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A literature review on thermal comfort performance of parametric façades

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Abstract

Thermal performance is a major part of the building envelope and is getting more attention globally. Nowadays, parametric design methods are used in building envelope design, such as facade design, for optimization of building envelopes, which could affect thermal performance and energy consumption. Moreover, new technologies applied to building design have not only changed the appearance of cities but also increased occupant comfort. This paper illustrates a systematic review that explains some tools and techniques that have been used in recent years to improve thermal comfort by applying parametric design panels to a second skin façade for residents. It attempted to collect and synthesize the most relevant evidence and methodologies. In this paper, 30 articles have been analyzed. They are classified by methodologies, years, and climate zones. Results suggest that simulation is the most accurate in comparison with other methodologies.

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Keywords: Parametric design; Façade; Thermal comfort; Energy-saving; Passive design

1. Introduction

It was in 1978 when Hillyard and Braid developed a framework that could combine two parameters, such as measurements and resistances, to plan a mechanical component, which can be viewed as the first instance of what is now known as a parametric approach [1]. However, according to Robert Stiles, the first appearance of parametric concepts was made in 1940 by architect Luigi Moretti, who wrote extensively about parametric design in his book Writings of an Architect (Writings of an Architect, 1940) Whatever the case may be, Daniel conducted an examination [2]. According to Dana [3], there was also a time when he used the language of parameters, factors,

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and proportions to describe how to draw an area of crystals. This language was used in his paper on the drawing of figures of crystals, which Dana cited.

Parametric architecture is "the discipline of connections between dimensions that are dependent on various parameters" [2]. The term parametric in mathematics can be modified in order to manipulate the equation outcome, such as Antoni Gaudi, who investigated the design environment by applying analog models [4]. Parametric design is a mathematical process in which the relationship between design elements is represented as parameters that can be reformulated to generate complex geometries; these geometries are based on the parameters of the elements, and by changing these parameters, new shapes are created concurrently. At the same time, CAD systems simplify the process of drawing a model based on geometric relationships with stated parameters and dimensions. Nevertheless, if we need to update or modify any part of the model, we may do it independently of other connected elements. Parametric design can be thought of as an upgraded version of CAD because it is based on "Generative Algorithms", which is a way to look at the design and algorithmic solutions with formulas instead of standard shapes [1].

Parametric design is a computational method for applying both generative and analytical approaches to design explorations, implying a fundamental shift away from design options and toward design logic [5]. As a result, computational features are used to expand the search area for diverse perspectives on the design space [6]. On the one hand, there is the 3D model interface, which displays the geometric configurations; on the other hand, there is an editor, which enables the designer to encode the algorithmic process [7]. The autonomous development of design solutions consists of four major processes: (i) Initial conditions and parameters; (ii) generative mechanism rules, algorithms; (iii) The act of generating variations; and (iv) The best variant selection [8,9].

Multiple skins have been described as DSFs (Double Skin Facade). They were intended to supplement traditional façades in colder regions, while their use in hot climates has been frequently documented [10,11]. DSFs are generally applicable to both new and renovated structures. According to, "the vented cavity acts as a thermal buffer, minimizing undesirable heat gains during the cooling season, heat loss during the heating season, and thermal discomfort caused by asymmetric thermal radiation" [12]. DSFs are used to cover numerous levels of a building with various skins and are characterized as either airtight or ventilated. Additionally, DSF typologies are categorized according to their cavity ventilation techniques.

Air-flow DSFs improve thermal insulation during the winter months, whilst ventilated DSFs absorb heat from the sun and reduce heat gain during the summer [13]. Moon expressed that DSFs are mostly classified according to their design. The first type covers the internal skin of each level of the building with an external skin while keeping the air cavity of that level separate from the others; the second type covers the entire internal skin with an external layer and connects the air cavities of all different floors (Fig. 1) [14]. DSFs are categorized according to four conditions of 'closed', 'mechanical exhaust', 'natural convection to outside' and 'window ventilation' [15,16].

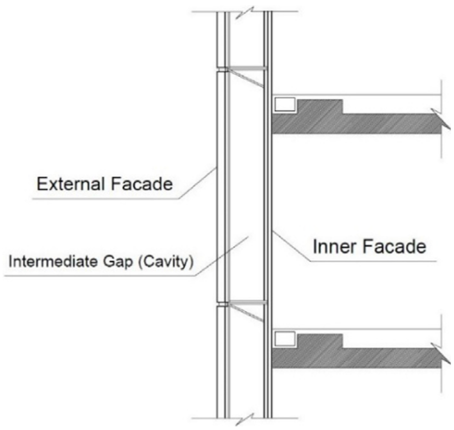

Fig. 1. Double-Skin Façade structure.

