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Table of Contents

Articles

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Using KRF Structures As An Adaptive Facade And Evaluation of Daylight Performance Based on Geometry: A Case Study in Ankara

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ABSTRACT

Adaptive facades are widely used today because they are energy efficient and sustainable. It is expected that kinetic facades will become more common in the future and new geometries are constantly sought. Kinetic Reciprocal Frame (KRF) structures are also one of the innovative and sustainable approaches. In this study, KRF structures are used as adaptive facades and are analyzed in two stages. As a test model, a standard high-rise office building in Ankara, Turkey is created and simulations are made on the south facade. In the first stage, the modules' applicability in different geometries is examined and the differences within the geometries are revealed. KRF modules are examined for cost-effectiveness and mobility. In the second stage, analyzes are made on the daylight performance of the geometries. Modules are evaluated based on spatial daylight autonomy (sDA), annual sunlight exposure (ASE), and average lux. As a result, in terms of daylight performance, the hexagonal KRF module gives the best result by drawing the most homogeneous values due to its high mobility. However, it is noticed that the daylight performance of the triangle KRF module is weak compared to other modules, the ASE values cannot be controlled and it is more difficult to implement because it is not effective in terms of cost per module. The fact that hexagonal modules give good results in terms of cost is found to be good in support of it. This study is also valuable study in terms of the application performance of KRF structures on the facade.

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1. Introduction

Adaptive facades, also known as kinetic or active facades, are building facades that have the ability to change their functions, features, or behavior over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performance (Loonen et al., 2015). They use automated systems such as sensors, actuators, and control systems to adjust the properties of the facade in response to external conditions, like solar radiation, temperature, and weather patterns. These adjustments can improve energy efficiency, natural lighting, and thermal comfort, and can also reduce the urban heat island effect. The goal of adaptive facades is to improve the energy efficiency and comfort of buildings, while also reducing the need for mechanical systems such as heating and cooling. Today, adaptive facades are widely used and will become more common in the future with the increasing climate and energy crises because buildings account for around 30 percent of the world's total energy consumption and a similar percentage of the world's greenhouse gas emissions as the main cause of climate change (Hong et al., 2007). As can be seen, the role of buildings in the energy crisis is enormous. One of the best ways to reduce energy consumption in buildings is to carefully design their facades.

A well-designed facade can help to improve the energy efficiency of a building, reduce its environmental impact, and improve the comfort of the building's occupants. Such as the use of sustainable materials such as locally sourced, renewable, or recycled materials help to reduce the environmental impact of the building over its life cycle. Incorporating adaptive facades, living walls or other vegetated elements on the facade can also help to improve the building's overall sustainability by reducing rainwater runoff, improving air quality, and providing a habitat for natural life.

This sustainable, environmentally friendly, and energy-efficient facade concept has been tried on static facades before kinetic facades. On static facades, Lim et al. (2012) measured the effect of sunshade systems on the space and compared the designs within themselves. Martokusumo et al. (2017) in addition to this study, algae panels are used, which is a sustainable approach, on the facade and measured its efficiency. Algae panels gave better results than vertical and sunshade static systems. Hachem & Elsayed (2016) investigated the energy production with photovoltaic panels by differentiating these folding movements and changing the repetitions in the number of modules.

Current literature research shows that there are experiments of environmentally friendly green facades on static facades, as well as studies that seek energy efficiency through geometric searches. As an example, Etman et al. (2013) made these sunshade elements with Mashrabiya geometries and analyzed their effect on space. Polat & İlerisoy (2020) examined the Voronoi geometry in terms of cost and symmetrical balance. Goharian et al. (2022) added thickness parameters to these facades and evaluated their effects on the space through solar radiance values. Rezakhani & Kim (2020) designed the Persian patterns, with a different geometric quest, as sunshades and made a concept study by experiencing them in virtual reality.

As can be seen, since the energy efficiency of buildings will gain more importance in the future, new geometries are constantly sought in facade designs, and in these geometries, kinetic systems come to the fore more than static systems. Thus, it has been revealed that kinetic facades are more economical in terms of energy consumption than fixed ones (Kim et al., 2015). In that case, adaptive facades are becoming increasingly popular in the design and construction of new buildings and are expected to play an important role in the future of sustainable architecture.

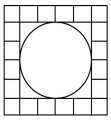
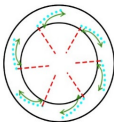
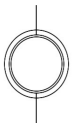
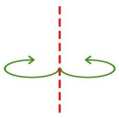
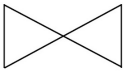
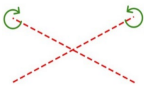
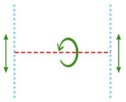
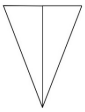
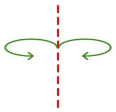
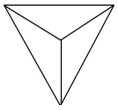
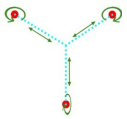
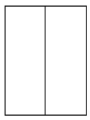
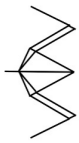
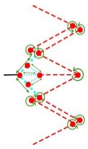
Each type of adaptive facade has its unique properties and functions and can be used in different ways to achieve specific goals. Fox & Kemp (2009) divided kinetic systems into three different categories. These are deployable, dynamic, and embedded systems. Embedded systems are systems that work permanently in a fixed place and maintain this position during operation. Deployable systems are systems that need a place temporarily and can be easily dismantled and transferred to another place after their mission. Dynamic systems are systems that can operate independently of the main architectural system. Kinetic facade systems belong to the embedded systems category among these systems.

There are different methods and movements in kinetic facade systems. Mahmoud & Elghazi (2016) classified the movements of kinetic facade systems as translation, rotation, and scaling as three basic movements. The movement of a facade, on the other hand, can include one of these movements, and it can also create complex movements with their combination. In that work, the author says that rolling motion is formed by the combination of translation and rotation movements. However, a basic movement can also become complicated on its own. For example, while the folding movement is a simple rotation movement, the rotational movement of SLE (Scissors Like Elements) will also bring about a translation movement, which in turn will create a scaling movement in a coating material attached to it.

Based on these basic movements, different adaptive facade designs have emerged. Mahmoud & Elghazi (2016) analyzed the illumination levels in the space by making a hexagonal facade module perform three basic movements, translation, rotating, and scaling. Associating the folding movement with origami, Lee & Leounis (2011) has revealed designs that differentiate these folding movements. Pesenti et al. (2015) and Elghazi & Mahmoud (2016) tried this origami-inspired design on the facade, and the daylight performance of this kinetic facade design is analyzed. Kim et al. (2015) compared a static facade design and a responsive kinetic facade design in terms of heating and cooling loads. The kinetic facade design controls the sun by opening and closing the panels according to the incidence angle of the sun vectors on the facade panels. Thus, it has been revealed that a building with a kinetic facade design is more sustainable and economical than a building with a static facade design. Studies on green facades are carried out on kinetic facades as well as on static facades. Globa et al. (2021) kinetic facades evaluated the concept of sustainability through green architecture. It has designed and prototyped a sustainable green facade module. The research aimed to grow plants in these modules and to benefit from solar energy in this way. These modules can rotate and make maximum use of sunlight.

The purpose and performance of adaptive facades consist of many parameters. With these parameters, adaptive facades can give different performances. Seyrek et al. (2021) revealed the parameters that make all kinetic facade designs energy efficient and evaluated the tools that analyze these parameters. The research classified the performance of the facades as daylight performance, thermal performance, acoustic performance, and resistance to decay. The performance of the facade is related to many parameters such as the location of the building, climatic conditions, and the purpose of use of the building. In Table 1, different kinetic facades are analyzed through building function, panel shape, kinetic module form, movement axis, material, movement type, facade function, and scale of kinetic module parameters. Although the facade function and building function are similar to each other, it is seen that there are new searches and tries in the geometry of the panels and the types of movements.

Table 1 Adaptive Facades and Analysis of Parameters

	Building Function	Panel Shape	Kinetic Module Form	Movement Axis	Kinetic Module Material	Movement Type	Façade Function	Scale of Kinetic Module
Instştude du Monde Arabe (IMA, 2016)	Office and museum	Rectangular, Circular			Stainless Steel	Aperture	Daylight Performance	Full-Storey High
RMIT Design Hub (RMIT Design Hub, 2013)	Research and post graduate education	Circular			Steel, Glass	Pivot	Enery Production	Multiple Number within Full-Storey High
ThysesenKrupp Quarter Essen Q1 Building (Q1, ThyssenKrupp Quarter Essen / JSWD Architekten + Chaix & Morel et Associés, 2013)	Office	Triangular			Stainless Steel	Folding	Daylight Performance	Full-Storey High
DOHA Tower (Karakuş, 2016)	Office	Butterfly			Alüminium	Retracting	Aesthetic	Multiple Number within Full-Storey High
Kiefer Showroom (Kiefer Technic Showroom/ Ernst Giselbrecht + Partner, 2010)	Office and Showroom	Rectangular			EIFS Panels	Folding, Sliding	Energy Effiency	Half-Storey High
South Denmark University Campus (University of Southern Denmark – Campus Kolding, 2022)	University	Triangular			Perforated Steel	Folding	Daylight Performance	Full-Storey High
Al Bahar Towers (Attia, 2017)	Office	Triangular			PTFE Panels	Folding	Daylight Performance	Multiple Number within Full-Storey High
India Expo 2020 Pavilion (Nagesh, 2022)	Pavilion	Rectangular			Rycled Industrial Aluminium	Pivot	Daylight Performans and Digital Show	Multiple Number within Full-Storey High
Apple Dubai Mall (Apple Dubai Mall/Foster+Partners, 2017)	Shopping Center	Rectangular			Lightweight Carbon Fibre	Folding, Sliding	Daylight Performance	Multiple Storey High
CJ R&D Center (Krymsky, 2011)	Research and Development Center	Triangular			Steel and Fabric Membrane	Folding	Daylight Performance	Half-Storey High

It is seen in the literature review that different movements and new geometry searches for different purposes in adaptable facades attract attention. KRF structures stand out with their potential at this point. It both contains new geometries within itself and has a different movement system. However, there are no reciprocal frame (RF) or kinetic reciprocal frame (KRF) structures in these kinetic facade systems. In addition, research on the architectural application of KRF structures is scarce and its application is very difficult. With the application of these KRF geometries as a facade system, a new solution will be found and these solutions need to be evaluated. This study aims to introduce KRF modules and evaluate their geometry and daylight performance by applying them on a facade. Therefore, it differs from other studies in that it discusses, researches and evaluates the applicability of KRF structures.

1.2 KRF Structures

Reciprocal frame structures are a type of structure that is made up of a combination of diagonal and vertical members that work together to provide strength and stability. Bavbrel & Olivier (2000) named each module that makes up this system a 'fan' and defined each element that makes up the fans as a 'nexor'. The book mathematically revealed the relationship between the elements of RF structures with each other. Asefi & Bahremandi-Tolou (2019), explained the process from the production to the use of these systems. The study is about the fabrication process, shared the connection details, and did a static analysis of several existing designs. Then determined which elements in this system had more stress.

Many static projects with Reciprocal Frame (RF) structures have been designed and studied without using columns such as sunshade pavilions, and circular houses (Pugnale & Sassone 2014; Popovic Larsen 2014; Chilton 2010). However, although these systems have kinetic potential in themselves, the number of studies on their applications is very limited or briefly mentioned at the end of the studies. RF structures, typically comprising interconnected elements that can move, change shape, and gain volume by rising in the z-axis, are constructed using a series of reciprocal bars or tubes, enabling a high degree of flexibility and movement. Such systems are called Kinetic Reciprocal Frame (KRF) structures.

KRF structures have low construction and maintenance costs as they can be used with sustainable materials, have high buckling resistance, replace damaged elements, offer design freedom as they can be produced with digital fabrication tools, and are lightweight Asefi & Bahremandi-Tolou (2019). In addition, since the system is integrally interconnected, even in complex designs, a small number of actuators can move the whole system. This reduces the energy consumption cost and construction cost of the system. Therefore, KRF structures can become an ideal solution for sustainable kinetic facade systems.

Chilton & Choo (1995) mentions a retractable roof design with the rotational motion of a roof formed with RF structures. This describes a design of KRF structures. These and many similar examples of KRF design remained at the conceptual stage and could not be elaborated. Nazarzadeh & Asefi (2022) discusses the movement mechanism of KRF structures in more detail and diversified and complicated the designs. By changing the support points of these designs, different types of movements have been achieved. It aims to increase structural performance by evaluating the movement mechanism.

The kinematic analysis of KRF structures is highly mathematical. A few input data determine all the remaining data. When the number of sides, element length, and thickness of the polygon are entered, many data such as the amount of elevation and the amount of translation at the joints are generated. Figure 1 shows the areas created by the KRF module moving. Data B describes the area of the polygonum, and data A describes the area created by the fans themselves. A=0 when the module is fully closed and A=B when it is fully opened. In order to make all these calculations easy, the fan thickness is assumed to be zero, but in a real model, the element thickness cannot be zero. That's why it is made by producing an algorithm for calculations.

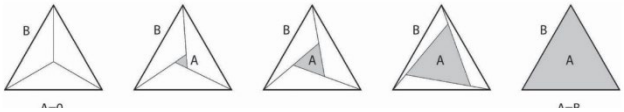
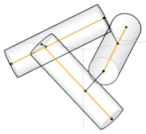
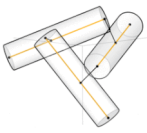
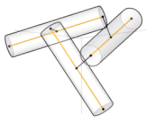
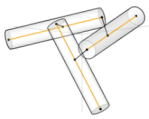
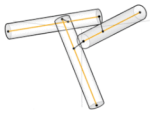
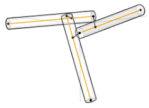
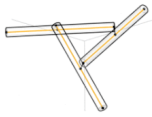
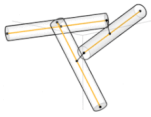
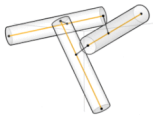
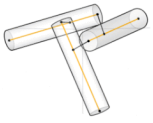
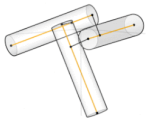
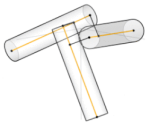
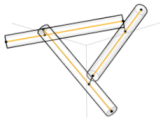
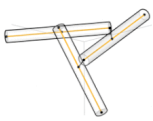
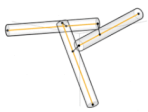
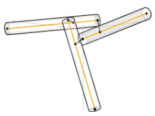
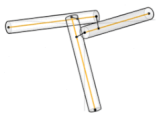
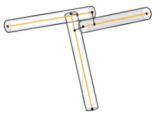


Figure 1 Openness and Closure Rates Created by the KRF mechanism (Nazarzadeh & Asefi, 2022)

Table 2 Movement Types of KRF Modules, (Vestartas & Petras, 2023) algorith is used to examine the action potential of reciprocal systems. Images are produced with this algorithm. For KRF modules new algorithm are produced.

	0.0	0.2	0.4	0.6	0.8	1.0
Moving Joints / Variable Thickness						
Fixed Joints/ Variable Thickness						
Moving Joints/ Fixed Thickness						

In order to make the application, calculations, and simulations correct, many algorithms are created by analyzing the KRF movements. Three movements can be made so that the ends of the elements can stay exactly on each other. These movements, as seen in Table 2, are divided into 6 different stages, as open 0.0 and closed 1.0, and examined. In the first part, the thickness of the elements should increase as the joints move. Otherwise, the system cannot be installed because there will be gaps between the fans. When the joints are fixed, the thickness of the elements must increase again in order for the ends of the fans to stay on each other. Else ways, the element length will be insufficient for closing and opening movement and the system will not be constructed. However, it is difficult to use an element with varying thicknesses in systems. When the fan thickness is kept constant, the joints must move to ensure that the ends of the fans stay on each other. Otherwise, the fans have to overflow over each other.

The fact that the joints move and the thickness and length of the fans change makes the applicability of these modules very difficult. Therefore, it is necessary to create a module where both the joints remain constant and the thickness and length of the fans do not change. In Figure 2, there are the stages of formation of a KRF module created using curvilinear fans instead of using flat fans. In this design, movement is made possible without changing the corners, element lengths, and thicknesses. Fans take a form in the curvature of the route drawn by the rotation movement from a corner point to the center point. Thus, a fourth type of movement is made possible.

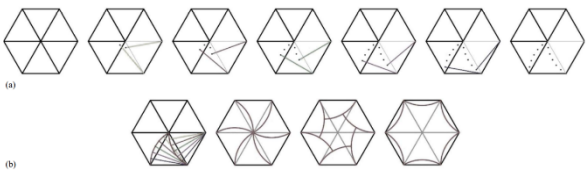
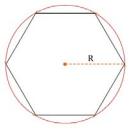
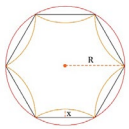
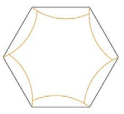
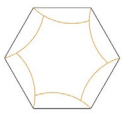
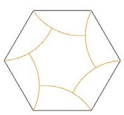
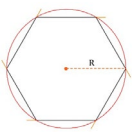
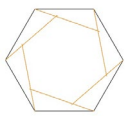


Figure 2 KRF Module with Curved Elements (Nazarzadeh & Asefi, 2022)

In Table 3, three different alternatives of the fourth movement type are compared from different angles and evaluated among each other. Since the radius of polygons is considered to be 2 meters, the length of a hexagon side is 2 meters. When curvilinear fans suitable for this geometry are used, one edge length increases to 2.1 meters. Module 1 is a KRF module with the same edge length but with flat elements. With this module type, the fans can move over each other at 0° to 5.4°, the system cannot be established between 5.4° and 54°, and the system can move again by overflowing over each other fans between 54° and 60°. As can be seen, the mobility of this module system is very limited.

Module 2 is an optimum module in which the fan length can be kept at a minimum level without overflowing with curvilinear fans. The mobility of this module is quite high and easy to be applied. Module 3 is a module formed with flat fans and has high mobility. However, in this module, the system closes properly only at 32°, and at all other angles, the fans overlap each other. While the element length is 2.1 m in the curvilinear module, it increases to 2.3 meters in this module. As the geometries change, the lengths of these elements increase, and the thickness of the fans in the real modulus will also affect the movement and may cause problems in the case of full closing and opening.

Table 2 Difference of Modules Created with Flat Elements and Curved Elements

	0° Rotated	5,4° Rotated	12,8° Rotated	19,2° Rotated	25,6° Rotated	32° Rotated	54° Rotated	60° Rotated	Module Info
Module 1									R = 2 meters Elements Length = 2.1 meters
Module 2									R = 2 meters Elements Length = 2.1 meters x = 0.28 m
Module 3									R = 2 meters Elements Length = 2.3 meters

2. Methodology

As seen in Figure 3, this study is analyzed in two stages. In the first stage, a geometric analysis of the KRF modules is performed. Using the Rhinoceros 3D/Grasshopper program, which is a parametric design tool, the algorithm of the kinematics of the KRF module is created, and then modules with different geometries are derived with this algorithm. Then these geometries are analyzed over cost, mobility, and geometry parameters. In the second stage, the daylight performance of KRF modules produced in different

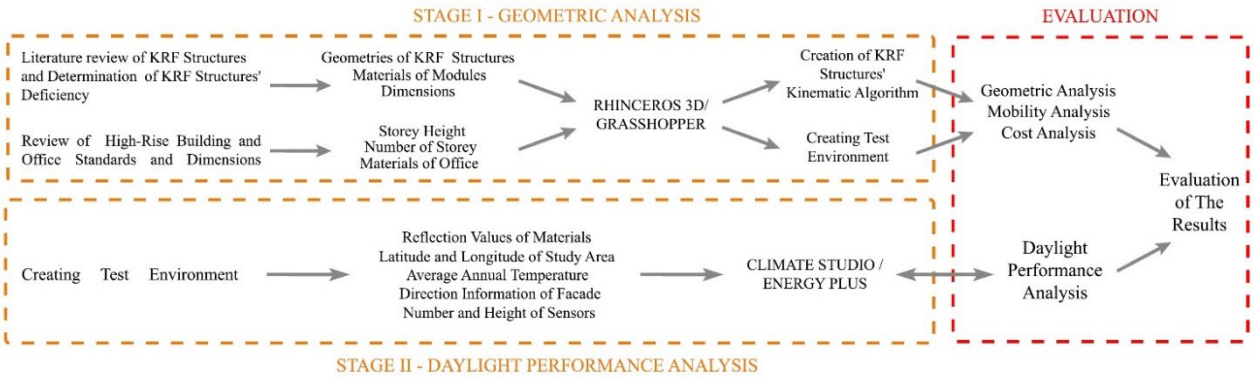


Figure 3 Workflow Chart

geometries is analyzed. For this evaluation, the south facade of a high-rise office building is selected as the test environment in Ankara, Turkey. Climate Studio, a fast and accurate simulation plugin created on EnergyPlus, is used for this analysis. With the results obtained here, the effect of KRF modules on the space is examined over spatial daylight autonomy (sDA), annual sunlight exposure (ASE), and average lux (avg. lux). Finally, by evaluating all these results together, it is aimed to find the most optimum one among the KRF modules in terms of use on the facade.

2.1 Case Study

The fans in the KRF modules are connected to each other with a single freedom sliding joint, allowing the fans to move over each other. Since one of the fans moving will move the other fans, the number of actuators required for the system has not changed from geometry to geometry, so it is not accounted for in the analysis. To define the open and closed surfaces on the module, a flexible fabric is attached to the gaps between the fans. Thus, the fans can change the open and closed surface ratios by stretching or relaxing the fabric while moving. The fact that the open and closed surface ratios can be controlled with the fan movements means that the modules can have control over the daylight.

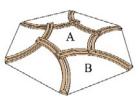
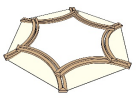
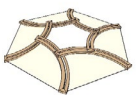
As the geometries of the modules change, many parameters such as fans lengths, areas of fabrics, sliding joints' lengths, mobility in unit rotation angle, closed area per angle, facade tesselation, and amount of elevation also change. It will not be fair and accurate to compare KRF modules with different geometries with these parameters. Therefore, an open and closed state will be defined for the modules over the ratios of their open and closed surfaces, and the stages between those definitions will be evaluated. The region marked with "A" in Table 4 and the area in the center of the modules represents the open area. "B" represents the entire area of the polygon in which the module is formed. In short, closed areas can be expressed as B-A. In other words, each module will act according to the size of its geometry and the evaluation will be made with these parameters.

The movement limit for all modules is set to 5A=B. In other words, the modules will continue to close until the open surface area is one-fifth of the entire polygon area. This ratio is determined by the fact that the light is not desired to be completely blocked, visual permeability, and the limited mobility of the octagonal module.

Table 5 shows all open and closed stages of the KRF facade modules in triangular, rectangular, pentagonal, hexagonal, and octagonal geometries. Since the story height is 4 meters for a standard office building, the diameter determined for the polygons is 4 meters. Each module is one story high. 20 cm wide and 5 cm thick wooden elements are preferred for the fans that make up the modules. A circular construction is created from pipe profiles with a diameter of 10 cm to carry the KRF modules. Since all polygons are derived from this circle, they can be supported in the construction regardless of the geometries.

The curvatures of the KRF modules are such that the fans that can form the module have the shortest length. As the number of elements of the KRF modules increases, the curvature of the fans increases, but the length of the fans decreases. This curvature value is constant for each geometry and depends on the diameter of the polygon, the thickness of the fans, and the amount of rise. However, no matter how short the curvatures are, all modules except the hexagonal module seem to overhang each other at least once during the opening and closing phases. While this curvature works perfectly in the hexagonal module, it becomes a limiting factor in polygons with more sides. The octagonal module at stage 1.0 in Table 5 cannot pass the ratio 5A=B. This is because the system locks itself at that stage and wants to get out of the sliding joint.

Table 3 KRF Modules' Open and Closed Stages

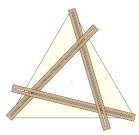
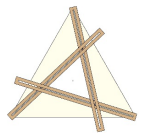
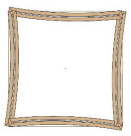
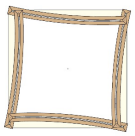
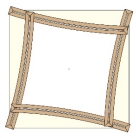
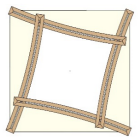
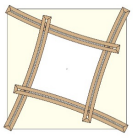
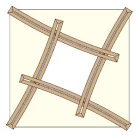
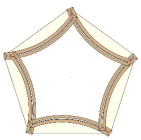
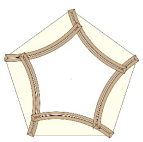
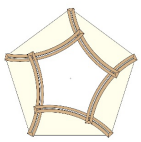
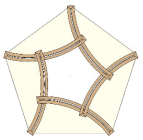
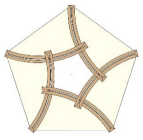
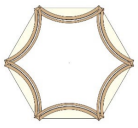
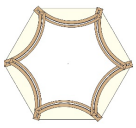
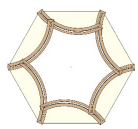
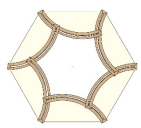
No Fabric, Open	With Fabric, Open	No Fabric, Close	With Fabric, Close
			

While all parameters are constant, it is observed that as the number of sides of the polygons increases, the amount of elevation increases. While there is not much difference in elevation between the triangular module and the rectangular module, the rising rate increases greatly after the pentagon module. In addition, as the number of edges increases, the angles that the modules have to close, that is, the distance that the fans have to move increases. While the angle of rotation required to achieve the 5A=B ratio is

17.1° for the triangular KRF module, it increased approximately 2 times to 32° for the hexagonal module. The closed area per angle value describes how much the unit angle change affects the amount of modulus closure. Since many parameters such as the curvilinearity of the geometries and the volume gained in the third dimension affect this value, these values do not seem to be proportional to the number of sides of the polygons.

Closed area per angle data is an average value since it is the total amount of closed area divided by the angle. The amount of increase in closed areas with changing angles is not homogeneous and varies from geometry to geometry

Table 4 KRF Module Geometries and Opening and Closing Stages

		0.0	0.2	0.4	0.6	0.8	1.0	Module Info
Triangle	Top View							Elements Length 3.46 m
	Side View							Amount of Rise 0.10 m - 0.16 m
	Rotation Angle	0°	3,4°	6,8°	10,2°	13,7°	17,1°	Closed Area Per Angle ~0,24 m²
Rectangle	Top View							Elements Length 2.84 m
	Side View							Amount of Rise 0.10 m - 0.17 m
	Rotation Angle	0°	4,9°	9,8°	14,2°	19,1°	24,5°	Closed Area Per Angle ~0,26 m²
Pentagon	Top View							Elements Length 2.45 m
	Side View							Amount of Rise 0.10 m - 0.24 m
	Rotation Angle	0°	5,5°	11°	16,4°	22°	27,4°	Closed Area Per Angle ~0,28 m²
Hexagon	Top View							Elements Length 2.19 m
	Side View							Amount of Rise 0.10 m - 0.27 m
	Rotation Angle	0°	6,4°	12,8°	19,2°	25,8°	32°	Closed Area Per Angle ~0,26 m²
Octagon	Top View							Elements Length 2.05 m
	Side View							Amount of Rise 0.10 m - 0.44 m
	Rotation Angle	0°	8,8°	17,6°	26,4°	35,2°	44°	Closed Area Per Angle ~0,2 m²

2.2 Performance Parameters

2.2.1 Study Area

Ankara, Turkey is a city where tall buildings are increasing in number and large glass facades appear without any control. The region is located at 39.925533 latitudes and 32.866287 longitudes. The location where the study is done is important because it affects the angle of incidence of the sun's rays, but parameters such as the direction of the facade and the height of the building or materials will not change the result since the evaluation is made between the modules themselves. In such harsh climates, energy consumption is higher and climate control becomes more important. The mobility of such facade designs makes them applicable on all facades. Table 6 shows the data obtained from the TMYx dataset for the region. TMYx dataset is data generated using the ISD (US NOAA's Integrated Surface Database) using the TMY/ISO 15927-4:2005 methodologies (Lawrie & Crawley, 2023).

Table 5 Study Area Climate Data (TMYx dataset)

Study Area Climate Data
Koeppen climate Zone: Temperate, Dry Warm Summer (Csb)
ASHRAE climate zone: Mixed (4)
Average annual temperature: 13 °C
Annual total solar radiation: 1,733 kWh/m2
Annual HDD for 18 °C is: 2,332
Annual CDD for 10 °C is: 2,052

2.2.2 Parametric Office Model

A standard high office building is preferred for the study. According to the Tall Building Council (CTBUH), a building with 14 floors or more than 50 meters is typically considered a tall structure. Since the floor height of an average office is 4 meters, the modules are designed with a diameter of 4 meters, and the dimensions are preferred as 4 and its multiples in order for the modulation to be smooth.

As seen in Figure 4 dimensions of the office space are 28 meters wide, 16 meters deep, and 4 meters high. The building has 15 floors and is 60 meters high. Only the south facade of the building is chosen as a glass facade, and the other facades are designed as closed. Although the facade designs change, the space dimensions remain the same. Thus, it is aimed to analyze the effect of facade designs on the space more clearly.

As for material preferences, it is aimed to choose standard materials that can be used in every office. Grey carpet material with 7,11% reflectance value is used for the floor, grey plaster material with 21,74% reflectance value is used for the wall material, IES LM-83 illuminated ceiling lm83 material with 70,00% reflectance value is used for the ceiling. The glass material is double-layered (from outside to inside, Solarban 70XL on Atlantica 6 mm, Krypton-EN673 12,7 mm, Clear Float Glass Clear 5.8mm) and has a U-value of 1,22 W/m².K, SHGC of 0,224. Galvanized steel with a value of 22.13% is used for the circular construction to be installed in front of the facade and to carry the panels. For the KRF modules, wood oak material, which is a sustainable material and has a reflectance value of 32.86%, is preferred. The membrane covering the modules is a white fabric material with 83.37% reflectance values.

2.2.3 Daylighting Simulations

For Daylighting simulations, LEED v4 design has been used as the standard and evaluations have been made according to these standards. According to IECC 2021 standards, the illuminance levels of office space should be between 300-500 lux. Evaluations are made by accepting 10 times these values as the limit so climate Studio parameters are set to measure between 500 lux and 5000 lux. Spatial daylight autonomy (sDA), annual sun exposure (ASE), and average lux (Avg. Lux) values are accepted as daylight performance measurement parameters.
Measurements are made on the first floor, eighth floor, and fifteenth floors (Figure 5). Sensors are placed on the floors decently 2 meters apart. A total of 135 sensors are used on every three floors. Annual measurements are made on these three floors while each module is at a different stage, and it is aimed to compare the performance of the facades by taking the average of these values. The office building is a closed system in itself with its glass facade. In these measurements, the KRF facade design plays the role of a parametric shading element. Since the construction required to carry KRF facade modules will change these values, the measurements are made without construction, with construction, and with facade modules.

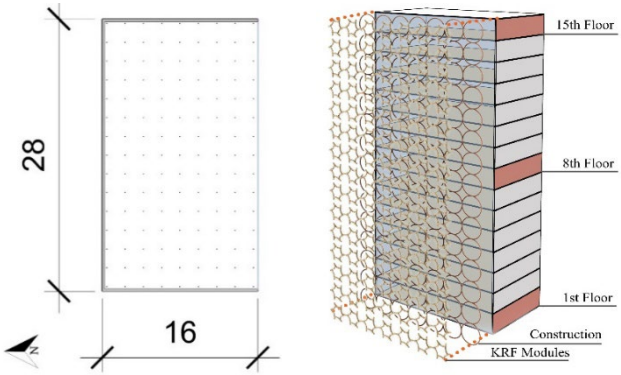


Figure 4 Sensor Placement on Test Model

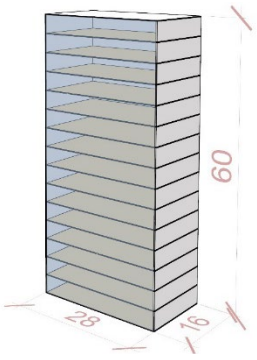


Figure 5 Test Model

3. Results

3.1 Stage I - Geometric Analysis

When the geometries of KRF modules change, their properties also change. As mentioned in the Case Study section, as the number of edges of the geometries increases, the modules get higher, and the shortening of the fans and their curvature increase. From the triangle to the hexagonal module, the mobility increases and improves, and after the hexagon, the mobility is restricted.

In Table 7, the costs of the facades created with different KRF modules have been analyzed and the construction cost has been ignored because the necessary sizes must be calculated with a static calculation. Current ministry unit price positions are used for the calculations, and the average of the values taken from several manufacturers is accepted for the data not included in these positions. Here, it reveals the relationship of the actual targeted prices with the geometries, independent of the original value.

Table 6 Cost Analysis of KRF Modules in Turkish Lira (TL)

	Waterproof Flexible White Fabric (200 ₺ for m²)	First Class Wood Elements	Metal Rail Joints (100 ₺ for metres)	Cost Per Module (₺)	Total Façade Cost (₺)
Triangle	834	888,8	1039,23	2762,03	290013,15
Rectangle	1296	969,21	1135,13	3400,34	357035,7
Pentagon	1640	1035,16	1222,69	3897,85	409274,25
Hexagon	1728	1088,63	1312,37	4129	433545
Octagon	1904	1371,78	1636,36	4912,14	515774,7

The cost analysis shows that the cost per fabric used for modules increases for triangular, quadrilateral, and pentagonal modules while it decreases for hexagonal and octagonal modules. This is related to the volume that the modules gain in the third dimension and the form that the fabric gains in line with this volume. The cost per wood used for modules decreases as the number of sides of the geometries increases. Therefore, the same can be said for the sliding joints (rail) installed on the fans. In terms of the total cost, the cost increases as the number of sides of the polygon increases. While the total cost of the facade for the triangular module is 290013 TL, the cost of the hexagonal module with twice as many elements did not double and cost 433545 TL.

Figure 6 shows the facade tessellations of the KRF modules. Although all geometries are derived from a circle, facade tessellations may not be smooth. When the modules are analyzed, the smoothest facade tessellation occurs in rectangular and octagonal modules. Since the joints do not touch each other in triangular, hexagonal, and pentagonal modules, irregular geometries appear in the gaps between the modules.

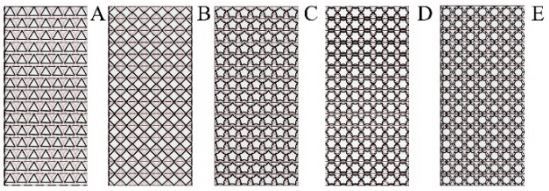


Figure 6 Facade Tessellations Triangle (A), Rectangle (B), Pentagon (C), Hexagon (D) and Octagon (E)

3.2 Stage II - Daylight Performance Analysis

The bare state of the facade is analyzed and then the one with the construction added is analyzed (Figure 7). In this way, by understanding the effect of the construction, clearer results are obtained regarding the effect of the KRF modules. The average lux value in figure 8A is 3098 lux, ASE is 33.3% and sDA is 84.9%. In figure 8B, the average lux value is 2617 lux, ASE is 33.3% and sDA is 76,8%. The added construction would not change the ASE value at all, it only slightly reduced the "over-lit" areas.

The values obtained as a result of the simulations are given graphically in Figure 8. In general, the triangular module and the

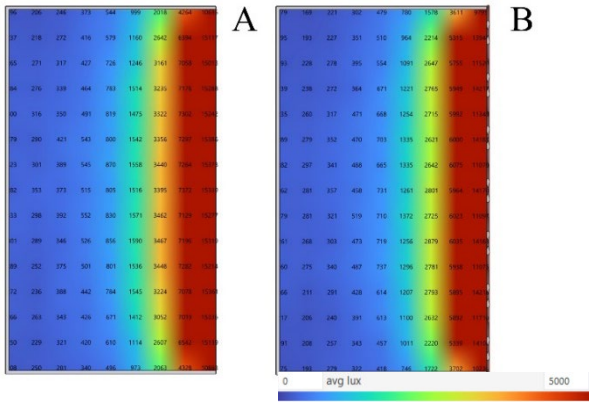


Figure 7 Average Lux Results Without Construction (A) and With Construction (B)

pentagonal module draw very unstable graphs, while the other modules draw more balanced graphs. Whereas the triangular module does not show a significant change in the sDA and ASE values, the pentagonal module shows a significant but unbalanced change and the hexagonal module shows a similar change in a more balanced way.

