Journal of Turkish

Operations Management

Exploring the relationship between technical and comfort factors in designing efficient buildings: a statistical analysis of a real-world dataset

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Article Info

Article History:
Received: 01.08.2023
Revised: 28.11.2023
Accepted: 14.02.2024

Keywords:
Facade Systems
Human Comfort
Efficient Buildings
Statistical methods
Reversible Jump Markov Chain Monte Carlo Method

Abstract

This study investigates the three factors that contribute to designing efficient buildings, namely technical solutions, facade systems, and occupant requirements, through the use of a real-world dataset consisting of 49 efficient buildings from various locations across the globe. Each factor comprises distinct elements that are essential in achieving building efficiency. Statistical methods, including correlation and Kruskal-Wallis methods, as well as advanced statistical methods such as the reversible jump Markov chain Monte Carlo method, were employed to estimate parameters that represent the conditional dependence between the elements of each factor. The undirected graphs were generated for each factor based on the conditional depence between the elements of the factor which is shown by a link. Through the analysis of these graphs, designers can enhance their comprehension of the correlation between the various elements of each factor, which can ultimately result in improved building efficiency. This, in turn, may lead to a decrease in air pollution and energy consumption while enhancing human comfort.

1. Introduction

Lovell (2010) states that 76% of electricity generated is consumed by buildings for lighting, heating, cooling, and plug loads. The primary source of electricity generation is fossil fuels, which leads to numerous issues such as air and water pollution, the emission of toxic substances, and the release of greenhouse gases that contribute to global warming. Consequently, Alternative methods are being explored to construct buildings that are environmentally friendly and utilize renewable energy sources to decrease their carbon footprint. The function of building envelopes, which act as a barrier between a building's interior and exterior, is crucial in this context. Manioglu and Yilmaz (2006) argue that building envelopes have a significant impact on energy consumption for heating and cooling. A well-designed facade not only increases efficiency but also reduces energy consumption, while a poorly designed one leads to higher energy consumption. High-performance facades, in particular, decrease the thermal load and reduce energy consumption in buildings (Bessoudo, 2008). Knaack and Klein (2009) state that external walls have a secondary function of regulating energy transfer between the interior and exterior of buildings, while their primary function is to separate interior spaces from exterior spaces. According to Brock (2005), high-performance facades must be able to control air leakage, resist water penetration, resist wind load, and be weather-tight. The key considerations in designing building facades include capturing solar energy while preventing heat transfer during the winter, preventing heat gain during the summer, blocking outside noise, and providing natural ventilation and daylight.

Architects and engineers are exploring the integration of various techniques on building facades to generate energy using renewable sources, as the large facade area in most buildings provides an opportunity for this. This optimization of energy consumption involves not only new mechanical techniques but also the use of renewable energy through building facades instead of relying on fossil fuels. To this end, different systems and techniques are under investigation to utilize renewable energy for lighting, heating, and cooling systems, with a focus on their application on building facades. These systems can be active or passive; passive systems directly apply renewable energies like solar energy for heating and cooling via building facades without the use of mechanical systems, while active systems utilize mechanical systems to convert renewable energy into thermal or electrical energy.

Aksamija (2013) and Moghtadernejad (2013) note that the types of facades used in buildings are the most critical factor in improving human comfort and reducing energy consumption and environmental pollution. On the other hand, Tam, Le, and Wang (2018) believe that facade design is an important factor ın achieving cost reduction in construction and maintenance while improving human comfort. Newsham, Brand, Donnelly, Veitch, Aries, and Charles (2009) believe that increasing indoor environmental quality results in enhancing resident satisfaction levels. Additionally, Lovell (2010) and Kubba (2010) state that human comfort in buildings depends on several parameters, natural ventilation, including indoor air quality, access to outside views, natural light levels, preventing glare, acoustics, preventing noise pollution, thermal comfort, building envelopes, facade systems, and finishing materials. They emphasize that these aspects should be taken into account during building design and construction. In addition, Lovell (2010) states that the building envelope accounts for approximately 35% of the building construction cost. Tam *et al.* (2018) believe that designing and constructing high-performance facades is more expensive than conventional building facades. However, high-performance facades have an impact on energy consumption, maintenance costs, indoor environmental quality, and human comfort levels. Muralikrishna and Manickam (2017) argue that human's non-responsible consumption of resources is responsible for environmental pollution, which cannot be processed or neutralized by the environment. They identify increasing energy consumption in buildings and industrial sectors, as well as population growth, as the most significant factors contributing to environmental pollution. Liu, Zhang, and Liu (2017) suggest two ways to address man-made pollution: preventing it from entering the environment and cleaning it if it does enter. In the construction sector, it is possible to prevent air pollution caused by fossil fuels by utilizing renewable energy for cooling and heating buildings through their facades. Moreover, building envelopes can help prevent heat loss or gain.