A double-skin facade, alternatively referred to as a double-envelope facade, is a multi-layer skin architecture consisting of an external skin, an intermediate area, and an internal skin found on the exteriors of modern buildings. Not only does it look attractive, but the DSF may also collect or evacuate solar radiation absorbed by the glazing facades and provide natural ventilation within the structure, enhancing thermal comfort and indoor air quality while conserving energy for heating and cooling. Due to the fact that the double-skin facade was intended for use in colder areas, it has received widespread acceptance and use. Recent economic growth has resulted in an increase in the number of new buildings with double-skin facades appearing in the hot summer and chilly winter. Indeed, the energy consumption of buildings with double-skin facades is entirely dependent on thermal performance, particularly thermal heat transfers and solar heat gain, which vary according to season and location. According to previous studies, the majority of research is performed in cold and moderate climates [17]. There has been very little research done on how double-skin facades perform in hot-summer and cold-winter climate zones [10].

The principle and implementation of parametric design efficient technologies are urgent to resolve the current issue of climate change. Buildings, which account for about 30%–40% of primary energy use, greenhouse gas emissions, and waste generation, should take responsibility for energy consumption reduction [18]. In Europe, 41% of energy is consumed in the building sector in 2004, most energy consumption in buildings is used for providing thermal and visual comfort through A/C systems (30%–60%) and artificial lighting (20%–35%) [19]. Nowadays, significant recognition has been focused on the contribution of daylight to thermal comfort and energy conservation in buildings [20].

To achieve the maximum benefits of daylight as a renewable energy resource, architects and engineers prioritize the use of passive design strategies early in the design process [21]. However, optimizing occupant comfort by using daylight is challenging because there are two distinct spaces including interior (inside) and the environment (outside), which are interacting together. However, optimizing visual and thermal comfort is difficult due to conflicts between them. In particular, the sun's diurnal movements giving rise to different hourly daylight circumstances that influence the indoor comfort conditions. However, interdisciplinary study through architectural design, light and human well-being could lead to the detection of optimal solutions regarding all aforementioned criteria. The façade is a complex interface between the inside of buildings and the outside that has the capability to function as a protective or regulatory element against severe fluctuations of the external climate [22].

The aim of this study is to review, categorize, and compare previous studies for determining how to improve thermal comfort for residential buildings in different climates by using the parametric design on the building façade. To achieve this goal, parametric façades as 3D facades are evaluated in terms of their thermal performances. Subsequently, by performing all assignments parametrically, an evaluation of thermal comfort regarding different methodologies which included experimental (real projects) and dynamic simulation (utilizing building simulation tools such as EnergyPlus, IES VE, etc.) [23,24] can take place in order to assess parametric façades.

2. Literature review

A large number of peer-reviewed research could be found regarding the parametric façade. We have divided them into two categories in this section: generation and assessment of parametric facade performance, as well as thermal performance efficiency.

2.1. Performance of parametric façades as a double-skin façade

There are two approaches to analyzing parametric façades. The first approach considers all façade designs to be parametric because they are based on parameters such as legal aspects, orientation, solar radiation, and wind, whereas the second approach considers parametric façades design using specific tools (Rhino, Grasshopper, Processing) to improve the design by integrating and coordinating design components together [25]. Architects can use parametric façade design technology to perform numerous interactions and monitor modifications during the façade design process [17,26].

The incorporation of a parametric façade as a double-skin façade in a building can be beneficial to its thermal behavior, contributing to both a reduction in energy demand and consumption and also an improvement in occupant comfort. Many studies in this field have been conducted in recent years. Ballestini [27] studied the use of a double-skin facade system with natural ventilation in the rehabilitation of a factory in the Mediterranean region. Kim et al. [28] investigated the energy-saving performance of a double-skin facade on a residential building with five-story on the Korean peninsula. The energy-saving potential of a photovoltaic double-skin facade was assessed by Peng et al. [29] for a cool-summer Mediterranean zone. Barbosa and Ip [30] used computational simulation models to predict annual thermal acceptance levels in naturally ventilated office buildings with double-skin facades in different Brazilian climates. The thermal and energy-saving performance of the double-skin facades was validated using measured data from an existing building in Sheffield, UK [31], as well as a dynamic simulation of the double-skin facades in different orientations in Barcelona, Spain [32].

2.2. Assessment of parametric façade's thermal comfort

The most widely accepted definition of thermal comfort is provided by ASHRAE [33], which describes thermal comfort as a "state of mind that expresses satisfaction with the surrounding environment". Thermal comfort formulations are numerous and vary depending on the approach used.