In Table 8, annual average lux values of six different phases between open and closed states of KRF modules with different geometries are given. Values are examined between 0 and 5000 lux, and values above 5000 lux are accepted as "over-lit" areas. As the values

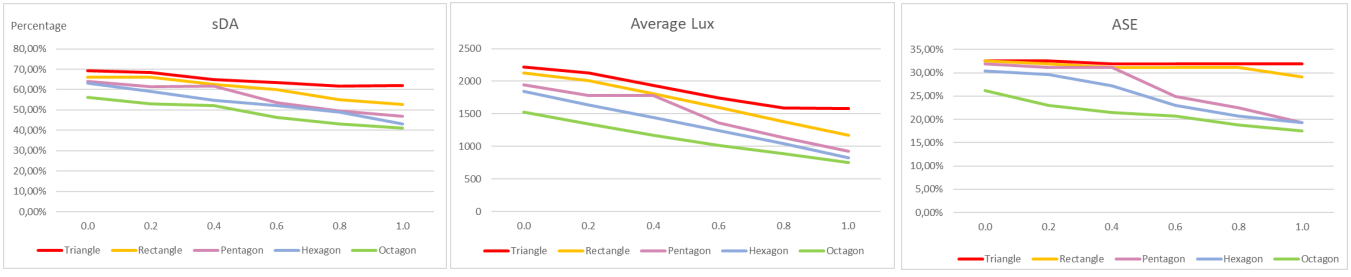


Figure 8 Spatial Daylight Autonomy (sDA), Average Lux (Avg Lux) and Annual Sunlight Exposure (ASE) Graphs by KRF Modules' Stages

approach 5000, the weight of the red color increases. The analysis of average values does not aim to measure whether the facade provides the necessary lighting for the office space but to analyze how much different geometries can control daylight. The 16-meter-deep office room is about 4 meters "over-lit" due to the light from the south facade. The triangular module is able to reduce this distance to about 3 meters when fully closed. All other modules are able to reduce the avg. lux value to below 5000 at stage 1.0 and provide the user comfort specified by the standards.

4. Evaluation Results

Without adding any facade to the design, all values are quite high and are far outside the comfort zone. The construction added before the KRF modules slightly change the values. While the ASE value is 33,3% and sDA is 84,9%, it is seen that the circular module construction designed to carry KRF modules does not change the ASE value, only reduces the sDA value by 8,1%. In other words, the areas that daylight can reach in the office space have decreased, but while doing this, their average lux value has decreased by 481 lux. Although these values seem to comply with IECC 2021 standards because the selected office building is very large, one-third of the space is outside the standards. It is understood from

Table 7 Daylight Analysis For KRF Modules

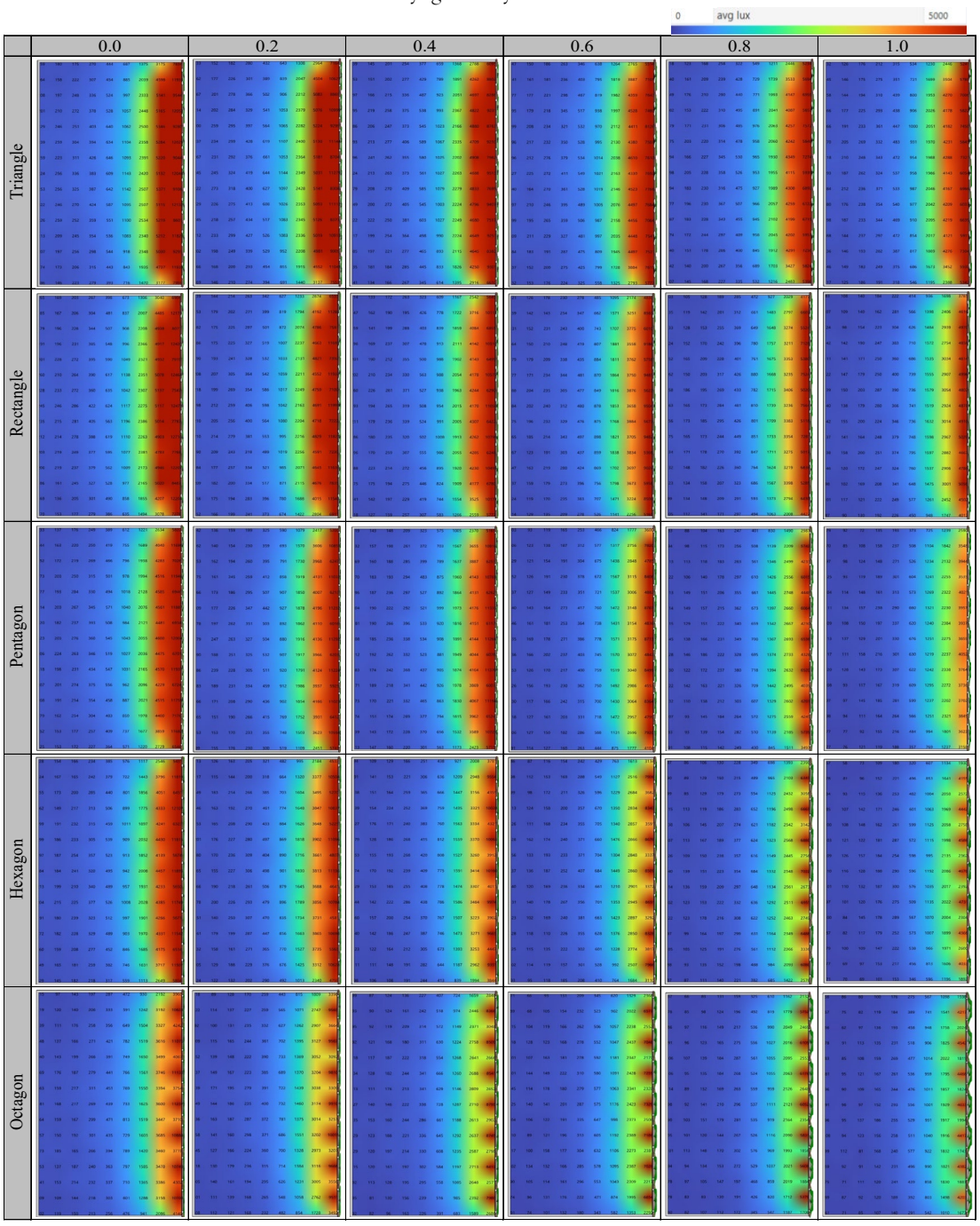


Table 8 that all KRF facade modules are effective in improving the visual environment and user comfort. Since the azimuth angle changes throughout the year, the facades need to gain volume in the third dimension to gain different angles for the control of these values. As seen in the values of the triangular KRF modules in Figure 7 it is seen that the greatest control is between the states of 0.2 and 0.8, and there is almost no difference between the stages of 0.8 and 1.0. It seems that there is almost no change in the ASE values. This shows that the triangular modules cannot provide sufficient solar control because they do not gain enough volume in the third dimension.

In rectangular modules, a homogeneous decrease is observed in the average lux value in direct proportion to the progress of the stages. However, despite this homogeneous decrease in lux value, a significant change in ASE values is seen only between 0.8 and 1.0 stages. The sDA values increased at the 0.2 stage and managed to stay above 60% until the 0.6 stage. Although rectangular modules provide better tessellation than triangular modules, there is almost no difference in the volume they gain in the third dimension. This explains the similarity of their graphics. Pentagonal KRF modules, on the other hand, can rise up to 14 cm from their existing height gain approximately 2 times more volume than triangular and rectangular modules. The most striking part of this module type is 0.4 to 0.6 phase. At this stage of transition, the ASE value decreased by 6,2% and the sDA value decreased by 8,1%. In the next stages, the values continue to decrease. As can be understood from here, the most effective form of pentagon modules is between 0.6 and 1.0 stages.

Hexagonal KRF modules draw homogeneous graphs at all values. Only 5.9% reduction is experienced in sDA value during the transition from 0.8 stage to 1.0 stage, the module closed itself and prevented the passage of sunlight to a large extent. The homogeneous decrease in all these values shows that the rising value and the ratio of open surface and closed surface are balanced, and this module type is ideal for climate control. When looking at the octagonal module in Figure 8, the octagonal module shows that the average lux value still draws a homogeneous graph, the sDA graph is irregular, and the ASE value does not change much after the 0.2 stage. In addition, in Table 8, it is seen that the system is good at blocking light, but it will have difficulties in getting light in winter months, which will create an increase in heating and cooling loads. It is seen that the average lux value is around 200 lux in December and January, even at the 0.0 stage, which is the clearest state (Figure 9). This shows that the system has problems receiving light.

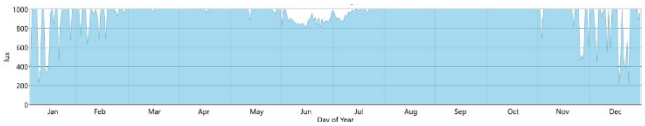


Figure 9 Average Lux Values of The Octagonal KRF Module At Stage 0.0 Throughout The Year

When the modules are evaluated in terms of cost-effectiveness, it is seen that the total cost increases as the number of edges of the geometries increases. Although the cost seems to increase as the number of sides of the polygon increases in Table 8, when the costs per element are considered, it seems that the costs decrease and reach a more optimum level. In this case, triangular KRF modules give the worst results in terms of both solar control and cost, hexagonal KRF modules are the most optimal module for solar control, and octagonal KRF modules are the most economical in terms of cost.

In terms of mobility and daylight performance, the hexagonal KRF module turned out to be the most optimum. This is evidenced by the fact that the system moves and rises sufficiently and thus can control the sun rays at different angles, then drawing more homogeneous graphics. In addition, the fact that it performs better than other modules in terms of cost-effectiveness supports this.

5. CONCLUSION

Although Reciprocal Frame (RF) structures are a system that is frequently used in architecture and a lot of research has been done about it, the applications of KRF structures in architecture are one of the points that have been overlooked. Each KRF module is energy efficient as it can move with a single actuator as it has its own kinematics compared to other kinetic systems. It has a strong potential for sustainable architecture as it has low construction and maintenance costs and can be used with sustainable materials. This study has produced kinetic facade modules based on the geometric analysis of existing KRF structures and aims to find the optimum one by comparing them among themselves in the simulation results. Although all KRF facade designs help in daylighting performance, triangular modules give the worst result among these designs, while hexagonal KRF modules give the most optimum result.

This study analyses the geometric and daylight performance ofKRF modules and evaluates them in terms of mobility, cost and visual comfort. In order to fully analyze the energy efficiency of KRF modules, the algorithm of the openness and closure ratios of the modules should be created in a way that changes depending on the sun. In addition, it is very difficult to analyze the energy consumption exactly as the fully closed modules will increase the use of artificial lighting. To improve this study, KRF modules can be used individually on the facade, as well as the entire facade can be designed as a KRF. Thus, a more holistic facade design can be achieved by getting rid of the uncontrolled blind spots caused by the tessellation of the modules.

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Conditions for Implementing Windowless Offices in High-Density Urban Centers of Malaysia: A Bibliometric and Systematic Review

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ABSTRACT

The dearth of land in high-density urban centres necessitates constructing structures with deep interiors, with little or no connection to the external environment. Additionally, the negative relationships between high-rise structures in the city centres in recent times are increasingly making contact with the outdoor environments undesirable. Whether in the built environment, decision sciences, healthcare, or technological disciplines, there is a need to understand the factors necessary for windowless office implementation, its prominent researchers, and geographical contexts, among other conditions for practical application. These background variables could assist in arriving at emerging themes, problems and gaps for concrete windowless office development in Malaysia. In this systematic review, the bibliographic information of title, abstract and keywords was mined from 255 documents on the Scopus database to generate scientometric maps and links showing relationships on co-authorship, co-citation, co-occurrences, and bibliometric coupling. The top trending variables in windowless office research are COVID-19, energy efficiency, indoor air quality, heart rate variability, performance assessment, visual reality, and workplace environment. Like other advanced economies in Asia, Malaysia is seen to attain a satisfactory level of development to implement the windowless office design module, with stable electricity power, technological advancement, and psychological stability of the people. The emerging variables in this review will give novel directions in exploring the developmental, psychological and health conditions for effective windowless office implementation in the country and similar economies in Asia, Africa and South America, where metropolises are fast becoming compacted due to ever-growing city centres.

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1. Introduction

From the earliest times, human beings have always sought protection from natural conditions. Paradoxically, since people began to live in buildings, conscious efforts have been made to reunite with the outdoor environment through fenestrations (Martin, Maris, & Simberloff, 2016; Sato & Inui, 1994). However, in urban centres today, air pollution, incessant noise, and other negative spatial relationships make contact with the outdoor environments increasingly undesirable.

Moreover, excessive construction of buildings in built-up sections of metropolitan areas has created an urgent need for ever more efficient use of space. As a result, buildings are becoming more prominent and compacted together, leading to complete windowless offices or virtual windowless spaces with considerable distance from windows. In many instances, efforts are increasingly being made to create more effective use of windowless underground spaces and basements as office spaces (Boubekri et al., 2020; Mahyuddin et al., 2022; Yap et al., 2021). Other times, fenestration is controlled in large building spaces for security considerations, disaster prevention, or production of precision equipment, such as factories and power plants, by creating windowless environments due to functional requirements. A windowless environment could therefore be seen as a spatial configuration without any windows or a space where workstations are far from windows, without any exposure to direct natural daylight (Boubekri, Cheung, Reid, Wang, & Zee, 2014).

Psychologically, Ko et al. (Ko et al., 2020) find a passive relationship between views from a window on thermal comfort, human emotion, and the cognitive performance of occupants. Nevertheless, these associations are modified in windowless offices. On their part, Sato and Inui (1994) found that windowless office spaces have adverse effects on human behaviour. Research indicates that people who feel tense and entrapped sometimes perceive claustrophobic symptoms when staying in windowless spaces for a prolonged period.

Additionally, findings indicate that windowless environments affect occupants' attention to work and sleep quality, with attendant effects on individuals and society in general, leading to workplace accidents, mistakes, and errors, thereby decreasing productivity (Boubekri et al., 2014; Canazei, Pohl, Bliem, Martini, & Weiss, 2017). Besides interior decorations to mitigate the psychological impact, workers in windowless offices also bring to their workplace items such as natural plants, pictures of plants and landscapes, among other personal items, to improve indoor air quality and control their stress levels (Bringslimark, Hartig, & Patil, 2011; Dolan, Foy, & Smith, 2016; Mahyuddin et al., 2022). Understanding the potential adverse effects of staying in windowless environments, according to Canazei et al. (2017), is, therefore, of necessity.

In practice, Goharian and Mahdavinejad (2020) note that deep-plan buildings, or windowless offices, require advanced light transmission systems to compensate for lighting demands for effective performance. Interestingly, technological advancements in lighting, ventilation, and air conditioning are also rapidly providing supportive solutions to physical openings in institutional buildings, resulting in the planning and design of windowless offices. Furthermore, research is being carried out to optimize daylight performance and obtain energy efficiency in the windowless indoor environment through digital windows, Circadian System Entrainment, Fiber Optics Daylighting System, and virtual reality, among other scientific monitoring procedures, theoretical calculations, and computational simulations (Chen, Zhang, & Du, 2020; Sithravel & Ibrahim, 2021).

Besides the psychological consequences, Bringslimark et al. (2011) see massive benefits of windowless office modules in compacted city centres, shielding buildings from pollution and noise, among other negative impacts between structures. Consequently, as buildings are increasingly becoming larger, deeper and more compact due to the windowless design style, more research is necessary to mitigate the attendant challenges associated with the design and developmental model. Whether in the built environment, decision sciences, healthcare, or technological discipline, there is a need to understand the current research direction in windowless offices, conditions for its practical application, environmental contexts, and prominent researchers of the system before arriving at the emerging problems and gaps for more productive studies. This study, therefore, reviews the physical, psychological, technological and economic conditions for effectively implementing windowless office design modules in Malaysia, among other fast-developing economies.

In brief, this article's introduction mentions the historical human quest for shelter and relates it to the current trend of windowless office spaces due to urban challenges. It also explores their psychological and practical impacts on occupants, emphasizing the need for research to optimize such designs in rapidly developing economies like Malaysia, addressing physical, psychological, technological, and economic aspects.

2. Methodology

The methodology for this study involves a systematic description of decisions made in selecting document sources, data screening, excluded materials, analysis tools, and data presentation choices, as shown in Figure 1. The data identification, screening, inclusion and exclusion in this study utilized the Systematic Review approach based on the principles of PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Page et al., 2021). Accordingly, the PRISMA principles include "identifying" articles through keywords, "screening" the sources to exclude extraneous materials and deciding on the materials to be "included" for further evaluation (p.5). In addition, this study was limited to the Scopus database in the materials identification to avoid complications accompanying data analysis from varying sources using the VOSviewer software in its current edition.

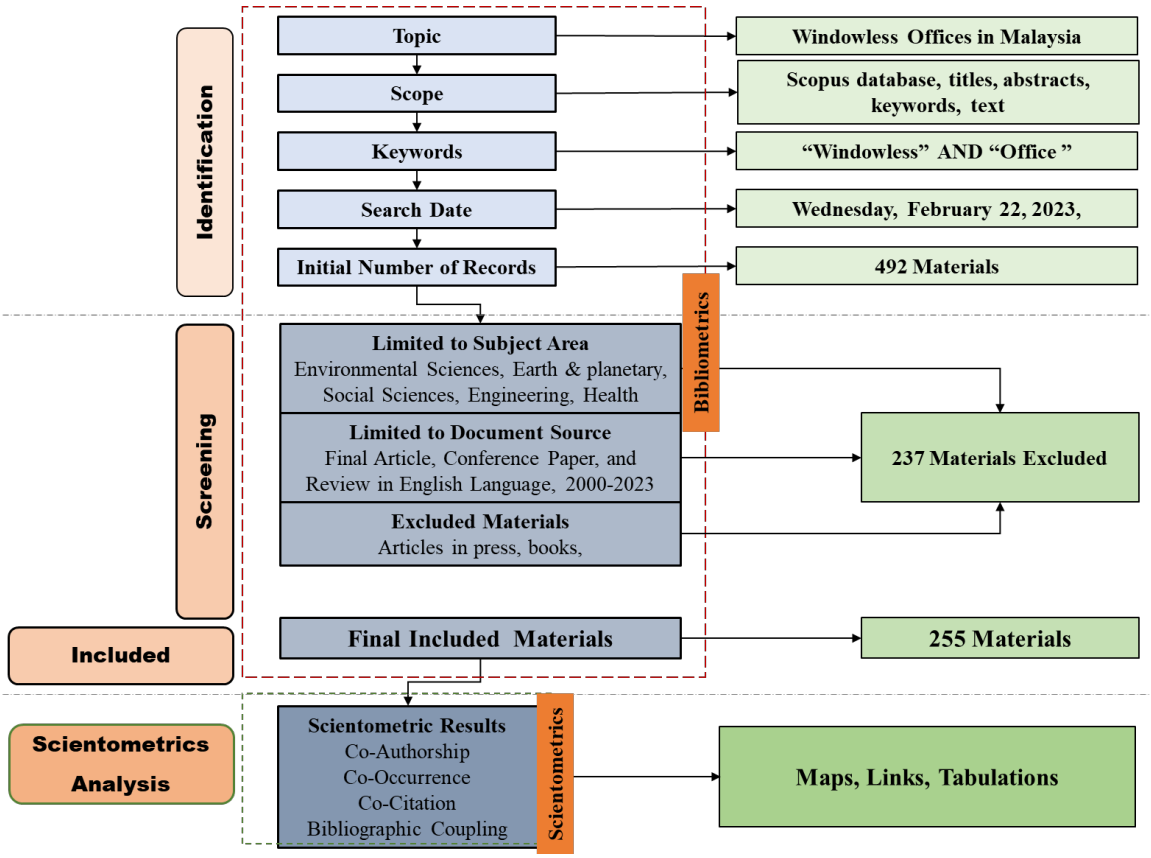

Figure 1 Systematic Data Source Identification, Screening, and Inclusion in Windowless Office Research

2.1 Database

In this study, a database could be seen as an organized collection of structured information, or data, typically stored electronically in a computer system. Therefore, the Scopus database was utilized as this study's source of materials owing to its broader pool of indexed publications. In addition, researchers recognize the Scopus database as a superlative archive regarding the number of satisfactory-quality materials (Peter, Majid, & Tukiman, 2023; Tanko & Mbugua, 2021). Therefore, the broader coverage of the Scopus database avails more materials in this study's search query. Furthermore, since its inception in 2004, the Scopus database has increasingly become a top choice for publication due to its comprehensive nature, including research from a wide variety of subjects (Abbas, Jusoh, Mas'od, Alsharif, & Ali, 2022; Ghaleb, Alhajlah, Abdullah, Kassem, & Al-Sharaf, 2022; Sahi et al., 2022). Another justification for choosing the Scopus database for this analysis is its provision for mining up to 2,000 documents simultaneously for scientometric data evaluation using the VOSviewer software (Zakka, Abdul Shukor Lim, & Chau Khun, 2021).

Therefore, the study relies on the comprehensive Scopus database, acknowledged for its vast, high-quality materials across diverse subjects, chosen for its broad coverage and suitability for mining up to 2,000 documents simultaneously for scientific data analysis using VOSviewer software. Furthermore, utilizing the Scopus database for this analysis is justified based on its broader coverage and provision to mine a more comprehensive range of materials into the VOSviewer analysis tool.

2.2 Data Identification

Data identification may be seen as a set of activities to systematically define the set of information processes of a study and establish clear prioritizing criteria (Ali & Faruquie, 2015). For example, identifying published materials in the "windowless office in Malaysia" subject area returned negligible results. However, expanding the query onto "windowless AND office" yields 492 initial documents. The resulting documents encompass all materials that mentioned the searched terms individually or collectively in their title, abstract, keywords, and paper body. The limited results of the search query carried out on February 22, 2023, confirm the novelty of the research area. Therefore, this study explores data identification as a systematic process to define information priorities, noting that a specific search for "windowless office in Malaysia" yielded minimal results while broadening the query to "windowless AND office" produced 492 initial documents, confirming the novelty of the research area by encompassing materials mentioning the terms in various contexts.

2.3 Data Screening

Data screening in systematic review involves an examination of data properties to eliminate variables that do not match the research questions but may affect the interpretation of results

from statistical models (Cheshmehzangi, 2015; Wang, McKee, Torbica, & Stuckler, 2019).

Data screening was necessary for this study to streamline the materials and attain the standards for utilizing the VOSviewer analysis tool. The search query was further examined to define the data and eliminate materials that are not directly related to the subject area. First, the document sources were restricted to journal articles, conference proceedings and review papers written in English, excluding articles in the press, book chapters, and editorial notes. A limitation was also placed on the subject area covering papers in engineering, built environment, social sciences, medicine and health disciplines.
Consequently, materials in mathematics, chemistry, biology, and veterinary medicine were excluded. Also screened were materials in the press, book chapters, and editorial notes, among other documents published earlier than 2000. With the screened materials identifying excluded and included documents, the final query search was executed as follows:

> ALL (windowless AND office) AND (EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "ECON") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "VETE") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "PHAR")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (PUBYEAR , 2000 - 2023)) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "d")) AND (LIMIT-TO (LANGUAGE , "English"))

The final results of 255 materials were included and utilized in the ultimate analysis from the data screening: As the Scopus database supports the export of up to 2,000 materials at a time to the VOSviewer software (van Eck & Waltman, 2022), the final query results were deemed sufficient to conduct further analysis.

In brief, data screening, a critical part of systematic review, involves refining materials to meet analysis standards; in this study, the process involved excluding irrelevant data sources and narrowing the subject area to disciplines like engineering, social sciences, and medicine, ultimately using 255 materials for analysis in VOSviewer, meeting the software's capability of handling up to 2,000 items from Scopus.

2.4 Data Inclusion

With the satisfactory results of including materials, the 255 materials were exported as CSV (comma-separated values) files into Microsoft Excel, along with their bibliographical and reference contents. Other important bibliometric information includes author names and affiliations, journal type, and rankings, most of which are available in the Scopus database. The included materials were finally exported and downloaded as a single Microsoft Excel file to the computer system and loaded into the VOSviewer software for the scientometric analysis (Krauskopf, 2018). Eleven documents that were found to incorporate "windowless office" directly in their title, abstract, or keywords were utilized for an in-depth systematic review, analyzing the variables, methods and tools to reveal gaps and trends for further studies.

In brief, after exporting the 255 materials from Scopus into Excel, important bibliometric data like author details, affiliations, and journal rankings were gathered, allowing comprehensive analysis using VOSviewer software. Out of these, 11 documents specifically addressing "windowless office" were further scrutinized for an in-depth systematic review, examining variables, methods, and trends to identify gaps for future studies.

2.5 Data Analysis Tool

The VOSviewer computer program version 1.6.18.0 was utilized for the bibliometric and scientometric evaluations. VOSviewer is a free computer software for scientific data analysis and producing graphical outputs (van Eck & Waltman, 2022). Scientometrics involves an objective and reliable review of defined material source(s), converting qualitative information into quantitative data by creating graphical relationships (Oladinrin, Gomis, Jayantha, Obi, & Rana, 2021). According to the software producers (van Eck & Waltman, 2022), VOSviewer is a software application for building maps based on network data, and displaying and investigating these maps. It is used for creating maps based on network data, graphical visualizations, and pragmatic explorations to create meaningful relationships. In reality, the computer software creates distance-based network maps where the distance among nodes indicates closeness and connections (Oraee, Hosseini, Papadonikolaki, Palliyaguru, & Arashpour, 2017).

Data previously exported from the Scopus database were inputted into the VOSviewer software, units of analysis were selected, and results were generated as map-based co-authorship, co-occurrence, and co-citation, among others. The results established relevant information concerning critical linkages to authors, journals, and research topics, highlighting novel areas for further productive research directions.
As an analysis tools summary, the study used VOSviewer, a software for scientometric analysis, to process data exported from Scopus, creating graphical representations like co-authorship, co-occurrence, and co-citation maps. These maps reveal meaningful connections among authors, journals, and research topics, identifying areas for further research directions.

3. Results and Discussion

The findings from this scientometric review were analyzed based on the bibliometric information obtained in the Scopus database and the network maps generated from the VOSviewer program. Subsequently, the results were examined regarding document type, prominent authors, top journal source, co-authorship, co-citation, co-occurrence and bibliometric coupling to reveal trending keywords in windowless office research.

3.1 Analysis of Documents

The analysis entails distributing mined materials into different disciplines concerning the application of windowless office design. A limitation was also placed on the Source Type of the mined materials from journal articles, reviews, and indexed conferences. By these search preferences, more than 83% of mined materials were journal publications, 15% were conferences, and the remaining two per cent were review articles. The higher percentage of indexed journals and sources affirms the data as authoritative and reliable (Oguntona, Aigbavboa, & Dywili, 2022; Zakka et al., 2021). Distribution of the Subject Area shows that about 24% of the material mined falls into Engineering, 20% Environmental Sciences, 16% Social Sciences, and 10% Medical and Health Sciences, among other traces of Agriculture, Psychology, Energy, Computer and Material Sciences, Art and Humanities. The document analyses were done using the bibliographic information in the Scopus database. The Modal frequency of publications on windowless offices in Engineering and Environmental Sciences confirms its importance and applications in the disciplines. As presented in Figure 2, the document analysis categorizes materials by discipline in the context of windowless office design, primarily sourced from journals, conferences, and review articles, highlighting the authoritative and reliable nature of the data. Over various fields, such as Engineering and Environmental Sciences, the modal frequency of publications emphasizes the significance and application of windowless offices in these disciplines.

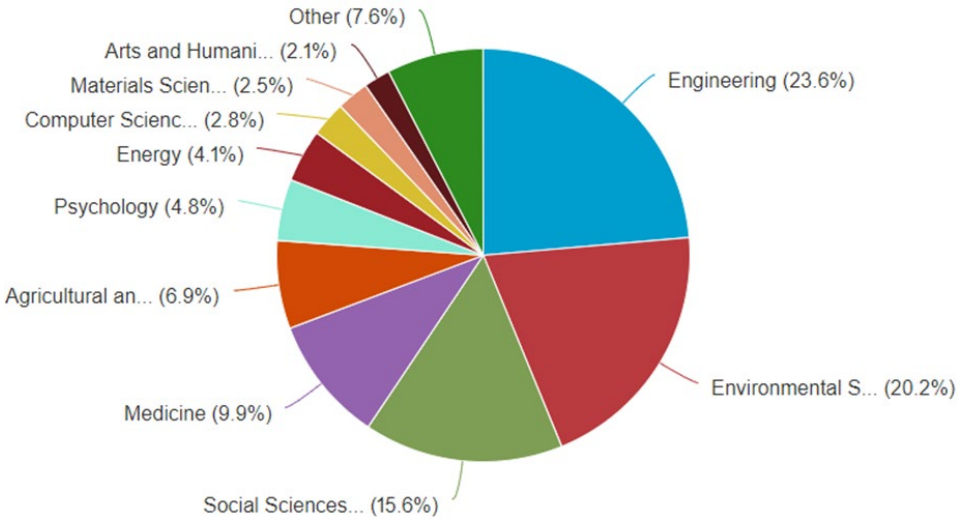

Figure 2 Distribution Documents Based on Subject Area

Furthermore, with the restriction in Year of Publication between 2000 and February 2023, the results show active research on windowless offices in 2000, as shown in Figure 3. However, it was not until 2010 that more than ten materials on the subject matter were published. The sudden rise of publications on windowless offices, reaching an all-time peak of 31 documents in 2020, indicates its potential and applications in the post-COVID-19 era. The surge of publications in 2020 may be better appreciated with the "two-period moving average" on the graph. The phenomenon confirms the increasing attention paid to windowless office buildings, especially in Europe, North America, and, most recently, Asia's more advanced countries (Chen et al., 2020).

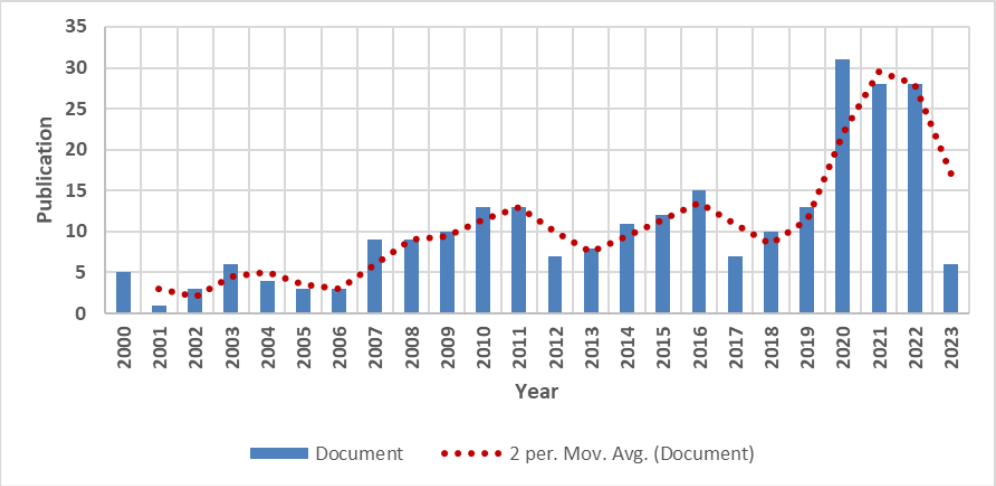

Figure 3 The Sudden Rise of Publication on Windowless Office in the Post-Covid 19 era.

In brief, the study restricts publication from 2000 to February 2023, revealing a significant increase in materials on windowless offices from 2010, peaking at 31 documents in 2020, signalling growing interest and potential applications post-COVID-19. The "two-period moving average" illustrates this surge, highlighting the increasing focus on windowless office buildings by different authours, notably in Europe, North America and emerging in Asia's more advanced nations.

3.2 Top Authors in Windowless Office Research

This section presents the prolific and most cited authors in Windowless Office Research (WOR), their respective disciplines, impact and links to other authors. In this study, the top authors include those with at least four documents from the query outcome. Knowledge of the top authors in the study area is necessary to spur research interest, encourage collaboration, and enhance interdisciplinary networking for interdisciplinary productivity (Khudzari, Kurian, Tartakovsky, & Raghavan, 2018; Yu, Wang, Zhang, & Zhang, 2018). Additionally, new scholars in the subject area will have direction concerning the authors to follow, their articles, and their impact. Besides the authors' names, their respective number of articles, citation metrics, and disciplines were also captured alongside their most cited publications and scientometric links, respectively, as shown in Table 1. Though the authors were ranked according to the resulting documents in the query string, their h-index impact, representing the citation ratio per document, was also computed.

Table 1: Bibliometric Analysis Showing Top Researchers on Windowless Office

S/N	Author	Discipline	Doc. in Query	Total Pub.	Total Cita.	h-index	Co-Auth. Link	Co-Cita. Link	Most Cited Article in Subject Area
1	Hong, T.	Architecture	5	238	5,610	40 (5)	16	31.00	(Yeom, et al, (2020)
s2	Patil, G.G.	Healthcare	5	44	1,859	21 (7)	11	31.97	(Grinde & Patil, 2009)
3	Soh, C.K.	Engineering	5	247	7,263	45 (4)	30	18.83	(Roberts, et al. 2016)
4	Andersen, M.	Architecture	4	145	2,495	29 (6)	13	53.76	(Andersen, Mardaljevic, & Lockley, 2012)
5	Boubekri, M.	Architecture	4	38	742	13 (9)	9	64.57	(Boubekri et al., 2020)
6	Car, J.	Healthcare	4	417	23,823	71 (1)	26	11.84	(Roberts et al., 2016)
7	Christopoulos, G.I.	Business	4	66	1,307	17 (8)	21	16.59	(Roberts et al., 2016)
8	Han, K.T.	Architecture	4	25	676	11 (12)	3	28.28	(Han, 2009)
9	Hartig, T.	Planning	4	129	15,454	56 (3)	7	268.22	(Bringslimark, Hartig, & Patil, 2009)
10	Lockley, S.W.	Healthcare	4	285	16,624	62 (2)	8	56.47	(Andersen et al., 2012)
11	Lohr, V.I.	Architecture	4	32	1,099	14 (10)	4	15.82	(Relf & Lohr, 2003)
12	Roberts, A.C.	Engineering	4	47	554	14 (11)	26	12.81	(Roberts et al., 2016)
13	Yeom, S.	Architecture	4	14	284	8 (13)	14	14.62	(Yeom et al., 2020)

Note: Doc. (Documents); Pub. (Publications); Cita. (Citations); Auth. (Author)

Bibliometric analysis of the search results shows that Hong, T., Patil, G. G., and Andersen, M., are the most prolific publishers on WOR, with five documents each. Other ten authors complete the prominent researchers in the subject area, with at least four publications each. Outside the query search, the bibliometric information of the top authors, as captured on the Scopus database, indicates that most of them published more than ten articles, with Car, J. (417); Soh C. K. (247), and Hong, T, (238) standing out brilliantly. In terms of research impact, representing the number of citations per document, Car, J. (71), Lockley, S. W (62), and Hartig, T. (56) are worth mentioning. More than 53% of the top authors in the study area are in Architecture and Planning, with the remaining shared in the 3:2:1 ratio among Healthcare, Engineering, and Business. The distribution also confirms the central position of Architecture as a discipline in the planning and designing of office spaces for optimum human comfort (Chantzaras, 2019; Jutraz & Zupancic, 2014).

Furthermore, the mined materials from the Scopus database, saved as CSV MS Excel documents, were loaded into the VOSviewer software as Bibliographic Data from Reference Manager File, producing co-authorship, co-citation, co-occurrence and bibliometric coupling. The Scientometric analysis generated co-authorship links among the authors with at least one document from the resulting query search. By definition, co-authorship entails establishing academic collaboration and teamwork among authors by publishing research materials to address some interdisciplinary concerns (Oladinrin et al., 2021; Peter et al., 2023). Emphasizing the need for co-authorship analysis, Adegoriola, Lai, Chan, and Amos (2021) view the lack of scientific collaboration as a signal of lower research output, evident in inadequate productivity. From the co-authorship analysis in VOSviewer, the top collaborators in windowless research include Soh, C.K., Car, J., and Roberts, A.C., each with more than 25 links with other scholars across disciplines.