Designing building facades involves considering numerous factors that can be grouped into three categories: Occupant requirements, appropriate technical solutions, and efficient facade systems. Human comfort is a fundamental consideration in building design, and it has been sought after since the earliest human existence.

2. Application

The researchers studied several efficient buildings that were featured in publications and dissertations. Afterward, they randomly chose 49 (see Appendix A) of these buildings to analyze based on three factors; Technical Solutions (TS), Facade Systems(FS), and Occupant Requirements (OR). The analysis of a dataset consisting of 55 binary variables representing TS, FS, and OR for 49 efficient buildings. The aim of this analysis is to explore the relationship within and between these factors and to categorize the buildings based on their quality. To explore the relationship between them the correlation analysis is conducted and finally, to show it in a graphical way, Copula Gaussian Graphical Models (CGGM) is applied within each factor.

2.1. Descriptive Statistics

Our dataset consists 49 rows and 55 cloumns. The first 25 columns of the dataset represent technical solutions, the next 14 columns represent active and passive facade systems, and the last 16 columns represent occupant requirements. To show the relationship within and between each factor, we calculated the ratio of 1s for every factor of each of the 49 samples. Descriptive statistics for each factor are presented in .

Table 1.

Table 1. The descriptive statistics of three facade quality factors of buildings.

Factor	Size	Mean	StDev	Minimum	Median	Maximum
TS	49	0.222	0.099	0.040	0.200	0.640
FS	49	0.122	0.072	0.000	0.142	0.428
OR	49	0.445	0.152	0.062	0.500	0.687

It can be seen that the OR variable has the highest mean value among the three variables, followed by the TS and then the FS variable. The TS variable also has a higher maximum value compared to the other two variables. Additionally, the TS variable has a higher standard deviation than the other two variables, indicating that its values are more spread out. The following boxplot in Figure 1 represents the distribution of the three building quality factors.

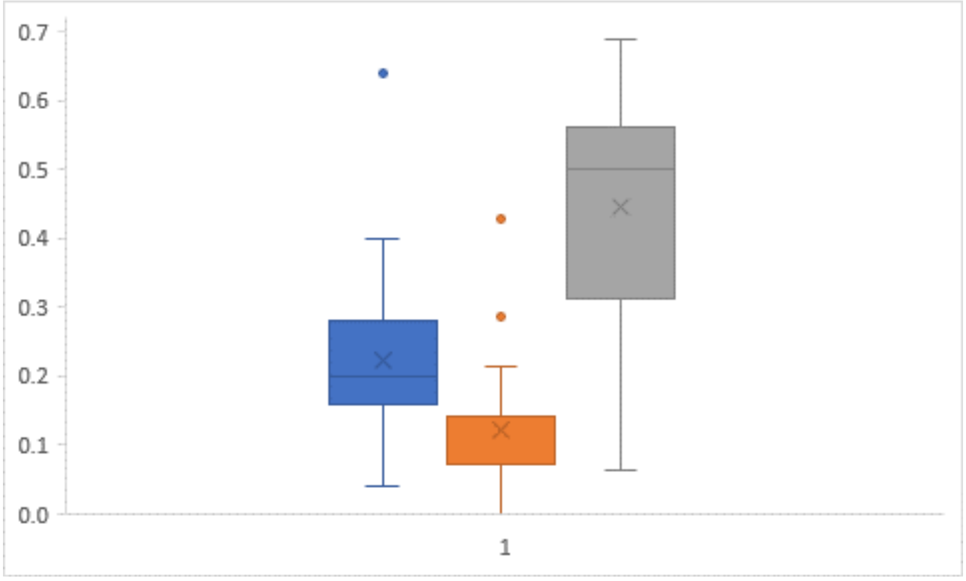

Figure 1. The boxplot of TS (Left), FS (Middle), and OR (Right).

