



## Review Article

# The impact of digital design on Façade performance: A literature review

Ayça AKKAN ÇAVDAR<sup>1,2,\*</sup> , Nilhan VURAL<sup>3</sup> 

<sup>1</sup>Graduate School of Natural and Applied Science, Karadeniz Technical University, Trabzon, 61080, Türkiye

<sup>2</sup>Department of Architecture, Recep Tayyip Erdogan University, Rize, 53100, Türkiye

<sup>3</sup>Department of Architecture, Karadeniz Technical University, Trabzon, 61080, Türkiye

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## ABSTRACT

Advances in technology and interdisciplinary collaborations have increased design efficiency through new materials and construction systems, and have supported innovations in the field of architecture. However, despite these developments, performance evaluation before construction remains crucial. Therefore, digital design methods and performance analysis software have become fundamental tools in the optimization process. This study examines the role of digital design in improving facade performance within the context of sustainable architecture. In this context, 96 studies obtained from the Web of Science (WoS) database were examined. Trends in the research were evaluated using bibliometric methods and content analysis applied via VOSviewer. The findings show that the majority of studies focus on daylight, energy efficiency, and solar radiation. In contrast, topics such as ventilation, indoor air quality, and acoustics were addressed to a more limited extent. In recent years, digital twin applications and artificial intelligence-supported facade optimization have gained more prominence. Simulation methods are dominant in the studies examined (65.6%). The most commonly used tools are Rhinoceros and Grasshopper. Only 58.3% of the studies received financial support. China stands out in terms of both the number of articles and the number of supported studies. This study presents a systematic classification for facade performance criteria and digital tools. It also draws attention to research gaps, particularly in the areas of ventilation and cooling performance. By highlighting these insufficiently addressed areas, the research differs from previous studies and offers a roadmap for future research towards developing digital facade design with a more comprehensive and multidisciplinary approach.

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## INTRODUCTION

From the twentieth to the twenty-first century, technological advancements and the emergence of new digital

tools have led to transformative changes in the field of architecture. Increased processing power and speed of personal computers, along with lower costs for tools such as building information modeling software, engineering analysis

### \*Corresponding author.

\*E-mail address: [ayca.akkan@erdogan.edu.tr](mailto:ayca.akkan@erdogan.edu.tr)

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systems, laser cutters, and CNC routers, have expanded the scope of influence for architects in this field [1]. Digital-based design technologies have significantly accelerated the adoption of unconventional architectural forms and production methods, including large-scale 3D printing [2]. This enables architects to play with complicated forms, while at the same time enhancing production and material efficiency. The precision of complicated designs increases aesthetic quality and construction efficiency [3].

Digital improvements also enable the development of responsive architecture, which transcends form with adaptive components that can respond to stimuli, internal and external. The combination of artificial intelligence and miniaturization enables buildings to respond more intelligently to the actions of the users and changes in the environment. This results in better sustainability and user experience [4]. Furthermore, the coupling of computational design with digital fabrication presents opportunities for more sustainable structures by reducing waste and optimizing resource use [5]. Buildings can be more energy efficient and more comfortable for the occupants using AI-driven adaptation in the design. This might be considered as a huge step towards smart architectural solutions.

Architects are increasingly using parametric design – where models are built on pre-existing relationships and rules – to make their designs more flexible. The parametric model, although useful for buildings, can be complicated and deterministic and thus makes the design process more difficult. Hence, architects frequently employ formal approaches of parametric design to build solutions [6]. To address these difficulties, the importance of promoting cooperation across disciplines. Regular communication and collaborative workshops between architects and engineers can contribute to a more amicable partnership between these players. This can result in a more holistic design process [7]. In addition, teaching both architects and engineers on parametric design tools helps improve communication. As stated by Huang et al. [8], transdisciplinary mutual learning can promote a collaborative atmosphere for teams to address the issues posed by parametric design collectively.

Facades are a prime example of how environmental parameters can be integrated into design through computational design. In this respect, facades play a significant role in increasing sustainability and efficiency. Facade panels significantly shape the appearance of a building by integrating structural, environmental, functional, and aesthetic elements [9]. These complex facade panels not only define the aesthetic character of the building but also benefit from technological advancements. Chang et al. [10] noted that the development of information technology enables the development of smart building envelopes which can actively control the thermal performance and energy consumption. According to Yaman [11], different facade systems can be very successful in controlling the internal

climate according to the outdoor weather conditions. This characteristic is significant for the comfort of buildings.

Gero and Sosa [12] say that computational tools enhance the capability of designers to solve complicated architectural challenges. Parametric processes let you quickly change a model based on pre-defined rules without the need to construct a new model for each iteration. In this way it improves efficiency in the design process [13].

Building envelopes not only play an aesthetic and structural role but also act as an environmental barrier to control heat, light and air. so they provide protection and help with energy efficiency. The building envelopes are at the origin of a basic interface which influences about 80% of the environmental performance of a building and contribute to the construction of buildings that may interact in an integrated manner with their environment [14]. They also incorporate passive tactics in the design, such as natural ventilation and the use of daylight, to enhance energy efficiency and indoor comfort. Well built facades can optimize solar gains, decreasing dependence on artificial systems [15–17]. Building orientation and massing are also crucial considerations that can help maximize these gains. This helps to a more sustainable and efficient design approach [18].

In this context, it is important to note that different performance criteria are considered in facades designed with digital design approaches. This review article aims to guide researchers by comprehensively examining and analyzing academic studies obtained from the Web of Science database that address facade performance through digital design. The goal of the study is to offer valuable insights into the existing literature in this field and to synthesize information. The originality of the study lies in the careful filtering and analysis of bibliometric data by the authors, resulting in the creation of detailed classification headings in this context.

### Digital Design in Architecture and Façade

The emergence of computer-aided design tools has created a significant transformation in the integrated circuit industry. Designers who were familiar with certain design methodologies have to extend their knowledge now to the whole design sector from product specs to the manufacturing process [19]. Designs do not have to adapt necessarily to new technologies but rather technology has to adapt to the necessities of design production. It is not as passive a role as frequently imagined for designers in the digital design process. They can express their intuitive thoughts more effectively in a rational and computational environment [20].

Digital design methods can be used in the design of structures that are difficult to design or construct with traditional design methods. Furthermore, while traditional design limits designers to two-dimensional forms, digital design allows for four-dimensional modeling. In this context, the fourth dimension represents the time-dependent performance of the design [21].

Due to advancements in digital manufacturing technologies, industrial robots are increasingly used in architecture. Changes in material approaches accompanying these developments also significantly impact architectural applications. Industrial robots are particularly noteworthy in projects that prioritize aesthetic and structural composition, such as pavilion structures [22]. Following the shift from stationary robot manipulators to mobile alternatives, the use of aerial robotic manipulators, commonly known as drones, has become increasingly visible. Renowned robotics expert Raffaello D'Andrea, in collaboration with the Swiss architectural firm Gramazio Kohler Architects, spearheaded the construction of a tower from polystyrene brick blocks [23]. CNC machines, on the other hand, have the capacity to produce a wide variety of textures on flat surfaces. The specific geometric properties of these textures are determined by the designer.

Graiz and Van de Rie [24] investigated the effect of different textured surfaces on solar control in facade panels. Their work showed that textures created with spherical end milling tools could provide a remarkable 32% reduction in solar radiation compared to traditional flat surfaces. Various software options are available that offer tools for applying parametric techniques. Computer-aided design software can be divided into two types according to their role in the design process: software that assists in the visualization and implementation of the design, and software that supports the designer throughout the entire design phase [25].

Façades, considered as complex building components, bring together structural, environmental, functional, and aesthetic parameters in a holistic manner. This holistic approach is important because the façade significantly shapes the overall image of the building [26]. The increasing energy footprint of commercial buildings, especially office buildings, has led to a shift from approaches focusing solely on non-Euclidean geometries to performance-oriented approaches. This change is also seen in the transformation of Building Information Modeling (BIM) models, initially parametric, into adaptive models that take performance and other analytical data into account [27].