In today's world, interdisciplinary research is encouraged as many problems are immune to treatment from a single discipline perspective. That is why co-citation analysis is necessary to establish relationships among published documents for concrete solutions to novel problems. According to Wang, McKee, Torbica, and Stuckler (2019), co-citations are carried out to gain insights into the disciplines contributing to an area of research. Co-citation analysis is a technique for scientometric mapping which assumes that some publications frequently cited together have some similarities in theme or structure (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2021; van Nunen, Li, Reniers, & Ponnet, 2018). Generally, researchers agree that article co-citation is a commonly deployed methodology for defining the relationships within a specific scientific domain (Estevão, Garcia, Filipe, & Fernandes, 2017; Hosseini et al., 2018). Additionally, Donthu et al. (2021) stressed the benefits of co-citation analysis, including finding the most influential authors or publications and discovering thematic clusters by scholars.

In this review, the author's co-citation links were extracted in the VOSviewer analysis of the published materials on WOR. The co-citation analysis was performed on authors with at least twelve publications from the data mined from the Scops database, a point with clearly defined themes. As van Eck and Waltman (2014, 2022) recommended, the fractional counting result identified five main themes or disciplines involved in WOR publications. In brief, the Top Authors section highlights influential authors and their impact on Windowless Office Research (WOR), emphasizing the importance of understanding these key figures to foster collaboration and interdisciplinary connections. The study showcases top authors, their publication metrics, and disciplinary impact, indicating Architecture's central role in designing office spaces for optimal comfort. Additionally, the analysis explores co-authorship and co-citation links among researchers, underscoring the need for interdisciplinary collaboration and thematic clustering for effective problem-solving in this field.

As presented in Figure 4, the five major disciplinary themes generated from the co-citation analysis, with their respective central authors included Ulrich, R. S. in Healthcare (deep yellow); Hartig, T. in Planning (green); Lohr, V. I in Architecture (blue); Veitch, J. A. in Psychology (red); and Lockey, S. W in Sciences (light yellow).

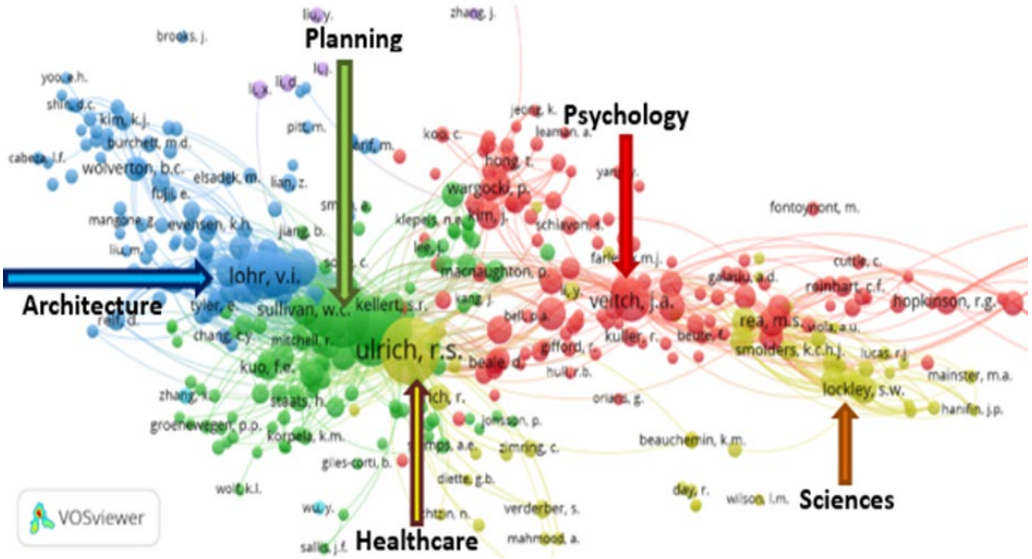

Figure 4 Five main disciplines emerged from the Co-Citation analysis of Windowless Office Research. (Available at https://tinyurl.com/2f88ppc5)

Interestingly, the co-citation analysis also reveals the passive contributions of Ulrich, R. S, Kaplan, R. S., and Veitch, J. A., whose works are extensively cited by many researchers in the subject area. From the analysis of top authors, co-authorship, and co-citations in WOR, the three most prominent authors are seen to be Hartig, T., Lohr, V. I., and Lockey, S. W., representing Planning, Architecture and Sciences, respectively.

In brief, the co-citation analysis identifies five major disciplinary themes in Windowless Office Research (WOR) linked to crucial authors like Ulrich, Hartig, Lohr, Veitch, and Lockey, showcasing their passive but substantial contributions, with Hartig, Lohr, and Lockey emerging as the prominent figures in Planning, Architecture, and Sciences within WOR research.

3.3 Journals Publishing Windowless Office Research

This section presents the top journals in which WOR outputs are published. Scholars setting out to contribute to the development of the subject area need to follow the top journals to identify current trends and topical issues, concrete research problems and substantial gaps for conducting practical research outcomes, as presented in Table 2. The journals were also first ranked according to the number of documents resulting from the query search in the Scopus database.

Table 2: Top Journal Sources with Publications on Windowless Office Research

S/N	Journal Name	Doc. in Query	Total Pub.	Total Cita.	Cite-Score 2022	Co-Cita. Link	Biblio. Coupl. Link	Most Cited Article in Subject Area	Publisher
1	Building and Environment	34	3,327	36,930	11.1	137.0	653.9	(Ko et al., 2020)	Elsevier
2	Journal of Environmental Psychology	12	488	5,042	10.3	284.2	428.5	(Aries, Veitch, & Newsham, 2010)	Elsevier
3	Horttechnology	11	837	883	2.3	137.5	157.8	(Lohr & Pearson-Mims, 2000)	American Society for Horticultural Science
4	International Journal of Environmental Research and Public Health	10	44,778	234,677	5.2	33.4	261.7	(Grinde & Patil, 2009)	Multidisciplinary Digital Publishing Institute (MDPI)
5	Lighting Research and Technology	9	234	1,360	5.8	55.9	203.8	(Jakubiec & Reinhart, 2012)	SAGE
6	Environment and Behavior	8	156	2,104	13.5	274.9	220.6	(Kaplan, 2001)	SAGE
7	Indoor and Built Environment	8	472	2,639	5.6	44.9	202.5	{Formatting Citation}	SAGE

8	Buildings	6	3,251	10,049	3.1	166.5	127.1	(Dolan et al., 2016)	Multidisciplinary Digital Publishing Institute (MDPI)
9	Hortscience	6	1,092	3,473	3,2	140.4	137.4	(Bringslimark, Hartig, & Patil, 2007)	American Society for Horticultural Science
10	Facilities	4	223	1,022	4.6	32.9	72.9	(Smith, Tucker, & Pitt, 2011)	Emerald Publishing
11	Health Environments Research and Design Journal	4	296	990	3.3	27.2	115.2	(Nejati, Shepley, Rodiek, Lee, & Varni, 2016)	SAGE
12	LEUKOS-Journal of Illuminating Engineering Society of North America	4	90	749	8.3	42.8	79.6	(Pechacek, Andersen, & Lockley, 2008)	Taylor & Francis

Doc. (Documents); Pub. (Publications); Cita. (Citations); Biblio. (Bibliometric); Coupl. (Coupling)

The bibliometric analysis of sources, ranked according to the number of articles in the query search, indicates that the Journal of Building and Environment is the top choice source for researchers on Windowless Office, with 34 documents, followed by the Journal of Environmental Psychology (12), Horttechnology (11), and International Journal of Environmental Research and Public Health (10), with more than ten documents respectively. Besides the top-four journal sources, the others produced less than ten materials in the query search, indicating the relatively novel disposition of research on windowless offices. In addition to the frequency of search results, the total publications, citations, impact, publishers, and most cited articles for each journal were extracted from the Scopus database. Most of the indices for the journal analyses were extracted from the bibliographic information extracted from the Scopus database.

However, the scientometric links were extracted in the VOSviewer analysis of the document sources, using fractional counting as recommended by van Eck and Waltman (2014, 2022) for more precise results. From the option to create a map based on bibliometric data, the documents extracted from the Scopus database were selected and loaded, and journal co-citations and bibliometric coupling analysis were performed to produce maps and links.

In this review, the journal co-citation links were extracted in the VOSviewer analysis of the published materials on WOR. According to Sahi et al. (2022), co-citation analysis creates themes and subthemes among extracted materials, defining the relationships between two or more cited sources. From the data mined, a co-citation analysis was performed on Cited Sources with at least 33 publications, a point at which the themes were clearly defined. Then, with fractional counting as recommended by van Eck and Waltman (2014, 2022), five main themes were identified, built around the primary journal sources. The five top journals co-cited in most publications on WOR include the Journal of Environmental Psychology, Environment and Behaviour, Buildings, Hortscience, and Horttechnology, all with fractional links of 137 and above co-citation links.

In brief, this Journal section focuses on top journals in Windowless Office Research (WOR), guiding scholars toward current trends, research gaps, and critical issues within the field. The analysis ranks the Journal of Building and Environment, Journal of Environmental Psychology, Horttechnology, and International Journal of Environmental Research and Public Health as primary sources, highlighting their significance in a relatively nascent area of research on windowless offices.

Furthermore, a bibliometric coupling was performed on the mined material sources to identify the influential journals referenced in most publications on WOR. This analysis also follows the same method as the option to Create a Map Based on Bibliometric Data; the document extracted from the Scopus database was selected and loaded. Bibliometric coupling analysis was performed based on sources with a minimum number of two referenced documents. As a result, the five top journals appearing in most WOR references include Building and Environment, Journal of Environmental Psychology, International Journal of Environmental Research and Public Health, Environment and Behaviour, and Lighting Research and Technology, as highlighted in Figure 5.

In brief, the bibliometric coupling identified the most referenced journals in Windowless Office Research (WOR), spotlighting Building and Environment, Journal of Environmental Psychology, International Journal of Environmental Research and Public Health, Environment and Behaviour, and Lighting Research and Technology as the top journals frequently referenced in WOR publications.

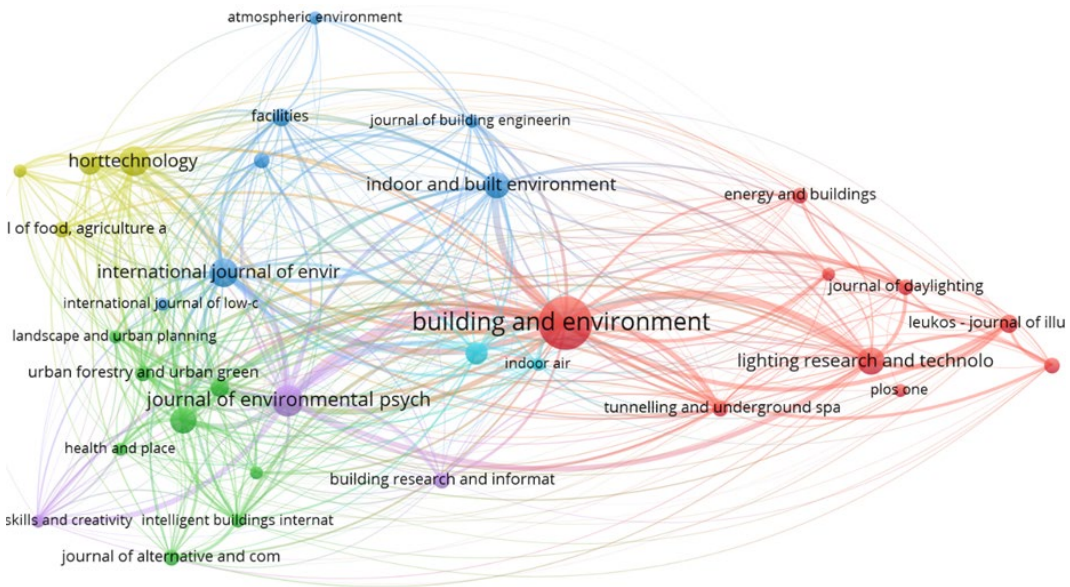

Figure 5: Bibliometric Coupling of Most Referenced Journals in Windowless Office Research (Available at https://tinyurl.com/2fpwkbwr)

3.4 Distribution of Windowless Office Research

In addition to information on articles, citations, and disciplines of the top authors on WOR, authors' geographical spreads were also extracted from the bibliographic information in the Scopus database. Khudzari et al. (2018) and Krauskopf, (2018) establish the need to be conversant with authors in various countries and continents working on similar research projects for possible collaboration and networking. Here, the contextual spread was also ranked according to the number of documents that emerged in the final query search.

The top countries with WOR shown in Table 3 indicate that the United States, United Kingdom, Netherlands and China lead in the number of documents and citations on the subject matter. Furthermore, the same countries head the co-citation, where at least two documents are cited together several times. Additionally, the bibliographic coupling, representing similarity in the reference list of the WOR, confirms the above countries and Australia as the top countries in the subject area. It could also be deduced from the table of the top ten countries with the most WOR publications that 47% are in Europe, 33% are in Asia, and the remaining 20% are in North America and Australia. While there is relative spread in the geographical spread among continents, as presented in Figure 6, it could be seen that the top countries in the research area all fall in the category of "developed" economies, with a stable government, advanced technology and, very notably, stable electricity power (World Economic Forum, 2019). Though Malaysia, as the country of interest in this study with three documents, does not make it to the top researching nations in WOR, the country is seen to possess the attributing qualities of a stable government with advanced technology, stable electricity energy, among other potentials to support the trending module in urban planning and design. Therefore, the Asian countries on the top researching nations in the subject area, especially Singapore, with a similar climate, form a reliable case study for experimentation and simulation of WOR in Malaysia.

Table 3: Windowless Office Research Publications Based on Countries

S/N	Name of Country	Document in Query	Citation Links	Country Co-Authorship	Country Biblio. Coupling	Continent
1	United States	94	435	24	2,560.4	North America
2	United Kingdom	32	180	18	2,295.2	Europe
3	Netherlands	20	196	10	961.7	Europe
4	China	19	104	12	823.7	Asia
5	South Korea	15	92	4	368.7	Asia
6	Canada	13	119	3	419.5	North America
7	Hong	11	68	7	518.2	Asia

	Kong					
8	Australia	10	62	6	903.3	Australia
9	Germany	10	51	7	766.1	Europe
10	Denmark	8	64	4	351.6	Europe
11	Italy	8	55	6	630	Europe
12	Japan	8	74	5	267.2	Asia
13	Norway	8	229	6	420.9	Europe
14	Singapore	8	72	6	673.1	Asia
15	Sweden	8	140	6	339.9	Europe

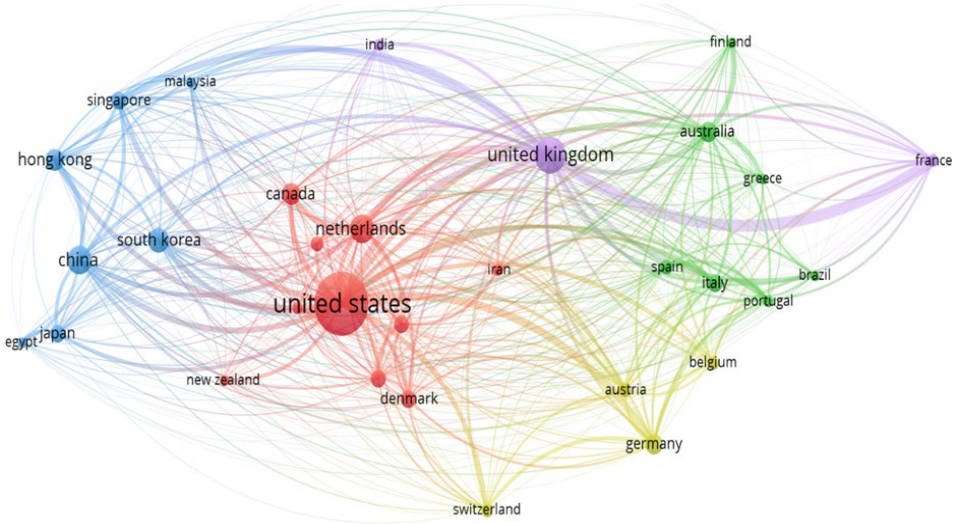

Figure 6 Bibliometric Coupling of Most Referenced Countries on Windowless Office Research (Available at https://tinyurl.com/2z7tnu6h)

In brief, this review not only details the top authors in Windowless Office Research (WOR), including their articles, citations, and disciplines but also examines the geographical distribution of these authors, emphasizing the importance of understanding and collaborating with researchers globally. The top countries involved in WOR, such as the United States, United Kingdom, Netherlands, China, and Australia, show a concentration of research in "developed" economies, with potential for collaboration and the study of similar climatic conditions in countries like Singapore for application in Malaysia.

3.5 Main Themes in Windowless Office Research

The five broad groupings of phenomena from which researchable topics arise are recognized as people, records, things, dynamics/energy, and ideas/thoughts (Ilesanmi, 2016; Leedy & Ormrod, 2010). Nevertheless, the multidisciplinary solution to research problems hardly fits into the packed categories, especially with the mundane issues of Sustainable Development Goals (SDGs) broadly classified into economic, environmental and social domains. The literature shows that WOR, as a blend of environmental design and sociological perception of people, involves the mundane dynamics of psycho-social actualization and energy optimization of the physical sciences.

Consequently, at the VOSviewer keyword analysis of three mentions, five themes emerged from the main disciplines involved in WOR, namely Humanity from Planning with 868 links, Psychological Perceptions from Psychology with 413 links, Workplace from Architecture with 382 links, optimal productivity from physical sciences, and healthcare from the Healthcare discipline with 221 links. Moreover, besides the main themes of Humanity, Psychology, Workplace, Productivity, and Healthcare, other new themes on WOR have been trending in the last two years, as presented in Figure 7.

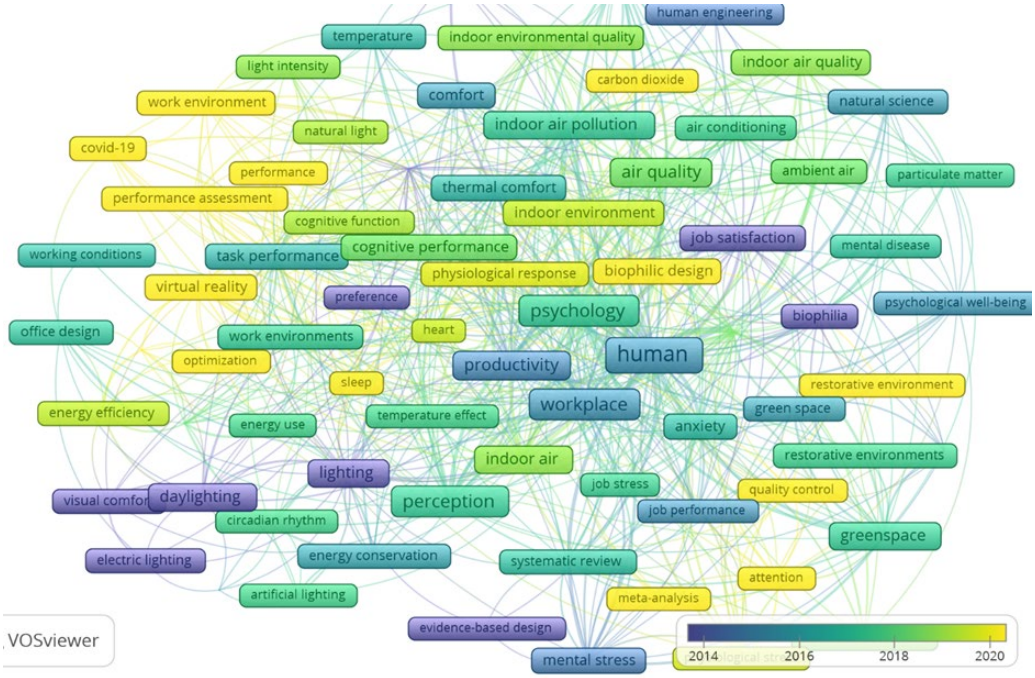

Figure 7: Keyword Co-Occurrence Showing Trending Themes in WOR investigation.
(Available at https://tinyurl.com/2q22hyf3)

With a frequency of three mentions, trending keywords in the WOR from 2020 include visual reality with 11 mentions, biophilic design (10), indoor environment (9), restorative environment (3), work environment (6), and spatial quality control (3). Trending keywords relating to healthcare performance assessment (6), physiological response (5), attention to work (4), cognitive function (3), and sleepiness (3). Furthermore, the healthcare discipline is trending with keywords such as COVID-19 (7), air quality (18), and heart rate variability of windowless office occupants (7). On the other hand, concrete studies on WOR in the physical sciences are trending with keywords of indoor air (14), ambience air (5), energy efficiency (5), natural lighting (4), energy optimization (3), and carbon dioxide control (3).

These themes agree with the finding by scholars that Covid-19, air quality, visual reality, and digital windows are essential concerns in the 2020s (Ibukun & Adebayo, 2021; Mahyuddin et al., 2022; Mouratidis & Hassan, 2020; Wohn, Kum-Biocca, Sharma, & Khandakar, 2020; Yap et al., 2021). Since Trisos et al. (2022) view emerging trends as themes that seek to address specific research gaps by leveraging new approaches to data and technology (p. 1330), young scholars in WOR should identify and explore one or more emerging themes for impactful contributions to the subject area.

In brief, the study identifies rending research themes within Windowless Office Research (WOR), emphasizing the multidisciplinary nature of WOR problems and the emerging trends in keywords, including concerns like COVID-19, air quality, visual reality, and digital windows. These findings highlight the evolving landscape of WOR, suggesting that young scholars should explore and contribute to these emerging themes for impactful advancements in the field.

3.6 Windowless Office Research Variables and Methods

To further zoom into the details of WOR, ten of the accessible documents on the Scopus database that directly mentioned "windowless office" in their title, abstract, or keywords were critically reviewed to reveal the variables, methodological instruments and tools utilized for the studies, as tabulated in Table 4. A systematic analysis is necessary to identify problems and gaps for tangible and impactful research into the subject area, especially by young scholars.

Table 4: Windowless Office Research Variables and Methodologies, Identifying Emerging Keywords.

Area/ Background	Attributes/ Variables	Methodology	
		Instrument	Analysis Tool
Windowless Office, Design and Spatial Psychology	**Design** Ambient room qualities, Digital windows, Illuminance performance, Light exposure, Productivity, Skylight, Workflow	Human experiment, Survey Questionnaire	**Soft Wares** Binary Logistic, Bonferroni, Correction factors, Mood scale,

(Bringslimark et al., 2011; Canazei et al., 2017; Ko et al., 2020; Weng et al., 2020; Wohn et al., 2020)	**Perception** Cognitive performance, Connectedness to nature, Control at work, Decision-making behaviour, Environmental perceptions, Job demands, Metacognitive status, Office type, Perceived restorativeness, Personal decoration, Personal pictures, Personal pictures of nature, Personal plants, Preferences, Satisfaction, Subjective evaluation, Thermal perceptions, **Emerging Keywords** Work environment, Biophilia design, Workplace performance, Performance assessment, Indoor environment, Restorative environment.	, interview	Oxford Happiness, Regression Analysis, Zero-Order Correlations **Tests** Analyses of Variance (ANOVA), General Symmetry Test, Attention test of PVT, Independent-sample T-Tests, Cognition Test of STROOP, Independence Test, Pearson's Chi-Square Test, Permutation Tests, Two-Way Mixed Repeated measures
Area/ Background	**Attributes/ Variables**	**Methodology**	
		Instrument	**Tool**
Windowless office, Health and Well-being (Boubekri et al., 2014, 2020)	Cognitive function, Emotional states, Eye-tracking, Eye symptoms, Genes, Human electroencephalogram (EEG), Medications, Melatonin production, Mental fatigue, Mental health, Perceived threat, Perceived stress level, Personal lifestyle, Physical health, Sleep quality, Stress levels, Visual comfort **Emerging Keywords** Covid-19, Physiological response, Attentiveness, Sleep Assessment, Heart rate reliability	Experiment on human Participants, Survey	Short Form-36, Pittsburgh Sleep Quality Index, Chi-Square Test of homogeneity
Area/ Background	**Attributes/ Variables**	**Methodology**	
		Instrument	**Tool**
Windowless office, Science and Engineering (Chen et al., 2020; Goharian & Mahdavinejad, 2020; Roberts et al., 2016)	Amount of illuminance, Circadian lighting, performances, Computerized tasks, Daylighting performance, Designed lighting layouts, distribution of Light, Electrodermal activity, Functional Magnetic, Lighting intensity, Light pipes efficiency, Noise level, Sun azimuth angle, Task control, Thermal comfort, Ray tracing simulation, Resonance Imaging, Visual environment, Visual indoor lighting performances. **Emerging Keywords** Carbon dioxide levels, Energy efficiency, Indoor air, Quality control, Optimization	Observation, Lighting simulations, Review	DIALux, Fibre Optics Daylighting System (FODS), Grasshopper plug-ins, Rhinoceros 3D Modelling software, Spectrum testing equipment,

Consequently, publications in the five themes from the co-citation analysis, namely architecture, planning, psychology, health, and sciences, were analyzed and grouped into three study background aspects of design and spatial perception, health and well-being, and science and engineering. Each document's research variables, instruments and tools were scrutinized to reveal current research directions and gaps. While the variables were identified as attributes, perceptions and emerging keywords, the analysis tools were classified as soft wares and statistical tests.

The systematic table presents three different studies that focus on the effects of windowless offices on different aspects of human well-being and productivity. The first study, which falls under Design and Spatial Psychology, investigates how different design features, such as digital windows and skylights, impact ambient room qualities, illuminance performance, workflow, and productivity. The study also explores the role of personal decoration and plants in influencing cognitive performance, job demands, and thermal perceptions. The researchers utilized a survey questionnaire and interview to gather data from human participants and employed different analysis tools such as regression analysis, binary logistic, and zero-order correlations to analyze the data.

The second study, which falls under the area of Health and Well-being, focuses on the impact of windowless offices on human cognitive function, emotional states, and sleep quality. The researchers used tools such as eye-tracking, human electroencephalogram (EEG), and survey to gather data on eye symptoms, perceived stress levels, and visual comfort. The study also explored the impact of external factors such as COVID-19 on human physiological responses, attentiveness, and heart rate reliability. Finally, the researchers analyzed the data using the Chi-Square Test of homogeneity, Short Form-36, and Pittsburgh Sleep Quality Index.

The third study, which falls under Science and Engineering, investigated the impact of windowless offices on lighting performance, thermal comfort, noise levels, and task control, among others. The researchers utilized tools such as Grasshopper plug-ins, Rhinoceros 3D Modelling software, and Spectrum testing equipment to simulate lighting scenarios and measure lighting intensity, distribution, and efficiency. The study also explored the impact of environmental factors such as carbon dioxide levels and indoor air quality on optimizing lighting and energy efficiency. The researchers utilized different analysis tools, such as Ray tracing simulation and Functional Magnetic Resonance Imaging, to analyze the data.

The table presents various studies highlighting the importance of windowless office design in human well-being and productivity. For example, studies show that design features such as digital windows, skylights, and personal decoration can influence ambient room qualities, cognitive performance, and job demands. The studies also highlight the importance of external factors such as COVID-19, carbon dioxide levels, and indoor air quality on human physiological responses, lighting optimization, and energy efficiency. The researchers utilized different tools and analysis methods to gather and analyze data, providing a comprehensive understanding of the factors influencing the windowless office design.

In brief, this section critically reviewed ten specific documents from the Scopus database on "windowless office" topics, examining variables, methodology, and tools used, revealing critical research gaps, especially for young scholars in this field. These documents highlighted the impact of windowless office design on human well-being and productivity, exploring variables like lighting, cognitive function, and external factors such as Covid-19, utilizing various tools like EEG, surveys, and simulation software to analyze their impact comprehensively.

4 Study Constraints and Limitation

This study holds the potential to inform policy development not only in Malaysia but also in analogous economies across Asia, Africa, and South America, especially in rapidly urbanizing areas. However, limitation lies in its exclusive reliance on the Scopus database, potentially excluding significant contributions from other reputable databases like Web of Science and PubMed. To ensure a comprehensive understanding, a more inclusive review incorporating diverse sources could enrich the variables established in this research. Additionally, further investigations should explore the interconnections between windowless office design and various emerging factors within space planning, healthcare, psychological perceptions, and technological innovations, all explored in this thorough bibliometric and systematic review. Expanding the scope to explore these connections can lead to more comprehensive insights and guide more effective policies and practices.

5 Conclusion

The scarcity of land in urban centers has spurred the rise of windowless office designs, particularly in densely developed city cores. Extracted from the Scopus database, this review aimed to identify critical authors' emerging themes across diverse geographical contexts and propose new research directions for effectively implementing windowless office systems, particularly in Malaysia.

The review emphasizes the pivotal role of creating work environments that prioritize employees' health and productivity, considering the substantial impact of office design on their well-being. Studies referenced in this review shed light on the effects of windowless office environments and propose strategies to enhance workplace design, offering a valuable empirical reference for researchers and practitioners in this field.

While several Asian countries are exploring windowless office designs, they notably reflect higher levels of development with stable economies, advanced technology, and reliable energy sources, crucial for powering the digital infrastructure integral to such systems. Conversely, Malaysia demonstrates a level of development capable of effectively implementing windowless office designs, supported by stable power sources, technological advancements, and the psychological stability of its populace. This review underlines the potential and suitability of Malaysia in adopting such design modules.

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Developing a Performance-Based Approach to the Effect of Roof Features on Fire Safety in Buildings with Atriums

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ABSTRACT

Developing technology, changing social structures, and the threat of resource depletion have changed the design of buildings. Therefore, design approaches are developed to increase user comfort and reduce energy consumption by utilizing natural ventilation and lighting. The design of the distribution of outdoor air and light into the spaces through vertical and horizontal gaps reduces the energy demand of the mechanical systems and increases occupant comfort. The atrium is the preferred vertical gap in modern buildings for distributing natural air and light to interior spaces under appropriate conditions. However, in buildings with atrium, there is a risk of fire spreading in the event of a fire due to the uninterrupted gaps between the rooms. It is necessary to ensure the operability of the design by monitoring the measures to be taken in the early stages of design using performance-based fire safety methods. This study develops design strategies for fire analysis in atrium buildings using computational fluid dynamics (CFD) simulation technology. Atrium height, roof type, and slope characteristics are analyzed for the stack effect, which is the main factor in the movement of smoke and flames. As a result of the numerical analyses consisting of flat, unidirectional, and bidirectional sloping roof type, 10, 20, 30-degree roof slope, and one-meter rising atrium roof variables, the effect degrees for smoke dispersal and temperature control are investigated. Fire Dynamic Simulator, which uses CFD capabilities, and Smokeview software, which can visualize the results, were used for the numerical analysis. Correlation analysis was used to determine the effect of variables on temperature. The results showed that flat roofs and designs with increasing height were effective in delaying the spread of smoke and increasing the stack effect in the atrium, while the contribution of roof slope to fire safety was weak.

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1. Introduction

Atriums are preferred to provide visually and functionally spacious spaces in buildings, to bring the outdoor environment indoors by bringing uninterrupted natural light from the roof into the atrium, and to increase human interaction. In addition, atriums contribute to the energy efficiency of the building by reducing the need for artificial lighting with natural lighting and providing ventilation and cooling in the interior spaces thanks to the chimney effect. As a result, atriums provide spacious and

comfortable living and working spaces by effectively connecting the outdoor environment with the indoor environment and reducing the burden of lighting, cooling, and ventilating the building with mechanical systems. Despite all the possibilities for efficiency, the fact that the atrium is an uninterrupted space means that in the event of a fire, there is a risk that the fire will spread to the other rooms. Therefore, in buildings where fire safety risks have not been assessed, useful design components will be lost in a potential fire, resulting in loss of life, property safety, and loss of business.

In traditional buildings, horizontal and vertical openings that cause the flow of air indoors are limited to corridors, staircases, lifts, electrical and mechanical shafts (Figure 1). In modern buildings, where user comfort and efficiency are important, openings such as mechanical and electrical shafts, atriums, galleries and double skin facades are added to these openings (Figure 2).

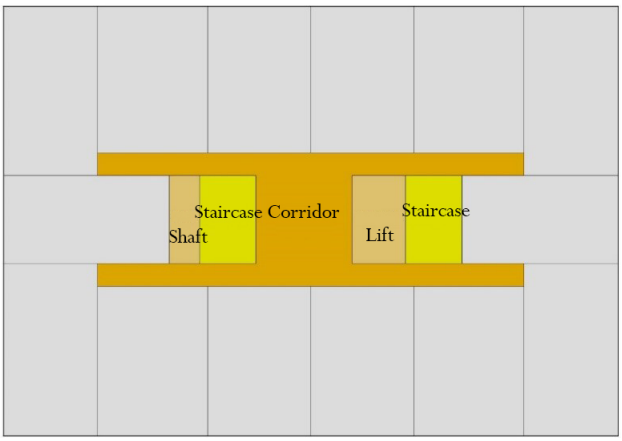


Figure 1 Basic vertical and horizontal openings in traditional buildings

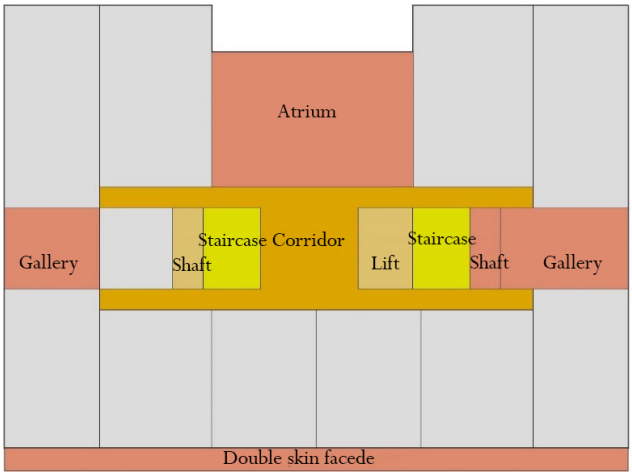


Figure 2 Vertical and horizontal openings in modern buildings

Ventilation in vertical spaces such as the atrium is based on the stack effect system, which is based on the principle of rising heated air. The main force for the stack effect is the difference in temperature and density between indoor and outdoor environments or spaces. When the air temperature interior is higher than outside, the air rises from the lower levels by heating through the gaps with the stack effect and is discharged to the outside through the upper openings of the building. Thus, indoor user comfort is provided by ensuring that the fresh air in the spaces adjacent to the gap is heated and discharged from the space through the gap. It allows the design of natural ventilation using the temperature and pressure difference between the gap and the adjacent spaces and the external environment.

The stack effect is a function of the height of the gap (between the bottom inlet and the top outlet) and the temperature difference between the inside and outside of the opening. In addition to environmental conditions, the stack effect is influenced by factors such as the building's air inlets and outlets, the size of the gap and the characteristics of the spaces associated with the gap. The fact that the gaps designed to improve the efficiency of natural ventilation create uninterrupted vertical and horizontal openings and cause the airflow to move uncontrolled in the interior space is contrary to the traditional methods of fire safety design, which are based on provisions (Doheim, 2012).

Due to the air movement caused by the stack effect in buildings, smoke moves from the high-pressure area to the low-pressure area in vertical spaces. In the case of a fire starting on the lower floors, the pressure inside the building must be higher than the pressure outside to evacuate the smoke from the upper point of the gap. The horizontal plane where there is no pressure difference between the inside and outside of the building is called the neutral plane, where there is no airflow (Mowrer et al., 2004). The neutral plane position is a function of the "absolute temperature ratio". The upward airflow that occurs when the interior is warmer than the external environment is known as the 'normal' stack effect, where warm air flows out of the building through the upper openings. The downward airflow that occurs when the interior is colder than the external environment is known as the "reverse" stack effect, where warm air enters the building through the upper openings and cold air exits the building through the lower openings (Figure 3) (Harrison and Spearpoint, 2006; Mowrer, 2009).