Rizi conducted research on a new methodology that was designed to incorporate the occupant's position within the area while addressing comfort problems. The paper suggests increasing visual and thermal comfort and also using parametric simulation and genetic algorithm optimization. Moreover, the suggested solution improved the occupant's visual comfort by 76% over the course of the year as compared to the standard shading state. Additionally, when the target function was adjusted to increase heat gain, there was an average 60% improvement in heat gain via the suggested adaptive façade as a parametric façade compared to the standard shading state. Additionally, when the goal function is adjusted to reduce heat gain, a 59% improvement over the no shading state is attained. Finally, the proposed adaptive facade and unique design strategy can be employed to address the user's position inside the area, hence improving visual and thermal comfort [34].

The goal of this study is to show a way to show how design knowledge is stored in a design workflow. We found design patterns at several stages of the parametric façade design process by looking at other design projects. Preliminary investigations toward developing a pattern language for parametric design, we demonstrate the implementation of parametric design patterns in practice [35].

The purpose of this research is to analyze the motion aspect of interactive facade design and to simplify the conceptual and performance design processes through the use of parametric strategies. This research will utilize a hybrid of parametric and simulation tools, such as Rhino Grasshopper, Ladybug, and Daysim, to create interactive facade designs that can be verified in a virtual reality environment while also generating performance outcomes that can be optimized in a holistic and efficient process [36].

To evaluate different methodologies used in double-skin building façade thermal performance, 30 relevant articles have been analyzed (see Table 1). They have been classified by climate zone, year, and their approaches. According to the methodologies that researchers used in their articles, there have been employed four methods included the dynamic simulation method, numerical method, experimental method, and literature review. Among these methods, dynamic simulation (Fig. 2) has been used the most (using various building simulation tools such as EnergyPlus, IESVE, CFD, TRNSIS, DesignBuilder, and so on). EnergyPlus has been used more than the other building simulation tools (Fig. 3).

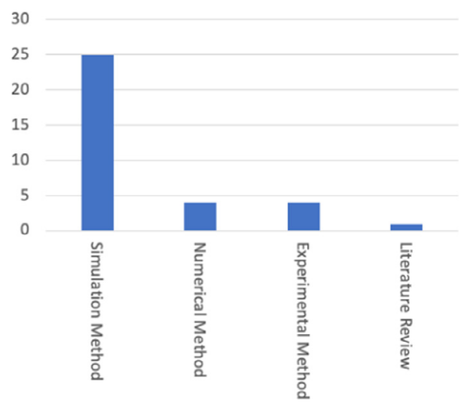

Fig. 2. Examined the use of different methods in evaluating thermal comfort in parametric facades among 30 articles.

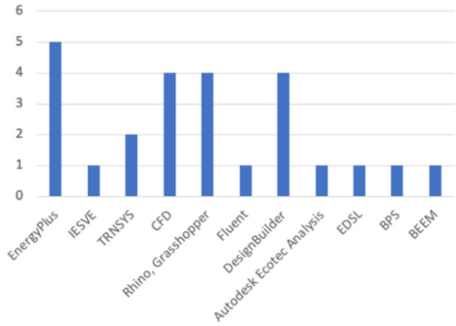

Fig. 3. Building simulation tools used in dynamic simulation method among 30 articles.

Table 1. The most relevant investigations in recent years (between 2015 to 2022).

Ref	Year	Climate	Method	Main Conclusion
[37]	2015	–	Digital Model by Grasshopper and Kangaroo and Comparing Result	Optimized Origami
[38]	2015	DFA	Simulation (CFD)	Natural ventilation
[39]	2015	BWH	Simulation (Rhinoceros Grasshopper (Ladybug and Honeybee))	design parameters on the thermal performances
[40]	2015	DFA	Simulation (IESVE)	Optimizing the annual acceptable thermal comfort
[41]	2016	–	Simulation (Fluent)	Shading inside the cavity/Airflow/heat transfer
[42]	2016	–	Simulation (BPS) and Literature Review	Ability to model energy and occupant comfort performance
[43]	2017	CFA, CSA, CSB, AW, BSK, DSB, DFC, AM	Parametric Simulation Model and Experimental Test and Comparing Results	performance of different dynamic shading typologies/energy saving/daylighting/solar insolation
[44]	2017	BSK	Simulation (TRNSYS)	Transparent thermal envelope, and an adaptive shading system.
[45]	2017	AS	Comparing result and Simulation (Building Energy and Environment Modeling (BEEM))	Comparative thermal comfort in tropical and temperate climates
[46]	2018	BWH	Simulation (EnergyPlus)	Thermal functioning/Optimize material characteristics
[47]	2018	CSA	Simulation (DesignBuilder)	Improvement insulation and ventilation
[48]	2018	DWA	Simulation (EnergyPlus)	Window design according to the type of the envelope
[49]	2019	BWH	Dynamic Simulation and Numerical	A comparative analysis of indoor thermal comfort
[50]	2019	CFA	Experimental (DOE) and Meta Modeling and Mathematical Model and ANOVA Test	Optimize building design for thermal comfort
[51]	2019	CFA	Simulation (EnergyPlus)	To evaluate the indoor climate
[52]	2019	CFA	Comparison and Simulation (EnergyPlus)	energy performances of the hypothetical models
[53]	2020	BWH	Experimental Test	A prototype Double Skin Façade integrated into a Double-Glazed Window