2.2 Comparison of the Three Factors

As the variables are all ratios, to compare them we used the Kruskal-Wallis test, which is a non-parametric statistical test used to determine whether there are significant differences between two or more groups of independent samples. This test is appropriate when the assumption of the normal distribution is not met, as is the case with our data, as evidenced by the boxplots. The Kruskal-Wallis test tests the null hypothesis that the medians of the groups are equal against the alternative hypothesis that at least one group has a different median. The test statistic is calculated as the sum of ranks within groups, and its distribution under the null hypothesis is approximated by a chi-squared distribution with degrees of freedom equal to one less than the number of groups. Based on the results, it can be concluded that there is significant evidence to suggest that the central tendencies of the three variables are not equal.

Table 2. Kruskal Wallis test

Method	DF	H-Value	P-Value
Not adjusted for ties	2	86.71	0.000
Adjusted for ties	2	87.37	0.000

2.3 Correlation Analysis

The correlation coefficient measures the strength of the linear relationship between the two variables especially in dealing with variables that are ratios. In other words, it approves how well the two variables are related to each other in a straight line. That is why in the inference of the relationship between three factors, the Spearman correlation coefficient is used because the normality assumption does not hold with the data that can be seen in the matrices shown in Figure 2.

Based on the correlation coefficients provided, we can make the following inferences about the relationship between the three quality factors. The correlation coefficient between TS and FS is 0.639, which indicates a moderate positive correlation between these two factors. This suggests that buildings with high-quality TS are likely to have high-quality FS as well. The correlation coefficient between TS and OR is 0.578, which indicates a moderate positive correlation between these two factors. This suggests that buildings with high-quality TS are likely to have high-quality OR as well. The correlation coefficient between FS and OR is 0.408, which indicates a weak positive correlation between these two factors. This suggests that buildings with high-quality FS are somewhat likely to have high-quality OR as well, but the relationship is not as strong as that between TS and either of the other two factors. Overall, these correlation coefficients suggest that there are some relationships between the three quality factors, but they are not extremely strong. It may be useful to explore other factors that could be influencing the quality of buildings as well.