Given that digital design primarily focuses on formal parameters, the façade is the first focal point in capturing people's visual perception of a building's design. Beyond their visual importance, façades also function as a shield protecting the building from external environmental conditions. Therefore, the selection of façade materials and designs is of great importance because these choices naturally affect performance characteristics.

Insulation has a great impact on energy performance. In a research performed in a residential building in Konya, the insulation application raised the energy class from level E, i.e. undesirable level, to level C, i.e. acceptable level. This data suggests that the design of the façade directly impacts the energy efficiency. Digital design methodologies can lead to greater optimization of façade layouts, improvement of

insulation performance and contribution to sustainability [28]. Besides, buildings need to be renovated or strengthened in view of wear and tear over a period of time or damage from natural disasters. Such interventions. The key issues in terms of user's health, efficiency and overall comfort are to ensure interior comfort with minimum energy consumption and exterior noise [29].

In this context, Digital Twin technology can advance this optimization process by providing a virtual representation of physical structures. Digital Twin helps optimize designs and resource management by simulating the physical world in a virtual environment; it supports the modernization of industrial structures and the digitalization of the construction sector [30]. In architecture, Digital Twin technology is widely used in design and renovation projects. It plays an important role in improving project implementation during the construction process. For example, Digital Twin is used in examining the structural integrity of historical masonry structures and enables improvement studies. It also contributes to the production of prefabricated concrete elements, supporting the development of modular construction and innovative solutions [31]. Digital Twin is also used in architecture for façade segmentation, preservation of cultural heritage, and increasing the energy efficiency of old buildings. It collects data through sensors and analyzes this data to offer solutions for better building performance. In addition, it helps predict safety risks and detect structural damage in prefabricated structures. Digital Twin technology is expected to play an important role in energy-efficient design, durability and prefabrication processes [32].

### Façade Performance and Digital Design Relationship

The selection of façade systems is of critical importance in the architectural design process due to its impact on environmental comfort and spatial use. Façades, which must protect the building from external environmental conditions while also exhibiting specific performance characteristics, have increasingly become standardized through consistent design practices. Unlike traditional façade designs, performance-based façade systems can be dynamic in nature and can provide solutions to design problems through computational design [33]. In addition, parametric design calculations can be used to perform kinetic movement analyses during the pre-construction design phase; thus, it is possible to propose configurations that optimize daylight performance [34].

Elements designed to provide daylight control, such as façade-integrated shading systems, play an important role in ensuring indoor comfort [35]. It is of great importance that these elements, which interact with external weather conditions, are wind-resistant and flexible. Using computational design methods, Baehr-Bruyère et al. [36] highlighted the usability of glass fiber-reinforced polymer (GFRP) materials as exterior shading elements due to their

resistance to rain and UV radiation and their ability to diffuse daylight into the interior (Fig. 1).

Velasco et al. [37], designed a dynamic façade with two free rotational directions, unit slabs on daylight performance. The façade was built by a computational design process utilizing the applications Grasshopper and Rhinoceros. The simulation analysis using simulation tools such as Honeybee, LadyBug and Radiance shows that this facade design distributes light more uniformly than conventional facade systems. The researchers claim that the logic of group-based behavior (Fig. 2) can improve the experimental investigation of a single panel.

Karagianni et al. [35] used parametric modeling in the sun shading system they designed as part of their master’s thesis. The daylight performance of the system was

simulated using different geometric configurations. The study also emphasized the significance of the relationship between the stages of parametric design, manufacturing, and performance control.

Freitas et al. [38] examined the use of Building Integrated Photovoltaic (BIPV) Systems to retrofit buildings in seven office buildings using Rhinoceros CAD software. Furthermore, the system’s suitability was assessed by running performance analyses with the Grasshopper and Ladybug plug-ins. Among the Building Information Modeling (BIM) systems, software that allows architects and architecture students to integrate different systems such as solar energy generating systems into the design is beneficial (Fig. 3).

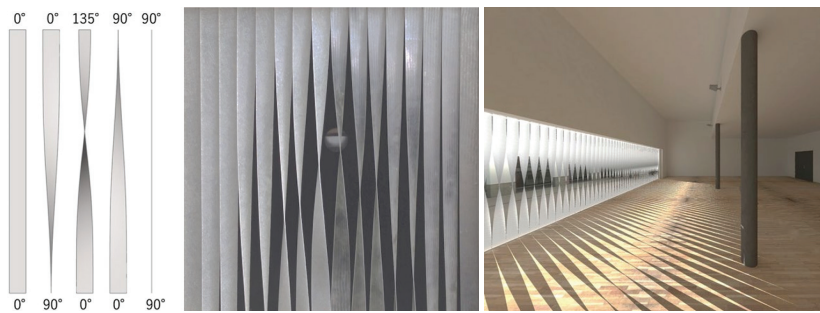


Figure 1. GFRP kinetic shading system and simulation [36] [recreated by Cavdar and Vural].

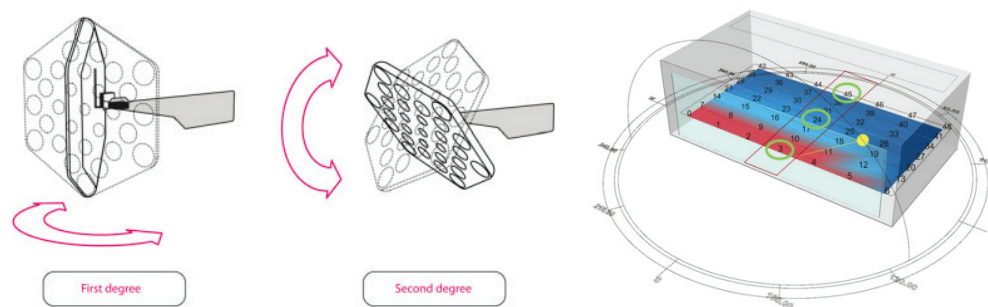


Figure 2. Unit plates designed with two degrees of rotational freedom and simulation model [37] [recreated by Cavdar and Vural].

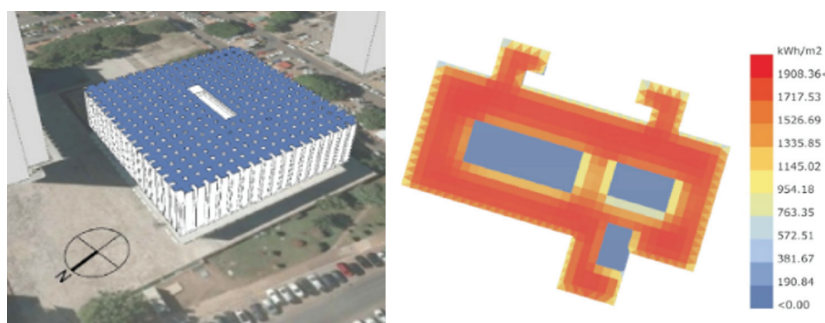


Figure 3. A model created using Rhinoceros CAD, and a sample radiation diagram from the roof [38] [recreated by Cavdar and Vural].

Sravani et al. [39] conducted a BIM-based LCA analysis on a reinforced concrete traditional residential building in India's hot-humid climate zone and discovered that the roof slab consumes more energy than the façade. Furthermore, the wall surfaces made of clay tiles, cool tiles, terrazzo tiles, and aerated concrete blocks added to the roof to provide insulation reduced carbon dioxide emissions by approximately 2-6%.

Koukelli et al. [40] reduced reflected solar radiation by 40% using a façade design with optimized faceted geometry and diagonal arrangement; it was discovered that the radiation has the potential to reduce the microclimate, particularly in areas close to the façade surface. With the proposed façade design, the cooling load could be reduced by 21%.

Marques and Eloy [41], used a shape grammar to create a pattern inspired by the microscopic structure of the fungus. The pattern was reinterpreted in this direction, and a two-layer system was created as a façade carrier and infill section. It is emphasized that this modular system can realize various designs and achieve various harmonies.