(*continued on next page*)

Table 1 (*continued*).

Ref	Year	Climate	Method	Main Conclusion
[54]	2020	BWH	Simulation (EnergyPlus)	passive cooling applications
[55]	2020	BWH	Simulation (Rhinoceros Grasshopper (Ladybug and Honeybee))	Optimizing the shape
[56]	2020	BSH	Comparison and Simulation (DesignBuilder and CFD)	Factors affecting the performance of coherent façades
[57]	2020	CSA	Simulation (DesignBuilder)	adaptive set point temperatures
[58]	2021	BWH	Simulation (Autodesk Ecotec Analysis)	enhance indoor thermal comfort
[59]	2021	CSA	Simulation (EDSL)	Enhance the atrium thermal performance without shading
[60]	2021	BWH	Simulation (TRNSYS)	Sensitivity analysis on the correlations between indoor thermal comfort and energy consumption
[61]	2021	CSA	Simulation (DesignBuilder)	Optimization of the double-skin facade
[34]	2021	BWH	Simulation (Rhinoceros Grasshopper (Ladybug))	Simultaneous optimization of both visual and thermal comfort
[62]	2022	BSK	Experimental and Numerical Modeling and Simulation (Rhinoceros Grasshopper (Honeybee))	Using microalgae
[63]	2022	DFB	R Software and Shapiro–Wilk Test and Statistical Methods and Q-Q Plot	Façade design on occupant satisfaction
[64]	2022	CFA	Simulation (CFD)	Thermal environment
[65]	2022	BSH	Simulation (CFD)	thermal comfort by natural ventilation

According to their methodology they can be classified in three groups;

Groups 1: One of the research projects is based on simulations using Grasshopper software, digital algorithms have been used. Grasshopper makes more use pre-defined scripts to facilitate information manipulation and update as needed. The initial stage in developing the algorithmic design is to take advantage of the opportunity using componentized scripts [66]. The generated geometry is determined by parametric inputs that cause the shape to vary from its initial state. To design the method, components must be connected in such a way that a collaborative assignment is generated. Each component completes a task using the data provided by the inputs; the output is then used as an input for the subsequent phase. The design algorithm gradually takes shape as a result of the order in which components are connected. The digital model can indicate which geometric properties are modifiable and which are not. Thus, change in design parameters serves as a design motivator for developing solution strategies based on the examination of the optimal [67].

Group 2: Experimental test is a type of test that includes modifying a variable in a system to determine how it impacts the outcome. In an ideal world, experiments would also include the control of as many additional variables as feasible in order to isolate the reason of the experimental results.

Group 3: Numerical Test is a normal distribution fit test. With the help of this test and its statistics, you can determine whether the data follow a normal distribution or not. This test was the first to discover deviations from normalcy caused by skewness, kurtosis, or both. Due to its superior power qualities, it has become the standard test [68].

3. Conclusions

This paper concentrates on presenting parametric façades as double-skin façades to improve the thermal performance of the building envelopes. According to previous investigations, a double-skin façade can improve thermal comfort and indoor environmental quality and also reduce energy consumption. Improving the environmental efficiency of buildings envelope is crucial in the goal of a sustainable society. The findings indicate that the multi-objective optimization and parametric method for façade building design is an excellent method to get optimized results. Additionally, for evaluating the performance of parametric double-skin facades there are methods included experimental method, dynamic simulation method, numerical method. This literature review demonstrated the use of dynamic simulation is more common among these methods to investigate the performance of parametric façades as a double-skin façade in saving energy and also thermal comfort efficiency. For this purpose, there are building simulation tools that can be utilized in dynamic simulation methods such as DesignBuilder, EnergyPlus, Grasshopper and IESVE which enable researchers to employ for evaluating parametric facades in different climates and contexts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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