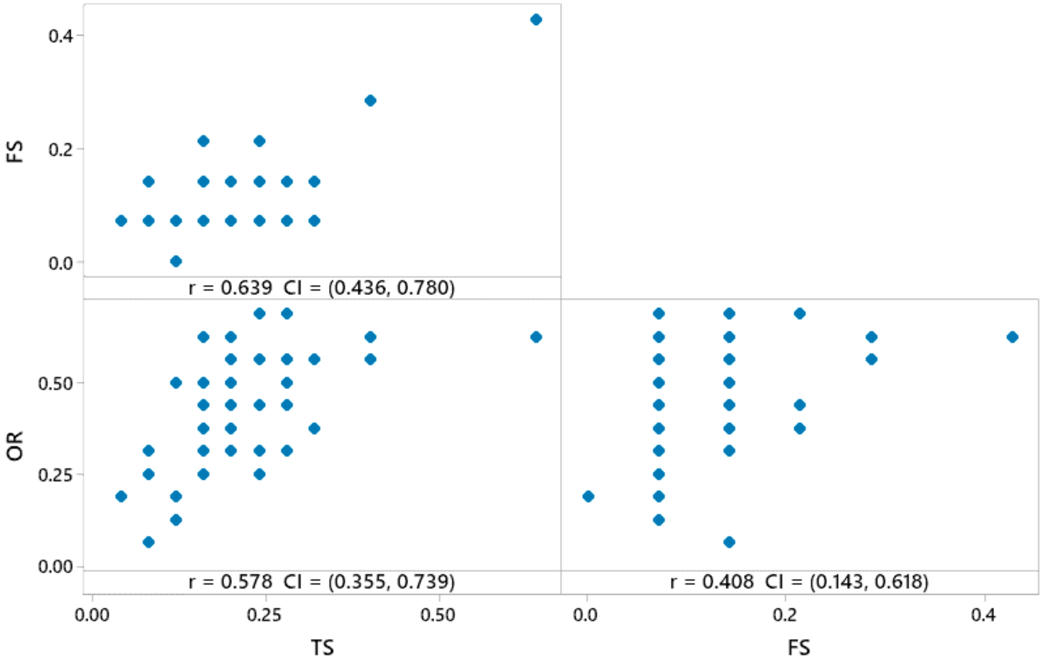

Figure 2. The matrix correlation plot of TS, FS and OR

2.4 Building Categorization

Finally, the three binary variables considered in our analysis were TS, FS, and OR. We constructed a joint contingency plot in Figure 3 to visualize the relationships between these variables and the resulting groupings of buildings. The plot shows the frequency of each combination of the three variables and the corresponding groupings of buildings. Four distinct groups of buildings are identified based on their combinations of variables. 11 buildings are in the first group consisting of zero values for all three factors meaning that their value of the three factors is all less than the mean. The second group consisted of 15 buildings with only one high value for any one of the three factors. The third group consisted of 12 buildings with two high values for any two of the three factors. Finally, the fourth group consisted of 11 buildings with high values for all three factors.

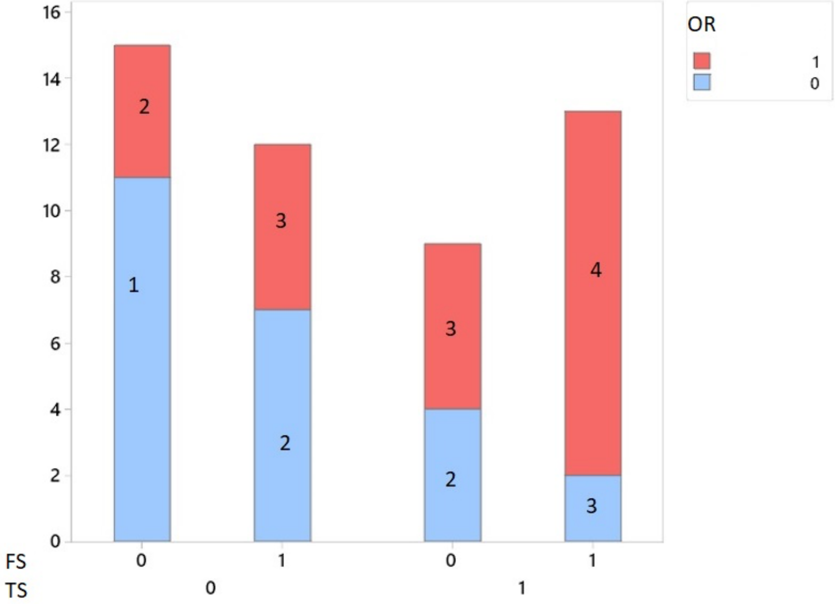

Figure 3. The joint distribution of TS, FS and OR levels (0 less than mean and 1 greater than mean)

2.5 Copula Gaussian Graphical Models

A copula Gaussian graphical model is a statistical model that describes the dependence structure between random variables. It combines copula theory, which characterizes the dependence structure between variables, with

Gaussian graphical models, which represent the conditional independence relationships between variables using a graph. The copula function is used to model the dependence structure between variables, while the Gaussian graphical model is used to represent the conditional independence relationships between variables. This approach is particularly useful when dealing with high-dimensional datasets with complex dependence structures which is held in the data used in this study. To estimate the inverse of the covariance matrix to explore the conditional dependence between the different elements of each factor with the elements of the other factor, Reversible Jump Markov Chain Monte Carlo Method (RJMCMC) is used. More information can be found in Farnoudkia and Purutculoglu (2019). In order to provide the graphical representation of the network, the *BDgraph* package in *R* is used. (Mohammadi and Wit, 2015)

The graphical model for TS is presented in Figure 4, depicting the interrelationship among 15 TS. A pivotal TS that can significantly enhance building efficiency is the opening orientation, which is linked to the exterior, interior, and in-cavity shading devices. This association is reasonable since shading devices are consistently designed based on the opening orientation to mitigate solar gain during summer days and increase solar gain during winter days. The correlation between plantation and air filtration system on the facade indicates that the implementation of plants on building facades not only mitigates air pollution but also diminishes ambient temperature. Moreover, the relationship between insulated glass and thermal insulation demonstrates that the employment of these two TS can effectively reduce energy consumption in buildings. As per the network depicted in Figure 4, employing durable and low maintenance materials can be advantageous in reducing the cost of building construction. Additionally, the use of modular prefabricated panels in facade construction can facilitate the optimization of the window-to-wall ratio (WWR). Balconies equipped with roofs on facades can function as shading elements, effectively preventing the ingress of solar radiation into interior spaces. It is imperative to take into account the placement of operable windows during the installation of photovoltaic panels, solar collectors, and water pipes embedded in facades, as failure to do so may result in a decrease in the percentage of operable windows, which can adversely affect natural ventilation in buildings.