Biomimetic façades are inspired by organisms that are well adapted to Earth's conditions and are thus thought to be effective in terms of improving performance. Mathematical modeling and digital simulation methods were used in a study to test the potential of a biomimetic façade to reduce energy demand. The tests on buildings with different climatic zones and functions (school, office, and elderly care home) revealed that the elderly care homes had the greatest difference in terms of energy consumption, with a 67.1% reduction in energy consumption. The tropical climate had the greatest energy reduction (55.4%) among tropical, humid continental, temperate oceanic, and hot desert climates [42].

A texture module with natural ventilation through a single thermal zone (classroom) was designed and applied to the window of an existing building via computer in a study to develop biomimetic adaptive building skins (Bio-ABS). The 188 modules that make up the window system have varying aperture and transparency ratios. Bio-ABS provided thermal comfort with a 23.18% reduction in discomfort hours and a 5.09% reduction in adaptive thermal comfort as a result of thermal analysis using Energy Plus software [43].

Numerous researchers employ digital design for enhancing façade aesthetics and form-finding [41,44,45]; while some focus on leveraging daylighting and associated energy performance to generate façade forms [27,46,47]. Less frequently, studies delve into ventilation efficiency [33,48–50], and acoustic behavior [51,52]. In recent times, the integration of building façades with emerging technologies like artificial intelligence, machine learning, digital twin, and IoT has become notably pronounced [53–55].

### Bibliometric Analysis

Bibliometric methods primarily have a quantitative nature, yet their main objective is to draw conclusions about qualitative aspects. Their fundamental purpose is to

convert intangible qualities, such as scientific quality, into measurable entities. Consequently, bibliometrics provides us with a scalable tool that can be applied at various levels to the global scale [56]. One of their aims is to understand the overall research trends in a specific field by examining academic publications from databases such as Scopus or WoS [57]. In addition, bibliometrics provides researchers with the freedom to select the relevant variables and quantitative methodologies that best align with their study objectives [58]. The most common bibliometric parameters are the number of publications and number of citations [59]. Kuzminska et al. [60] concluded through surveys and interviews that bibliometric analysis is useful for early career researchers and that bibliometric analysis is not limited to a specific field.

Özdemir and Arslan Selçuk [61] identified 461 articles published in different journals over the last 10 years in the Web of Science database. It was determined that these studies mainly focused on six keywords, particularly the concepts of “machine learning” and “geometric pattern”. Notably, the field of architecture received the highest number of citations, with 365 citations. The study reveals that artificial intelligence technology can be further developed in the field of architecture. It is expected that integrating this technology with the discipline of architecture will yield significant and promising results.

In a separate bibliometric study, the Web of Science database was used to analyze scientific research on digital design in the field of architecture. The analysis results revealed that digital design has shown continuous development in architecture over the years; this highlights the potential of the topic for future research and its integration with other disciplines [62]. Eltaweel and Su [63] conducted a literature review focusing on the application of parametric design in architecture, particularly in daylight and solar radiation applications. The aim of the study was to demonstrate how this approach can significantly improve access to natural light and contribute to energy efficiency.

When bibliometric analysis studies are examined, VOSviewer-based mapping techniques are widely used. These studies generally address scientific research through broader categories such as year, university, institution, author, journal, citation count, and keywords. However, a comprehensive review of these studies is lacking in the existing literature; important details such as the subject matter and the software used are often omitted.

This study stands out not only for its examination of articles obtained through the mapping method but also for its comprehensive analysis conducted within the scope of author-defined classifications. The results of the study are expected to provide valuable contributions to researchers working in this field.

### Background of The Study

With the development of computer technologies and the integration of computational methods into architecture,

it has become possible to realize complex designs that go beyond the possibilities of traditional methods. Façades, being the exposed surfaces of the structures, are one of the key construction elements that could leverage such a computational design method. The performance of façades designed using computational methods is of great importance due to their role in protecting buildings from external influences.

The main objective of this study is to obtain findings from research that primarily focuses on façades designed using computational methods and emphasizes façade performance. By analyzing these findings, the study aims to identify performance criteria that have been relatively underemphasized in computational façade design studies, despite the widespread use of these methods today. Thus, it provides a guiding and inspiring framework for researchers who wish to work in this field. This study offers unique value by examining scientific articles within this context and providing guidance for both researchers and designers.

The hypotheses formulated in alignment with the study's objectives are as follows:

- Digital design is frequently encountered not only for visual façade design but also in studies aimed at improving façade performance.
- Many different performance criteria can be taken as basis for façades designed with digital design method.
- The utilization of digital design techniques in studies pertaining to façade performance has exhibited a consistent rise over the years.

## MATERIALS AND METHODS

Ensuring optimum building comfort conditions largely depends on the performance of façades. In this context, numerous studies proposing innovative technological solutions utilize digital design approaches. This study examines digital design approaches in relation to façade performance; it aims to identify common performance criteria highlighted in the literature and to analyze current research trends in this field. To this end, selected academic studies within a defined scope were analyzed using VOSviewer and AntConc software.

## The Process of Searching

Keyword search has the great advantage of being easy to use because users don't have to learn a sophisticated query language. The user pleasant keyword search provides the user the ability to simply perform queries, hence increasing the overall user experience and allowing the user to quickly access data [64]. Web of Science (WoS) is the first comprehensive international bibliographic database that has become one of the most successful bibliographic data sources typically used for journal selection, research appraisal, and bibliometric analysis [65]. In this study, a search was conducted in the WoS database using the keywords "digital design" and "façade performance", and a total of 96 relevant scientific studies were identified as of May 2023. The main objective was to draw conclusions regarding which performance characteristics these façade studies aim to improve through digital design methods. The obtained academic studies were organized according to their citation counts in the Web of Science database and presented in tables for further analysis.

## The Process of Analysis

The obtained studies were initially analyzed using the VOSviewer software, which stands out as one of the most favored tools for bibliometric analysis due to its capability to import data from diverse sources and offer effective visualization [66]. Thus, firstly, the countries where the studies were conducted, authors, keywords, and their inter-relationships, both with each other and with citations, were analyzed.

As part of the study, a closer examination was conducted on the top 10 most cited studies to ascertain the predominant research topic. After scrutinizing all 96 articles, classifications were established for performance types, study issues, and software/tools used, and corresponding markings were applied in the tables. The AntConc software was employed to analyze all the information gathered in the tables and facilitate the counting process. AntConc is a corpus analysis toolkit designed for specific use in the classroom. It includes various features that aid in the analysis of linguistic data [67] (Fig. 4).

The collected studies were subjected to bibliometric tabulation and were further analyzed through content

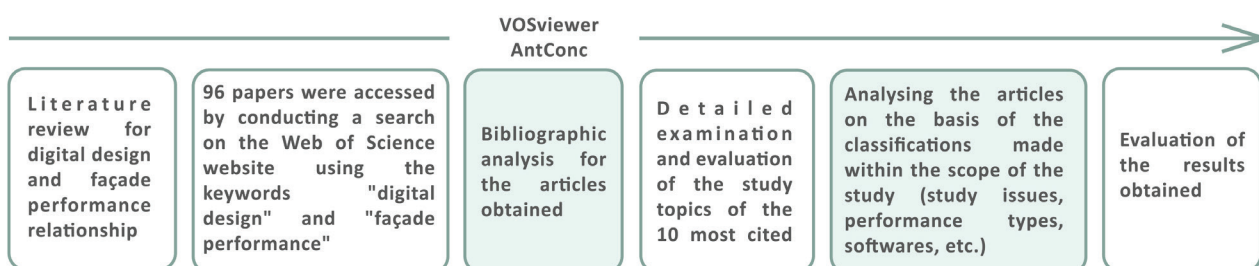


Figure 4. Flow chart of the study.

