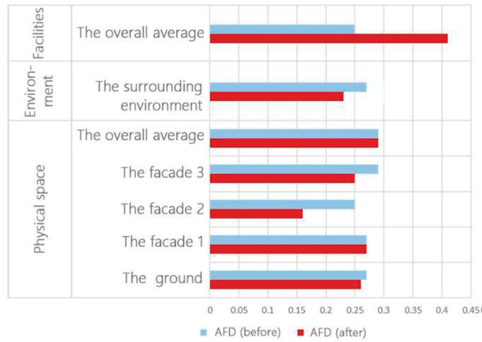
In terms of summation index, after optimization, the TFD of total observation time of facilities was more than that before optimization, and the TFD of environment and physical space was less than that before optimization. The TFD gap between the three types of material spatial elements was reduced. It proved that after the spatial elements were sorted out, the various spatial elements in this space became more homogeneous.

Table 3. Comparison of eye-tracking data of the third-floor terrace before and after optimization.

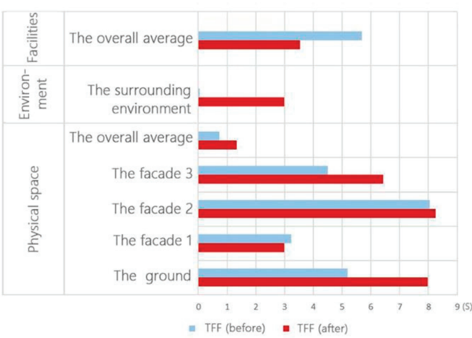
TFD



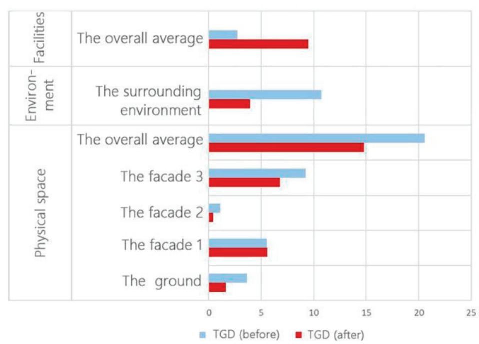
AFD



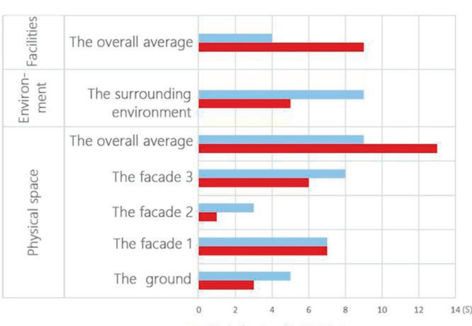
TFF



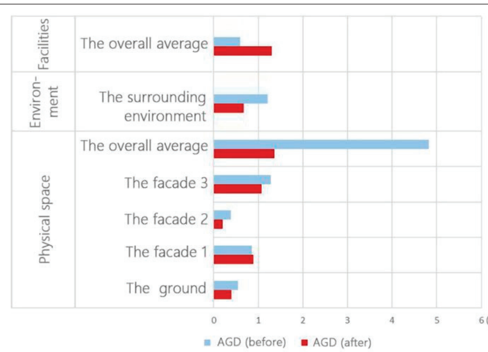
TGD



GC



AGD



As for the averaging index, the AFD in the facility increased after optimization. It proved that the addition of the seats required for the ILS helped to complete the space.

For the observation sequence, after the optimization, the TFF for the surrounding environment increased. This proved the decrease in the influence of the surrounding environment on users' attention after the optimal design.

(2) Visual search (TGD, GC, and AGD)

In terms of summation index, after optimization, the TGD and the GC of facilities were more than those before optimization, and the difference among the three spatial factors was reduced. This proved that the integrated design of greenery and seating improved the visibility of facilities and attracts users to stay.

In terms of the averaging index, the difference between the AGD of the physical space, environment, and facilities was reduced after optimization. This proved that the spatial elements work well and created a harmonious and natural atmosphere. A comparison of eye-tracking data of the third-floor terrace before and after optimization is shown in Table 3.

4. Conclusions

The ILS in universities is receiving more and more attention as China's higher education enters a new stage with the development model characterized by stock optimization. Based on Weber's four-quadrant theory and field investigation, this paper proposes a revised theoretical research of campus ILS classifications and spatial elements more applicable to the study of architectural spaces. Then, two case studies were made to explore optimal design methods from the three spatial elements of physical space, facilities, and environment. Visual perception experiments using visual perception technologies were made to verify the effect of optimal design by studying the relationship between users' visual perception and spatial elements for further improvements to optimal design methods. This paper draws the following conclusions:

(1) For the optimization of ILS in universities, it is worth paying attention to the physical space, such as size, enclosure, richness, transparency, and other elements of the space. For example, the facade can be homogenized to lower the impact of visual interference of facade information to users. Removing the unrelating elements on facades can reduce the excessive visual attention of users. Hence, if the facade applies the materials with complicated context, it should be placed in a larger space to make the space more identified. Besides, adjusting the colors and materials on the facade is suitable to establish an active and vivid space. It is also helpful to optimize facilities' number, location, and accessibility. Besides, facilities can be combined with landscape elements to create a natural atmosphere.

(2) Visual perception experiments and quantitative analysis demonstrate that the quality of ILS after optimization is much improved. Comparisons of both visual observation factors (TFD, AFD, and TFF) and visual search factors (TGD, GC, and AGD) in the two case studies show that optimized space (exterior space with natural landscape) and facilities were more attractive.

Due to resource and time constraints, there are some points in this paper that need to be improved:

(1) It is also necessary to increase the sample size of subjects and to study two other types of spaces, namely the spaces of Private/Alone (Individual learning), and Private/Shared (Group learning), to further refine the experimental design and overall study content.

(2) The verifying process can be supplemented with questionnaires and other methods to better understand users' feelings.

(3) The perceptual data in this study, especially for human visual perception, need more technical means and more types of human perceptual data, such as EEG, to obtain more comprehensive and integrated analysis results.

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