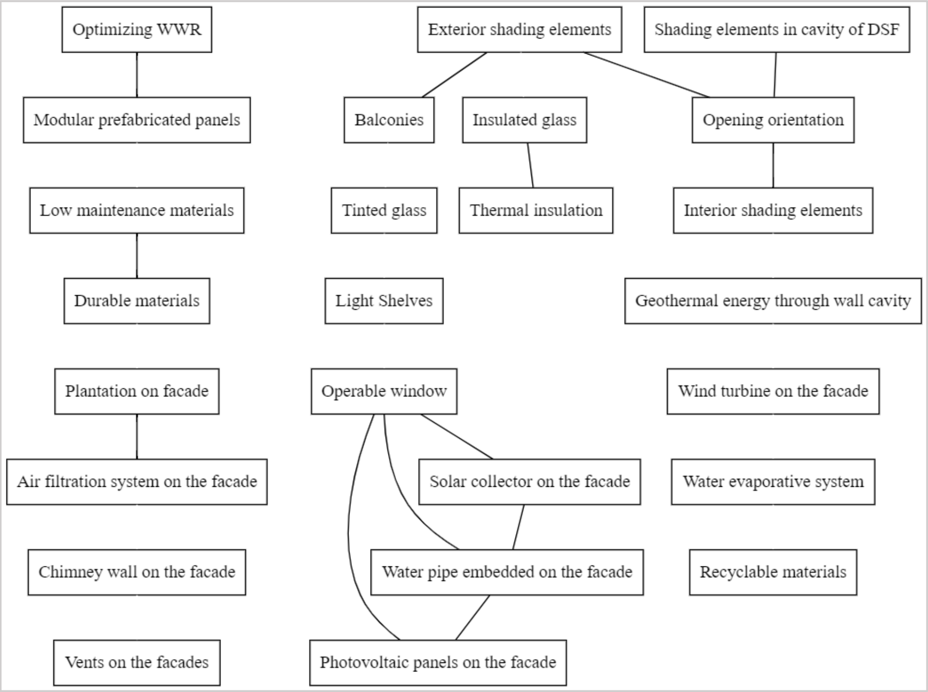

Figure 4. Copula Gaussian graphical model showing the relationship within TS.

The graphical model illustrated in Figure 5 exhibits the correlation among FCs, which are categorized as active (denoted in red) and passive FCs. There are 8 links between 5 passive and 4 active FCs. The installation of movable shading devices on facades, which track the sun's position, prevent solar gain during summer and enhance natural ventilation by considering the direction of the prevailing wind. Building rotation and movable facades that follow the sun's radiation not only prevent or increase solar gain during summer and winter, but also improve natural ventilation by tracking wind directions. Photovoltaic panels and collectors can be installed in the cavity of double skin facades or can be utilized as fixed shading devices on facades, serving as a solar energy integrated facade. A self-shading facade is a type of fixed shading facade that covers the entire facade.

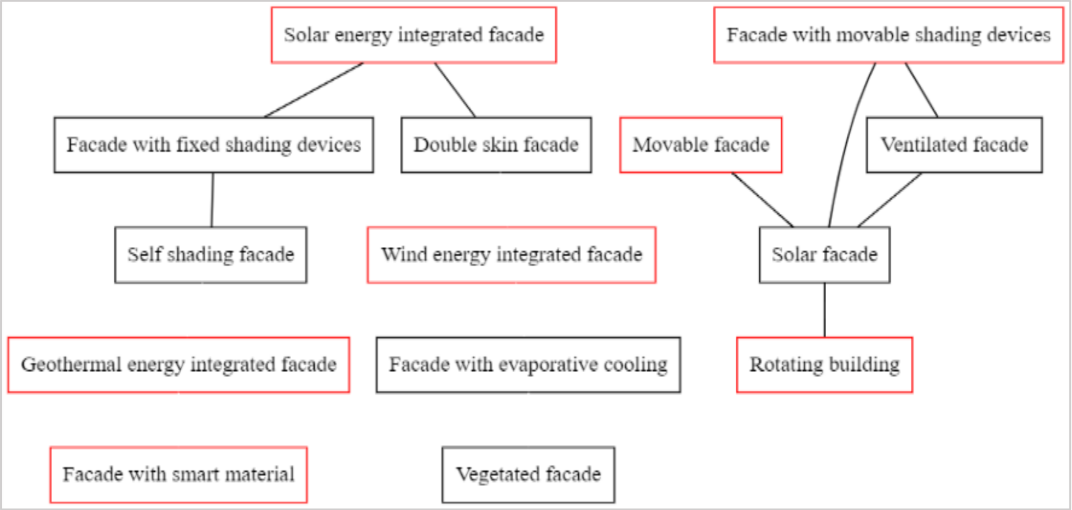

Figure 5. Copula Gaussian graphical model showing the relationship within FS.