**Table 1.** Classifications created in the light of the data obtained by the authors within the scope of the study

	Type of Study Issues	Type of the Performance	Used Software or Tools
1	Adaptive façade	Daylight	Rhinoceros
2	Materials	Energy	Grasshopper
3	Façade	Solar radiation	EnergyPlus
4	Biomimicry	Digital tools	Revit
5	City scale	Geometric quality	Ladybug
6	Windows	Thermal	Radiance
7	Digital twin	Mechanic	Honeybee
8	Prefabricated façades	Sustainability	Diva
9	Sustainable (Green)	Lighting	DAYSIM
10	Lifecycle	Acoustic	Python
11	Pixels	Air quality	ANSYS
12	Building automation	Air temperature	Ecotect
13	Joint system	Humidity	MATLAB
14	Knowledge based engineering	CO2	Abaqus
15	Multi agent systems	Biological growth resistant	Arduino
16	Presentation	Chemical resistance	Autocad
17	PV	Construction	3DSmax
18	Shading systems	Cooling	Galapagos
19	Active noise control		Cyber
20	Active solar system		Façade
21	Automated blinds and dimmable lighting system		Geo-visualization
22	BIM		Kinetic
23	Box counting		Technical implementation
24	Bridge		Visualization

examination within specific classifications. Table 1 displays all subheadings falling within the scope of the classifications created for these analyses.

## RESULTS AND DISCUSSION

In this study, 60.4% (n:58) of the 96 studies obtained are articles and 39.6% (n:38) are proceeding papers, which examines numerical design through academic studies on façade performance.

Based on the classification of methods employed in the articles under study, it is observed that 15.6% (n:15) of the studies utilized reviews, 47.9% (n:46) employed in situ/experimentation, and 65.6% (n:63) relied on simulation methods. Notably, in 32.3% (n:31) of the studies, a combination of experimental and simulation methods was utilized. Importantly, it's noteworthy that numerical design methods commonly utilized in studies concerning façade performance are primarily simulation-based.

The top five most used words in titles and abstracts of academic studies are 'façade' (n:47/n:276), 'building' (n:38/n:231), 'design' (n:29/n:247), 'system' (n:23/n:134), and 'performance' (n:16/n:127). In particular, terms in the

names such as 'energy' (n:9), 'solar/sun' (n:9) and 'daylight' (n:8) are often used as performance indicators. Moreover, a performance keyword analysis in the abstracts of the summaries showed a predominance of the words 'energy' (n:124), 'solar' (n:43) and 'lighting' (n:36). This comment points out the importance of façades planned according to the sun and the favor of energy-performance studies done with similar considerations.

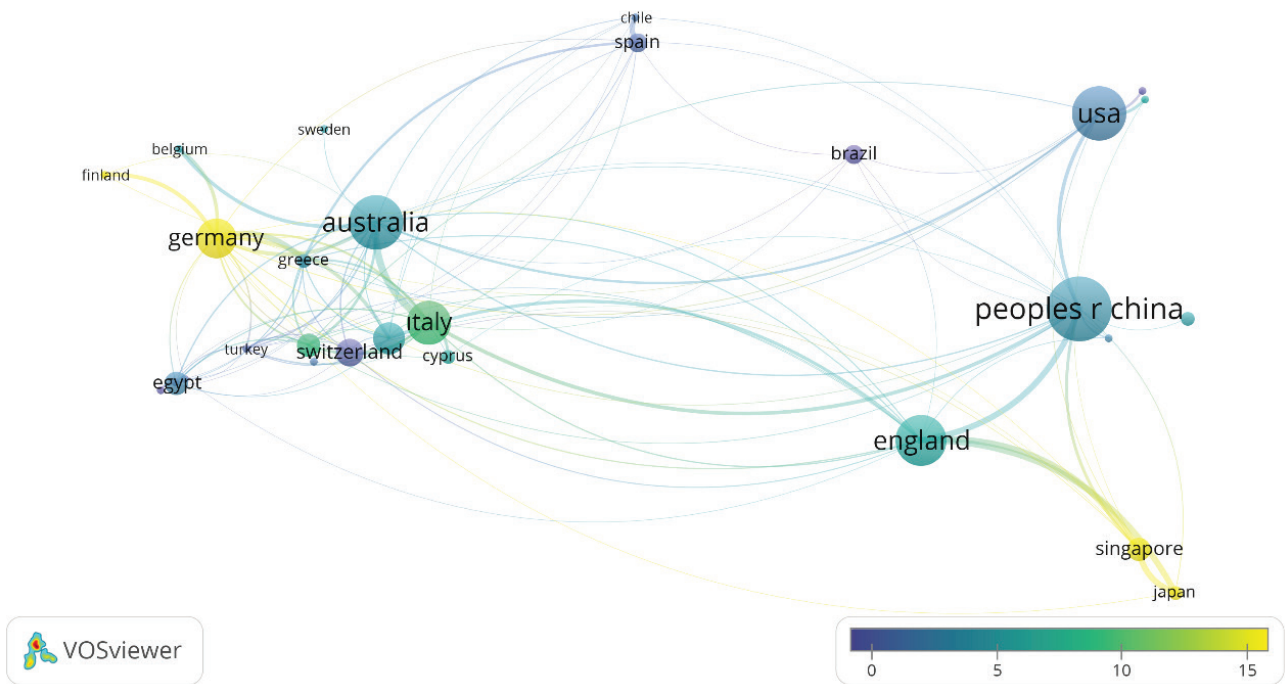
Analysis of the study areas classified in the WoS database reveals that the top five research area categories are as follows: "engineering" with 39.6% (n=38), "construction technology" with 35.4% (n=34), "architecture" with 20.8% (n=20), "science and technology other topics" with 20.8% (n=20), and "computer science" with 18.8% (n=18).

Only 58.3% (n=56) of the studies received financial support. The National Natural Science Foundation of China (NSFC) ranked first, funding approximately 8% (n=7) of the research. In terms of the number of studies, the People's Republic of China ranked first with 15.6% (n = 15). China was followed by Australia (n = 12), the United States (n=12), the United Kingdom (n=11), Italy (n=9), and Germany (n=8).

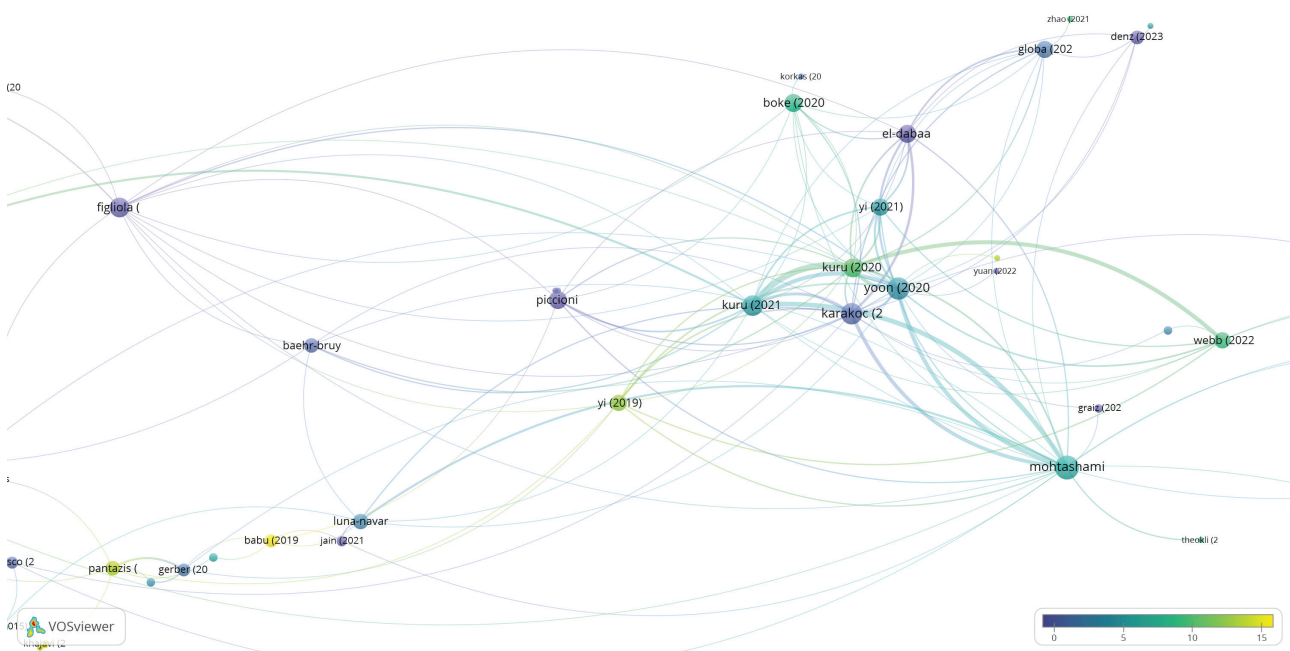
China appears to lead in both the number of studies and the level of financial support received. However, it is noteworthy that Australia, the USA, and Italy are among the top five countries in terms of the number of studies despite receiving relatively less financial support. In contrast, it is

unexpected that China, which has the highest number of articles, ranks fifth with 59 citations (Fig. 5).