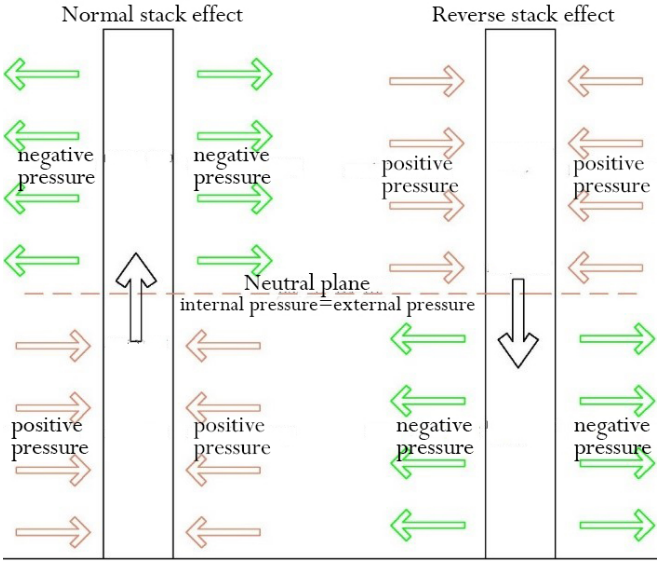


Figure 3 Working principle of the stack effect (Cammelli and Mijorski, 2016)

Natural ventilation strategies based on the rise and fall of heated air in atria create a high-pressure zone in the lower part of the atrium, a low-pressure zone in the upper part, and a neutral plane in between. In this case, as the height of the neutral plane in the atrium increases, the temperature in the upper part of the atrium must be high, as the air heated by the gap is evacuated from the upper part of the atrium without spreading to other rooms (Figure 4) (Cammelli and Mijorski, 2016).

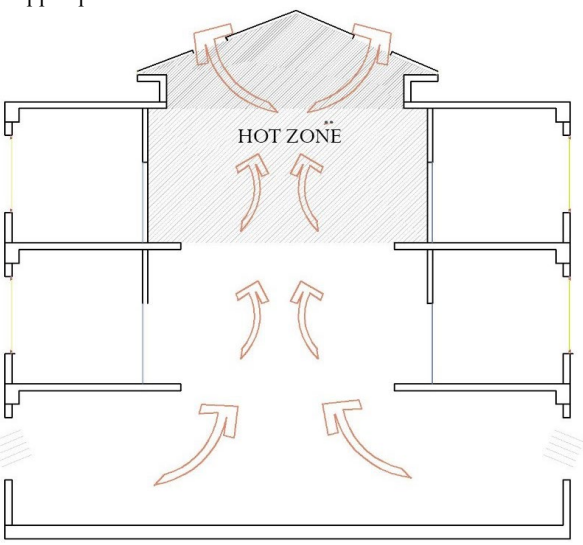


Figure 4 Ventilation in the atrium with the hot zone at the top

Experimental and numerical studies of fire hazards in atria have investigated the characteristics of mechanical smoke exhaust systems, the characteristics of natural ventilation gaps designed in the lower and upper zone of the atrium, the characteristics of ventilation gaps in spaces adjacent to the atrium, and the location and size of the fire. In line with the basic ventilation principle of the atrium, criteria for a high-performance smoke extraction system have been established by analyzing the characteristics of the upper and lower ventilation openings and the design of the smoke extraction systems. Some of these studies have primarily investigated the suitability of mechanical exhaust systems, while others have proposed natural smoke exhaust systems as an alternative to mechanical systems for energy efficiency. Smoke extraction from the atrium ceiling and ventilation openings on the upper floors of the building increased efficiency and reduced the need for mechanical extraction systems (Zhang et al., 2021; Fang et al., 2022; Al-Waked et al., 2021; Chow and Li, 2010). Some studies have compared full-scale experiment and computational fluid dynamics analysis with scenarios consisting of natural and mechanical exhaust systems and fire origin location and size to analyse smoke layer, pressure and temperature levels in the atrium. Since the smoke, temperature, and pressure levels of the full-scale experimental results and the computer simulation results were similar, it has been demonstrated that results can be obtained more quickly and economically for atrium fire design without full-scale testing. (Cantizano et al., 2023; Montes et al., 2009; Montes et al., 2008; Barsim et al., 2020).

In the scenarios consisting of the variables of fire starting in the center of the atrium or the spaces adjacent to the atrium, changing the characteristics of the mechanical smoke exhaust systems, it was found that the spread area and speed of the fire starting in the center of the atrium were high. In addition, mechanical exhaust systems and the design of smoke barriers in appropriate locations have been effective in limiting and reducing the spread of smoke (Jiao et al., 2023; Brzezinska and Brzezinska, 2022). Numerical analyses of scenarios consisting of the rate and position of ventilation openings in the atrium and the spaces adjacent to the atrium have shown that the location of ventilation openings in the roof and upper parts of the atrium is efficient for smoke removal and temperature rise at the upper points. Increasing the size of the natural smoke evacuation openings has effectively improved smoke evacuation (Wang et al., 2021; Qin et al., 2009). In recent studies, horizontal and vertical obstacles have been designed to control smoke by interfering with conventional natural ventilation systems in high-rise atriums with inlet openings at the bottom and outlet openings at the top. In these studies, a segmentation panel was used to divide the atrium horizontally into upper and lower sections to limit the movement of smoke (Sha et al., 2022; Sha et al., 2023). In addition, smoke curtains were designed to separate the atrium area vertically. In atrium designs with similar ventilation configurations, the smoke curtain and panel layout have been effective design tools in managing smoke diffusion and the pressure differential between the atrium and the outside (Gomez et al., 2020; Yuen et al., 2019).

This study investigated the effects of atrium height, atrium roof type, and slope on smoke removal and temperature levels to contribute to studies of mechanical and natural smoke removal systems, ventilation opening size, and position. It was found that designing the atrium height above the building height and increasing the volume of the atrium at the upper level contributed to smoke evacuation and temperature control.

2. Methodology

Computational fluid dynamics (CFD) computer simulation for fire analysis and smoke control systems has been widely used in recent years. CFD technology solves complex equations and analyses the movement and time behavior of fluids in three-dimensional systems. The atrium is the subject of CFD analysis as it is critical for human safety in a fire. The Fire Dynamics Simulator (FDS), which includes CFD features, is used in this study to control smoke layer height and temperature.

This study, based on stack effect ventilation strategies in the atrium, examines smoke spread and temperature levels as a function of pressure change in the event of a fire starting in the atrium space. Unlike the physical modeling studies in the literature, the effect of atrium roof type, slope, and height on fire is investigated. The effects of the most popular flat, unidirectional, and bidirectional roof types and the height of the rooftop on smoke propagation and temperature are analyzed. The study only analyses roof type, slope, and height and ignores other design components that affect fire spread.

Correlation analysis was performed with the simulation results obtained to determine the degree of contribution of the roof design features to the stack effect in the atrium and the temperature levels in the rooms. Correlation analysis, which is a statistical analysis method, calculates the measure of change between variables. For the correlation coefficient, which mathematically takes a value between -1 and +1, a value close to 0 indicates a weak effect, close to 1 indicates a strong positive effect, and close to -1 indicates a strong negative effect. In addition, a negative correlation coefficient indicates that one of the variables is increasing while the other is decreasing, and a positive correlation coefficient indicates that one of the variables is increasing while the other is increasing.

2.1. Prototype Building Design

The 3-storey prototype building, with an atrium space of 400 x 600 x 1050 cm (width x length x height) in the center and 400 x 400 x 350 cm rooms on each floor around the atrium space, was designed without taking into account the effect of climatic elements such as location and prevailing wind. Two air outlets are placed on the atrium ceiling (Figure 5).

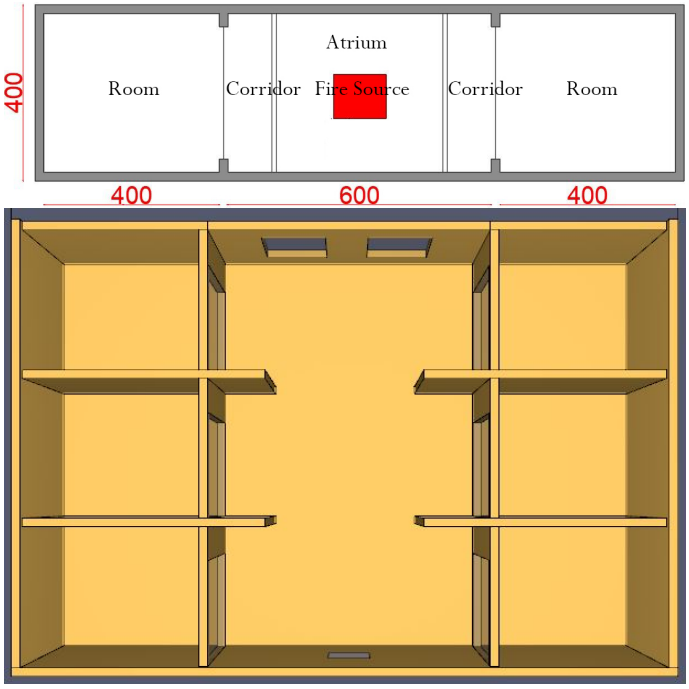


Figure 5 Prototype building plan and section

In order to examine the effect of roof type, slope, and height on fire in the prototype building, three types of design scenarios were determined flat roof, one-way and two-way sloping. For the flat roof, four scenarios were designed starting from the building height level and rising at 1-meter intervals. For unidirectional and bidirectional sloping roofs, the roof slope is determined as 10, 20, and 30 percent and the design scenarios are given in Table 1.

Table 1 Numerical model design scenarios

Scenario	Roof type	Height (cm)	Slope (%)
A1	Flat	1050	0
A2	Flat	1150	0
A3	Flat	1250	0
A4	Flat	1350	0
B1	Unidirectional	1100	10
B2	Unidirectional	1170	20
B3	Unidirectional	1240	30
C1	Bidirectional	1100	10
C2	Bidirectional	1135	20
C3	Bidirectional	1175	30

2.2. Design Fire and Numerical Model Features

Studies presenting performance-based approaches use the t-squared fire, where the rate of combustion varies in proportion to the square of time. The curve expressing the ratio of burn rate to the square of time for a t-squared fire shows the time required to reach the highest heat release rate. The heat release rate gives the most important information about how much heat is released when combustible materials burn. If the heat release rate is known, the smoke temperature, smoke layer thickness, smoke flow rate, radiant heat flux and the result of the effect on combustible materials and structural elements in the enclosed volume are known. T² fire, that is the rate of heat release, is given by equation 1:

$$Q=\alpha t^{p} \quad \text{(Eq. 1)}$$

Q:Heat release rate Btu/s (kW)
α:Fire growth coefficient Btu/s3 (kW/s^2),
t: Time from ignition (s)
p:Positive exponent

According to the NFPA 92 Standard of Smoke Control Systems, the fire growth rate is classified as slow, medium, fast, and

ultra-fast and the reference heat release rate is 1055 kW. The fire growth curve for slow, medium, fast and ultra-fast growth rates to achieve the reference heat release rate of 1055 kW is shown in Figure 6 (NFPA, 2021). In the study, the reference heat release rate is calculated as 1055 kW and the fire growth rate is calculated as fast.

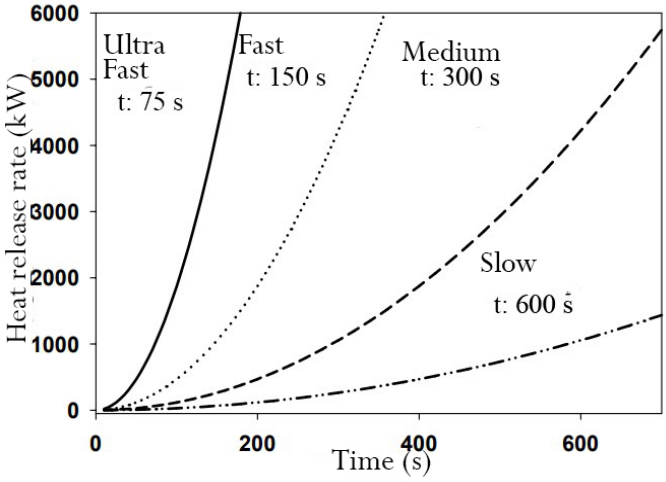


Figure 6 Fire growth curve and time for the fire to reach the reference heat release rate (Bwalya et al., 2004)

The time to reach the reference heat release rate for the fast fire growth curve is 150 seconds, and the fire growth coefficient (α) is calculated to be 0.047 kW/s^2 from Equation 1. The 100 x 100 cm reaction source on the atrium floor was selected as the polyurethane GM27, consisting of 1.00 carbon, 1.7 hydrogen, 0.3 oxygen, and 0.08 nitrogen atoms. For this reaction source, smoke production is 0.198 g/g and carbon monoxide (CO) production is 0.042 g/g. Table 2 shows the characteristics of the design fire (Hurley, 2016).

Table 2 Design fire features

Feature	Value
Fire type	Flaming fire
Reaction type	Polyurethane GM27
Fire growth	t2 fire
Smoke production	0,198 g/g
CO production	0,042 g/g
Heat release rate	1055
Fire growth coefficient	0,047
Simulation time	150 s

FDS software, which can present computational fluid dynamics together with simulation, and Smokeview software, which can visualize the results, were used for numerical analysis. CFD generates solutions for the conservation of mass, momentum, pressure, and turbulence using the Navier-Stokes equations (Mc Grattan et al., 2013). The study used the Pyrosim program, which includes FDS functions and Smokeview visualization, to define boundaries and create geometry. To generate the three-dimensional model in Pyrosim, the lengths of the mesh cell structure where the boundary conditions were determined were set to 0.2x 0.2 x 0.2 m. Three thermocouples were placed at the atrium floor level, ceiling level, and in one of the last floor rooms to measure the temperature, and slices were placed in x2 direction to monitor the temperature and smoke movement (Figure 7).

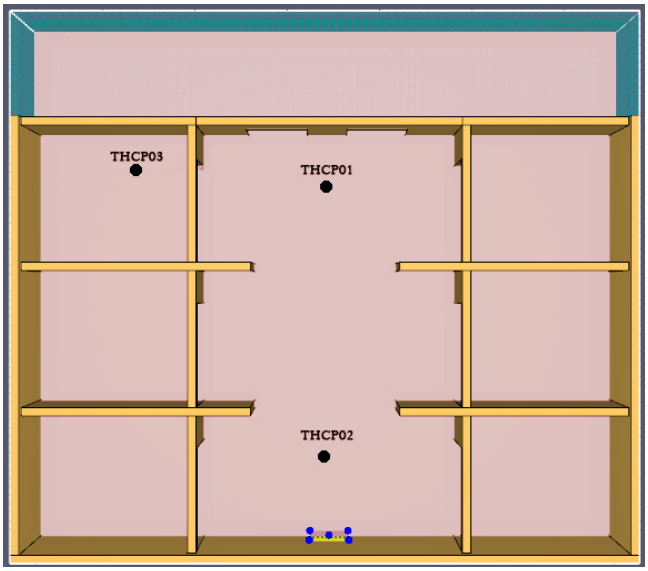


Figure 7 The numerical model obtained from Pyrosim

3. Findings

In the A1 scenario, the smoke reached the atrium ceiling at the 23rd second and exited through the air outlet. At the 45th second, smoke began to spread to the last floor rooms, at the 64th second to the first floor rooms, and at the 90th second to the rooms on the ground floor. At 105th second, the last floor and 115th second, the first floor rooms were completely smoke-filled (Figure 8). While the highest ambient temperature of 300.17 ^{0}C was reached at 148th second, the highest temperature was 86.81 ^{0}C at the ceiling of the atrium and the highest temperature was 37.55 ^{0}C in the last floor room (Figure 9).

Figure 8 A1 scenario smoke view

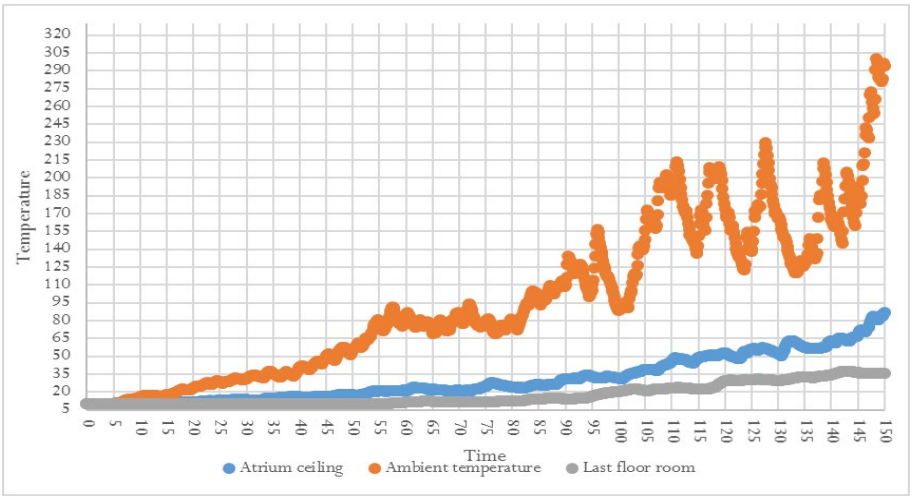


Figure 9 A1 scenario time-dependent temperature values

In the A2 scenario, the smoke reached the atrium ceiling at the 28th second and exited through the air outlet. At the 54th second, smoke began to spread to the last floor rooms, at the 64th second to the first floor rooms, and at the 90th second to the rooms on the ground floor. At 105th second, the last floor and 115th second, the first floor rooms were completely smoke-filled (Figure 10). While the highest ambient temperature of 308.95 ^{0}C was reached at 138th second, the highest temperature was 70.55 ^{0}C at the ceiling of the atrium and the highest temperature was 35.27 ^{0}C in the last floor room (Figure 11).

Figure 10 A2 scenario smoke view

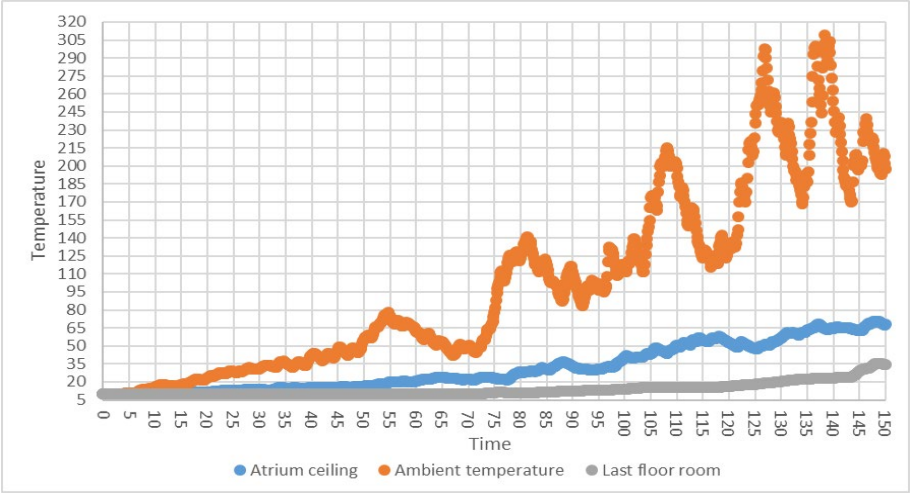


Figure 11 A2 scenario time-dependent temperature values

In the A3 scenario, the smoke reached the atrium ceiling at the 30th second and exited through the air outlet. At the 60th second, smoke began to spread to the last floor rooms, at the 67th second to the first floor rooms, and at the 96th second to the rooms on the ground floor. By the 115th second, the last floor and the rooms on the first floor were filled with smoke (Figure 12). While the highest ambient temperature of 307.42 ^{0}C was reached at 133th second, the highest temperature was 82.83 ^{0}C at the ceiling of the atrium and the highest temperature was 33.09 ^{0}C in the last floor room (Figure 13).

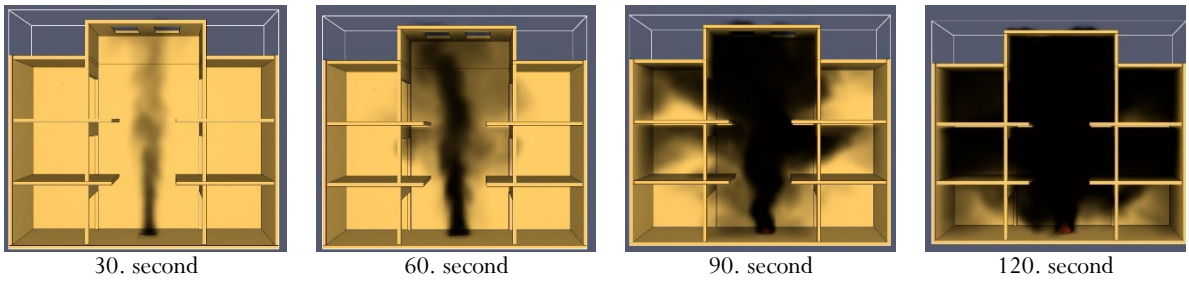


Figure 12 A3 scenario smoke view

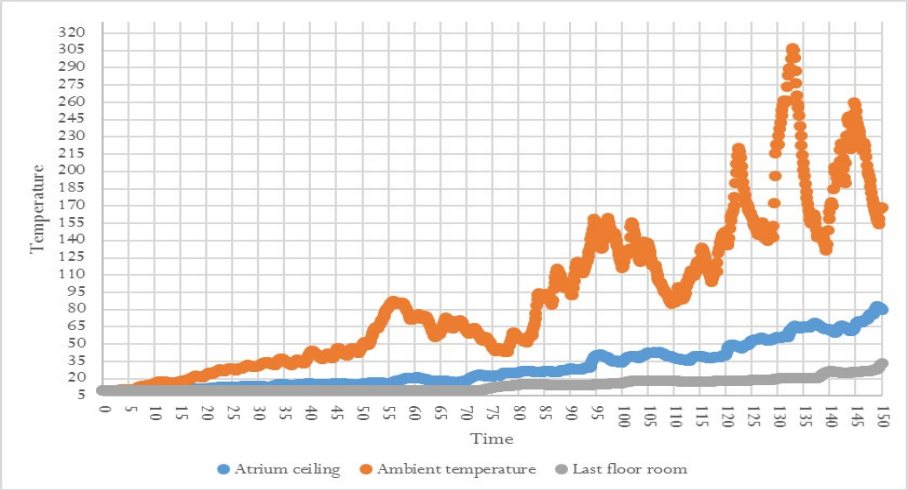


Figure 13 A3 scenario time-dependent temperature values

In the A4 scenario, the smoke reached the atrium ceiling at the 31th second and exited through the air outlet. At the 66th second, smoke began to spread to the last floor rooms, at the 69th second to the first floor rooms, and at the 100th second to the rooms on the ground floor. By the 125th second, the last floor and the rooms on the first floor were filled with smoke (Figure 14). While the highest ambient temperature of 300.64 ^{0}C was reached at 146th second, the highest temperature was 84.24 ^{0}C at the ceiling of the atrium and the highest temperature was 21.96 ^{0}C in the last floor room (Figure 15).

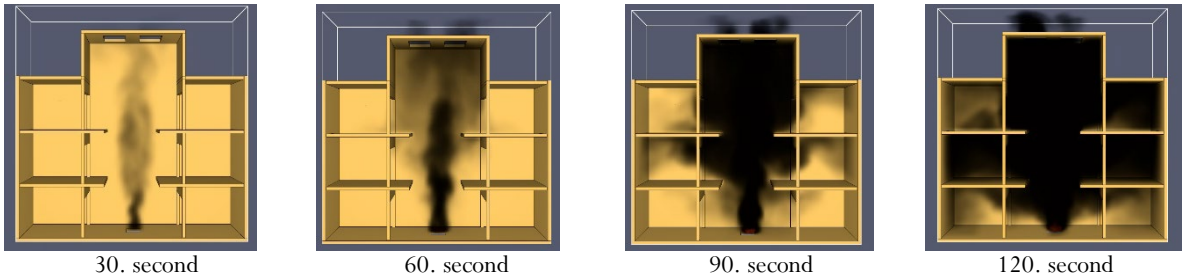


Figure 14 A4 scenario smoke view

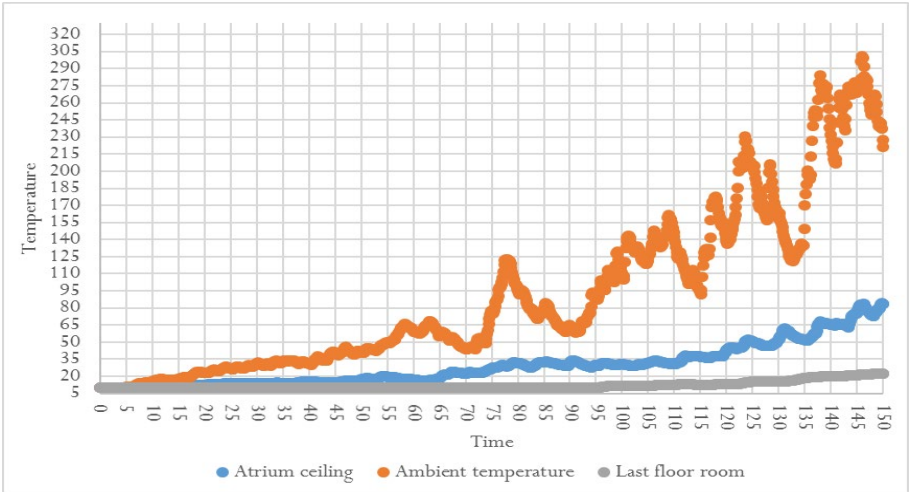


Figure 15 A4 scenario time-dependent temperature values

In the B1 scenario, the smoke reached the atrium ceiling at the 24th second and exited through the air outlet. At the 50th second, smoke began to spread to the last floor rooms, at the 65th second to the first floor rooms, and at the 82nd second to the rooms on the ground floor. At 105th second, the last floor and 120th second, the first floor rooms were completely smoke-filled (Figure 16). While the highest ambient temperature of 276.64 ^{0}C was reached at 149th second, the highest temperature was 67.46 ^{0}C at the ceiling of the atrium and the highest temperature was 42.30 ^{0}C in the last floor room (Figure 17).

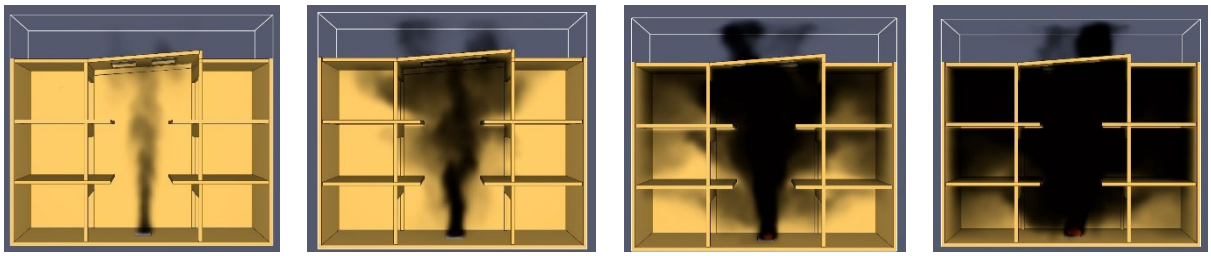


Figure 16 B1 scenario smoke view

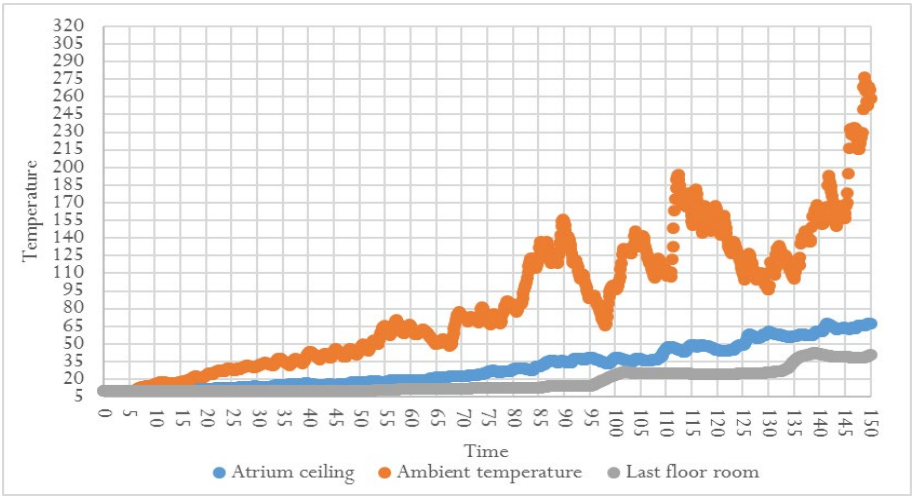


Figure 17 B1 scenario time-dependent temperature values

In the B2 scenario, the smoke reached the atrium ceiling at the 24th second and exited through the air outlet. At the 50th second, smoke began to spread to the last floor rooms, at the 60th second to the first floor rooms, and at the 90th second to the rooms on the ground floor. At 100th second, the last floor and 115th second, the first floor rooms were completely smoke-filled. The tendency of the smoke to spread into the rooms was mainly towards the rooms on the side where the roof slope was high (Figure 18). While the highest ambient temperature of 192.39 ^{0}C was reached at 104th second, the highest temperature was 76.74 ^{0}C at the ceiling of the atrium and the highest temperature was 36.46 ^{0}C in the last floor room (Figure 19).

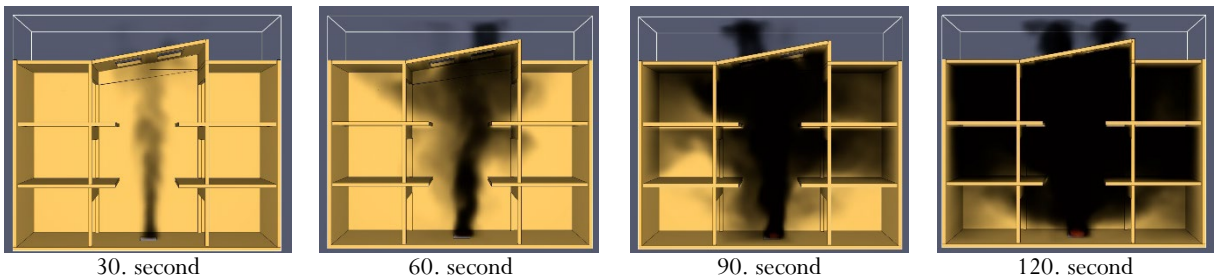


Figure 18 B2 scenario smoke view

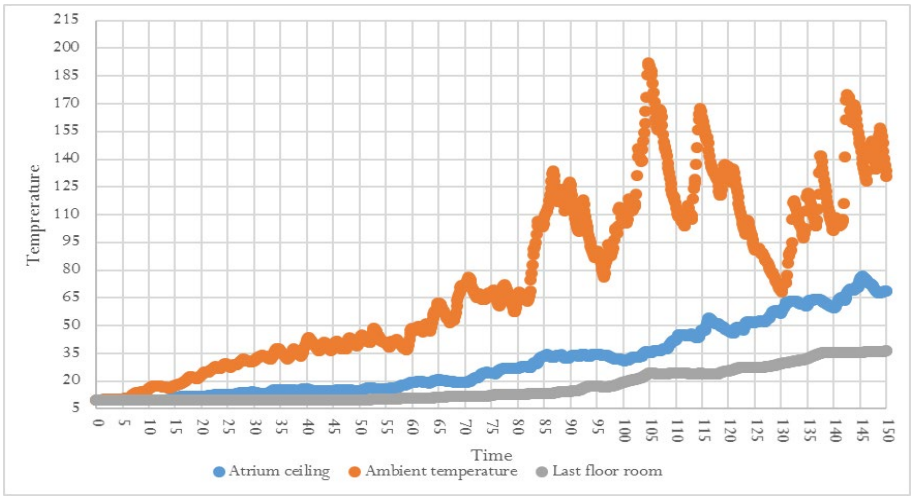
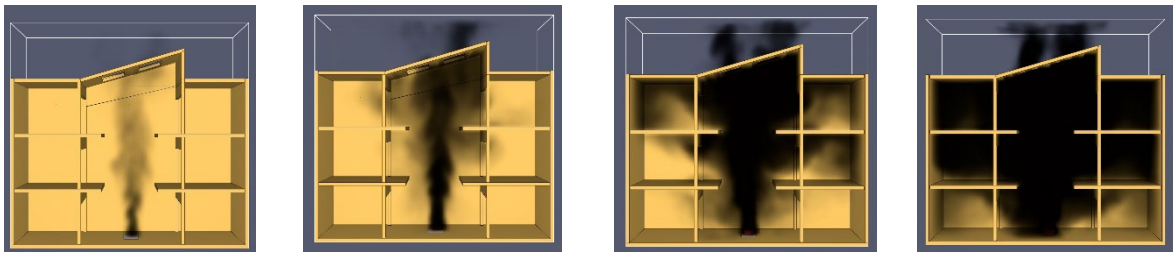


Figure 19 B2 scenario time-dependent temperature values

In the B3 scenario, the smoke reached the atrium ceiling at the 24th second and exited through the air outlet. At the 52nd second, smoke began to spread to the last floor rooms, at the 62th second to the first floor rooms, and at the 95th second to the rooms on the ground floor. At 105th second, the last floor and 120th second, the first floor rooms were completely smoke-filled. The tendency of the smoke to spread into the rooms was mainly towards the rooms on the side where the roof slope was high (Figure 20). While the highest ambient temperature of 300.82 ^{0}C was reached at 137th second, the highest temperature was 74.35 ^{0}C at the ceiling of the atrium and the highest temperature was 27.96 ^{0}C in the last floor room (Figure 21).



30. second 60. second 90. second 120. second

Figure 20 B3 scenario smoke view

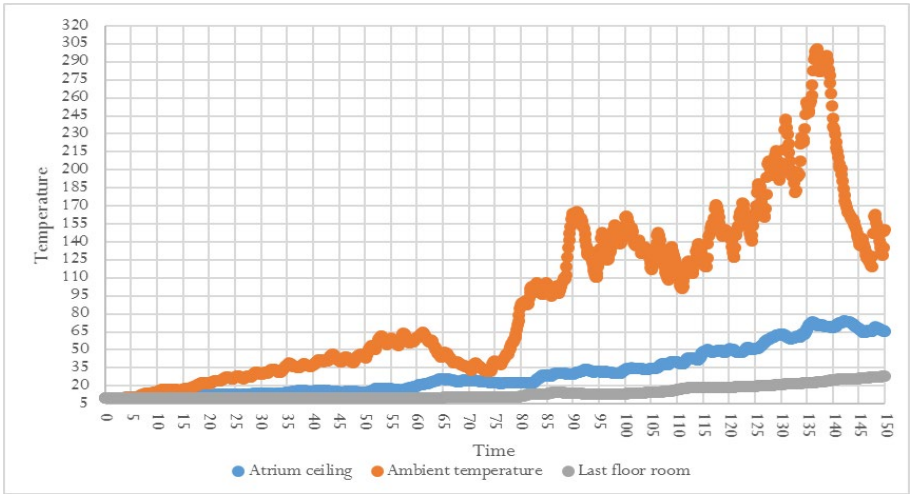


Figure 21 B3 scenario time-dependent temperature values

In the C1 scenario, the smoke reached the atrium ceiling at the 24th second and exited through the air outlet. At the 52nd second, smoke began to spread to the last floor rooms, at the 67th second to the first floor rooms, and at the 88th second to the rooms on the ground floor. At 100th second, the last floor and 115th second, the first floor rooms were completely smoke-filled (Figure 22). While the highest ambient temperature of 267.54 ^{0}C was reached at 138th second, the highest temperature was 75.02 ^{0}C at the ceiling of the atrium and the highest temperature was 46.19 ^{0}C in the last floor room (Figure 23).