The graphical model presented in Figure 6 displays the 14 links among ORs. To decrease air pollution by reducing energy consumption, it is recommended to utilize passive systems that do not require mechanical operation. Furthermore, the implementation of low emission materials can significantly enhance the air quality of interior spaces. The implementation of renewable energy sources not only reduces energy consumption and pollution but also enhances thermal comfort during both summer and winter. To improve thermal comfort in summer, it is recommended to enhance natural ventilation. However, the reduction of outside noise has an inverse relationship with natural ventilation during both day and night, as the use of operable windows for natural ventilation can lead to increased noise levels. The correlation between affordable systems and installation costs reveals that utilizing affordable systems for the construction of building facades can result in decreased installation costs. In order to have daylight and outside view, it is essential to prevent glare, which can significantly reduce visual comfort.

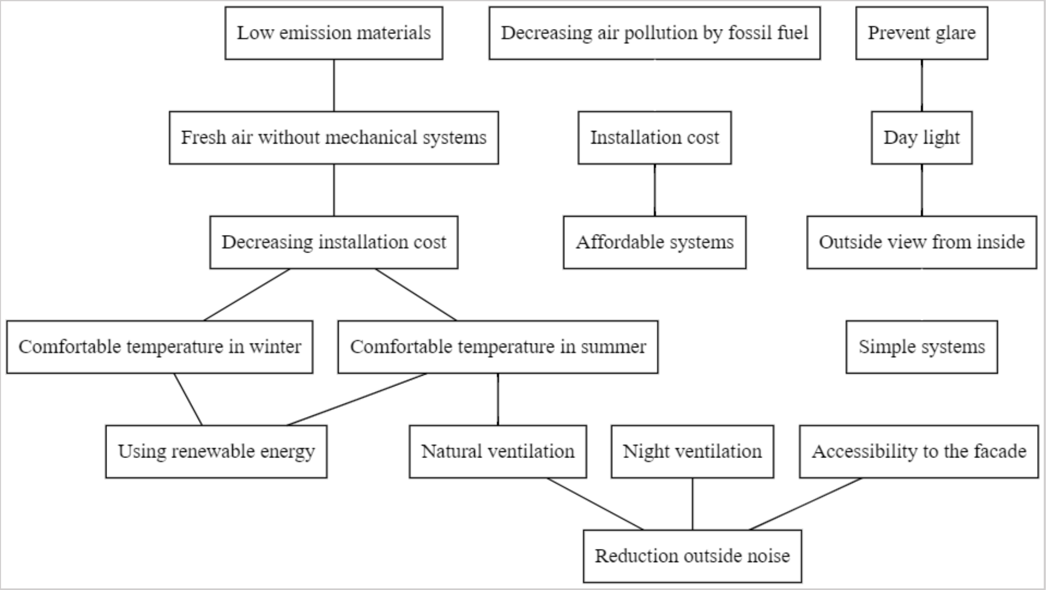

Figure 6. Copula Gaussian graphical model showing the relationship within OR.

3. Conclusion

This study aims to investigate a sample of efficient buildings in terms of three important technical and comfort factors named shortly by TS, FS, and OR. The descriptive statistics and the plot of these factors show that they are not symmetrically distributed and OR has the highest mean and median that is proved by Kruskal-Wallis test as well. In continue, it is approved that there is a significant positive correlation between these factors which show that they are linearly dependent to each other. This study has also categorized buildings into four groups based on their level of factors. The results show that most buildings have two high levels of factors, while over 20% of buildings have no high levels or all high levels with the same percentage. This information provides valuable insights into the distribution of building efficiency across different types of buildings. Finally, some advanced statistical methods help us to provide a graph to represent the structure of the internal elements of each factor. The results of the analyzing these graphs suggest that employing durable and low maintenance materials, optimizing window-to-wall ratio, and utilizing passive systems by using solar energy are crucial in reducing building energy consumption while improving air quality and thermal comfort. The findings of this study can help inform future building designs to achieve greater efficiency and sustainability.