Figure 6 illustrates a robust interconnectedness among five articles [43,68–71]. These studies primarily delve into thermal performance, energy efficiency, and sustainability. The subjects of the studies encompass biomimicry, adaptive



**Figure 5.** The relationship between the number of articles of countries and citation rate (circle sizes: document; color chart: citations).



**Figure 6.** Map of document links by citations (circle sizes: linked documents; color chart: citations).

façades, and materials. Notably, it is observed that these closely connected studies have been predominantly conducted in recent years.

The acquired documents were thoroughly examined within the framework of the classification of ‘study issues’ and ‘performance types’ established by the researchers.

Subsequently, content analysis was used to identify gaps in the literature and present them.

#### Analysis: Most Cited Articles

Out of the 96 studies, this article focused on analyzing the 11 most cited ones based on their citations. Table 2

**Table 2.** Most cited articles and citations [72] [created by author]

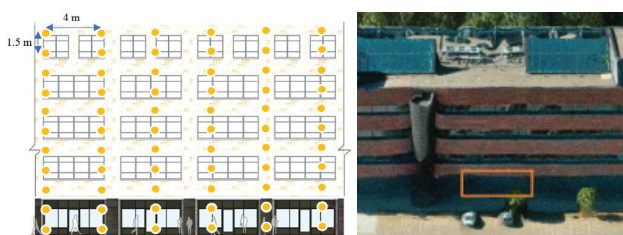
	Source	Year	Citation	Journal	Conference	Review	Experi. In-situ	Simula.	Software	Study Issue	Performance type
1	[1]	2019	129	●		-	●	-	Python Minitab Excel	Digital twin BIM	Daylight Air Temperature Humidity
2	[2]	2021	32	●		●	-	-	-	Active Noise Control	Acoustic (Noise)
3	[3]	2008	30	●		-	●	-	-	Shading systems	Daylight
4	[4]	2019	18	●		-	●	●	Radiance Ecotect EnergyPlus Evalglare	Automated blinds and dimnable lighting system	Daylight, Lighting
5	[5]	2017	17		●	-	-	●	Rhinoceros Grasshopper Ladybug Honeybee Energy Plus Radiance DAYSIM	Innovative concrete shading device system	Energy Lighting
6	[6]	2021	14	●		-	-	●	Revit Python Rhinoceros Grasshopper Wallacei-X KUKA SimPro	The reach of the robot arm.	Construction
7	[7]	2021	14	●		-	●	●	Faro Scene 5.5 Revit Matlab	Prefabricated façades Digital twin	Geometric quality
8	[8]	2018	13	●		-	-	●	Rhinoceros MAS design tool	Multi-agent systems	Daylight, Energy
9	[9]	2017	13		●	-	●	-	-	DIY approach Building automation	Lighting Air quality Air temperature Humidity
10	[10]	2019	12	●		-	●	●	Rhinoceros Grasshopper Python GDI	Adaptive façade	Daylight Energy Geometric quality
11	[11]	2018	12	●		-	●	-	-	3D-printed façade	Air temperature

illustrates that among these 11 studies, five were conducted within the last 5 years.

Upon examining the study topics, it becomes evident that the concept of ‘digital twin’ takes the forefront, with a focus on performance features such as ‘daylight’, ‘air temperature’, ‘lighting’, and ‘energy’.

In the study by Khajavi et al. [55], which received the highest number of citations, with 129 citations, a digital twin application based on a sensor network was used to create a real-time digital model of a building. The authors investigated the technical constraints of this method using experimental approach. Without utilizing simulation program. The study emphasized that existing digital twin applications are insufficient for collecting real-time experimental data from buildings. The authors created a digital twin that included more than 25,000 sensor readings for a façade element. Data on light, temperature, and humidity parameters were collected and analyzed within the scope of the study. The aim of the study was to reduce maintenance costs, increase user comfort, and reduce overall management and operating expenses (Fig. 7).

Lam et al. [73], in their study, which received 32 citations, explained the concept of Active Noise Control (ANC) and provided answers to 10 questions regarding its applications in the built environment. The study adopted a review-based approach and used literature sources to highlight areas where the active reduction of environmental noise is possible. Importantly, the study was not experimental or simulation-based. The results indicated that there is a need for further research to enable ANC application in the built environment. Also the study found that there is an increasing interest in intelligent ANC applications due to



**Figure 7.** Sensors’ mesh on the building and chosen façade for digital twin data collection [55] [created by author].



**Figure 8.** A scale model and a real-life situation of a sample classroom [74] [recreated by Cavdar and Vural].

the complexity involved with the evolution of technology and AI techniques.

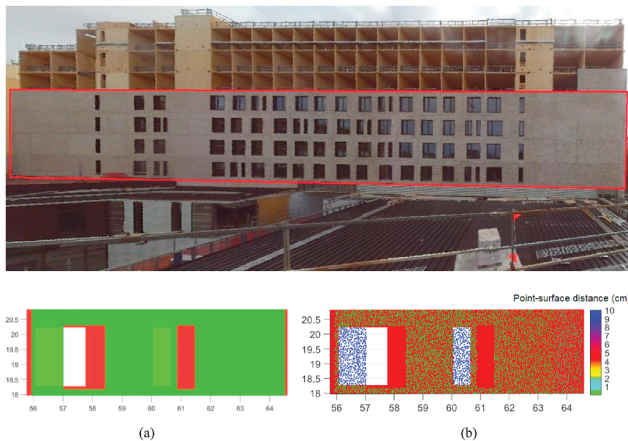
Aghemo et al. [74], in their study, which received 30 citations, developed nine different shading system combinations for the south façade of a sample high school classroom. The study used shading elements with different geometries and locations. The researchers then comparatively evaluated these combinations using measurements obtained from a 1:10 scale model. This method was proposed as an alternative to numerical simulation-based prediction tools; no simulation program was used in the study (Fig. 8).

Babu et al. [75] have 18 citations in their work on the application of automatic shutters and automatic dimming lighting systems in tropical environments. The researchers said that energy savings in lighting can be obtained by “carefully considering the façade orientation, system design and control algorithms using Radiance, Ecotect and EnergyPlus software”. Importantly, the study used experimental and modeling approaches.

Similarly, in their study (17 citations), Zani et al. [76] advocated for a balance between transparent, opaque and shaded surfaces in the façades of office buildings in modern architectural design. This balance is necessary to prevent problems such as warmth and too much daylight, and to control the perception of the outer environment. The research team conducted a simulation-based investigation utilizing Rhinoceros, Grasshopper and EnergyPlus software. Here, a computational design approach for a static shading system made of high performance concrete was described. Then the system was optimized by genetic algorithms with respect to numerous parameters.

Tran et al. [77] received 14 citations for their proposed optimization process. This process facilitates the automatic adjustment of the robotic arm’s accessibility during the assembly of façade unit elements in the construction industry. The aim of the study was to streamline the robot positioning process and increase construction efficiency. To this end, the researchers examined the limitations of modular robot assembly simulation processes. Achieving the optimal accessibility ratio is expected to reduce the robotic arm’s operating time, thereby increasing productivity and reducing risks.