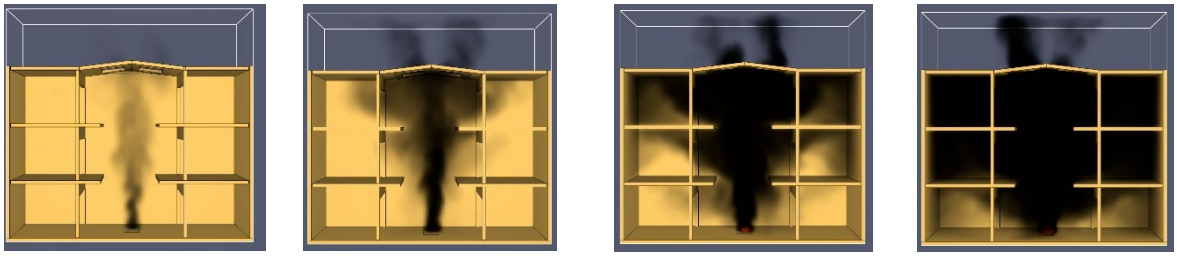


Figure 22 C1 scenario smoke view

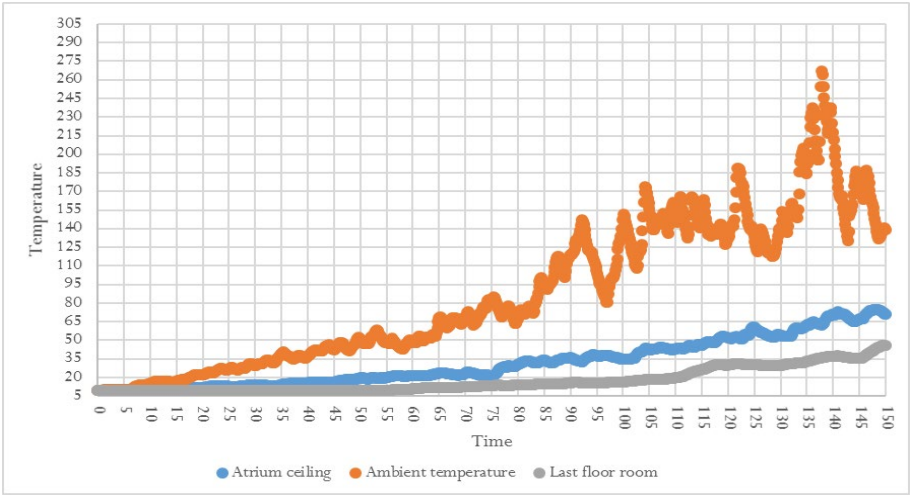


Figure 23 C1 scenario time-dependent temperature values

In the C2 scenario, the smoke reached the atrium ceiling at the 23rd second and exited through the air outlet. At the 48th second, smoke began to spread to the last floor rooms, at the 65th second to the first floor rooms, and at the 85th second to the rooms on the ground floor. At 100th second, the last floor and 115th second, the first floor rooms were completely smoke filled (Figure 24). While the highest ambient temperature of 249.65 ^{0}C was reached at 145th second, the highest temperature was 79.33 ^{0}C at the ceiling of the atrium and the highest temperature was 42.76 ^{0}C in the last floor room (Figure 25).

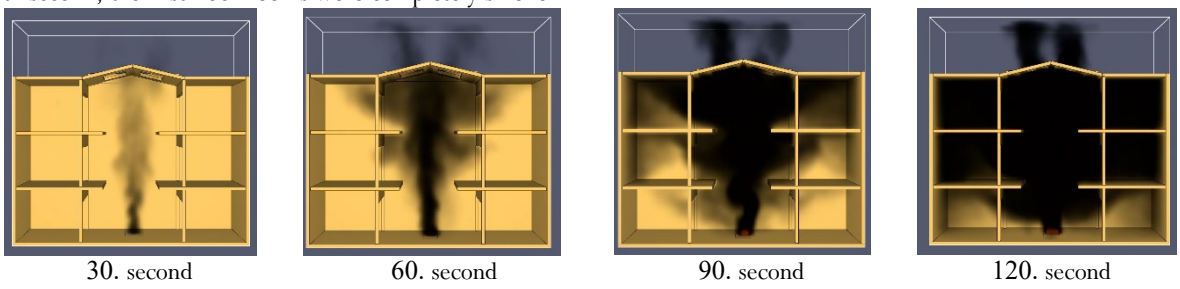


Figure 24 C2 scenario smoke view

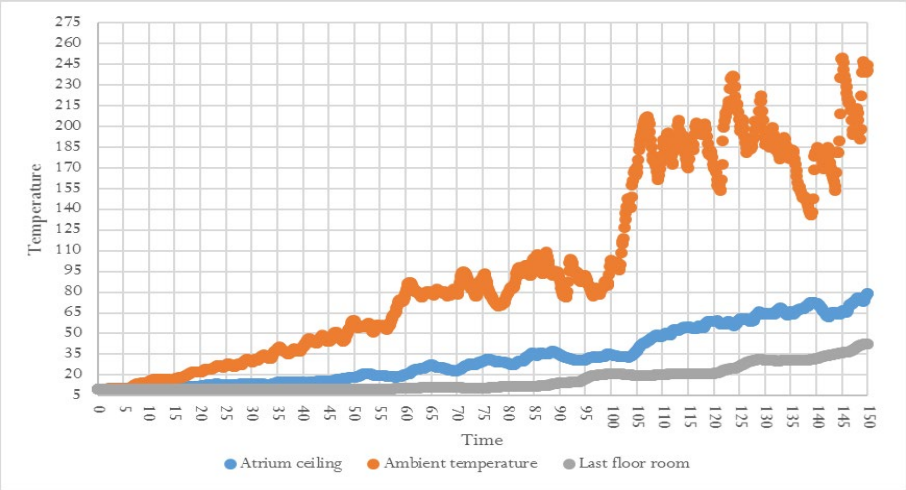


Figure 25 C2 scenario time-dependent temperature value

In the C3 scenario, the smoke reached the atrium ceiling at the 24th second and exited through the air outlet. At the 47th second, smoke began to spread to the last floor rooms, at the 62nd second to the first floor rooms, and at the 88th second to the rooms on the ground floor. At 105th second, the last floor and 115th second, the first floor rooms were completely smoke-filled (Figure 26). While the highest ambient temperature of 266.51 ^{0}C was reached at 148th second, the highest temperature was 76.35 ^{0}C at the ceiling of the atrium and the highest temperature was 34.10 ^{0}C in the last floor room (Figure 27).

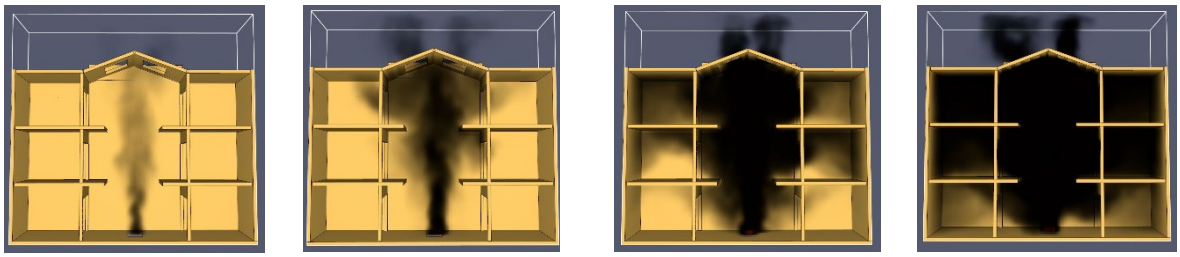


Figure 26 C3 scenario smoke view

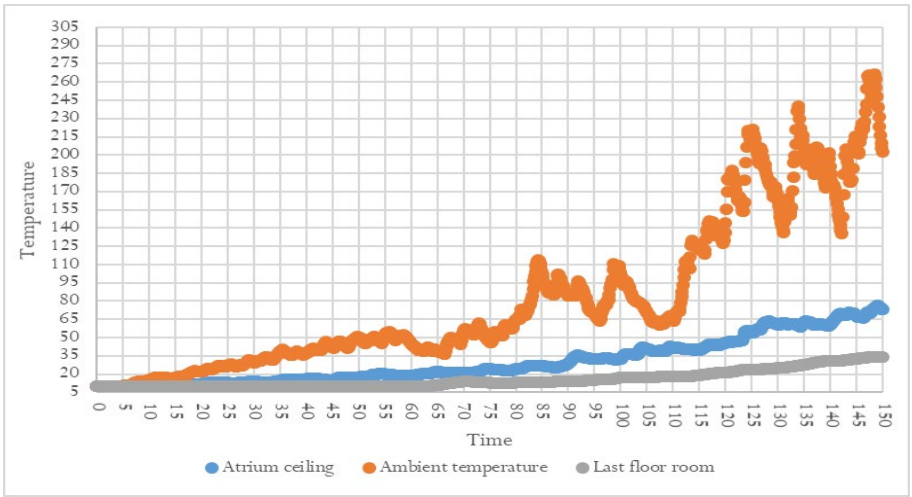


Figure 27 C3 scenario time-dependent temperature value

4. Evaluation and Conclusion

In a fire event, smoke rises rapidly vertically until it encounters a horizontal obstacle. When the smoke reaches the horizontal obstacle, it slowly spreads along the horizontal surface and moves downwards again. In the scenarios in this study where this theoretical knowledge is analyzed in practice, the smoke rises rapidly until it reaches the atrium ceiling and then moves along the ceiling surface and downwards. As a result of increasing the height of the flat roof in the A scenarios, the duration of the smoke on the roof surface increased, and the process of smoke penetration into the rooms was delayed. In the A1 scenario where the roof surface is at the level of the building height, the first spread of smoke into the room started at 45 seconds, while in the A4 scenario where the roof surface is designed to be 300 cm above the building height, the smoke spread into the room started at 66 seconds. This situation shows that taking into account the fast fire growth rate in the numerical analysis, designing the atrium roof flat and increasing its height contribute positively to the escape time of people.

In Scenarios B and C, where the roof is designed as a unidirectional and bidirectional sloping roof, the change in volume area at the building height is small between the scenarios, so the downward movement time of the smoke from the ceiling surface is not different. In the B scenarios, where the roof sloped in one direction, as the smoke spread towards the area where the slope increased, the smoke spread from the ceiling into the rooms was also in the direction where the slope was higher.

As the stack effect in the cavity increases with temperature due to the increase in pressure, the higher temperature level at the upper level of the atrium compared to the lower regions raises the position of the neutral plane in the gap and assists the evacuation of smoke from the atrium roof. Since the ambient temperature level is variable in the scenarios, the rate of the temperature at the upper level of the atrium to the temperature at the floor level of the atrium was calculated and compared.

Measures of central tendency were used to statistically describe the temperature values. Measures of central tendency are critical points that provide an interpretation of the distribution and are expressed by the mean or median for numerical data. If the numerical data show a normal distribution, the mean is used, and if the numerical data show an irregular distribution, the median is used. Looking at the graphs of the temperature values in the Results title, we can see that the temperature has an increasing graphic, so the mean was calculated for the analysis. The mean temperatures of the atrium floor, the atrium ceiling and one of the rooms on the last floor in the scenarios are shown in Table 3.

Table 3 Mean temperature values of the scenarios

Scenario	Roof type	Height (cm)	Slope (%)	Atrium floor	Atrium ceiling	Last floor room	Atrium temperature rate*
A1	Flat	1050	0	151.99	48.4	22.73	0.32
A2	Flat	1150	0	103.63	39.9	22.14	0.39
A3	Flat	1250	0	89.36	45	21.54	0.50
A4	Flat	1350	0	115.71	46.77	15.98	0.40
B1	Unidirectional	1100	10	134.45	38.45	25.43	0.29
B2	Unidirectional	1170	20	70.27	39.29	23.23	0.56
B3	Unidirectional	1240	30	80.1	37.62	18.98	0.47
C1	Bidirectional	1100	10	74.58	40.58	28	0.54
C2	Bidirectional	1135	20	127.15	44.66	26.38	0.35
C3	Bidirectional	1175	30	106.47	41.44	22.05	0.39
* Rate of atrium ceiling temperature to atrium floor temperature							

Considering the temperature rate in the atrium, it can be seen that the stack effect is efficient for A3 of the flat roof type scenarios, B2 of the unidirectional sloping roof type scenarios and C1 of the bidirectional sloping roof type scenarios. Scenario A4, with the lowest room temperature, has the most appropriate design for the user limit.

Due to the numerical analysis of the scenarios determined by CFD with the variables consisting of the roof design characteristics, a statistical analysis was used for the degree of change of the temperature values of the scenarios with the increase of height, slope, and roof type. In this case, correlation analysis was performed for the dependent variables of atrium temperature rate and last floor room temperature to determine the degree of influence of the variables. The correlation of the atrium temperature raw, which gives an idea of the strength of the stack effect in the atrium, between the variables is shown in Table 4. According to the table, roof type has an effect of 0.12, height has a positive effect of 0.30, slope has a positive effect of

0.17 on the dependent variable, and since the correlation value is far from 1, there is a positive weak correlation.

Table 4 Correlation of variables with atrium temperature rate

	Atrium temperature rate	Roof type	Height	Slope
Atrium temperature rate	1			
Roof type	0.124934366	1		
Height	0.299287613	-0.31478	1	
Slope	0.174066669	0.743256	-0.009256556	1

The correlation between the temperature value of the room on the last floor with the highest temperature increase among the rooms on all floors and the variables is shown in Table 5. According to the table, roof type has a positive effect of 0.60, height has a positive effect of 0.81, and slope has a positive effect of 0.10 on the dependent variable. There is a strong negative correlation between height and temperature, and the temperature decreased as the height increased. As the roof type is a qualitative variable, it was not interpreted as a positive or negative correlation, but the lowest temperature values were observed for the flat roofs and the highest for the bidirectional roofs.

Table 5 Correlation of variables with last floor room

	Last floor room	Roof type	Height	Slope
Last floor room	1			
Roof type	0.604520209	1		
Height	-0.811536301	-0.31478	1	
Slope	0.102912665	0.743256	-0.009256556	1

In this study, in which the numerical analysis of the fire safety design was carried out using a performance-based modeling approach, only the characteristics of the atrium roof were considered as design variables, neglecting climatic data and other active and passive design features. The design of the atrium ceiling above the building height increased the atrium chimney effect and contributed positively to the extraction of smoke through the air outlet on the atrium ceiling. In flat roof scenarios with atrium heights of 2 and 3 meters above building height, the

time for smoke to reach the atrium ceiling was reduced, and the time to remain smoke on the ceiling for occupant evacuation was increased compared to unidirectional and bidirectional pitched roofs. In scenarios with sloping roof designs, smoke density and residence time of smoke at the atrium ceiling level were shortened, and the orientation of smoke to the spaces was increased compared to flat roofs. The studies in the literature where the physical properties of the atrium are the subject of fire safety design have examined the height and width of the atrium, its location, its relationship with the spaces in the building, and the atrium form by numerical analysis. As a contribution to the studies in the literature, this study examined the physical properties of the atrium roof with air outlets for natural ventilation and natural smoke exhaust system. It examined the relationship between the most suitable roof shape and height and the chimney effect caused by internal and external temperature and pressure differences. Thus, atrium roof design criteria for smoke extraction and temperature control through the atrium roof were presented for both academic studies and the building industry.

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Residential Zones of Students around a University in Ho Chi Minh City: Characteristics and Preferences

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ABSTRACT

The student housing market has had free and unsystematic development in developing cities with a high density of universities. In Ho Chi Minh City, the situation has resulted in specific negative urban issues and low life quality for students. This study aimed to clarify how students allocate around a university, the residential zones' characteristics, and preferences for the residential zones. We analyzed survey data of 304 students at a university in Ho Chi Minh City. We addressed the differences among residential zones through statistical analyses of group differences. A multinomial logit model was deployed to explore students' choice of residential zones. Results show significant characteristics that affected the students' choice, including academic levels, motorcycle usage, employment status, family income, household member, household size, and gender. Some implications for policymaking in the student housing market were raised regarding residential zones, integrating transport systems, travel behavior, and employment opportunities. The study enhanced knowledge of the student housing situation (i.e., residential zones or residential allocation) and the student's preferences. Policymakers and practitioners developing student housing markets, built environments, and related services can benefit from this study. The findings apply to the specific city under investigation and are useful to other Southeast Asian cities with similar socio-cultural contexts.

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1. Introduction

University cities with many students moving to for studying have become popular in many countries. In the cities, the urban environment has a social integration of student housing, considering its locations. Moreover, studentification in neighborhoods or student housing can drive urban change (Kinton et al., 2018; Prada, 2019). Generally, the students' residential choice has specific characteristics for many reasons. First, students' location is temporary, relating to their studying period. Second, the group is primarily young, single, and independent. They can participate in many social and cultural activities. Third, students' residential choice might impact their studying life, including academic performance (Adama, et al., 2018). The increase in student housing near campuses has had added economic, cultural, and social impacts on urban areas (Gregory, 2020; Gu and Smith, 2020).

In literature, the residential locations have been considered a characteristic that impacts the students' residential choice rather than a choice. Thomsen and Eikemo (2010) impressed three critical aspects for student housing satisfaction, including

housing type characteristics and location, while demographic factors and facilities were insignificant. In developing countries, distance to campus, renting price, housing type (Kolawole and Boluwatife, 2016), age, and academic level (Adama et al., 2018) were found to be related to residential students' choices. Modest studies seek factors affecting location choice, including explorations by Krishnapriya and George (2020) and Ralph and Brown (2019) that showed a relationship between students' travel behaviors and residential location. Frenkel, Bendit, and Kaplan (2013) presented the impacts of the built environment on location choices besides housing price and commuting time. Additionally, McBride (2017) found that the number of students interested in on-campus living will be reduced in the future as a trend. Moreover, campuses will be transformed (Susanti et al., 2020).

The student housing market has been developed with high-standard flats in developed countries (Verhetsel et al., 2017) as a submarket specific to age segregation (Revington, 2021). Franz and Gruber (2022) impressed student housing as a social infrastructure. However, the function has been overlooked under the influence of private providers. Student housing is a pressing planning issue with changes for studentification and amenities (Revington et al., 2020). The phenomenon of student housing from private providers is similar in developing countries. There is a minimal capacity for dormitories and substantial investment opportunities in the student housing market. However, the market has been noticed modestly (Sulaiman et al., 2018). Moreover, private student housing has been developed free and unsystematically. Many student-rented houses are converted from family houses (Baba Hammad et al., 2013; Donaldson et al., 2014), including apartments, condominiums, and semi-detached or detached houses. Some studies reported that the student housing market is resilient and promising (Garg et al., 2014; Sulaiman et al., 2018). Figure 1 summarizes the relationship between the student's residential choice and relevant factors shown in the literature.

This study uses Ho Chi Minh City (HCMC) as a case study. The city is a high-density city with a population of 9.2 million people, and the population density in urban districts was around 20 thousand persons per square kilometer (Ho Chi Minh City Statistics Office, 2022). The city has the most universities and institutes in South Vietnam, providing an educational program for almost 600 thousand students (General Statistics Office, 2022). Many students in HCMC are from nearby provinces and must seek accommodation for their studying life. The striking demand pressures the housing market in the city. Research on the student housing market is modest in this area. A previous investigation showed the low quality of student housing and students' dissatisfaction with their accommodation (Pham and Nguyen, 2021). Additionally, location has been demonstrated as an essential factor in the students' residential choice (Vi et al., 2020; Pham and Nguyen, 2021).

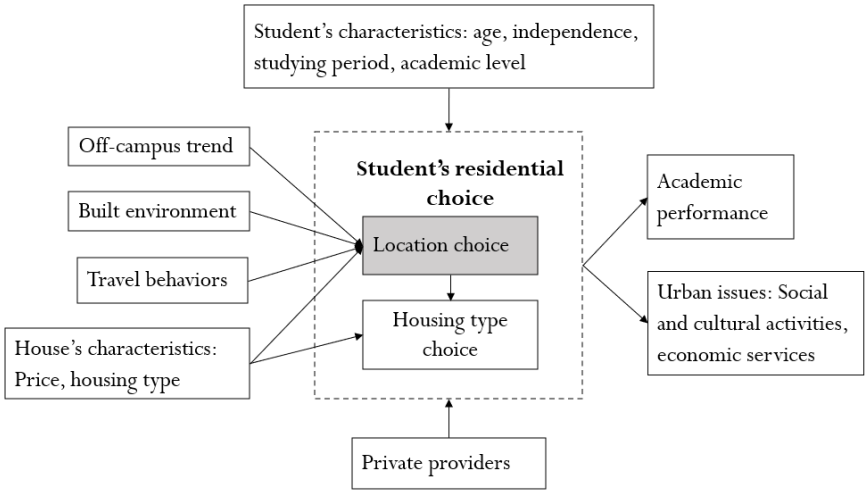


Figure 1 Student's residential choice and relevant factors

Because of the increasing demand for off-campus student housing and its potential urban issues, the students' residential location needs to be investigated for further public and professional discussions in meeting student housing demand and its social integration in the urban environment. To our knowledge, no previous studies about students' residential location zones around a university exist. Drawing from the existing literature on residential choice (refer to Figure 1), we concern with factors of the built environment (i.e., open space, bus system, industrial park, etc.), travel behaviors (i.e, transport mode usage), house characteristics (i.e., type, area, cost, etc.), and student's characteristics (i.e., age, gender, household size, etc.). Also, we introduce the role of the student's part-time job (i.e., the job status, workplace, travel time and travel cost to the place, etc.) to the location zone choice. Taking Ho Chi Minh City context, this study addresses the differences among residential zones and significant individual characteristics impacting students' preferences. The results are expected to be helpful for policymakers to examine built environment and social-economic segregations for residential

zone allocation toward a harmonious and quality student housing market.

2. Methodology

2.1 Questionnaire and Survey Design

We designed a questionnaire to collect information about the residential zone choice of students at the Industrial University of Ho Chi Minh City (IUH). Students are asked to show their location and relevant information, including distance from home to university, housing type, ownership status, area, household size, payment fee, built environment characteristics in the location (i.e., open market or supermarket, park or green space, bus system, plants, or industrial park), distance from home to their workplace (if any), residential time, and residential changes. Students were also asked about their part-time job, vehicle usage to the university, and workplace (if any). Finally, students' social characteristics were addressed with information about the school year, the number of days they go to the university, their income, family income, whom they live with, and gender. The questionnaire was pre-tested with a sample of 20 students. The students were asked to read and note which details were difficult to understand. The questionnaire was then checked and revised based on their notes.

We used the revised questionnaire in a survey with an expected sample of 300 as a requirement for unbiased parameter estimation for a multinomial logit model with covariates are normal, positively skewed, or categorical, as suggested by Hamid et al (2016) and Hamid et al (2020). We applied a face-to-face survey with trained interviewees and an online survey using the Kobo toolbox to speed up the data collection. The survey was conducted between March and May 2023.

2.2 Data Analysis

We addressed the characteristics of residential location zones using the Kruskal-Wallis test to identify if there is any difference in the characteristics across the zones. For binomial characteristics, we used the Chi-squared test to examine differences in proportions among zones. Additionally, we used the Wilcoxon rank sum test to examine differences in travel time and travel cost between motorcycles and buses in residential zones.

Regarding the influence of individual characteristics on the residential zone choice, we deployed a multinomial logit model. According to the theory of Random Utility Maximization, an alternative with the highest utility will be chosen in a choice set (Train, 1986). The multinomial logit model is deployed to address the utility term of individual i (Equation 1) for his or her decision on choosing a residential zone Z in the choice set $z = \{1, \ldots, M\}$. The probability that a residential zone Z is chosen can be written as Equation 2.

$$u_{iz} = \alpha x_z + \beta_z y_i + \varepsilon_{iz} \quad (1)$$

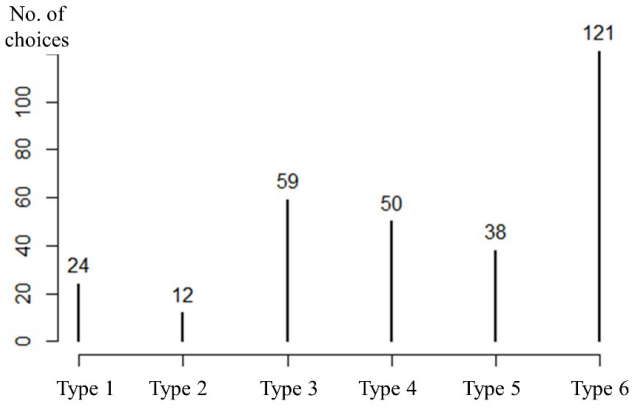
$$\Pr(Z_i = z) = \frac{e^{\alpha x_z + \beta_z y_i}}{e^{\alpha x_z + \beta_z y_i} + \sum_{t_m \neq t} e^{\alpha x_{z_m} + \beta_{z_m} y_i}} \quad (2)$$

where u_{iz} is the utility function of student i when choosing a residential zone z, x_z is a variable that represents characteristics of alternative z, y_i is a variable that represents characteristics of student i, α and β_z are the parameters of variables x_z and y_i, and ε_{it} is the error term. R language and environment (R Core Team, 2023) was used to estimate the parameter by maximizing the model's log-likelihood.

3. Data

A dataset of 304 students who are studying at IUH was obtained. Respondents are first-year students (31%), second-year students (20%), third-year students (27%), and fourth-year students or more (21%). The description of the sample is in Table 1. Students must go to the university four days a week on average. They have an average household size of four and used to change their home once. In Vietnam, students have subsidized from their families rather than government loans to pay living costs, including the budget for housing. Therefore, their family income might impact the students' choices. The data shows students' monthly family income is from 20 to 25 million VND. Besides, many students (33%) have part-time jobs and mainly have a monthly income lower than 6 million VND. Most students drive motorcycles daily to university and workplaces (if any) instead of a bus. That might be because of the city's poor bus system and heavy traffic congestion (Nguyen et al., 2020).

Additionally, most students (65 %) live with their friends (i.e., hometown friends and other students). The others live with family (18%), relatives (12%), or alone (3%). Regarding housing types, most students (39.8%) live in peer-shared houses with private toilets and kitchens and not in the same house with the landlord (Type 6). 19.41% live in tube houses (Type 3). The number of students living in dormitories (Type 1) occupies the smallest ratio of 7.89% (Figure 2).



Type 1: Dormitory
Type 2: Apartment
Type 3: Tube house
Type 4: Peer-shared house without private toilet and kitchen
Type 5: Peer-shared house with private toilet and kitchen in the same house with the landlord
Type 6: Peer-shared house with private toilet and kitchen and not in the same house with the landlord

Figure 2 Housing types

Table 1 Demographic and residential description (N = 304)

Characteristics	Min	Max	Median	Mean	SD.
Gender: male = 1, female = 2	1	2	2	1.54	0.5
Education level: 1 (first year), 2 (second year), 3 (third year), 4 (fourth year or more)	1	4	2	2.38	1.13
Number of days at university (day/week)	0	7	4	3.79	1.44
Household size (persons)	1	16	4	4.12	2.47
Residential characteristic: 1 (first place), 2 (second place), 3 (third place or more)	1	3	2	1.75	0.66
Take a part-time job: 1 (yes), 2 (no)	1	2	2	1.67	0.47
Individual income (10^6 VND/month): 1 (<3), 2 (3–4), 3 (4–5), 4 (5–6), 5 (6–7), 6 (7–8), 7 (8–10), 8 (10–15), 9 (15–20), 10 (>20)	1	10	3	3.45	2.22
Household income (10^6 VND/month): 1 (<5), 2 (5–10), 3 (10–15), 4 (15–20), 5 (20–25), 6 (25–30), 7 (30–40), 8 (40–50), 9 (50–70), 10 (>70)	1	10	5	5.08	1.99
Frequency of bus use to university: 1 (never), 2 (less than once per month), 3 (less than once per week), 4 (1-2 times a week), 5 (3-4 times a week), 6 (almost daily)	1	6	1	2.22	1.51
Frequency of motorbike use to university: 1 (never), 2 (less than once per month), 3 (less than once per week), 4 (1-2 times a week), 5 (3-4 times a week), 6 (almost daily)	1	6	5	4.93	1.38
Frequency of bus use to workplace: 1 (never), 2 (less than once per month), 3 (less than once per week), 4 (1-2 times a week), 5 (3-4 times a week), 6 (almost daily)	1	6	1	1.56	1.12
Frequency of motorbike use to the workplace: 1 (never), 2 (less than once per month), 3 (less than once per week), 4 (1-2 times a week), 5 (3-4 times a week), 6 (almost daily)	1	6	6	5.27	1.53

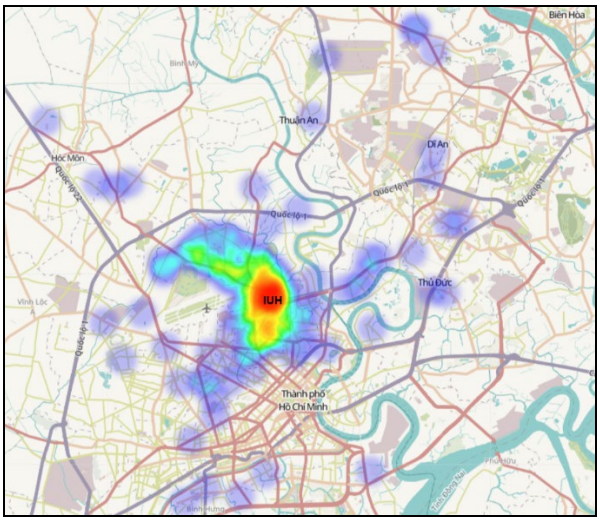


Figure 3 The density of student residence

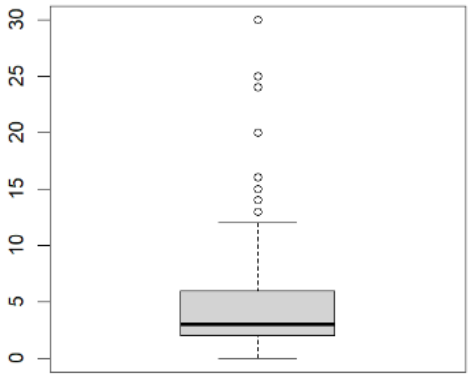


Figure 4 Distance from home to the university

Figure 3 shows that students tend to live near the campus. Based on the distribution of distance from home to university (Figure 4), the residential zones were classified into four zones. Zone 1 covers residential locations with distances lower than 3 km, Zone 2 covers residential locations with distances from 3 to 6 km, Zone 3 covers residential locations with distances from 6 to 10 km, and Zone 4 covers students with distances from 10 km. Table 2 describes the distributions of zones. The zones were used for further analysis of zones' characteristics and students' choices.

Table 2 location zones of students (N = 304)

	Zones			
	Zone 1	Zone 2	Zone 3	Zone 4
Range from IUH	< 3km	3 – 6 km	6 – 10 km	>10 km
Number of students	124	85	50	45

4. Results and discussion

4.1 Characteristics of Residential Location Zones

Table 3 presents differences relating to the built environment among zones. Besides the difference in distance from home to university, we found significant differences in distance from home to workplace, home ownership, residential area, residential cost, distances to a bus stop from home and workplace, number of bus transfers to the university, travel time and travel cost to the university by either bus or motorbike, travel time and travel cost to the workplace by motorbike, and some other built environment characteristics including open spaces, bus system, and industrial park.

Generally, students who live in farther zones have farther distances from home to the workplace. More students live in homes with ownership, more extensive area, and less cost in the farther zones. Additionally, the areas are more likely to have parks/open spaces and near industrial parks/plants. However, they are less likely to have a bus system across. Students living in the farther zones must walk farther to see a bus stop, take more bus transfers to go to the university, and spend more travel time and cost to go somewhere. Comparing travel time and travel cost between using a motorcycle and bus within each zone shows significant differences in most cases (Table 4), reflecting a challenging transportation situation. Severe traffic congestion in the city, shown by Nguyen et al. (2019), might be a reason why travel time by motorbike is less than by bus. Along with the comparison of travel time and travel cost in Table 3, the Wilcoxon test confirms a negative difference in travel time and a positive difference in travel cost within the zones.

We found insignificant differences in the proportions of open markets or supermarkets among zones. That might be because retail services have covered a wide range and grown in HCMC and nearby as shown in the study of Tran et al. (2015).

Table 3 Characteristics of residential zones and tests for residential zone differences

Characteristics	Zone 1	Zone 2	Zone 3	Zone 4	Test result
	Mean (SD)				**Kruskal-Wallis chi-squared**
Distance from home to university (km)	1.29 (0.65)	4.00 (0.89)	7.06 (1.02)	14.20 (5.51)	277.99***
Distance from home to the workplace (km)	1.65 (1.20)	4.25 (3.89)	4.00 (1.92)	5.71 (3.56)	34.87***
Residential area (m^2)	20.35 (18.94)	27.22 (22.38)	34.88 (25.24)	62.82 (36.90)	79.79***
Residential cost (10^6 VND/month)	1.37 (1.32)	1.41 (1.19)	1.09 (1.72)	0.77 (1.38)	30.98***
Distance from home to a bus stop (m)	178.55 (177.29)	266.38 (203.45)	393.50 (295.41)	310.66 (256.71)	45.93***
Distance from workplace to a bus stop (m)	124.09 (186.93)	199.87 (165.79)	713.90 (1182.55)	173.06 (219.61)	22.36***
Number of bus transfers to go to the university	0.97 (0.51)	1.27 (0.60)	1.46 (0.54)	2.02 (1.25)	66.08***
Number of bus transfers to go to the workplace	1.12 (0.48)	1.45 (0.93)	1.20 (0.41)	1.38 (1.54)	2.91
Travel time to go to the university by motorbike (min)	6.67 (5.47)	12.67 (5.39)	19.32 (6.33)	29.24 (11.23)	178.85***
Travel time to go to the university by bus (min)	9.73 (7.81)	21.32 (11.17)	35.78 (15.92)	43.22 (24. 73)	157.35***
Travel cost to go to the university by motorbike (10^3 VND)	6.11 (4.06)	8.14 (4.28)	19.66 (31.60)	42.22 (100.75)	103.12***
Travel cost to go to the university by bus (10^3 VND)	2.90 (1.57)	3.78 (1.79)	4.26 (1.61)	6.07 (4.00)	51.93***
Travel time to go to the workplace by motorbike (min)	7.23 (5.00)	12.67 (8.31)	10.55 (5.01)	13.20 (9.66)	13.47**
Travel time to go to the workplace by bus (min)	10.85 (8.94)	21.70 (16.45)	18.30 (9.98)	216.73 (770.05)	19.22***
Travel cost to go to the workplace by motorbike (10^3 VND)	5.82 (3.06)	9.57 (8.57)	7.45 (3.27)	11.07 (12.39)	8.81*
Travel cost to go to the workplace by bus (10^3 VND)	3.35 (1.43)	4.10 (1.84)	3.60 (1.23)	3.21 (2.19)	4.10
	Proportion				**X^2 value**
Ownership (self, family, or relative ownership)	0.06	0.13	0.40	0.76	102.1***
Near open market or similar	0.98	0.95	0.94	0.93	3.34
Near supermarket	0.81	0.84	0.90	0.84	1.65
Near park/open space	0.56	0.68	0.78	0.73	9.48*
Have a bus system	0.95	0.84	0.80	0.77	13.61**
Near the industrial park/plant	0.26	0.40	0.58	0.73	39.03***

*Significant codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1*

Table 4 Wilcoxon rank sum test for travel time and travel cost between motorcycle and bus in zones

Characteristics	W value			
	Zone 1	Zone 2	Zone 3	Zone 4
Travel time from home to university (min)	5353***	1295***	434***	600***
Travel cost from home to university (VND)	12034***	6153***	2442 ***	1754***
Travel time to go to the workplace (min)	394*	239**	84**	68·
Travel cost to go to the workplace (VND)	908***	758***	348***	162*

*Significant codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1.*

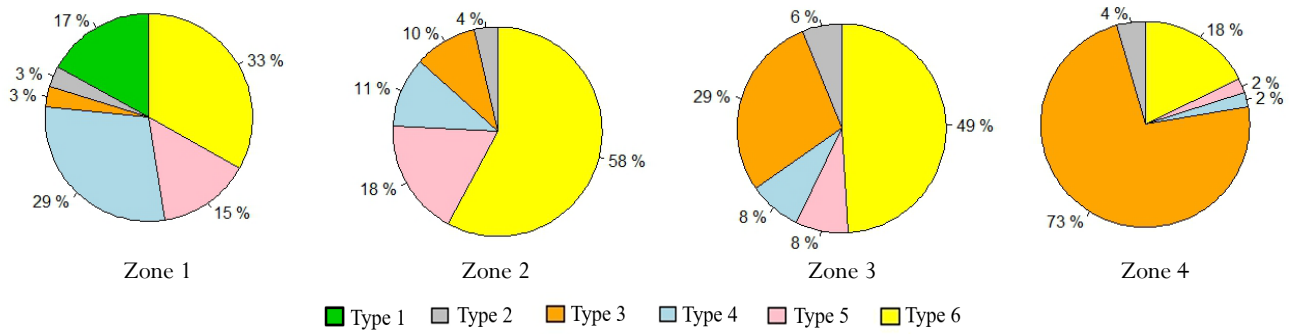


Figure 5 Allocation of housing types in zones

Except for the dormitory belonging to the campus, the other housing types are varied among zones, as shown in Figure 5. Type 2 has become more prevalent in farther zones. Generally, peer-shared houses are more prevalent in Zone 1, 2, and 3 than in Zone 4. In contrast, Type 3 shows the opposite tendency.