In addition, as a future study, we plan to investigate the high performance of buildings in more detail, exploring potential trade-offs between building efficiency and other design considerations such as aesthetics and comfort.

Declaration of conflicting interests

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

Funding

No financial support was received for this study.

Contribution of authors

Contribution of authors The authors have equal contribution in all the writing, modeling.

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Appendix A

	Buildings	Location	Climate Zone	Building Type	Area	Number of Stories	Architects
1	US Census Bureau Headquarters	Suitland, USA	Humid Subtropical Climate, Cfa	Office Building	139,355 m^2	8	SOM
2	Santa Monica Civic Center Parking Struct	California, USA	Humid Subtropical Climate, Cfa	Parking Garage	27,758 m2	8	Moore Ruble Yudell Architects & Planners
3	Building Block Social Nestle Graneros	Graneros, O'Higgins, Chile	Semi-arid Climate, Bsk	Office Building	2,800 m^2	3	GH+A / Guillermo Hevia
4	3M Italia S.P.A Headquarters	Pioltello, Milan, Italy	Humid Subtropical Climate, Cfa	Office Building	10,300 m2	5	Mario Cucinella
5	Burj Doha	Doha, Qatar	Hot Desert Climate, Bwh	Office Building	110,000 m^2	49	Jean Nouvel
6	Hanwha Headquarter Remodelling	Seoul, South Korea	Humid Continental Climate, Dwa	Office Building	57,696 m^2	30	UN Studio
7	King Fahad National Library	Riyadh, Kingdom of Saudi Arabia	Hot Desert Climate, Bwh	Library	-	5	Gerber Architekten
8	New Kuwait University Sabah AL-Salem	Shidadiyah, Kuwait	Hot Desert Climate, Bwh	Educational Building	59,458 m^2	5	Perkins+Will
9	South Australian Health	Adelaide SA, Australia	Mediterranean Climate, Csa	Health and Medical Research	25,000 m^2	10	Woods Bagot
10	Juvelen- a new landmark in Uppsala	Uppsala Resecentrum, Sweden	Humid Continental Climate, Dfb	Travel Center, Fitness Center, Restaurant	10,000 m^2	6	Utopia Arkitekter
11	Habitat Items Leon	Leon, Mexico	Humid Subtropical Climate, Cwa	Educational Building	1,180 m^2	2	SHINE Architecture & TA arquitectura
12	Rey Juan Carlos Hospital	Madrid, Spain	Mediterranean climate, Csa	Hospital	24,923.20 m^2	9	Rafael De La-Hoz
13	John and Frances Angelos Law Center	Baltimore, USA	Humid Subtropical Climate, Cfa	Educational Building	17,873 m^2	12	Behnisch Architekten, Ayers Saint Gross
14	Soho Hailun Plaza	Shanghai, China	Humid Subtropical Climate, Cfa	Office Building	-	33	UN studio
15	Embassy of the United States	London, England	Oceanic Climate, Cfb	Embassy Building	-	12	Kieran Timberlake
16	Sony City Osaki	Tokyo, Japan	Humid Subtropical Climate, Cfa	Office Building	-	25	Nikken Sekkei
17	Hospital Manuel Gea Gonzales	Mexico City, Mexico	Subtropical Highland Climate, Cwb	Hospital	2,500 m^2	5	Berlin-based Elegant Embellishments
18	Green Cast	Odawara-shi, Kanagawa prefecture, Japan	Humid Subtropical Climate, Cfa	Multipurpose building	1052 m^2	5	Kengo Kuma & Associates
19	Yishun Community Hospital	Yishun, Singapore	Tropical Rainforest Climate, Af	Hospital	-	15	GENSLER
20	Unilever Haus	Hamburg, Germany	Oceanic Climate, Cfb	Office Building	37,997 m^2	6	Behnisch Architekten
21	The Crystal and the Cloud	Copenhagen, Denmark	Oceanic Climate, Cfb	Office Building	6,850 m^2	7	Schmidt Hammer Lassen Architects
22	Manitoba Hydro Place	Manitoba, Canada	Subarctic Climate, Dfc	Office Building		22	KPMB- Architects