Tran et al. [54], in their study which received 14 citations, presented a new framework for evaluating the geometric quality of prefabricated façades constructed during the construction process. The approach is based on the use of a 3D as-built semantic model and a 3D design model. Based on digital twin methodology, the study enables a quantitative comparison between a 3D as-built digital replica reconstructed from lidar point clouds and a 3D design model. This innovative approach is effective in visually evaluating the quality of prefabricated structures and provides valuable support during the construction process (Fig. 9).



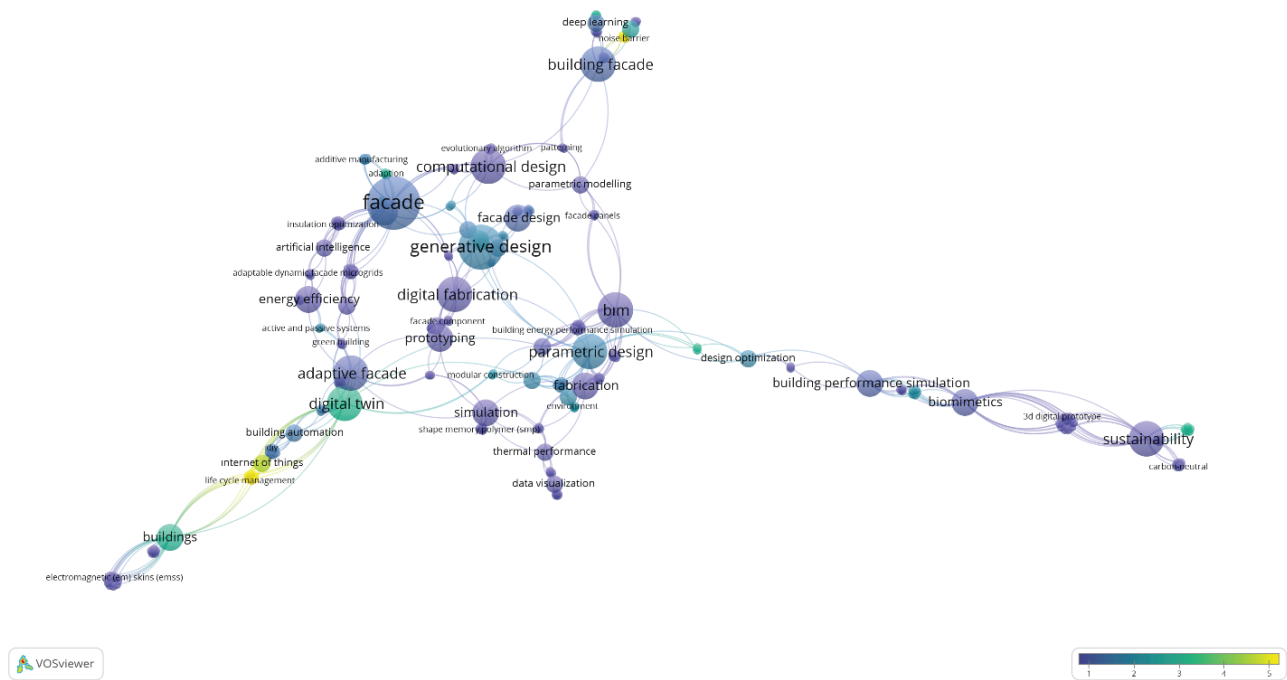
**Figure 9.** Overlay of the as-built and as-design panels and dense points colorized [54] [recreated by Cavdar and Vural].

In architecture, digital design paradigms are generally geometry-based, which can have a limited impact on buildings with complex features. Currently, computational design methods capable of predicting performance within the existing digital design process remain limited. Often, the necessary analyses are carried out after the design is completed. However, the new design approach developed by Pantazis and Gerber [27], which has received 13 citations, differs from this common practice. This method offers a design toolset for a multi-factor system that includes a comprehensive evaluation of different environmental

performance metrics. This toolset integrates three-dimensional modeling and analysis software.

In Salamone et al. [78] (13 citations) two devices were designed with a Do It Yourself (DIY) approach to control Indoor Environmental Quality (IEQ) and reduce energy usage. The study was based on the development of sensors using wireless communication systems with a low-cost commercial available transmission module and Infrared LED. Most of these sensors were embedded in the internal environment, however the air flow fan sensor was placed within the windows, specifically the façade. The chassis for these devices was made on a 3D printer, using PLA, which is made from renewable resources, as the printing medium. This DIY method allows people to design, build and sell things adapted to their own needs at a lower cost. In this case, the deployment of an automated control system may efficiently analyze the illumination, air quality, air temperature, and humidity.

Yi et al. [79] (12 citations) proposed a responsive building façade through the integration of on-site sensors, building performance simulation (BPS), machine learning, and 3D geometry modeling inside a unified design interface. For this purpose, they used an optimization method that is directly connected to wireless sensor data transmission using the Rhino Grasshopper interface. Therefore, the authors proposed a Tabu based Adaptive Pattern Search Simulated Annealing (T-APSSA) technique. This unique approach allowed for quick performance calculations and created a digital prototype of a responsive façade design.



**Figure 10.** The relationship between the use of keywords and the number of citations (circle sizes: document; color chart: citations).

The 3D printing method is well-suited to improve the thermal performance as it allows to manipulate the size and shape of the material cells to provide insulating materials with low thermal conductivity. Sarakinioti et al. [80] (12 citations) There is an opportunity to explore polymers with low thermal conductivity values where increase of both thermal and waterproofing performance is crucial. Besides, the authors point to the importance of studying the deformations and endurance of materials at extreme thermal conditions.

As seen in Figure 10, the terms ‘façade’ and ‘generative design’ appear as the most prominent ones across the publications. However, when examining the citation rate, the phrases “wireless sensor network” and its related terms, “solid modeling,” “life cycle management,” “real-time systems,” “building information modeling,” “three-dimensional displays,” and “object-oriented modeling,” emerge more prominently.

These 96 scientific studies show a chronological increase over the years. It can be seen that there is a significant tendency and the number of studies conducted between 2006 and 2011 is rather small. But the application of digital design technologies to improve facade performance has increased considerably since 2019. It is interesting to see that studies carried out in the period 2021–2022 account for 24% of all research, representing a considerable improvement of the connection between digital design and the architectural sector (Fig. 11).

**Analysis: Most Preferred Study Issues**

This study, which aims to investigate the role of digital design in articles related to façade performance, examined 96 articles in detail. The studies were comprehensively

evaluated according to their thematic categories. As a result, the most common themes were determined to be “adaptive façade” (21.43%), “materials” (14.88%), and “façade” (11.31%).

Articles on adaptive façade studies generally aim to establish clear performance criteria for façades and mostly encompass designs shaped by external environmental conditions. The adaptive façade category also includes studies focusing on kinetic and dynamic façades. In addition, a significant number of studies address façade materials and their performance characteristics.

Studies focusing on conventional façades, which do not adapt to external environmental conditions or include an innovative approach, form a separate category and rank third after the adaptive façade topic. There are also a notable number of studies dedicated to biomimicry, urban scale, and windows, as well as digital twin applications. These are followed by studies on prefabricated façades, sustainability, life cycle management, and pixel-based research (Fig. 12).