4.2 Individual Choices

The result of the model of residential zone choice is shown in Table 5. It reveals differences in residential zone preferences based on socio-economic characteristics.

Students in the second year are less likely to live in Zones 2 and 3, while students in the third or later are more likely to live in Zone 3. After the first year, many students might realize the pressure of a heavy studying schedule, including taking courses in the evening. Therefore, Zone 1 might become the better choice for them. From the third year, students become familiar with studying at the university. Also, this is a period when students have internships and do theses, so they will not have to go to the university for classes frequently. Therefore, Zone 1, with a higher price and smaller area (see Table 3), is less attractive and less likely to be chosen.

Students who frequently drive a motorbike to university will likely choose Zones 2 and 3. This might relate to the distance from the student's home to the university. With a motorbike, a student might have more freedom to stay in a farther place. In another aspect, students can choose more transport modes to live in Zone 1 because of the short distance, requiring less travel time. Bus usage was not significant, which might relate to a low rate of transport mode usage (see Table 1). The result is in line with the findings of Krishnapriya and George (2020); and Ralph and Brown (2019) for the relationship of mode choice behavior and residential location. Also, it extends to the issue of the mode usage frequency in residential locations.

Students who do not have a job tend to live near the university in Zone 1 rather than in Zone 4. In other words, students might choose Zone 1 not because of the opportunities for their part-time job. This is consistent with the fact that students with higher family incomes are less likely to choose farther zones, such as Zone 3 and Zone 4, to stay, or students living near the university have less pressure to have an income.

Another reason for the residential zone choice is because of whom they are living with. The result shows that students are less likely to live with friends in Zone 3 and 4 than in Zone 1 and with family. Students live in Zone 1 with their relatives rather than in Zone 4. Many students from other provinces choose to stay with relatives in HCMC. However, this depends on how far their relative's home is from the university. Unsurprisingly, Zone 4 is less attractive than Zone 1 in this case.

Finally, the probability of choosing Zone 2 reduces with the household size. This relates to the housing type of dormitory with the highest household size within the campus in Zone 1. The low magnitude of the factor shows less effect than other factors. Many students live in Zone 4 with their families, so their household size is also high. However, this parameter is not significant. Females are less likely to choose Zone 4 for their location than males. As anticipated, the zone's farthest distance makes it inconvenient and unsafe for a female student. Similarly, students who live alone or with others also do not choose Zone 4 for their stay. It can be said that Zone 4 is an inconvenient choice for students except for students living in their families with home ownership.

If the variables are omitted, the constants imply that students choose Zone 4 rather than Zone 1. However, they are less likely to choose Zones 2 or 3. This might be related to the ratio of home ownership and the level of convenience of the zones, as shown in Section 4.1.

Table 5 Multinomial logit model of residential zone choice

Variables	Zone 2		Zone 3		Zone 4	
	Coeff.	z-value	Coeff.	z-value	Coeff.	z-value
Constant	-0.45	-0.43	-1.23	-0.84	**2.43***	**2.06**
Study in the second year	**-0.79**.	**-1.73**	**-1.27**.	**-1.66**	-0.60	-0.77
Study in the third year	0.73	1.64	**1.50****	**2.64**	-0.87	-1.14
Study in the fourth year or more	0.72	1.46	**1.26***	**2.04**	0.21	0.27
The frequency of motorbike usage to the university is higher than twice a week	**1.42***	**2.44**	**2.31***	**2.09**	1.11	1.43
Do not have a part-time job	-0.34	-0.97	-0.57	-1.36	**-1.04**.	**-1.85**
Family income is 50 mil. VND/month or higher	-0.82	-1.09	**-2.23***	**-1.87**	**-3.18***	**-2.32**
Live with friends	-0.14	-0.19	**-1.83****	**-2.87**	**-5.24*****	**-7.20**
Live with relatives	1.12	1.38	-0.59	-0.73	**-2.63*****	**-3.39**
Live with others	-0.15	-0.13	-0.002	-0.002	**-3.11***	**-2.35**
Household size	**-0.20***	**-1.89**	-0.06	-0.50	0.06	0.51
Female	-0.50	-1.56	-0.37	-0.92	**-0.93**.	**-1.84**
Log-likelihood at convergence	-290.56					
McFadden Rho-squared	0.27					

*significant codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1*

4.3 Implications for Policymaking

Embedded in socio-cultural similar contexts, the student housing markets in Southeast Asian cities might share common characteristics and the discussions here can provide stakeholders with an understanding of residential zones and implications for developing the market.

- Residential zones from a university are appropriate for analyzing students' allocation. They could be used in analyzing the student housing market.

Because significant differences are found in residential zone characteristics and individual preferences for the residential zones, policymakers could consider the differences and influential factors in managing and developing the student housing market. Also, housing providers could show attractive characteristics in their products relating to the residential zones. Furthermore, universities can refer to the residential zones to monitor their students' residence and prevent the negative impacts of off-campus student housing.

- Residential zones should be considered simultaneously with transport systems and travel behavior.

The differences in transport systems such as bus system, bus stop, bus transfer, travel time, and travel cost of transport modes for commuting trips increase the differences among zones. In another aspect, the frequency of transport mode usage as a motorcycle impacted residential zone choice. If the transport system changes, there will be a change in travel behavior and then residential zone choice. This adds a rebound influence direction to the findings of the impact on travel behavior of residential locations (Ralph and Brown, 2019). If student houses are developed in certain areas, specific bus lines could be set up to support students' travel demands.

In contrast, projects in developing student houses should be in an area with a good public transport network. It can be in farther zones but through metro lines. In the case of IUH in HCMC, the Suoi Tien area, where a metro line will work soon, could be used as a good example.

- Opportunities for part-time jobs and relevant built environment variables are remarkable in residential zones.

The results show that students living in farther zones have more difficulty accessing part-time jobs because of farther distances and limited transport conditions. However, they are the group likely to have a part-time job. This clarifies a disadvantage for students who cannot live in nearer zones for specific reasons, including low incomes. Therefore, considering opportunities for part-time jobs in residential zones is necessary for developing the student housing market.

5. Conclusion

We have classified students' residential zones around a university, taking a case in HCMC, addressed their differences, and examined influential factors in students' preferences. Significant differences were found in the distance from home to workplace, home ownership, residential area, residential cost, transportation, and other built environment characteristics relating to market/supermarket, open spaces, bus stop, and industrial park/plants. Significant student preference factors to the zones include academic levels, motorcycle usage, employment status, family income, household member, household size, and gender.

The results suggest that policymakers and practitioners should consider residential zones as students' allocations in developing the student housing market. Transport systems, travel behavior,

and opportunities for part-time jobs are remarkable aspects that should be considered simultaneously. The implications could help other developing cities, especially those in Southeast Asia, where the social and cultural situations are similar.

A limitation of the scope meant that we focused on the residential zone around a university and could not consider mutual interference with other universities' student location zones. For a comprehensive review of a city's student housing market, mutual interference must be investigated. In this aspect, the study could work as a basic. If residential location zones investigated in this study can represent residential locational zones around a university in the city, mutual interference could be generalized. Also, we suggest that both questionnaire data and map data should be mined to explore spatial information besides behavior and enhance policy analyses of the student housing market.

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The Role of Animal-Aided Design in Sustainable Architecture

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ABSTRACT

Environmentally insensitive practices such as the unconscious use of natural resources, industrialization and unplanned urbanization cause the rapid destruction of natural habitats and even the extinction of some species. Today, as the importance of sustainable architecture has increased, architectural approaches that are compatible with nature have been adopted and thus the protection of natural life has been tried to be supported. As a definition, sustainability is a form of practice that aims to harmonize the built environment with natural life. In this context, the impact on animals whose habitats we are destroying is a significant topic within sustainability discussions. Studies show that the role and importance of human-animal based sustainable architectural habitats for enhancing animal welfare have not been extensively investigated. This study aims to discuss the importance of animal-aided designs within the sustainability approach. In addition, it is to carry out studies to improve the quality of life in society by strengthening the human-animal bond. In line with this purpose, animal-aided designs at urban, infrastructure, and building scales were analyzed within sustainability approaches, and their contribution to the sustainability approach was evaluated. As a result, it is emphasized that the sustainable animal-aided design approach provides innovative solutions for structures to be designed for animals and it also contributes to environmental, social, and economic sustainability, but in order for these designs to be successful, it is underlined that living spaces suitable for the needs of animals should be created and the negative effects of environmental impacts on animals should be considered. It is also emphasized that in addition to the principles of sustainability, factors that pay regard to the lives of animals contribute to the understanding of sustainability. It is expected that the discussion of the relationship between sustainability and animal-aided design, which is put forward through this study, will create an important discussion ground for future research and application examples.

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1. Introduction

This study investigates the place of animal-aided designs in the understanding of sustainable architecture. The basis of the study is how a concept such as sustainability, which should be handled in a multifaceted and comprehensive manner, will be related to animal-aided designs. Sustainability is a concept that emerged in the 1970s in order to reduce the adverse effects of urban density on living things. It is an ecological term that has been used since the early 1970s with the meaning of 'ensuring a continuous flow of what each part of the system needs for a healthy existence and maintaining the adequacy of the system'. When applied to an ecosystem inhabited by humans, the term implies certain limitations on the ability of the biosphere to absorb the impacts of human activities (Madge, 1997).

Analyzing the relationship between animal-aided designs and sustainability also addresses the problems created by the rapidly increasing human population. While industrial and construction activities have significantly damaged the nature we live in, such issues as environmental problems, depletion of natural resources, decrease in biodiversity, pollution, and energy use have come to the forefront. While the environmental impacts created by humans are increasing rapidly today, the living population is also gradually decreasing. According to the 'Living Planet' report of the World Wide Fund for Nature, the population of other living things decreased by 60% between 1970 and 2014 (McLellan et al., 2014: 9).

Conservation of biodiversity helps to keep natural ecosystems healthy and thus helps us to have a sustainable future. In many developed countries, the approach of planning for the sustainability of urban systems by utilizing the ecosystem services of the natural environment and green infrastructure has become an important component of urban planning efforts (Apfelbeck et al., 2020). However, current urban planning and architectural design practices often ignore biodiversity in the general sense and wildlife in particular. Furthermore, the destruction of habitats results in increased competition between species, ultimately leading to a decline in the number of species. To mitigate these negative impacts on urban wildlife, it is of necessity to develop wildlife-integrated planning strategies (Hess et al., 2014).

This study focuses on the significance of animal-aided designs in comprehending sustainable architecture. It provides a framework for understanding the connection between sustainable architecture and animal-aided designs that do not include humans. In this way, it is aimed to contribute to making future designs more sustainable for humans and other living beings.

2. Literature Review

2.1 Sustainable Architecture Approach and Animal-Aided Design

In the second half of the 18th century, the Industrial Revolution caused a rise in the number of people living in cities. Uncontrolled population growth brought along significant problems; rapidly increasing industrial and construction activities led to considerable damage to the environment. Toxic gases, fumes, and wastes from factories polluted water resources and reduced soil fertility. It was only in the 20th century that the importance of the issue was realized (Ciravoğlu, 2006). After the 1980s, researchers and planners working on environment and environmental problems developed strategies for the sustainability of society and the environment.

Due to the multidimensional nature of the concept of sustainability, different disciplines working on this subject have developed various definitions. Meadowcroft (1997) defines sustainability simply as a concept that can be sustained, that is, that can be continued; Tekeli (2001) defines sustainability as the correct establishment of the relationship between society, which is the socio-economic system formed by humans, and the environment of the ecological system consisting of non-human living things and non-living things, which constitute the two subsystems of the ecological system.

After the 1970s, sustainability discussions have generally been shaped within the framework of sustainable development. The most accepted definition of the concept of sustainable development in the international arena is the definition in the Our Common Future report published by the World Commission on Environment and Development in 1987, which states that "sustainable development is the ability to meet the needs and expectations of today without compromising the ability of future generations to meet their own needs and expectations" (WCED, 1987). As a continuation of the steps taken towards sustainable development, "Agenda 2030: UN Sustainable Development Goals/Aims" was adopted (MFA, 2022). The 2030 Sustainable Development Goals basically reflect these expectations by aiming to stop the destruction of the natural and social habitats of the global community and to achieve the welfare of all segments in a more balanced and fair manner (Messerli et al., 2019). In this regard, the 2030 Agenda emphasizes that human well-being depends on the health of the global ecosystem and that the welfare of all animals is essential for a sustainable ecosystem in the future (Folke et al. 2016, as cited in Olmos Antillón et al. 2021).

Visseren-Hamakers (2020) states that animals are ignored in sustainable development discussions, because sustainable development is a very human-centred concept. Maulana (2018) emphasizes that the practice of sustainability is generally human-oriented, and in fact, the basis of sustainability should be a continuous harmony between human and nature. On the other hand, Apfelbeck et al. (2020) point to the relationship between biodiversity, ecosystem services and sustainable and healthy cities and clearly state that urban design focuses on the needs of all living things, including wildlife.

Sustainability in the context of building construction refers to the understanding of balancing economic, environmental, and social factors from the design of the buildings to their construction, from their use to maintenance (Aghimien et al., 2018). Today, sustainability has become a priority in the field of architecture. The impact of a building is not only limited to its users and its immediate surroundings, but also includes societies and nature. The building's construction, operation and demolition can

consume natural resources and increase environmental impacts. Therefore, a sustainable design should consist of factors such as energy efficiency, waste management and water saving.

The role of animal-aided designs within the sustainable architecture approach has an important place both in reducing the environmental impacts of buildings and in protecting the habitats of animals. Throughout history, unplanned human construction has damaged the habitats of animals, disrupted the natural balance, and increased the risk of species becoming extinct. Moreover, the human-animal relationship is generally shaped by a human-centred approach, and studies into animals aim to increase the yield to be obtained from them in almost all disciplines. Instead of focusing only on efficiency and usefulness in animal studies, a broader perspective such as the continuation of the species and the balance of ecosystems should be adopted. For this purpose, interdisciplinary studies are carried out to protect/enhance the natural ecosystems of animals (Clevenger and Huijser, 2011; Weisser and Hauck 2017; Apfelbeck et al. 2020).

Animal-Aided Design (AAD), developed by Weisser and Hauck (2015), focuses on the protection of natural ecosystems and the improvement of animal habitats. AAD is a species-centred conservation approach that aims to increase the habitats of animal species and combines this effort with space design. It is also applied in urban areas where people live, aiming to design spaces that are suitable for both the needs of people and the needs of local wildlife. Weisser and Hauck (2017) state that the essential requirement of AAD in a design process requires knowledge of all the needs that arise throughout the life cycle of a species from birth to reproduction. Another study involves the design of so-called "animal lines" to provide a connection to the old city centre of Lucca, which surrounds the ancient city walls and disused green spaces. Different zones are created along these lines, accessible to both humans and animals. This approach aims to increase the interaction between humans and animals in urban areas (Granai et al., 2022).

Articles carried out into animal-aided design show that projects can be realized in urban areas that make it possible to both sustain the existence of local wildlife and design suitable spaces for humans. For the successful realization of animal-aided design, cooperation and communication between different disciplines is of great importance from the first design stage. In this way, it is aimed to design the most suitable living spaces by considering the protection of natural life and the welfare of animals.

3. Methodology

As a result of the sustainability literature review, certain common concepts were identified between the sustainable architecture approach and animal-aided designs in terms of functional and structural aspects. The functional design dimension of animal-aided designs with the understanding of sustainability aims both to increase the welfare of animals and to consider sustainable architectural approaches. Functionally, sustainable animal-aided designs within the scope of the study were evaluated under thirteen headings as a result of the literature analysis (Figure 1).

The structural design dimension of animal-aided designs with sustainability understanding aims to consider sustainable architectural approaches in the building production process and to minimize environmental impacts. From a structural point of view, both sustainability principles and the life cycles of animals have been effective in the issues to be considered in sustainable animal-aided designs (Figure 2).

FUNCTIONAL PARAMETERS	GENERAL EXPLANATION
That it is a structure suitable for the natural life cycle of the animal	In order for the species to survive and continue its generation, meeting all of the critical needs in the life cycle should be determined as a priority goal (nutrition, reproduction, etc.) (Weisser & Hauck, 2017).
That it is an environment suitable for animal welfare (*five domains)	Considering the physiological, behavioural and psychological needs of animals, it is important to create environments that can sustain and support their lives in sustainable animal-aided designs. In order to improve the welfare of animals, five basic welfare dimensions to be considered are: 1- Nutrition 2- Environment 3- Health 4- Behaviour 5- Mental State (Mellor et al., 2020; Salgırlı Demirbaş, 2023).
That it is made in accordance with the environment	It should be suitable for the local texture (topography) where it is located, it should be designed considering the climatic conditions and the structure should be positioned according to the current sun-wind situation (Emekci, 2021).
Use of materials resistant to environmental conditions	It should also care about the safety of animals and their protection from environmental factors. The health of animals is directly or indirectly affected by the effect of increasing temperatures, especially due to climate change (Nardone et al. 2010 cited in Rojas-Downing et al. 2017).
Providing adequate natural lighting	Natural lighting is important for animals to maintain their natural behaviour, regulate their sleep patterns in a healthy way and reduce their stress. In addition, it should be kept in mind that ecological light pollution has negative effects on living things (Longcore and Rich, 2004).
Ensuring natural ventilation and indoor air quality	Natural ventilation can provide effective cooling by taking into account the land structure surrounding the building, its location and surrounding areas, as well as air movements at different times of the day and the direction of wind flow (Özmehmet, 1999).
Ensuring acoustic performance	For the health and welfare of animals, it is of great importance that the acoustic performance of the environment is appropriate (Newbury et al., 2010: 17).
That it is an environment suitable for health conditions and animal comfort	It has been revealed that the most important environmental factor affecting the health and physiological functions of animals is temperature (Bengtsson and Whitaker, 1986). Temperature stress in animals varies depending on temperature, humidity, species, genetic potential, age and nutritional status (Rojas-Downing et al., 2017).
Use of natural / local materials	It is associated with animals' preference for living spaces made of natural materials (Denneboom et al., 2021).
Effective use of material	In resource management, which is one of the basic principles of sustainable architecture, it is aimed to reduce environmental pollution and create healthier living environments through the effective use of materials such as the reuse of existing buildings, material-saving design and construction, the use of renewed and recycled materials (Zindane, 2010).
Use of renewable energies	The use of renewable energy in animal-supported designs provides a more effective and efficient use of energy resources.
Preservation of existing vegetation	As a requirement of sustainable design, it should be aimed to ensure the continuity of plant and animal species in the area by protecting the existing vegetation and increasing the amount of green space. The use of green tissue in the appropriate direction, spacing and type in the design plays an important role in the control of climatic elements (Colombo et al., 1994: 37).
The design suitable for human-animal interaction	The human-animal bond, as defined by the American Veterinary Medical Association, is a mutually beneficial and dynamic relationship between humans and animals. This relationship is influenced by behaviours that are important for the health and welfare of both parties. It includes emotional, psychological and physical interactions between humans, animals and the environment (Avma, ?). The human-animal bond is an important relationship that has positive effects at both individual and societal levels and improves the health and well-being of humans and animals.

Figure 1 AAD Functional Design Dimension

STRUCTURAL PARAMETERS	GENERAL EXPLANATION
Modular and repetitive	It is observed that in environments where animals are housed in an excessive way densely, dominance behaviours occur between species from time to time. For this reason, it should be ensured that sufficient space can be created in case of an increase in the number of animals (Salgırlı Demirbaş, 2023).
Fast and easy construction and installation	This approach ensures more efficient use of resources as it requires less time and labour. This makes a significant contribution to reducing environmental impacts and protecting existing natural resources.
Establishment with a small number of technical staff	Building installation with a small number of technical staff reduces labour costs and makes designs more economical. It also minimises environmental impacts such as noise, waste and energy consumption.
Long service life	The longevity of the building is possible with the right material selection, the use of quality construction methods, and the design in accordance with local data and climatic conditions.

Figure 2 AAD Structural Design Dimension

The research content consists of international and national animal-aided design examples in relation to sustainability. The selected urban, infrastructure, and building scale projects will undergo detailed analysis with a sustainable design perspective. The study examines urban planning initiatives in the Ruhr-Germany region, which prioritize the protection and enhancement of natural habitats, the Trans-Canada Highway wildlife crossings, which boast the world's highest number and diversity of wildlife crossings, and the Bat Bridge, which enables shared use by humans and bats. Additionally, the research encompasses nine buildings across various typologies, including shelters, refuges, and farms, situated in varying geographies and countries.

3. Evaluation of the Place of Animal-Aided Designs in Sustainable Architecture Approach at Urban, Infrastructure and Building Scales

In the sustainable architecture approach, the importance of animal-aided designs is linked to protecting the natural environment, strengthening the human-animal relationship, and improving the quality of life. These designs encourage people to live in harmony with nature while helping animals to live a healthy and happy life similar to their natural environment.

3.1 An example of Animal-Aided Sustainable Approach At The Urban Scale: Ruhr Region

The Ruhr Region Urban Regeneration Project makes significant contributions to region's sustainability by bringing abandoned industrial areas back into the use of society. When it comes to sustainability, the reuse of buildings plays an important role in terms of protecting the city's integrity (Takva Y et al., 2023). In the applications in this region, the textures of the industrial period of the past are evaluated by attributing new meanings (Dağ and Özberk, 2012).

The Ruhr Region Urban Regeneration project in Germany includes many measures for the protection of animals and the expansion of their habitats and contributes to protecting the ecological integrity of the region. Many projects have been implemented in urban areas called 'industrial nature' where nature develops freely, and important arrangements have been made to develop unique biotopes and rare species (Kurtay and Sağlam, 2011). In the implementation phase of the project, measures such as combining green areas to form a network, taking natural landscape features into account during the reuse of industrial areas, and cleaning the Emscher River were taken to create a healthier and more livable environment for people, animals, and plants in the region (Figure 3).

Figure 3 Ruhr Region (YouTube, 2021a)

This project provides significant environmental benefits through the restoration or conversion of existing buildings. This approach minimizes negative environmental impacts by reducing the use of raw materials and energy required to construct new buildings. It contributes to a more efficient use of natural resources by reducing waste production and enables more economical use of energy resources. The Ruhr region offers areas compatible with the natural life cycles of living organisms. With the sustainable protection and utilization of natural areas in the region, the existing vegetation cover has been preserved, thus ensuring the continuity of plant and animal species. In addition, the presence of areas suitable for human-animal interaction contributes significantly to increasing social welfare. The project adopts an economically cost-effective approach by saving on material and construction costs through the reuse of industrial areas.

3.2 Examples of Animal-Aided Sustainable Approach At The Infrastructure Scale

The increasing population and the resulting need for settlement and transport directly affect natural areas and wildlife habitats,

leading to habitat fragmentation, isolation of populations and destruction of important habitats (Whittington et al. 2019). In this context, ecological bridges have emerged as structures that provide wildlife crossings (Doğan and Şahin, 2015). In order for these crossings to be effective, objectives should be determined and monitored.

3.2.1 Trans-Canada Highway Wildlife Bridges, Canada

Wildlife bridges linking Banff National Park and Lake Louise are located on the Trans-Canada Highway (Parks.canada.ca, 2022). These crossings provide wildlife conservation by connecting fragmented habitats (Figure 4). Also, fences are installed to prevent wild animals from interacting with traffic. Infrared cameras, tracking devices, and other technologies are used to monitor the passage habits of animals and the effectiveness of corridors (Alexander and Waters, 2000; Sawaya et al., 2019; Barrueto et al., 2020). In addition, vegetation sustainability is targeted through ecosystem protection and restoration.

Figure 4 Wildlife bridges (Clevenger, 2007)

3.2.2 Bat Bridge, Hollanda

Bat Bridge is part of Park Poelzone, an ecological corridor in the Netherlands. The bridge is characterized by being located on the flight route of several bat species, providing suitable habitats for different bat species in different seasons, and being suitable for shared use by humans and animals (Lola.land, 2015).

For hibernating bats, there is an empty area designed from reinforced concrete in the lower section of the bridge. The bridge deck and under the masonry parapet are designed as suitable areas for breeding. The openings have a rough surface for bats to cling to. Openings for roosting bats have been created on the bridge along the red brick wall line (Figure 5) (Archdaily, 2015).

Figure 5 Bridges sections and façades (Archdaily, 2015)

The wildlife crossings on the Trans-Canada Highway and the Bat Bridge projects were designed by interdisciplinary teams in accordance with the natural life cycles and behaviour of animals. These examples can be considered as critical corridors to prevent habitat fragmentation and thus protect biodiversity. In order to prevent wild animals from being affected and stressed by vehicle noise and headlights, local vegetation has been emphasized at the crossings. The vegetative design of the habitat passages allows animals to pass through passages similar to their natural habitats. Both examples are built according to climatic data in accordance with the environment and consist of structures and materials resistant to environmental conditions. In addition, it is likely that there is sufficient natural ventilation and lighting so that the ambient air quality can be provided for animals. It is also likely to mention the use of natural/local materials with the use of local vegetal elements and the use of wooden materials as seen in the Bat Bridge example. In the studies conducted for wild animal crossings on the Trans-Canada Highway, it was pointed out that animal crossings were recorded less at crossings open to human use and that these crossings were not suitable for human-animal interaction. In the Bat Bridge project, spaces suitable for the life cycle of bats were created and designed to encourage human-animal interaction. Repetitive structures and materials in these projects enabled rapid installation and low-cost construction. Research has shown that Trans Canada wildlife bridges reduce animal-vehicle collisions and increase the cost-effectiveness ratio in the long term (Conteches, 2017). In this respect, wildlife crossings on the Trans-Canada highway have provided low-cost projects in the long time from a structural point of view. There needs to be a study on the cost comparison of the Bat Bridge project.

3.3 *Examples of Animal-Aided Sustainable Approach At Building Scale*

By analyzing the different types of buildings constructed in detail in various countries, the study will provide results that are to play a critical role in the planning of sustainable animal-aided projects. The analysis of building types in different climatic zones aims to provide valuable information for the design of environmentally and climate change friendly buildings in future urban developments.

3.3.1 Petting Farm, Almere/ Netherlands (2008)

The farm in Almere, the Netherlands, is used as a children's farm (Figure 7) (Stadennatuur, 2008).

Figure 6 Petting farm (Archdaily, 2009)

Figure 7 Petting farm (Archdaily, 2009 and Stadennatuur, 2008)

Thanks to the open façade system of the upper half of the building, the air circulation in the building is provided naturally and the whole farm is ventilated. The barn section was built as a single storey building with two floors in height. In the other half of the building, the toilets and storage are located on the first floor, while the office and hay storage are located on the second floor (Figure 8). Access to the building is provided by six shutters. The shutter system can be opened automatically or manually with the effect of the morning sun (Figure 6) (Archdaily, 2009). Salgırlı Demirbaş (2023) emphasized the suitability of the project for animal welfare and stated that the design was arranged to meet the needs of animals.

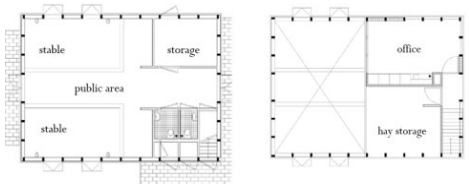


Figure 8 Petting farm floor plans (Archdaily, 2009)

It is clear that the spaces in the farm are built in a way that allows the animals to live in a comfortable and healthy way and thus support the natural behaviour of the animals. In the barn sections, animals have enough space for their natural movements. Thanks to the fact that the barn section is a single storey with a height of two storeys and the overall structure is designed with intermittent wooden panels, good ventilation, and sufficient natural light environment is provided. Thus, the risk of respiratory diseases of animals is minimized. Providing sufficient natural light also helps to maintain the biological rhythms of the animals. The renewable energy source and solar-powered modular wooden panels used in the building have increased energy efficiency and contributed to environmental sustainability. Tall thuja, a tree species that does not grow naturally in the Netherlands, was used on the facades. This may have caused the construction cost to increase. Modular natural wood elements in the form of panels used in facades contribute significantly to speeding up the construction and installation processes. The use of panel systems makes the construction process more efficient by requiring fewer technical staff. Looking at the project in general, it is observed that the material is used effectively and therefore resources are used efficiently. Within the scope of the project, the existing vegetation cover has been preserved with the sustainable protection and utilization of natural areas in the region, thus ensuring the continuity of plant and animal species. In addition, the presence of areas suitable for human-animal interaction contributes to the increase in social welfare. The longevity of the structure is ensured by designing the farm in accordance with the climatic conditions of the period when it was built, selecting the right materials, and constructing it with quality construction methods.

3.3.2 Women and Children Therapy Centre, Iraq (2016)

Located in Iraq, this centre is a modern therapy centre for children and women victims of war. By emphasizing the importance of using traditional building materials and techniques, the project aims to reduce the effects of trauma by identifying with the past (Zrsa, 2019). The centre, which is made up of eleven simple earthen volumes, is arranged around a series of courtyards, creating a village-style atmosphere. Light shading elements connecting the different volumes increase the comfort of the users (Figure 9) (Archdaily, 2017). Salgırlı Demirbaş (2023) emphasized the project's compliance with animal welfare and stated that the design is organized to meet the needs of animals.

Figure 9 Women and Children Therapy Centre (Archdaily, 2017)

The Women's and Children's Therapy Centre is designed to provide animals *a comfortable and healthy environment that supports their natural behaviour*. In the pens in the example, animals have enough space for their natural movements. Designed with a courtyard plan scheme, it also improves the ambient air quality by *providing adequate natural lighting (as well as the use of renewable energy) and ventilation.* This project emphasizes not only the *importance of traditional building materials and techniques* but also *the importance of human-animal interaction,* providing a design that meets the needs of both users. *Thanks to the use of adobe material, the temperature inside the building is regulated naturally, which is beneficial for energy saving.* Furthermore, the adobe material is vital for the users' health by preventing dampness inside the building. It *is also an environmentally friendly material as it is reusable and recyclable. The use of traditional materials in the building has ensured that construction costs are low and technically, a structure that anyone can easily build has emerged.* The spaces in the project have a modular and repetitive structure. This approach helps to reduce maintenance and repair costs and allows the building to be built quickly. The longevity of the building was ensured *by designing the facility by the climatic conditions of the period in which it was built, selecting the suitable materials, and constructing it with quality construction methods.*

3.3.3 Bear Sanctuary, Vietnam (2018)

The bear sanctuary, located in Cát Tiên National Park in Vietnam, was built to protect bears victimized by the illegal bear trade. It is a naturally ventilated and environmentally friendly structure built with modular design, local materials, and an eco-friendly approach (Figure 10). The shelter comprises six bear houses, a training centre, a hospital, a quarantine section, and an administrative office (Archdaily, 2019a).

Figure 10 Bear Sanctuary (Archdaily, 2019a)

It is observed that the spaces in the Vietnam Bear Shelter are built in a way that allows the animals to live comfortably and healthily and thus support the natural behaviour of the animals. There is a large area in the project where they can move freely. In addition to free movement opportunities, the shelter lacks areas covered with trees, bushes, etc. where they can hide. It can be stated that the living conditions for bears rescued from their previous inadequate cage environment have been enhanced in this area. They are given the opportunity to live in a large area where they can sunbathe. They are also provided with natural ventilation instead of tiny cages where they are deprived of sunlight and health. With the provision of natural ventilation, the risk of respiratory diseases is minimized. The provision of sufficient natural light also helps to maintain the biological rhythms of the animals. The use of traditional materials in the building ensures that construction costs are low and technically it is a structure that can be built easily by anyone. This project emphasizes not only the importance of traditional building materials and techniques but also the importance of human-animal interaction, offering a design that meets the requirements of both users. The spaces in the Vietnam Bear Sanctuary have a modular and repetitive structure. This approach helps to minimize maintenance and repair costs and allows the building to be constructed quickly. The longevity of the building is ensured by designing the building by the climatic conditions of the period in which it was built, selecting the suitable materials, and constructing it with quality construction methods. In addition, with the integration of the green roof into the building, energy efficiency has been increased, the surrounding air quality has been improved thanks to the plants, and a positive contribution has been made to local biodiversity.

3.3.4 Haven the Eternal Experience Pavilion, India (2022)

The cow shelter is located in the village of Peermade, India (Earthscapestudio, 2022). The most important aspect of this project is that the architect has preserved the concept of "the idea of protecting nature" from selecting materials to the constructing building. The shape of the building follows the natural landform without disturbing the natural landscape and the surrounding trees (Figure 11).

Figure 11 Cow Shelter (Earthscapestudio, 2022)

In the Cow Shelter, it is seen that spaces that allow animals to live comfortably and healthily are created in a way to support the natural behaviour of animals. The purpose of the building is to provide protection for animals from heavy rainfall or other bad weather conditions. The façade design has been shaped by paying attention to the climatic data and the needs of the animals. Considering the cases of the heavy wind and precipitation, the building has a sloping form and openings are designed to help direct the flow of rainwater into the deep valley. The air circulation inside the building is provided naturally through the openings in the facade, thus minimizing the risk of respiratory diseases for the animals. The building is situated in an area that affords animals more leisure time to graze and play freely. Both the façade and the carrier system have been created by using a small number of materials. It is also designed to maximize the use of natural ventilation and natural light. The land where the building is located has a very green environment. Thanks to this green area, it is ensured that the sounds that may occur in the environment are absorbed, and their effect is reduced so that the animals will not get stressed. The use of traditional materials in the building has ensured that the construction costs are low and technically, a structure that anyone can easily build has emerged. Since it is a suitable environment for animal carers, human-animal interaction is favourable for both. The longevity of the building is ensured by designing the building by the climatic conditions of the period in which it was built, selecting the suitable materials, and constructing it with quality construction methods.

3.3.5 Palanga Art and Architecture Farm, Turkey (1888)

Kutluğ Ataman spearheaded the project to revitalize the farm established in 1888 (Soistanbul, 2018). Aiming for a sustainable agriculture and animal husbandry model with animals using biodynamic methods, the farm also aims to maintain environmental sustainability (Attec.design, 2019). The project was shaped by Kutluğ Ataman's love of nature and Hasan Çalışlar's collaboration.

3.3.5.1 Palanga House of Chickens (2018)

The most important aspect of the Chicken House is that the design team created the structure according to design principles based on the daily routines of the chickens. Each design principle is based on the observation of chickens and the previous

experiences of local people. At each stage of the design, design diagrams were created to reveal whether they meet the daily routines of the chickens. Another critical factor affecting the design was the behavioural relationship between humans and animals. A corridor was created on the centre axis of the building so that people could collect eggs without disturbing the chickens. The side parts serve basic needs such as shelter, incubation, rest, and sleep (Figure 12). After collecting the data resulting from all these studies, low-cost materials and traditional construction techniques that are easy to maintain according to the climatic and regional characteristics of the region were preferred. Reinforced concrete was used for the foundations, wood for the carcass and cladding elements, and sheet metal for the roof (YouTube, 2021b).