23	Council House	Melbourne VIC, Australia	Oceanic Climate, Cfb	Office Building	12,526 m^2	10	DesignInc
24	Surry Hills Library and Community Centre	New South Wales, Australia	Humid Subtropical Climate, Cfa	Library	898 m^2	4	FJMT
25	KFW Westerkade	Frankfurt, Germany	Oceanic Climate, Cfb	Office Building	39,000 m^2	14	Sauerbruch Hutton
26	Q1 Thyseen Krupp Quarter	Essen, Germany	Oceanic Climate, Cfb	Office Building	-	14	JSWD Architekten, Chaix & Morel et Associés
27	Rmit Design Hub	Melbourne, Australia	Oceanic Climate, Cfb	Educational Building	13,000 m^2	9	Sean Godsell and Peddle Thorp Architects
28	Kiefer Technic Showroom	Austria	Humid Continental Climate, Dfb	Office Building	-	2	Ernst Giselbrecht +Partner
29	CJ Cheiljedang Research & Develop. center	Seul, Korea	Humid Continental Climate, Dwa	Office Building	-	15	Yazdani Studio
30	Mercella Niehoff School of Nursing	Chicago, USA	Humid Continental Climate, Dfa	School	5,574 m^2	4	Solomon Cordwell Buenz
31	Al Bahar Towers	Abu Dhabi, UAE	Hot Desert Climate, Bwh	Office Building	-	29	Aedas Architects
32	Kinetower (Kinetura)	Belgium,Stakendijik	Temperate oceanic climate, Cfb	-	-	-	Barbara van Biervliet and Xaveer Claerhout
33	Abu Dhabi Central Market	Abu Dhabi - UAE	Hot Desert Climate, Bwh	Shop Center	689,416 m2	3	Foster + Partners
34	Richard J. Klarchek Information Commons	Chicago, USA	Humid Continental Climate, Dfa	Library	6,410 m^2	4	Solomon Cordwell Buenz
35	POLA, Ginza	Tokyo, Japan	Humid Subtropical Climate, Cfa	Commercial Building	-	14	Yasuda Atelier, Nikken Sekkei
36	Vivian and Seymour Milstein Family Heart	New York, USA	Humid Subtropical Climate, Cfa	Hospital	11,613 m2	8	Pei Cobb Freed & Partners
37	Gemini Haus	Weiz, Austria	Warm-summer humid continental climate, Dfb	Part of the Styria County Energy Exhibition	-	2	Roland Mösl
38	Sliding House by DRMM	Suffolk, England	Oceanic Climate, Cfb	House, Residential	200 m^2	2	dRMM; Alex de Rijke, Joana Pestana Lages Goncalves
39	GucklHupf	Vienna, Austria	Oceanic Climate, Cfb	Recreation House	48 m^2	2	Hans Peter Wörndl
40	M-vironments by Micheal Jantzen	Valencia, Spain	Cold semi-arid climate	Houses, Office facilities and Pavilions	-	1	Micheal Jantzen
41	Dynamic Tower, Rotating Tower	Dubai, UAE	Hot Desert Climate, Bwh	Offices, Hotel, Apartments, Villas	1200 m^2	80	David Fisher
42	Wind Shaped Pavilion By Michael Jantzen	Frankfurt am Main, German	Oceanic Climate, Cfb	Public or Private Pavilion	-	6	Michael Jantzen
43	Heliotrop	German- Bavaria, German	Oceanic Climate, Cfb	Dental Laboratory	-	3	Rolf
44	Suite Vollard	Curitiba, Paraná, Brazil	Subtropical Highland Climate, Cwb	Residential	270 m^2	2	Bruno de Franco
45	Rotating Dome Home	New York, USA	Humid Subtropical Climate, Cfa	Hous	215 m^2	2	Patric Marsili
46	Everingham Rotating House	Wingham, Australia	Humid Subtropical Climate, Cfa	Hous	-	2	Luke Everingham
47	Rotating Home by Johnstone	Southern California, USA	Humid Subtropical Climate, Cfa	Residential, House	475 m2	2	Al Johnstone
48	55° Dubai – Time Residences	Dubai, UAE	Hot Desert Climate, BWh	Holiday Apartments	-	30	Glenn Howell Architects
49	Rotating Ecohome – The Dumble Project	Snelston, England	Oceanic Climate, Cfb	Residential, House	930 m2	4	Robin Hamilton