**Analysis: Most Preferred Performance Types**

Analysis of the studies reveals that research focusing on elements or materials in façade design, particularly daylight evaluation, is predominantly structured around performance types such as “daylight” (n=26), “energy” (n=20), and “solar radiation” (n=17) (Fig. 13). These are followed by “digital tools” (n=15), which examine digital environments; “geometric quality” (n=14), which is related to façade design aesthetics; “thermal” (n=13) and “mechanical” (n=11) performance analyses, which address environmental thermal comfort; and “sustainability” (n=7) performance analyses. It is noteworthy that performance categories such as “air quality” (n=4), “humidity” (n=3),

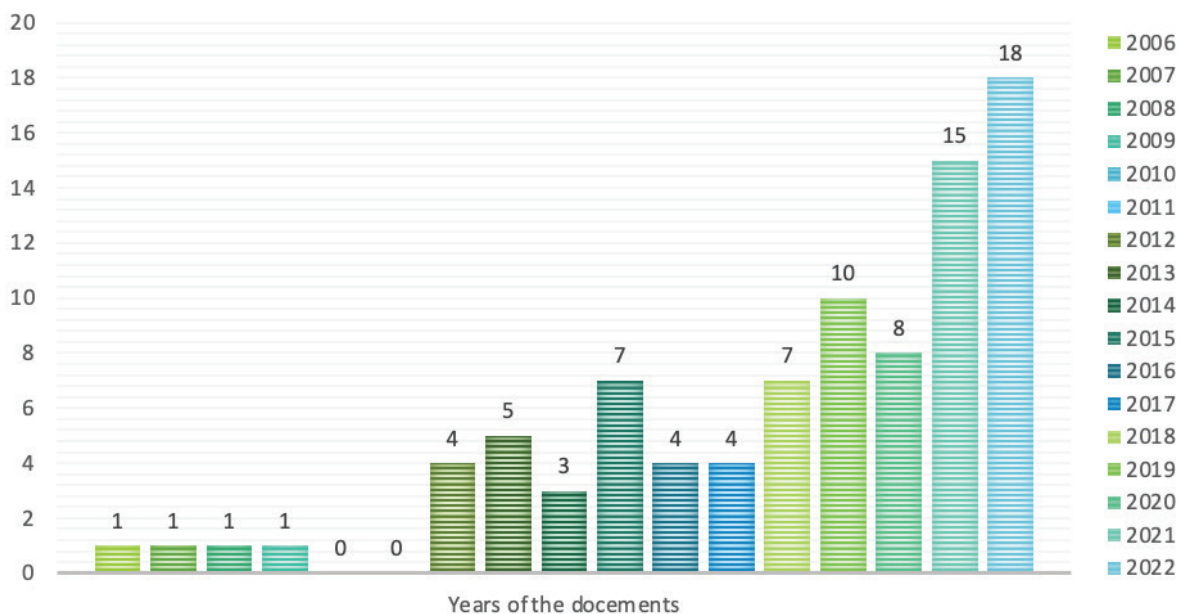


Figure 11. Number of documents by year.

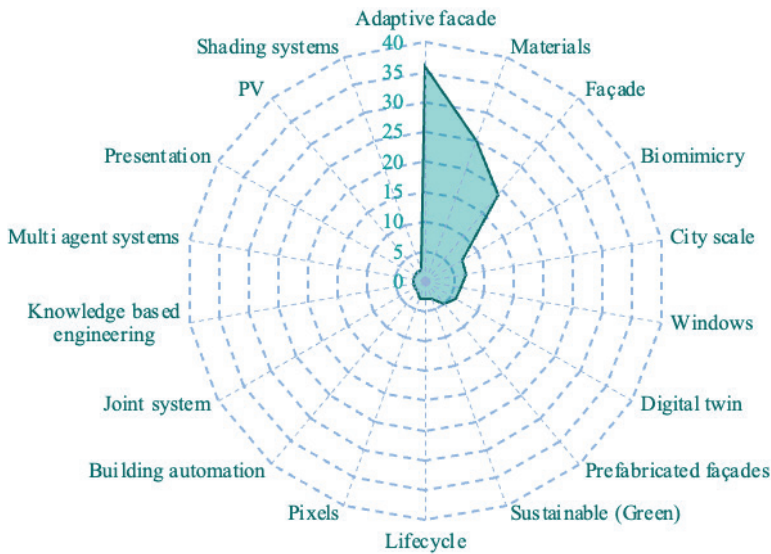


Figure 12. Chart of the study issues of the documents.

and “cooling” (n=1), which are frequently associated with ventilation, are less frequently addressed in the studies. Furthermore, research output on acoustic performance appears to be relatively limited.

Díaz-López et al. [81] conducted a review of scientific studies pertaining to passive cooling strategies. The findings revealed that among the cooling methods employed, natural ventilation, green roof systems, insulated windows, and solar shading emerge as the most commonly utilized. Conversely, studies investigating ventilated façades and evaporative cooling systems remain scarce. Notably, the

examination underscored the limited focus on aspects of acoustic comfort and adaptation to climate change—areas that are less emphasized compared to the frequently highlighted subject of thermal comfort and its connection to sustainability.

**Analysis: Most Preferred Software-Tool Types**

Rogers & Schnabel [82] examined the use of nine prominent instruments used for the digital design process in both education and professional practices in line with expert opinions. Six of the applications, including Rhinoceros and

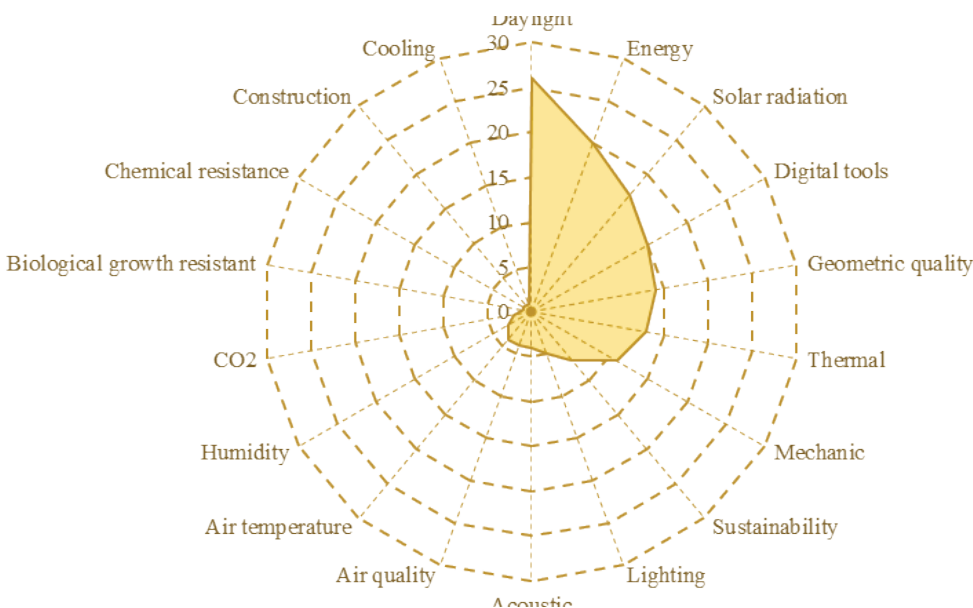


Figure 13. Chart of the performance types used of the documents.

Grasshopper, were found to be more suitable for use in both education and professional practices. In this direction, it is emphasized that new architects' preference of these tools in their design processes will improve creativity.

When it comes to studies on digital design and façade performance, it can be said that the methods to be used will generally focus on simulation programs, softwares and tools. In this direction, 30.2% of the 96 studies examined preferred Rhinoceros, while 28.1% also used the 'Grasshopper' plug-in. It is followed by 'Energy Plus' with 11.5%, 'Revit' with 11.5% and 'LadyBug' with 10.4%. Grasshopper plugins 'Radiance', 'HoneyBee' and 'DIVA' were preferred by 8.3%, 7.3% and 7.3% respectively (Fig. 14).

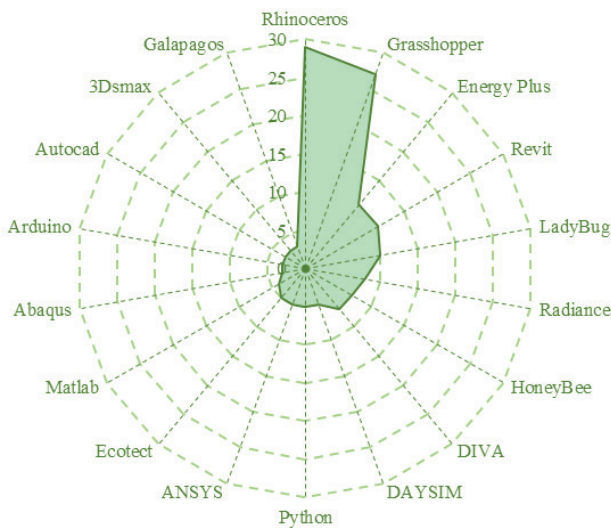


Figure 14. Chart of the softwares/tools used of the documents.