Figure 12 Chicken House images (Archdaily, 2019b)

The design of the Palanga Chicken House is to support the natural behaviour (daily routines) of the animals, allowing them to live in a comfortable and healthy way. In the poultry house sections in the example, animals have enough space for their natural movements. The semi-open space located on the central axis of the building allows animals to socialize even in bad weather conditions. In addition, this space provides shading in hot weather conditions. Thanks to the pivot panels used in the facade design, good ventilation and a sufficient natural light environment are provided. Thus, the chickens are not exposed to heat stress and the risk of respiratory diseases is minimized. The balanced use of pivot panels ensures a homogeneous distribution of light entering the space. Providing sufficient natural light helps to maintain the biological rhythms of the animals. The raised structure and the large sloping roof form allow the chickens to spend time outside on hot days. The nesting boxes are connected to the outside so that people can collect eggs without disturbing the chickens. The other most important factor that influenced the design was the behavioural relationship between humans and animals. The nesting boxes are connected to the outside so that people can collect eggs without disturbing the chickens. The use of traditional materials in the building has ensured that construction costs are low and technically, a structure that anyone can easily build has emerged. The spaces in the Palanga Chicken Coop have a modular and repetitive form. This approach helps to reduce maintenance and repair costs and allows the building to be built quickly. The longevity of the building was ensured by designing the facility by climatic conditions of the period in which it was built, selecting the right materials, and constructing it with quality construction methods.

3.3.5.2 Palanga Newborn Calf Shelter (2019)

The Calf Shelter is a shelter that meets the needs of the calves by selecting materials that are compatible with the environment. (Figure 13) (YouTube, 2021b).

Figure 13 Newborn Calf Shelter (Nsmh, 2019)

The aim of the project is to create a shelter that will provide health care for newborn calves (Nsmh, 2019). The building is mostly designed as an open space, especially suitable for harsh climatic conditions, and aimed to make the best use of sunlight. The building has an open side for animals to enter comfortably, while the roof slope is designed to provide protection against harsh weather conditions. The walls are made of robust and maintenance-free materials and have a rough surface to meet the scratching needs of the animals. In this way, they are allowed to exhibit their natural behaviour (YouTube, 2021b).

The design of the Palanga Calf Shelter is to support the natural behaviour (daily routines) of the animals, allowing them to live in a comfortable and healthy way. In the pens in the example, animals have enough space for their natural movements. As the façade design is shaped according to climatic data and animals' needs, the south façade's open design provides natural ventilation and a sufficient natural light environment. Thus, the risk of respiratory diseases is minimized. Providing sufficient natural light also helps to maintain the biological rhythms of the animals. The use of traditional materials in the building has ensured that construction costs are low and technically, a structure that anyone can easily build has emerged. The longevity of the building is ensured by designing the building by the climatic conditions of the period in which it was built, selecting the suitable materials, and constructing it with quality construction methods.

3.3.5.3 Palanga Goat Shelter (2021)

In the design process, user requirements were taken into consideration and in this context, goat physiology was given importance. In addition to other factors such as the geographical characteristics and climate of the project location, the seismic requirements of the building were taken into consideration due to its location in an earthquake zone. In addition, it is aimed to seek sustainable solutions, ensure compliance with today's conditions, use natural materials, and adopt traditional stone-earth-wood workmanship as a construction technique (Figure 14). The building was constructed entirely using local and natural materials. The foundation of the building was constructed using stones from the stream in the farm (YouTube, 2021b).

Figure 14 Goat Shelter (Ecarch, 2021)

The design of the Palanga Goat Shelter is to support the natural behaviour (daily routines) of the animals, allowing them to live in a comfortable and healthy way. In the pens in the example, animals have enough space for their natural movements. The façade design is shaped by considering the climatic data and the needs of the animals. It is designed to protect the goats from harsh weather conditions and a chimney form has been considered considering the health of the animals. In this way, natural ventilation is provided, and the risk of respiratory diseases is minimized by increasing the air circulation inside the building. It is a structure that allows the animals to spend more free time and an area where they can freely graze and play around. The existing vegetation has been preserved in these areas. The use of traditional materials in construction has ensured low construction costs. In today's architecture, the importance of methods such as rammed earth and adobe, which were frequently used in ancient times, has unfortunately decreased. For this reason, it has become a structure that cannot be easily applied by everyone because it is a structure that requires technical competence to learn about these methods. The building is a structure that fits the climatic conditions of its location and responds to the user' needs. The longevity of the building is ensured by designing the building by the climatic conditions of the period in which it was built, selecting the suitable materials, and constructing it with quality construction methods.

4. Evaluation and Conclusion

Today, architectural design approaches have been transformed due to the emergence of various environmental problems such as climate change, population growth, unplanned urbanization, pollution, and depletion of natural resources (Aslan, Selçuk and Avinç, 2022). This has resulted in the development of architectural approaches that are compatible with nature through the adoption of environmentalist techniques in the selection of building materials and construction techniques. The significance of sustainable architecture is on the ascent, as it seeks to harmonize building practices with the natural environment, supporting the protection and longevity of natural life. In this context, the role of animals whose natural habitats are being destroyed has an important role in sustainability debates.

The aim of sustainable animal-aided design is to create habitats where animals can live healthily and comfortably, suited to their natural life cycle. These habitats should be designed according to local climate, well-ventilated with natural lighting, and constructed from materials that can withstand natural and environmental conditions. Before designing animal shelters, it is crucial to comprehend the specific climatic requirements of each animal species and the negative impacts environmental factors can have on them. For instance, regions with cold winters require animal shelters to have sufficient heating systems and accessible areas that are shielded from temperature drops. Similarly, animals located in hot regions should have access to cooling systems and shaded areas. To avert negative environmental impact on animals, specific measures should be taken when designing their habitats. For instance, shelters to address water pollution concerns should be equipped with effective treatment systems to prevent harm to water resources caused by animal waste. Designs that do not consider the environmental needs of animals can harm their health. This can result in the use of additional resources such as veterinary services, improved building heating-cooling systems, and re-evaluating the building waste system. As a result, more materials are used, and construction costs increase. For sustainable animal-aided building designs to work, create living spaces that meet animal needs, fully understand the impacts of the environment on animals, and adapt designs accordingly. These structures shield animals' welfare and health while promoting the efficient use of resources.

In this study, focusing on the importance of sustainability in animal-aided building design, the Ruhr Region example at the urban scale, examples at the infrastructure scale, and nine selected building scale sample projects from Turkey and around the world are analyzed comparatively.

The comparative analysis is based on interdisciplinary studies, and the findings highlight the benefits of animal-aided sustainable designs at urban, infrastructural, and building scales. Technical term abbreviations are explained when first used. Consistent citation and footnote style are followed. Quotations are clearly marked, and filler words are avoided. The building-scale findings reveal that animals' welfare and quality of life improve in spaces tailored to their natural behaviours and needs. The use of natural materials, lighting, and ventilation in design heightens animal comfort and diminishes stress levels. Such architectural features positively influence the animals' well-being.

Findings at the urban and infrastructure scale demonstrate that the inclusion of animals in urban areas has a positive impact on environmental balance and contributes to biodiversity conservation. It is important to recognize these benefits to facilitate their adoption and expansion in urban planning. The implementation of such designs yields numerous beneficial effects, including the expansion of green spaces, diversification of ecosystem services, and safeguarding of natural habitats. The examined instances have a crucial function in preventing species extinction, facilitating scientific inquiry, establishing spaces for human-animal interaction, promoting social consciousness, and emphasizing its significance in the sustainable architecture approach. Despite this, the scarcity of animal-aided sustainable designs, especially at the national level, is noteworthy. Increasing the number of animal-aided sustainable designs at

urban, infrastructure, and building scales is deemed a vital measure in safeguarding environmental and ecological harmony. Addressing this issue shall not only bridge a scientific gap but also promote the adoption of sustainable animal-aided designs that benefit humans and animals alike.

The parameters evaluated in the urban, infrastructure and building scale examples selected within the scope of the study reveal the main elements that need to be considered in order to design animal-aided buildings in a sustainable and animal welfare-oriented manner. Consideration of these elements helps designers to construct spaces that are designed in accordance with the needs of animals and thus help the sustainability of the species. Furthermore, these parameters ensure the environmental, social, and economic sustainability of the buildings. Therefore, it is extremely important to consider these parameters in the design of animal-friendly buildings and thus, sustainable-animal welfare-oriented buildings and urban areas can be built. The discussion of the relationship between sustainability and animal-aided design, which has been put forward through this study, constitutes an important discussion ground for future research and application examples.

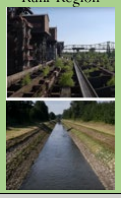
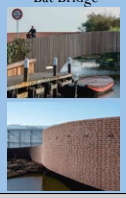
Animal Aided Design Parameters in Sustainable Architecture Approach	**Animal-Aided Design at the Urban Scale**	**Animal-Aided Design at Infrastructure Scale**		**Animal-Aided Designs at the Building Scale**	
	Ruhr Region 	Trans Canada Highway 	Bat Bridge 	Petting Farm 	Thearpy Centre 
FUNCTIONAL					
That it is a structure suitable for the natural life cycle of the animal	-Suitable habitat environment -Beginning of species appearance	-Ecological bridges made from natural materials -Variation of genre-specific bridge characteristics	-Suitable environment for different bat species in four seasons -Rough interior surfaces for their attachment	Suitable habitat environment	Suitable habitat environment
That it is an environment suitable for animal welfare (*five domains)	Nutrition, environment, health, behaviour and mental state	Nutrition, environment, health, behaviour and mental state	Nutrition, environment, health, behaviour and mental state	Nutrition, environment, health, behaviour and mental state	Nutrition, environment, health, behaviour and mental state
That it is made in accordance with the environment	Suitability to local color	Suitability to local color	Suitability to local color	Suitability to local color	Suitability to local color
Use of materials resistant to environmental conditions	Selection of the right materials suitable for the climate	Selection of the right materials suitable for the climate	Selection of the right materials suitable for the climate		Selection of the right materials suitable for the climate
That it is suitable for the climate (insulation details suitable for the climate)	Selection of plants suitable for the climate	Selection of plants suitable for the climate and structural details	Selection of the details suitable for the climate	Selection of the details suitable for the climate	Selection of details and materials suitable for the climate
That it is suitable for the topography (local color)	Suitability to local color	Suitability to local color	Suitability to local color	Suitability to local color	Suitability to local color
Positioning of the structure according to the sun and wind				Design according to climatic elements	Design according to climatic elements
Providing adequate natural lighting	Wide openings	Open / semi-open areas	Open / semi-open areas	-The upper half of the structure is open -Facade panels that move with the sun	-Open / semi-open spaces -Courtyard design
Providing natural ventilation	Wide openings	Open / semi-open areas	Open / semi-open areas	The upper half of the structure is open	Open / semi-open areas
Monitoring indoor air quality	Adequate natural ventilation	Adequate natural ventilation	Adequate natural ventilation	Adequate natural ventilation	Adequate natural ventilation
Ensuring acoustic performance	Adequate use of plant elements	Use of herbal elements to prevent stress from vehicle noise			
That it is an environment suitable for health conditions and animal comfort	Adequate natural ventilation and lighting	Application of type-specific architectural details	Application of type-specific architectural details	Application of type-specific architectural details	Application of type-specific architectural details
Use of natural materials	Vegetation suitable for the local color	Vegetation suitable for the local color	Use of wood on the façade	Use of wood on the facade	Use of adobe
Use of local materials	Vegetation suitable for the local color	Vegetation suitable for the local color			Use of earth-straw mixture bricks
Use of renewable energy	Open / semi-open areas	Open / semi-open areas	Open / semi-open areas	Open / semi-open areas	Open / semi-open areas
Effective use of material	Utilisation of existing structures	Preservation of existing vegetation		Preservation of existing vegetation	Preference for local ingredients
Preservation of existing vegetation	Protection of existing natural areas	Protection and interconnection of existing natural areas	Protection and interconnection of existing natural areas	Protection of existing natural areas	Protection of existing natural areas
Efficient use of resources	-Utilisation of existing structures -Preservation of the existing green field	Preservation of the existing green texture Effective use of material	-Preservation of the existing green texture -Effective use of material	-Preservation of the existing green texture -Effective use of material	-Preservation of the existing green texture -Effective use of material
Design suitable for human-animal interaction	-Ecosystem protection -Increased social welfare	-Decrease in traffic accidents caused by wildlife -Increased social welfare	-Multi-purpose wooden platfrom -Increased social welfare	-Use as a child farm -Increased social welfare	-Keeping the village atmosphere alive -Increased social welfare
STRUCTURAL					
Modular and repetitive	Modular natural landscape elements	Modular structural elements	Modular structural elements	Modular structural elements	Modular plan scheme and structural elements
Fast and easy construction and installation	Modularity	Modularity	Modularity	Having modular façade elements	Modularity
Establishment with a small number of technical staff	Modularity	Modularity	Modularity	Modularity	Modularity
Simple yet high strength of the load-bearing system					Use of sun-dried bricks
Long service life	Design according to local data	Design according to local data	Design according to local data	Design according to local data	Design according to local data
Low cost	Protection of existing structures	Decrease in traffic accidents			Use of local materials

Figure 15 Evaluation table of selected samples over the determined parameters - 1

Animal Aided Design Parameters in Sustainable Architecture Approach	Animal-Aided Designs at the Building Scale				
	Bear Sanctuary 	Cow Shelter 	Palanga 1888, Erzincan, Turkey		
			House of Chickens (2018) 	Newborn Calf Shelter (2019) 	Goat Shelter (2021) 
FUNCTIONAL					
That it is a structure suitable for the natural life cycle of the animal	?	-Suitable habitat environment -Having a shelter to protect them from heavy rainfall	-Suitable habitat environment -Having both roosting and resting areas	-Suitable habitat environment -Provision of scratching needs with materials from the front line	-Suitable habitat environment -Ensuring the release of toxic gases into the air by leaving the centre axis of the building open
That it is an environment suitable for animal welfare (*five domains)	Nutrition, environment, health, behaviour and mental state	Nutrition, environment, health, behaviour and mental state	Nutrition, environment, health, behaviour and mental state	Nutrition, environment, health, behaviour and mental state	Nutrition, environment, health, behaviour and mental state
That it is made in accordance with the environment	Suitability to local color	Suitability to local color	Suitability to local color	Suitability to local color	Suitability to local color
Use of materials resistant to environmental conditions	Selection of the right materials suitable for the climate	Selection of the right materials suitable for the climate	Selection of the right materials suitable for the climate	Selection of the right materials suitable for the climate	Selection of the right materials suitable for the climate
That it is suitable for the climate (insulation details suitable for the climate)	Selection of details and materials suitable for the climate	Selection of details and materials suitable for the climate	Selection of details and materials suitable for the climate	Selection of details and materials suitable for the climate	Selection of details and materials suitable for the climate
That it is suitable for the topography (local color)	Suitability to local color	Suitability to local color	Suitability to local color	Appropriate to the local color Earthquake resistant building	Appropriate to the local color Earthquake resistant building
Positioning of the structure according to the sun and wind	Design according to climatic elements	Design according to climatic elements	Design according to climatic elements	Design according to climatic elements	Design according to climatic elements
Providing adequate natural lighting	Open / semi-open spaces Courtyard design	Having catenary arched facades	Open / semi-open spaces Courtyard design Balanced use of facade panels on the facade	Open / semi-open areas	Semi-open spaces
Providing natural ventilation	Open / semi-open areas	Semi-open spaces	Open / semi-open areas	Open / semi-open areas	Semi-open areas
Monitoring indoor air quality	Adequate natural ventilation	Adequate natural ventilation	Adequate natural ventilation	Adequate natural ventilation	Adequate natural ventilation
Ensuring acoustic performance		Adequate use of plant elements			
That it is an environment suitable for health conditions and animal comfort	Application of type-specific architectural details	Adequate natural ventilation and natural lighting	Adequate natural ventilation and natural lighting	Adequate natural ventilation and natural lighting	Adequate natural ventilation and natural lighting
Use of natural materials	Made with gobion wall technique	Local brick for the façade and load-bearing system; use of recycled sticks and local plants in the mortar mix for rigidity	Use of wood in the load-bearing system and facades	-Use of wood in the roof carrier system -Using straw-soil mixture for floor insulation	-Use of river stones in building foundations -Use of adobe -Use of lime and horasan mortar
Use of local materials	Using natural stone	Using 'Sithu kal' brick consisting of three layers	Use of wood	Use of wood and straw-soil mixture	Use of stream stones, soil-straw mixture
Use of renewable energy	Open / semi-open areas	Semi-open areas	Open / semi-open areas	Open / semi-open areas	Semi-open areas
Effective use of material	Preference for local ingredients	The fact that the load-bearing system and the facade are solved at the same time, Preference for local ingredients	Preference for local ingredients	Preference for local ingredients	Carrier system and facade are solved at the same time
Preservation of existing vegetation	Protection of existing natural areas	Protection of existing natural areas	Protection of existing natural areas	Protection of existing natural areas	Having a genre-specific design Effective use of material
Efficient use of resources	-Preservation of the existing green color -Effective use of material	-Preservation of the existing green color -Effective use of material	-Preservation of the existing green color -Effective use of material	-Having a genre-specific design -Effective use of material	-Having a genre-specific design -Effective use of material
Design suitable for human-animal interaction	Having indoor and outdoor areas that can be used together for both species	-Design in accordance with the local color -Increased social welfare	-The connection of the nesting boxes with the outside -Semi-open social area in the centre axis of the building	Having wide open spaces	Having wide open spaces
STRUCTURAL					
Modular and repetitive	Modular plan scheme and structural elements	Modular plan scheme and structural elements	Modular plan scheme and structural elements	Symmetrical plan scheme	
Fast and easy construction and installation	Modularity	Modularity	Modularity	Modularity	Using traditional construction techniques
Establishment with a small number of technical staff	Modularity	Modularity	Modularity	Modularity	Using traditional construction techniques
Simple yet high strength of the load-bearing system	Gobion wall technique	Surprisingly placed local bricks	Use of modular timber structural system	Earthquake resistance	Using adobe walls
Long service life	Design according to local data	Design according to local data	Design according to local data	Design according to local data	Design according to local data
Low cost	Use of local materials	Use of local materials	Use of local materials	Use of local materials for roofing and flooring	Use of local materials

Figure 16 Evaluation table of selected samples over the determined parameters - 2

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Assessment of Cost Influences in Rail Projects from Contractor's Perspectives

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ABSTRACT

Rail transportation had been receiving more attention in the Government's effort to enhance the Malaysian economy internationally. Nevertheless, rail projects involve various stakeholders, massive budgets and are susceptible to cost overrun. This paper aims to evaluate the cost influences concerned with rail projects in a developing nation from contractors' perspectives. The existing studies lack the consideration of the correlation and relationship between the cost influences, which this paper emphasizes. The data collection was performed by distributing questionnaires to 200 cost managers which are quantity surveyors, project managers, and contract executives across the rail projects in Malaysia. The data analysis uses Statistical Package for Social Sciences Version 27 (SPSS V27) and Structural Equation Modelling (SEM). Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy showed appropriate internal consistency of the research instrument, whereas the Confirmatory Factor Analysis (CFA) showed acceptable Goodness-of-Fit Indices (GFI) within the constructs of the structural model. The SEM calibration resulted in 23 significant cost influences which were clustered into five groups of cost influences. Each of the five groups is associated with different parties in construction projects. A notable causative direction was observed in the relationship between the cost influences. Each cost influence can be connected to each project phase based on the PMBOK Guide. This study adds to the various cost management research along the project management of rail construction. It is able to contribute to the policymakers and consultants in strategizing their cost management plans which is crucial, especially in developing countries such as Malaysia. Emphasizing the critical particulars of cost management in rail projects, this paper also delivers its finding based on stakeholder and system aspects in relation to cost management, which can be referred to by any developing country.

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1. Introduction

Rail system is the earliest transport network in Malaysia. It has a massive influence on economic performance, especially as a significant public transportation mode for inter-state and inter-city travel (Fariq & Ab Rani, 2020). The Malaysian railways have significant potential to play an important role in developing a sustainable transportation system.

Rail transport has received the most attention in the national plan as an alternative to road transport which has accounted for almost 90% of public transportation in Malaysia (Jaafar, 2018). Consequently, many rail projects were launched in Malaysia such

as the Mass Rapid Transit (MRT), Light Rail Transit (LRT), Electrified Double Tracking Projects (EDTP), Express Rail Link (ERL), Rapid Transit System (RTS), and the East Coast Rail Line (ECRL) (Ministry of Economic Affairs, 2018). Other than that, there are many projects under development in the urban area such as the latest LRT3, MRT2, and KVDT2 as well as the Johor Bahru – Singapore RTS (Chen et al., 2018).

In the rapid development in the rail industry, there is a need to realize the significant challenge of delivering rail projects successfully (Sadullah et al., 2018). Rail projects are known for their high uncertainties, complexity, and cost, which involve a massive amount of taxpayers' money (Olawale & Sun, 2015). Cost overrun had been identified to be a severe issue in construction projects worldwide (Ullah et al., 2017). In the Asian region, Park & Papadopoulou (2012) found an average of 13.46% cost overrun specifically in rail projects while in China, 30.6% of rail projects suffered a cost overrun. The metro rail of India suffered an average of 31% cost overrun. Andrić et al. (2019) established a 48% average cost overrun in Asian rail projects while stating that rail projects are most inclined to face cost overruns.

There had been no study focusing specifically on the cost performance of Malaysian rail projects. Nevertheless, Malaysian construction projects have suffered cost overrun for years (Olawale & Sun, 2010). Shehu et al. (2014) identified cost overrun in more than 50% of Malaysian projects while Rahman & Abdullah (2016) found that 89% of projects faced cost overruns in the southern Peninsular. Cost overrun denotes the phenomenon when the project's actual cost exceeds the estimated cost (Invernizzi et al., 2017), especially in mega projects due to the significant costs incurred. Prominent researchers such as Flyvbjerg established the root causes of cost overrun and stated that the root causes need to be addressed at an early stage to avoid a huge loss (Flyvbjerg et al., 2018).

Cost overrun had been reported to occur in a few rail projects in Malaysia. The EDTP Ipoh-Padang Besar was reported to incur RM1.5 billion in Variation Order claims, MRT had a 15% cost overrun (Tee Lin, 2012), EDTP Ipoh-Rawang had RM1.14 billion cost overrun (Lee Yuk, 2009) and the ERL extension had RM29 million cost overrun (AG Report, 2015). The indications of cost overrun had been advertised to the public however they were not discussed in detailed research.

A few studies have gone at length to establish the main factors of cost overrun in rail projects. However, a major gap is identified whereby most of the studies lack the identification of correlation among the various factors involved in the cost management of rail projects. Such factor correlations can help identify the structure that lies beneath these cost influences which would be beneficial in decision-making by project managers in rail projects. Furthermore, many studies on cost influences for rail projects overlook the importance of the contractor's perspective in evaluating the cost influences. The contractor's perspectives should be taken seriously as they are directly employing and engaging construction workers or managing the construction work. In mega-projects such as rail projects, contractors hold the most crucial influence on project cost performance. Thus, an empirical study on the quantitative assessment of the correlation among various cost influences in rail projects through contractors' perspectives is needed.

Reflecting on the high impact of the cost influences, such assessment is even more critical for mega-projects in developing countries during each phase of the project. The existing literature lacks exploration of the contractor's viewpoints and the underlying correlations in their understanding of cost influences in rail project planning and construction. Existing researches have not identified the critical cost influences relative to the contractor's viewpoint. This research attended to this need by performing a systematic correlation study of rail projects and contractors' perspectives, using Structural Equation Modelling. The aim is to assess the cost influences associated with rail projects in Malaysia and identify the correlational structure that exists among the cost influences.

2. Literature Review

Cost overruns in rail projects persist mainly due to the cost it incurs (Narayanan et al., 2019). Researchers have revealed that cost overruns in multiple rail developments such as the Edinburgh tram system, which was completed 100% over the budget (Love et al., 2017). In the United States (US), cost overrun had been found in the Central Link Light-Rail project in Seattle (38%), the East Valley light-rail project in Phoenix (31%), the Airport Heavy-Rail project in San Francisco (30%), and heavy-rail red line project (47%) in Los Angeles. Meanwhile, Cantarelli et al. (2012) found cost overrun averaging in 10.6% in the rail projects of the Netherlands.

This should become a major concern not just in developed countries but also in developing countries, as rail projects consume a massive capital (Ismail et al., 2021). To illustrate the detrimental impact of cost overrun, a 1% cost overrun in a US$10 billion project shall amount to US$100 million loss in budget and profit.

A significant study by Love et al. (2017) has explored the probability of cost overrun between 1% to 30%, however it needs to attend to the non-linear perspective which can reveal the causal influences among the factors influencing rail project cost performance. Other researchers by Flyvbjerg et al. (2004), Hwang et al. (2020), and Ismail et al. (2021) have also studied cost overrun causation in rail projects but without considering the dynamic causative interaction.

The analysis of this study aims to fill in this gap in research. Drawing on this knowledge background, this study analyses the cost influences associated with rail projects through a Structural Equation Modelling approach. Assessing various factors that can impact project performance can belong to the risk management area of study. In various studies, risk assessment of transportation megaprojects uses the Relative Importance Index (RII) that uses a numerical calculation to place values on each risk factor, however this method cannot quantify the correlation between the factors (Yan et al., 2019).

Structural Equation Modelling is employed in this study to remove this problem, as it incorporates various factors into a

structured model of causations. Cui et al. (2022) developed a structural model for the impact of social responsibility programs on the efficacy of urban rail projects. Mesbah et al. (2022) used SEM to explore the quality of rail services to passengers and trip characteristics. Liu et al. (2018) used SEM to assess multiple factors to identify if urban rail transit in China discourages people from using cars. Niu et al. (2022) uses SEM to assess the relationships of coopetition between international joint ventures for High-Speed Rail projects. Shaaban & Hassan (2014) produced a structural model of factors that affect the propensity of commuters to use the new rail service in Doha. However, these studies are not focused on project cost performance.

Competent project cost management is important to avoid detrimental cost overrun. Unfortunately, the evidence gathered has led to cost overruns being a regular occurrence in rail projects (Love et al., 2016). This paper discusses the non-linear causal relationship among the cost influences in rail projects. Based on the data collected, the analysis is aspired to generate information that can be useful in understanding the dynamic causal relationship among multiple cost influences in rail projects.

The current literature on rail project cost management also needs a fresh viewpoint from contractors towards the cost influences. Contractors are the major stakeholders in mega projects such as the rail project as they are not only involved in project management but also the design and cost management as stipulated in the contract agreement. The aim of this study is to elaborate on the gap in current researches by providing a comprehensive analysis of cost influences on rail projects in developing countries from the perspectives of contractors. This paper also aim to add to the body of knowledge with a detailed structural model of the causative cost influences of rail projects in Malaysia. In this structural model, the cost influences are structured according to different project phases as well as different project parties (the client, main contractor, consultants, and sub-contractors).

3. Methodology

Stratified random probability was used as the sampling approach for data collection. The instrument for data collection consists of respondents' demographic profiles and measures of constructs. The responses for demography were collected in nominal and ordinal values while the constructs were measured by a five-point Likert scale. A pilot survey was conducted before the instrument was administered using a small group of experienced cost managers and academicians. The selection of pilot respondents was by convenience to validate the survey instrument. The feedbacks were used to enhance the instrument quality in regards to the question style, language, ambiguity, and related statements. After that, 200 questionnaires were given out to cost managers (quantity surveyors, project managers, and contract executives) in rail projects across Malaysia. The respondents were selected from the main contractors in the rail industry. In total, 51.50 percent of the questionnaires were filled and given back. The results were then coded and inserted into the Statistical Package for Social Sciences Version 27 (SPSS V27). The analysis starts by performing the normality test referring to the skewness and kurtosis to verify the normality of the data. The reliability of the instrument was also examined to confirm the understanding of the respondents as they respond to the questionnaire (Vaske et al., 2017). Cronbach's α coefficient was used to test the reliability of the data collected.

Then using the SPSS V27, Exploratory Factor Analysis (EFA) was performed to discover the underlying structure within the variables. Kaiser-Meyer-Olkin (KMO) and Bartlett's test of sphericity were utilized to validate the sampling adequacy and multivariate normality within the variables. After that, Confirmatory Factor Analysis (CFA) was conducted by the AMOS software to establish the measurement models and validated by the acceptable goodness-of-fit (GFI) indices among the variables. Results from the CFA shall then be the basis of the Structural Equation Modelling (SEM).

4. Results and Discussion

4.1 Demographic of Respondents

The research uses questionnaire as a method for data collection. The data collection resulted in 103 respondents from multiple range of experience and professional qualifications as shown in Figure 1 and Figure 2.

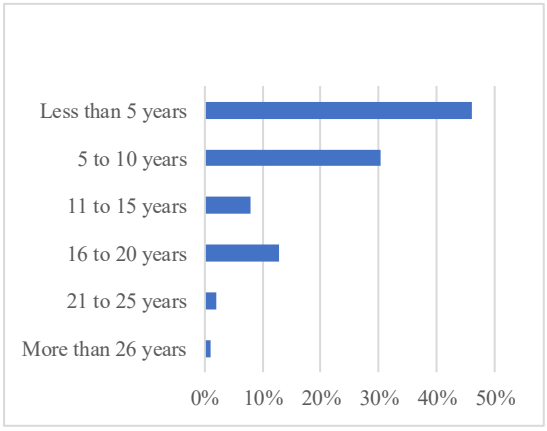

Figure 1 Respondents' working experience

The data from Figure 1 shows that all the respondents have had the necessary experience and knowledge in the construction industry to provide a quality response to the research instrument. From the 103 responses received, 54 percent had at least five years of experience, while the other 46 percent had less than five years of experience in the construction industry.

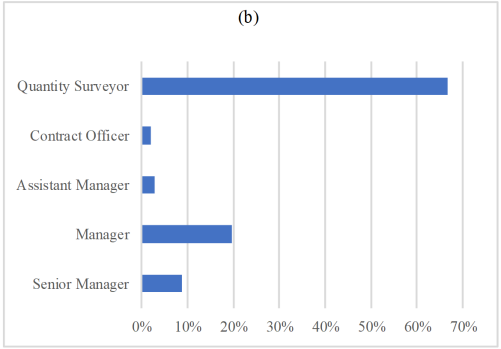

Figure 2 Respondents' positions

The data in Figure 1(b) indicates the respondent's career position in the rail industry. Due to the cost-focused nature of this study, it is apparent that 69 percent of the respondents are quantity surveyors and contract officers. The other 31 percent are managers and assistant managers. The data shows that the respondents are selected from the domain area of study in this research which is cost management in rail projects. This provides credibility to the data that is to be analysed in the later phase of the research.

4.2 Identification of Cost Influences

Studies on cost management have explored the factors influencing cost performance of projects. Unfortunately, there has been no study that assesses the relationship between cost influences and the project cost specifically in rail projects. Therefore, in this research, the cost influences in rail projects are assessed by the respective professional construction cost managers. The cost influences are listed in Table 1.

Table 1 Identified cost influences from literature

Studies identified cost influences	References
• Extensiveness of feasibility study	• Famiyeh et al. (2017); Mohammad et al. (2016)
• Accuracy in estimation of project duration	• Olawale & Sun (2010)
• Accuracy in estimation of risks	• Flyvbjerg (2014); Sarmento & Renneboog (2017)
• Adequacy of site investigation	• Hingham (2016); Shibani (2015)
• Changes in design & specifications	• Abbas & Painting (2017)
• Clarity of contract provisions	• Shane & Molenaar (2009)
• Sufficiency of project preparation	• Peters (2010); Sarmento & Renneboog (2017)
• Error/defect in works	• Park & Papadopoulou (2012)
• Clearness of project management process	• Venkateswaran & Murugasan (2017)
• Applicability of construction method	• Potty & Irdus (2011)
• Efficiency in management of works	• Potty & Irdus (2011); Ullah et al. (2017)
• Proficiency in monitoring of works	• Cárdenas et al. (2018)
• Effectiveness in work scheduling	• Al-hazim et al. (2017)
• Delay in project implementation	• Cantarelli et al. (2012)
• Financial condition of client	• Gunduz & Maki (2018); Cárdenas et al. (2018)
• Financial condition of contractor	• Vaardini et al. (2016); Abbas & Painting (2017)
• Proficiency in work schedule management	• Potty & Irdus (2011)
• Effectiveness of material planning	• Adam et al. (2017)
• Productivity of cost planning and monitoring	• Vaardini et al. (2016); Ullah et al. (2017)
• Competence of risk management	• Olawale & Sun (2010)
• Dependency on specialist works	• Potty & Irdus (2011)
• Experience of contractor organizations	• Lu et al. (2017)

Studies identified cost influences	References
• Experience of design consultants	• Lu et al. (2017)
• Experience of technical consultants	• Lu et al. (2017)
• Experience of personnel in supervisory duties	• Mohammad et al. (2016)
• Experience of executives in organization	• Mohammad et al. (2016)
• Efficacy of communication contractor and client	• Adam et al. (2017)
• Efficacy of communication between designer and contractor	• Alghonamy (2015)
• Availability of materials	• Famiyeh et al. (2017); Venkateswaran & Murugasan (2017)
• Size of project	• Park & Papadopoulou (2012); Catalao et al. (2019)
• Length of project implementation	• Cantarelli et al. (2012); Sarmento & Renneboog (2017)
• Complexity of design	• Shibani (2015); Zhang et al. (2017)
• Difficulty of construction procedures	• Mevada & Devkar (2017)
• Relocation of existing services	• Kim et al. (2017)
• Relocation of existing infrastructure	• Adam et al. (2017); Venkateswaran & Murugasan (2017)
• Inconsistent scope changes in construction	• Love et al. (2017); Ullah et al. (2017)

Referring to PMBOK Guide, these cost influences are associated with four (4) phases of construction projects which are initial, planning, execution, monitoring, and control (PMBOK Guide, 2021) and they were extracted from the literature review and preliminary survey . The influences were then enhanced by considering the judgments from multiple cost management professionals in the rail industry through the process of interview and pilot study. Initially, the cost influences were drafted into a preliminary questionnaire and went for a pilot study with twenty (20) professionals. The dataset were ensured to have normal distribution and reliability before the actual survey were performed for data collection.

Cost influences are essentially the elements or conditions related to rail projects for which money must be spent and this study intends to identify the correlation between them in influencing the project cost. As shown in Table 1, a number of academics looked into the cost influences of construction projects for different objectives, hence generating multiple outcomes. Other scholars are interested in figuring out the cost factors that have the most effects on certain construction project aims. However, the cost factors differ from one nation to another.

Therefore, by referring to the judgements of competent professionals in cost management in Malaysia, the factors that are crucial for effective cost performance in rail projects were distinguished. This study recognizes and prioritizes the cost influences for effective cost management in rail projects in Malaysia, and collects the data from literature and pilot survey to derive the cost influences.

4.3 Factor Analysis

The Kaiser-Meyer-Olkin (KMO) examines the adequacy of the sample as well as the multivariate normality of the influences in the dataset. It is calculated to substantiate the validity of the survey instrument. Meanwhile, Bartlett's test of sphericity checks if the correlation matrix is an identity matrix (Cho & Kim, 2015). The results show a KMO value of 0.81, which is over the required minimum of 0.6, and Bartlett's tests of sphericity are significant. Additionally, the extraction of the latent influences within the whole cost influences was built on the total variance explained which produced eigenvalues of 1 and above. Thus, the five components of the cost influences justify the total variance of 57.15 percent.

Oblique (Promax) rotation was selected where the correlations among variables and loadings among the latent variables are indicated. The variable loadings carried to the CFA represent the correlation coefficient to its latent variables. Meanwhile, the loading of each variable displays the variance that is explained by the variables correlated to it.