Upon examining the software employed, it becomes apparent that the tools designed to analyze energy, daylight, and solar radiance performance take a prominent role. This correlation aligns directly with the favored performance types in the studies. The realms of adaptive façades, materials, and façade topics exhibit a significant synergy with Rhinoceros, Grasshopper, and EnergyPlus software, particularly in the domains of daylighting, energy efficiency, solar radiation analysis, digital tools employment, geometric quality, and thermal performance optimization. (Fig. 15).

Within the scope of this study, conclusions were drawn based on four evaluation categories: most cited articles, most frequently addressed research topics, performance types, and software/tool types.

- Researchers examining façade performance in the field of digital design generally rely on simulation software. Experimental studies are mostly conducted in research focusing on mechanical [50, 83–86], daylight [27, 33, 34, 46, 47, 75, 79, 87–89], and thermal performance [43, 69, 81, 90–95], and digital tools are also used in these studies. It is noteworthy that articles specifically addressing cooling and ventilation performance are not only limited in number but also largely confined to simulation-based approaches.
- The number of research that are focused on diverse climates is limited; studies focused on specific climates are mostly focused on hot climate types. Most of these research are concerned with façade elements that are intended to lessen solar effects and to function as shading devices. In addition to daylight and temperature, which exert great influence on the indoor comfort, it is important to consider the humidness. This is particularly relevant in humid areas, where natural ventilation techniques can greatly influence both building performance and human health. Up to now, there is still little

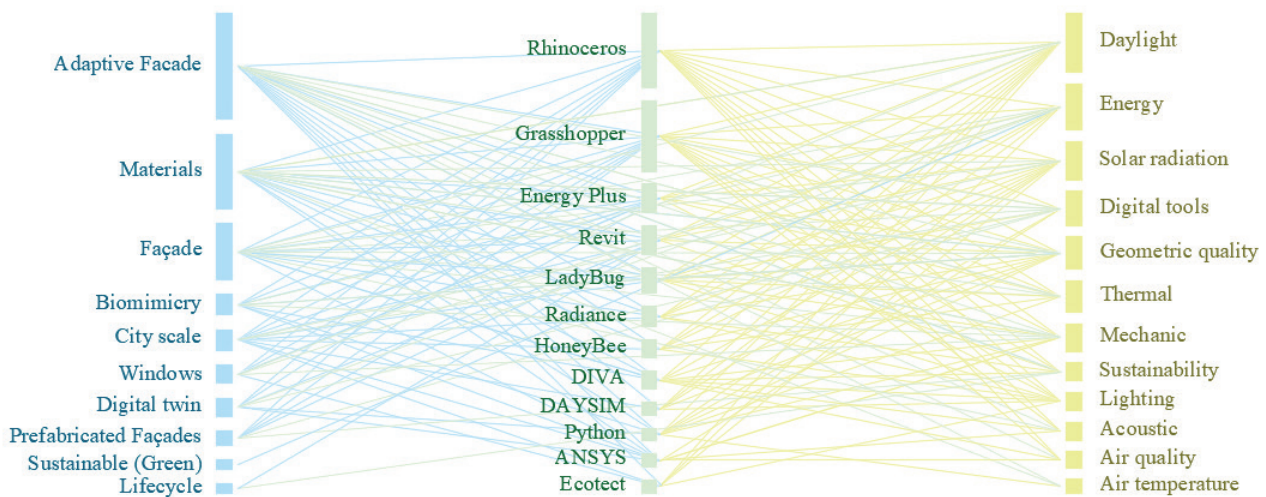


Figure 15. Chart of relationship between software, study subjects and performance types.

research, especially on the performance of ventilation and cooling, where the literature could be strengthened.

- In warmer regions, the main aim is generally to reduce the indoor temperature and improve thermal comfort. These objectives can be attained efficiently by using modern numerical modeling techniques [96]. However, in cold temperature areas, the focus is on avoiding heat loss and maintaining airtightness to improve energy efficiency [97]. Façade design techniques for cold climates have to deal with issues such as frequent temperature changes and humidity and consequently require a different approach than those applied in hot climates [98]. But parametric investigations in cold settings are more restricted. Much research concerns themes such as energy efficient double-skin façades, however there are less studies than in hot regions. Bande et al. [99] talk on the design of innovative facades integrated into buildings in the United Arab Emirates. There is more interest in parametric design in warmer regions. Moreover, while Attia et al. recognize the potential of adaptive façades in cold climates, the total study conducted in this field is comparatively less than the research conducted on warm climates [100]. Similarly, studies emphasizing sustainability often focus primarily on energy efficiency and daylight performance [87, 101]. Especially when sustainability is a key evaluation criterion, several factors need to be considered in façade selection. These include façade material properties, CO<sub>2</sub> emissions, breathability, urban context, and other relevant factors.
- With the development of technology, there is a tendency to employ simulation software that supports and complements experimental studies. These simulation methods are progressively becoming more popular than the experimental approaches owing to their more economical viability. While simulations allow for speedy exploration of many scenarios, they may not always capture the entire complexity of real-world conditions as well as physical experiments [102]. Interestingly, the concept of digital twins that connect actual places with simulation software via digital design has gained considerable popularity, especially in recent years [53–55, 103, 104]. The simulation results can be confirmed by comparison with experimental data. For example, Reato et al. [105] employed the twin simulation method to compare their conclusions with experimental data collected from a MEMS electromagnetic actuator. The increasing use of digital twins is seen as promising, particularly for obtaining more precise data for evaluating and comparing facade performance. Furthermore, the use of simulation tools in conjunction with advanced computational methods can increase the reliability of the results. For example, the use of multiple physics approaches allows simulations to capture complex interactions between different domains [104]. In addition, the development of distributed simulation frameworks

suggested by Yahiaoui [106] can improve building performance assessments and eliminate the necessity for expensive and time-consuming trials. This approach highlights the fact that simulation tools can supplement, rather than replace, experimental methodologies.

- In studies using simulation software, 8% of researchers used fluid dynamics tools, 3% used acoustic tools, and 13% used mechanical software. In contrast, the usage rates of software tools were 35% for daylight performance and 32% for energy performance. Furthermore, researchers analyzing energy performance tend to base their findings mostly on daylight performance.

## CONCLUSION

In today's age of computers and artificial intelligence, architecture has been significantly affected by digital developments. This study examines digital design methods that improve facade performance by interacting with environmental conditions. An analysis of 96 scientific studies selected according to specific criteria shows that although digital design is often associated with aesthetics, only 14.6% of the studies focus on the visual dimension. In contrast, 85.4% of the studies address broader performance factors such as energy, daylight, thermal conditions, acoustics, and sustainability. The research also reveals an increasing interest in digital tools, mechanical properties, CO<sub>2</sub> levels, cyber dimensions, and kinetic systems. Remarkably, studies on digital facade performance have increased over time, with 32.3% of the studies conducted in the last three years.

One of the most important gaps in the literature is ventilation. This shortcoming is especially apparent in regard to indoor air quality and temperature regulation. A lot of studies are on daylighting for energy efficiency and thermal comfort. However, research on managing humidity and temperature by effective air circulation is still restricted. This is especially apparent in hot, humid regions. Further research in this area would contribute significantly to the literature.

The link between architectural design and science is growing stronger. Unlike traditional methods, digital design techniques offer significant opportunities to improve design and create more comfortable living spaces for users. This study aims to guide researchers examining the relationship between digital design and facade performance.

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## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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