There is no cross-loadings found, however according to Tabachnick et al. (2019), cut-offs can be used from 0.32 (very poor), 0.45 (poor), 0.55 (acceptable), 0.63 (good), or 0.71 (very good). The EFA indicated five cost influences that have loadings below 0.55 which are B6 (0.30), G3 (0.36), G4 (0.42), H2 (0.36), and C5 (0.51), hence removed from further analysis. Modification indices were also referred to solve the discrepancies that exist in the model (Hermida, 2015). Four variables which are D5, E3, E4, and E11 have error terms among variables across different factors, which gives a negative effect on the model fit. Therefore, they are removed from the model. Standardized Residual Covariance (SRC) indicates discrepancies between the

proposed and estimated models. SRCs with an absolute value of more than 2.58 is considered significant and reduces model fit (Hildreth, 2013). Four variables with significant SRCs, A1 (2.62), D8 (2.53), I4 (-2.56), and I2 (many SRC values above 1) were removed to increase the model fit.

Referring to the result of factor analysis, the cost influences of rail projects are categorized into five: Project Planning (PP), Project Complexity (PC), Project Management (PM), Technical Expertise (TE), and Project Estimating (PE).

4.4 Reliability of Instrument

According to Wasiu (2018), in order to ascertain the understanding of the respondents, instrument reliability should be employed to evaluate the study variables effectively. Hence the use of Cronbach's α to identify the internal consistency within the dataset. The Cronbach's α values of the cost influences are: PP =0.04; PC=0.92; PM=0.90; TE=0.88; and PE=0.85. As the values obtained are above the suggested minimum of 0.70, the results are deemed highly significant (Pallant, 2020).

The tenacity of establishing the causal influence of the cost influences and rail project cost performance is to develop a structural model of the cost influences that will aid the effort of stakeholders to improve the performance of rail projects in Malaysia. The measurement model in Figure 2 indicates the relationship strength between the constructs. It shows that PC has a strong correlation with PE (0.55), and PE has a strong correlation with PP (0.32). TE has a strong correlation with PP (0.33) while PP correlates with PM (0.52). These correlations form the basis of the modelling which is adapted to the stages of a construction project from the PMBOK Guide.

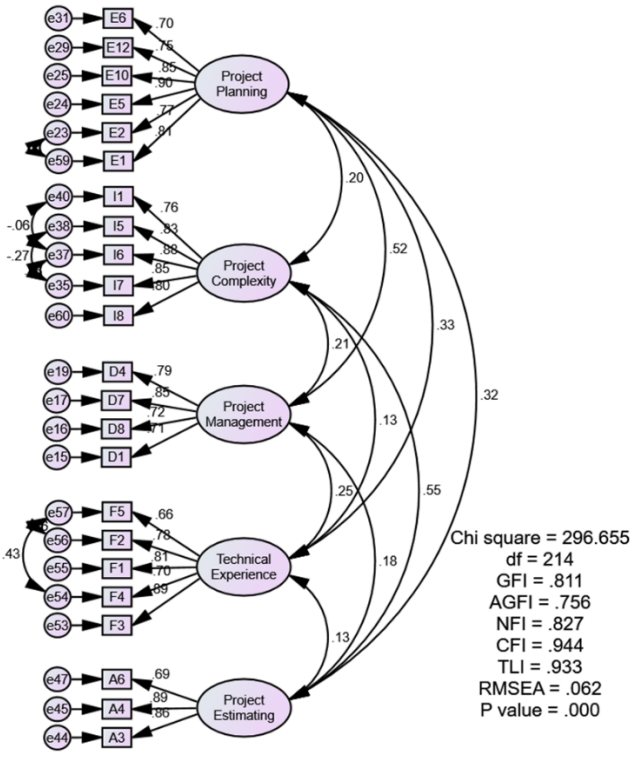

Figure 3 Measurement model

CFA is used to assess whether the constructs are consistent with the research understanding. The consistency of the data with the theoretical findings in construction cost management was constantly deliberated throughout the refinement process of the model. In evaluating the data fit indices, the base limits as specified by Hair et al. (2017), Kline (2016), and Massey & Miller (2016) were utilized. The p-value is stipulated as $p<0.05$, Comparative Fit Index (CFI) $\geqslant 0.90$, Goodness of Fit Index (GFI) $\geqslant 0.90$, Root Mean Square Error of Approximation (RMSEA) $\leqslant 0.05–0.80$ and CMIN ($\chi 2/df$)<5.

As displayed in Figure 2, the p-value is at 0.00, the CFI is 0.944, and a GFI of 0.811, a $\chi 2/df$ of 1.36, and an RMSEA of 0.062. The statistical result shows a sufficient fit within the outcome and under the acceptable range to establish the convergence validity of the measurement model. The GFI index also established the positively hypothesized covariance among the constructs.

Upon completing the measurement model, SEM was initiated to extract the causal relationships among the constructs which are the cost influences influencing cost performance of rail projects. The structural model presented in Figure 3 shows that the results have satisfied the acceptable bases on all of the statistical parameters for a good model fit. The model contains a p-value of 0.000, a CFI value of 0.946, a GFI of 0.810, a $\chi 2/df$ value of 1.36, and an RMSEA of 0.06. The tested influence of each construct towards another construct in influencing the cost performance of rail projects has been validated by the results from data analysis. Therefore, the influence of the cost influences was validated by the measurement and structural models as shown in Figure 3 and Figure 4..

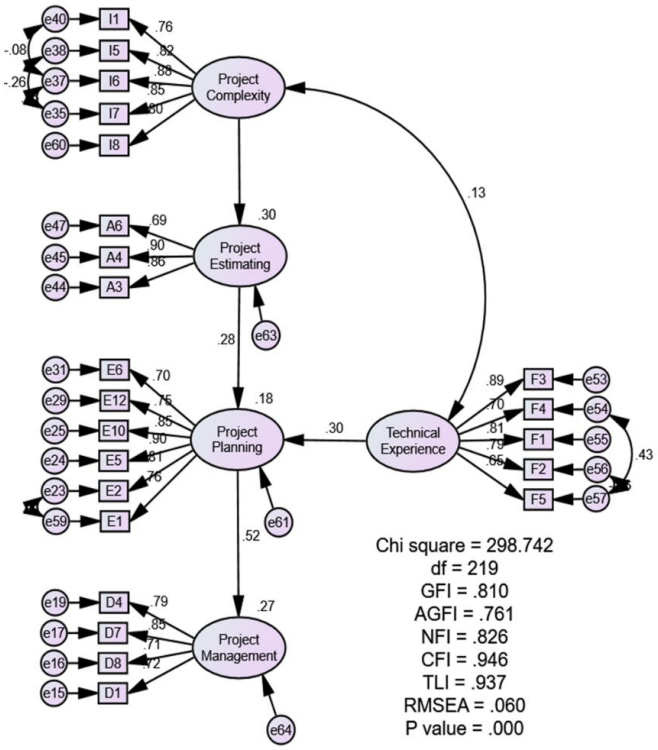

Figure 4 Structural model

The framework of cost influences influencing the cost performance of rail projects in Malaysia is presented in Figure 5. The framework was then validated by established cost managers in the Malaysian rail industry by responding to the questions below:

1. Is the framework easy to understand?
2. Does the sequence in the framework represents the actual rail projects?
3. Are the five elements in the framework compatible with the requirements of cost management in the rail industry?
4. Are the influences within the five elements well set up?
5. Does the framework show the process involved in carrying out cost management?
6. Does the framework highlight the future need to improve cost management in the rail industry?

The validation survey was joined by 20 participants out of the 50 invitations sent with a response rate of 40 per cent. The participants have a minimum of ten years of experience in the rail industry. In total, 30 percent (6) of the experts are contract managers, 30 percent (6) are project managers, 20 percent (4) are project directors, and 20 percent (4) are the head of departments. Hence, indicating that all of the experts had a considerable position as cost managers. In terms of experience, 55 percent (11) of the participants had 10–15 years of experience, 25 percent (5) had 16-20 years of experience, while 20 percent had more than 20 years experience. The experts were then requested to share their thoughts on the framework to establish an adequate acceptance of the framework

The results showed that only one participant mentioned that the framework need to be simpler. Other than that, respondent's average response showed a convincing acceptance of the framework in terms of overall quality, content, and sequences of the framework-encapsulated cost management practices in Malaysian rail projects. Altogether, 92.31 percent (12) of the respondents comprehended the framework and agreed with the setup. And so, the overall experts in the study have agreed that the framework is suited to be applied.

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The respondents also agreed that the overall structure of the framework can highlight the future need to prevent cost overruns in Malaysian rail projects. However, there are moderate scores in content association with project parties while the sequence of project phases is coherent with the characteristics of complex rail projects, especially in terms of contractual obligations. However, due to the unique procurement system, project parties might have work scopes beyond the scope that is usually agreed (Love et al., 2017).

Respondents also were asked to give suggestions to improve the presentation or practicality of the framework. Despite the optimistic responses, the respondents suggested to include contract specialist/construction law practitioner/claims consultant as part of the respondents and to include risk management, project procurement methodologies, funding sources, and contracting plans in the framework. Other than that, six respondents have suggested to add new cost influences that are significant in their experience. The suggested cost influences are "compliance with authorities' requirements", "transfer of technology in projects", "compare cost structure against the base cost before identifying any cost variance", "unexpected factors i.e. government change / policy change / covid-19 pandemic" and "political stability". The suggestions had been recorded but not added to the framework to retain the statistical validity of the existing variables.

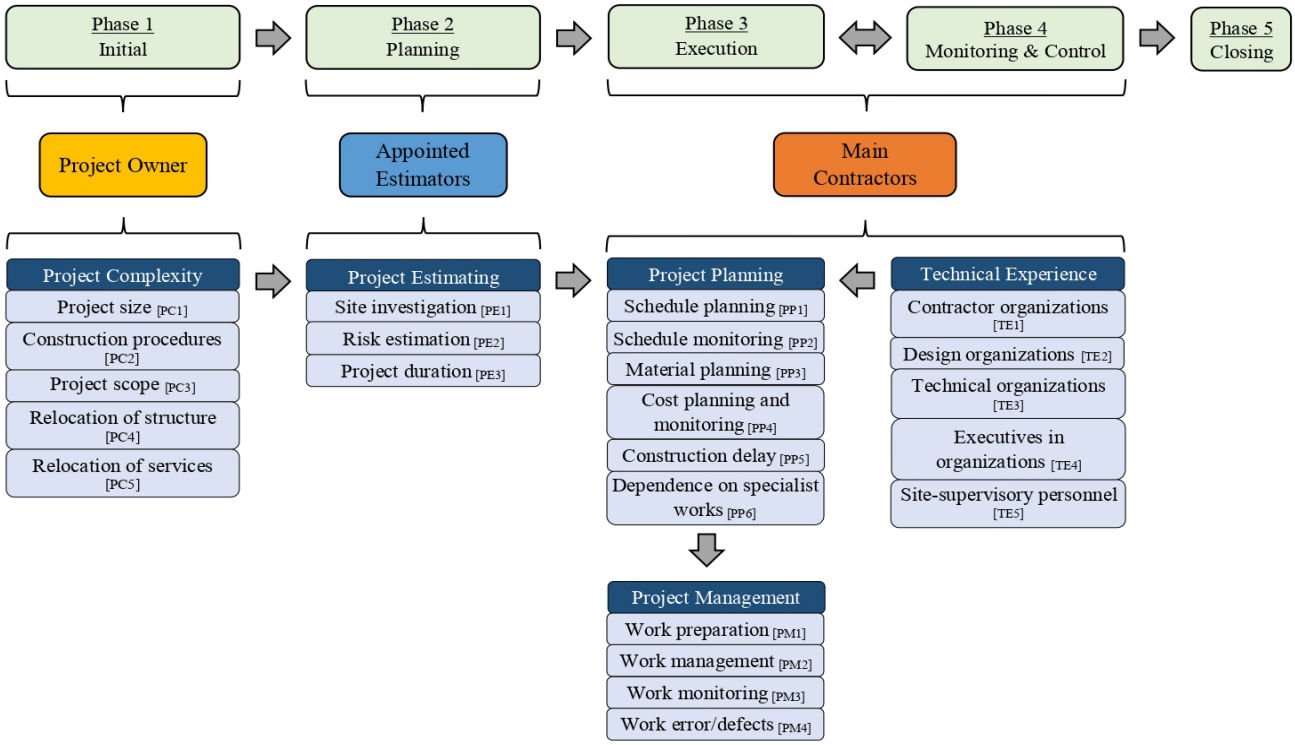

Figure 5 Framework of cost influences influencing the cost performance of rail projects in Malaysia

In summary, the proposed framework adequately unearthed the principle concerns regarding cost management in Malaysian rail projects. The feedback gathered from the verification interviews indicated that the proposed framework managed to capture positive reactions from the respondents, confirming the validity of the framework presented in this study. It asserts that a good congruity is managed to be documented between the framework developed and the respondent's perceptions in this study. Therefore, no substantial changes or improvements is needed to be introduced in its effect. For this reason, the proposed framework was taken as valid to be used as a basis to improve cost performance in Malaysian rail projects.

It is vital to observe that most of the researches on cost management in developed and developing nations did not focus specifically on rail projects. Therefore, this research assessed the key cost influences in rail projects. The study highlights the important aspects in cost management that need adequate attention by cost managers to ensure successful acheievement of rail projects.

5. Conclusion

This study seeks to identify the cost influences involved in rail projects specifically from contractors' perspectives in Malaysian conditions, using Structural Equation Modelling. The key conclusions of this research are as follows:

1. Upon ascertaining 78 cost influences of rail projects from literature, 37 are found to be significant factors influencing the cost performance of Malaysian rail projects based on the high frequency of occurrence and influence on the cost performance of rail projects.
2. Subsequently, the research established the relationships between the significant cost influences by following three different steps which are EFA, CFA, and finally SEM.
3. The EFA extracted five latent factors that grouped the 37 significant factors according to the factor loadings and correlations.
4. The CFA generated a measurement model with a good fit to validate the loadings and correlations between the factors and latent factors. Seven variables were eliminated due to the low loadings in correlation, four variables were eliminated due to the covariance between errors that cross different latent factors and three variables were eliminated due to their significant SRC.
5. Finally, SEM created a structural model that illustrated the causal relationships between the five latent factors influencing the cost performance of Malaysian rail projects.
6. The results focused on the relevant factors to implement effective management. This was to be construed according to the extracted latent factors and the causal influence between the factors influencing the cost of rail projects.

The findings can benefit the industry personnel to allocate their focus on managing the significant cost influences according to the groups with high correlations and loadings among each other. As the latent factors have been modeled with sequential causal influences, each latent factor represents different phases of the project delivery. Therefore, the information can be applied as early as the planning stage of rail projects while also making comprehensive contingency plans for the occurrence of unlikely events.

The findings from this study would help enhance the decision-making process at multiple phases of rail projects. As Malaysia is presently developing and planning to develop multiple rail projects for its connectivity enhancement. This research is critical for all the current and future rail projects in Malaysia as well as other developing countries.

6. Limitations and Recommendations

The primary limitation in this study is the absence of thorough validation of the cost influences. For an impactful finding, the cost influences that had been analyzed have to be evaluated on a case by case basis. Future research can be conducted by exploring data in rail projects from around or outside Malaysia. Researchers may perform a comparative analysis of the different cost influences based on developed and developing countries. To create a richer outcome, the data collection can be expanded to other associated parties such as designers, consultants, government bodies, and academicians.

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Assessing E-Compliance Maturity of Public Procurement Processes in Nigeria

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ABSTRACT

The manual approach to public procurement is plagued with inefficiencies. To address these problems, efforts were made to digitize the processes in Nigeria. However, the e-compliance readiness of procurement processes is not known. This study attempts to assess e-compliance maturity of public procurement lifecycle in Nigeria. The study adopted a mixed research approach. A qualitative research method was used to establish criteria for evaluating the readiness of public procurement processes for digitization. Focus group interview with Six (6) automation and procurement professionals was conducted to arrive at the parameters used for the readiness assessment. Consequently, a questionnaire survey was administered on experienced public procurement professionals to evaluate the e-compliance readiness of some identified public procurement processes. Best to Worst Method (BWM) was used to evaluate e-compliance maturity level. The study shows that the processes are readily compliant for digitization.

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1. Introduction

The widely known approach to public procurement of goods, works and services is the conventional manual paper-based procedure. This approach has however, been found to be inefficient due to several factors, particularly its susceptibility to manipulations & error, complicated procedures, lack of transparency and aiding of corruption (Adebiyi et al., 2010; Song, et al., 2014; Ogbu & Asuquo 2018; & Abdullahi et al., 2019a). According to a World Bank (2000)'s Country Procurement Assessment Report (CPAR), about 60% of every US $1 spent on public procurement is being misappropriated in Nigeria. Thus, indicating how government resources are ineffectively managed. This has resulted in billions of dollars siphoned from the country's treasury through the abuse of public procurement procedures, inflated final contract sum, incompetent contractor selection, influence peddling, sycophancy, and use of primordial considerations (Oboirien 2006; Ayangade et al. 2009). To curb these challenges, studies have indicated the application of electronic procurement approach as the solution to deficiencies associated the manual based methods and several e-procurement systems have been developed.

Globally, there are several electronic/web-based procurement systems available for public use, most of which capture some processes within the manual procurement lifecycle include the Korean KONEPS, Malaysian ePEROLEHAN, Japan JETRO, USA FACNET, Philippines PHILGEPS, Scotland ePS, JEPP of Belgium, DOIP of Denmark, UK Tender Direct and NPS-eTender (European Dynamic SA; EDSA, 2004; Mohamad et al., 2010; EGMR, 2011; Abdullahi et al., 2019a). However, most of these processes being deployed in Nigeria, do not represent the entire manual procurement cycle (Abdullahi, et. al., 2019a) or even capture critical processes (Aminu, 2021). The absence of a fully digitized e-procurement system results in untimely

procurement process, lack of transparency, inadequacy in audits, unconformity to regulations, documents mismanagement as well as projects abandonment. All these are in contravention with the goals of the Nigerian Public Procurement Act (NPPA, 2007).

The research efforts made in Nigeria to digitize procurement processes range from procurement planning to contract award (Adebiyi et al., 2010; Afolabi et al., 2017; Abdullahi et al., 2019a, 2019b & 2019c). These attempts are limited to the tendering phase of the public procurement lifecycle. Thus, leaving out processes like contract administration and contract management. Some studies attributed this to the lack of explicit backing by the law, supporting the complete automation of most processes within a typical procurement cycle (World Bank MENA, 2012; Aminu, 2021). Thus, a major barrier affecting the full digitization of the public procurement lifecycle (Afolabi et. al., 2020; UNICITRAL, 2014; & The World Bank MENA, 2012). One of the critical steps to developing a robust system that covers the entire lifecycle is establishing whether the entire lifecycle processes are matured enough for digitization or not. A process maturity assessment is very important towards ascertaining which process is ready for digitization (Afolabi et. al., 2020) as well as assessing the status quo and guide decision makers to potential improvements (Wernicke et al., 2021). Although a number of studies have been conducted to digitize public procurement processes in Nigeria (Adebiyi et al., 2010; Afolabi et al., 2017; Abdullahi et al., 2019a, 2019b & 2019c; Yamusa et al, 2020), the assessment of the maturity of the entire processes for digitization has been overlooked. Findings from Sehlin et al., (2019), buttressed that lack of resources and knowledge on areas mature for digitization is among the major factors limiting any automation process. In fact, about 70% of change initiatives fail due to inadequate maturity assessment (The World Bank, 2000; & Aminu, 2021). The importance of having a digital maturity assessment for procurement proceesses cannot be over emphasized, as the absence of such can affect the design and adoption of efficient web-based e-procurement systems. As developing web-based system for processes that are not ready for automation is not only uneconomical, but yields to the deployment of redundant systems. Furthermore, as the e-procurement is gaining serious significance in public sector organizations, the necessity of applying performance measurement approach for measuring and improving the e-procurement processes is also gaining increased attention. This study aims to assess the maturity of the processes in the Nigerian public sector procurement towards complete digitization. This paper establishes areas where attention should be focused on to achieve the digitization of the entire procurement lifecycle of public entities in Nigeria. The remaining sections of this article are as follows: literature review; methodology; results and discussion; and finally, conclusion.

2. Literature Review

2.1 E-Procurement Development

In recent times, technology has become an integral part in increasing efficiency and effectiveness on public procurement service delivery. Government and Organizations around the globe have also begin to realize the benefits associated with utilization of e-procurement systems towards effective procurement of public works, goods, and services (Adebiyi et al., 2010; Expert Group Meeting Report (EGMR), 2011; Afolabi et al., 2017; Abdullahi et al., 2019a). Some of these benefits include; transparency, savings on administrative cost, reduction on bureaucratic process, obtaining best value for money and cutting down corrupt practices associated with the manual processes (Singer et al., 2009; Albano and Dae, 2010 & Mahmoud, 2013). Most of these challenges have affected the effective delivery of businesses today. According to Korea Public Procurement Service (2016), in other to eliminate possibilities of corruption due to face-to-face contact, strengthen transparency and trust in public procurement, there is the need to transit from the manual paper based to an automated environment. Several countries have designed and deployed e-procurement systems which captures areas within the public procurement lifecycle. Example of such systems are; Korea ONline Electronic Procurement System (KONEPS), In Philippines, the PhilGEPS, Canada's MERX, Scotland's ePS, JEPP of Belgium, Malaysia's ePerolehan, Japan's JETRO, DOIP of Denmark, FACNET of the United States, and UK Tender Direct (EGMR, 2011 & Abdullahi et al. 2019b). Most of these systems have been found to either capture some aspect of the manual procurement lifecycle. Also, these processes are either represented in the countries central e-procurement system or only represented in the system of some procuring entities (Organization for Economic Co-operation and Development, 2019).

2.2 E-procurement System Design and Development

Several countries around the globe have now commence the digitization of processes within the manual procurement circle. Table 1 summarizes procurement systems of Thirty-Four (34) countries around the globe and their automated processes. The shaded circle (●) indicates processes that are completely automated and are avail on the countries national e-procurement portal, the plane circle (◯) represent process that are both on the central portal as well as that of some procuring entities, the plane square (□) represents processes that are only available on the portal of some entities and multiplication sign (x) indicates areas that are yet to be digitized. From the table countries like Korea, Austria, Costa Rica, Lithuania, Finland and Portugal have automated processes within the manual procurement circle. Processes like announcing of tender notices, provision of tender documents, submission of bids, submission of invoices and online cataloging are available on their national central e-procurement system. While in some other countries these processes are only available on the e-procurement system of some specific procuring entities.

In countries like India, Japan Italy and Germany, some of these processes are not only recognized by some specific procuring entities, but are present in the central portal. This indicates that there is some level of disagreement as to what processes is be automated even within the same countries. Globally, this issue has been one of the major challenges affecting the design and implementation of e-procurement system.

However, in Korea the Korea ONline Electronic Procurement System (KONEPS) by the government of Korea, is currently leading the design and implementation of a fully integrated e-procurement solution as it integrates other electronic government operations, including financial management systems, company registrations, Payment Guarantee, Bid management and evaluation system, tax systems and a user management system for buyer and supplier registration and bid participation management (Aminu, 2021, EGMR, 2011 & Korea Public Procurement Service, 2016).

Since its deployment in 2002, the system has undergone series transformation towards accommodating more areas within the procurement cycle. This transformation involved creation of various sub-system to capture critical aspect within the procurement cycle (KPPS, 2016). Some of the critical development over the years includes Online Technology assessment & evaluation system, Construction cost management system, Biometrics based bidding, subcontract management system and Mobile KONEPS (Figure 1). The online technology & evaluation system has transformed the conventional tender evaluation to a real-time tender evaluation of bids with the presence of all relevant parties. Unlike the conventional approach, where all parties have to be physically present. Also, the construction cost management system provides a standard and up to date price catalogue for material, equipment, labor and other resources against which the submitted tender will be evaluated. Another unique feature of the KONEPS is that it allows contracts to be written and altered online using e-signatures. The system also allows for online inspection and subsequent payment. Full details of the various units of the KONEPS are captured in Table 2.

As a result of this, other countries around the globe went into partnership with the Korea government with the aim offering similar services. Some of these countries include Costa Rica, Vietnam, Mongolia, Jordan, Tunisia, Rwanda, and Cameroon (see Figure 1). The World Bank also have recognized this worldwide spread of e-Procurement systems like KONEPS, and has encouraged others to take similar drive towards increasing public procurement transparency and efficiency in developing countries. Figure 2 captures various collaborations with the KONEPS across the globe.

In Africa, apart from Tunisia, Cameroun and Rwanda countries like Nigeria have since joined the race of designing and deploying e-procurement system. According to the World Banks' MENA regional procurement conference (2012), African countries like Morocco are also developing their homegrown e-procurement system, the initial goals focused on monitoring, information and decision-making management, with more extensive e-procurement features like bulk purchasing, fully electronic tendering process, creating a database of suppliers reserved for a later phase. In Tunisia, a more advanced system was adapted from Korea with a US$5.7 million grant from the Korean Agency for International Cooperation.

Similarly, in Nigeria, although most of the development are research based. Some of the proposed systems were for potential bidders to register & manage their profile, view tender advertisement, download tenders and receive tender award notification (Adebiyi et al. 2010 & Afolabi et al. 2017). Abdullahi et al. (2019a, 2019b & 2019c) also designed a web-based e-procurement system that caters for the entire tendering stage of the procurement circle. The countries Bureau for Public Procurement also has an existing central portal NOCOPO (Nigerian Open Contracting Portal). The web portal allows contractors, consultants, citizens and civil society organizations to track procurement processes on planning, available tenders, awards, on-going contracts and their implementation stages. It also provides an online guide for procuring entities for prepare their annual procurement plan and also uploads their procurement record. In order to meet the global trend, the Federal Government also invested about US$3.5 million in 2020 to support the design & development of a central e-procurement system. Presently, the Federal Government of Nigeria is making strives to deploy an e-procurement system for public entities across the country. This makes it more imperative to assess maturity of the entire process to ascertain their readiness for digitization. This will help Nigeria bridge the existing gap and meet up with the current global trends and directives e.g., EU directives requiring full e-procurement use.

2.3 Procurement Maturity Model

Higher level of procurement maturity is linked to improved overall performance for organizations (Schiele, 2007). This led to several research efforts to assess the level of maturity and develop maturity models to measure and improve procurement processes. Rendon (2008) developed the Contract Management Maturity Model (CMMM) to assess, measure and improve procurement processes for organizations. The study found the CMMM to be beneficial to performance measurement and for improving processes. Bemelmans et. al. (2011) developed a procurement maturity tool using design science research approach. The model serves as a basis for organizations to ascertain their level of procurement maturity and provides performance improvement possibilities. van Lith et. al. (2015) later validated the model using the same organizations. They found the organizations to have improved in their general procurement maturity, and specifically, in strategic relations management. The organizations have also attained a level where they are coordinating their procurement activities. More recently, Abduh et. al. (2022) assessed the maturity of procurement units to handle public construction projects. The study used location groupings, overall maturity index, dimensions, and elements. The study found the procurement units' maturity in handling construction projects to be at a low level. Table 3 presents a summary of some prior studies related to procurement maturity model.

Building on the existing studies, this study will assess the maturity of the processes in the Nigerian public sector procurement towards complete digitization. The scope of this study will cover Goods, Service and Construction within the Public Sector Procurement.

Table 1 Global review of E-Procurement system and automated processes (Adapted from OECD, 2016)

S/No	Countries	Announcing Tenders	Provision of Tender Documents	Submission of bids	E-reveres auctions	Notification of award	E-submission of invoices	Online catalogue
1	Australia	●	●	●	×	●	×	×
2	Austria	◯	◯	◯	□	●	●	□
3	Belgium	●	●	●	●	●	□	●
4	Canada	●	●	×	×	●	□	□
5	Chile	●	●	●	×	●	×	●
6	Denmark	◯	□	◯	□	◯	◯	×
7	Estonia	◯	◯	●	●	●	□	×
8	Finland	●	●	●	●	●	●	□
9	Germany	◯	◯	◯	×	◯	×	×
10	Greece	●	●	●	●	●	×	×
11	Hungary	●	●	×	×	●	×	×
12	Iceland	●	●	×	×	●	●	×
13	Ireland	●	●	●	×	●	×	×
14	Israel	◯	◯	×	●	●	●	×
15	Italy	◯	◯	◯	□	◯	●	●
16	Japan	◯	◯	◯	×	◯	◯	◯
17	Korea	●	●	●	●	●	●	●
18	Latvia	◯	◯	●	×	◯	×	×
19	Mexico	●	●	●	●	●	×	×
20	Netherlands	●	●	●	×	●	×	●
21	New Zealand	●	●	●	●	●	□	●
22	Norway	●	●	□	×	●	□	*
23	Poland	●	□	×	●	●	×	●
24	Portugal	●	●	●	●	●	×	●
25	Slovak Republic	●	●	●	●	●	×	×
26	Slovenia	●	●	×	●	●	●	●
27	Spain	●	●	●	×	●	●	●
28	Sweden	□	□	□	□	□	□	×
29	Turkey	●	●	●	×	●	×	×
30	United Kingdom	●	□	□	□	●	□	□
31	Columbia	●	●	●	×	●	●	●
32	Costa Rica	●	●	●	●	●	●	●
33	India	◯	◯	◯	◯	●	×	□
34	Lithuania	●	●	●	●	●	●	□

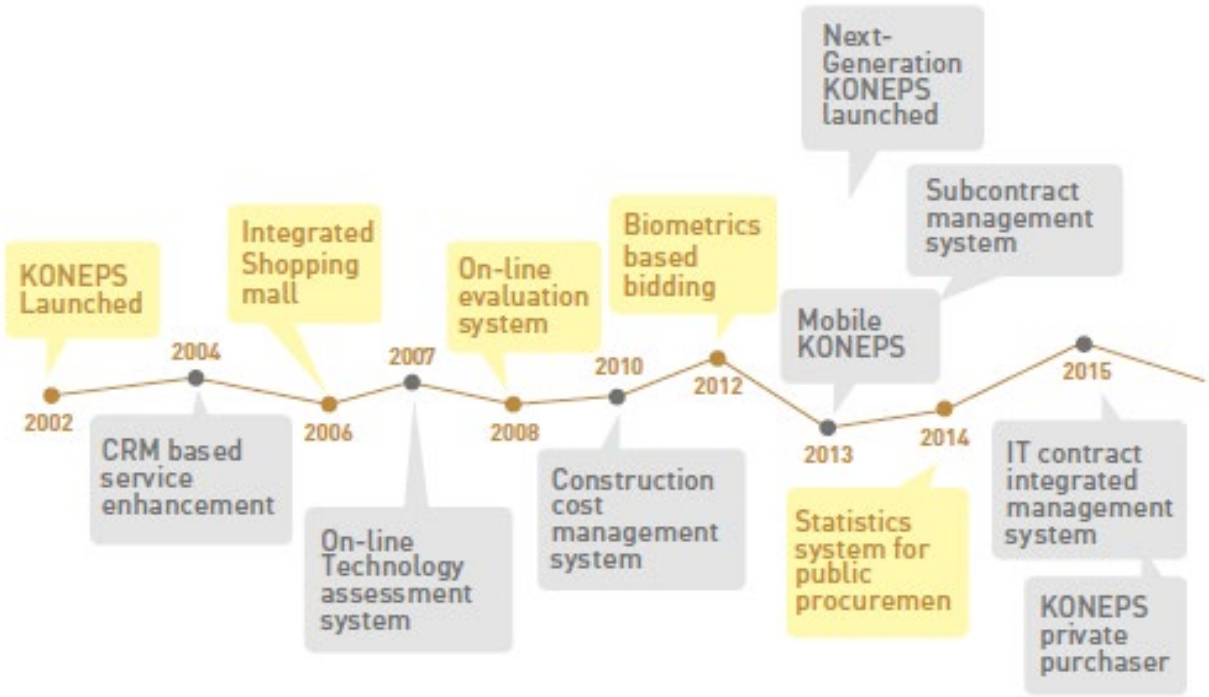

Figure 1 Evolution of the KONNEPS (Adapted from KPPS, 2016)

Table 2 Units Task for the Early Stage of KONEPS

KONEPS System	Service for Public Agencies	Service for suppliers	Service for Operating Agency
Portal System	- Provide integrated information - User community - Online education - Notifications for operator and public agencies	-Provide integrated information - User community - Online education	-Counseling service Management -Survey management
Integrated Notice	- Bidding notice registration management - Search integrated notices - Bid opening Management	- Search integrated notices - Check bid opening result - Check integrated contract information	-Integrated notice classification management
User Registration Management	Request for public agency, user registration - Search suppliers - Agency user authority management - Ineligible supplier registration	- Request for bidding participant registration and alteration - User, bidding agent registration	- Public agency, supplier's registration management - User authority management
e-Procurement Processing	Procurement request - e-Bidding and	- Goods demand management ordering management	- Unit price contract management

	negotiated contract - Contract management	- Conclusion of joint supply agreement, bidding, Request for evaluation	- Procurement statistics - Service status management
e-Guarantee	- Request for e-Guarantee (bidding, contract, payment, defect)	-Submit e-Guarantee	- Guarantee agency management
Goods List	- cataloging process - Assignment of classification and identification number	- Request for cataloging - Search list	- Classification system management - Request and processing status management
Catalog	- Search cataloged products - Shopping basket, order	- Product detailed information registration	- Cataloged products registration
e-Payment	- Inspection - Receive request for payment	- Request for inspection -Request for payment	- Determine commission - Issue notice
Management of Documents Subject to Examination	- Check suppliers' performance - Check information of technical experts	- Check registered Information - Request for update of registered Information	- Suppliers' performance information management - Information update processing

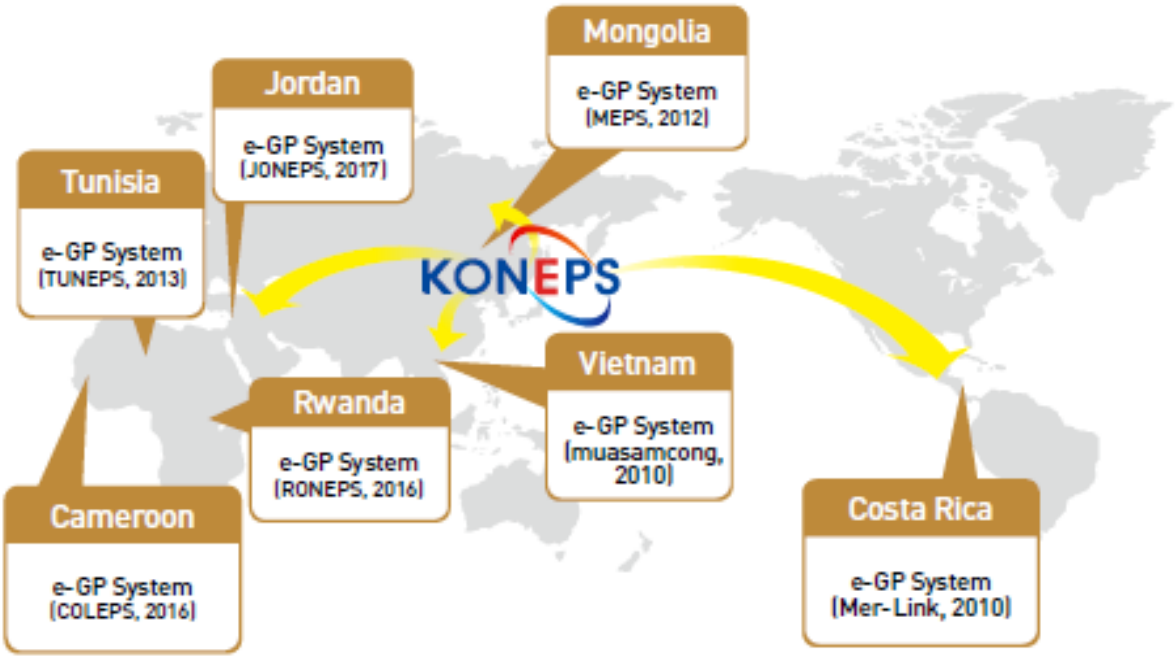

Figure 2 Global KONEPS Collaborations (KPPS, 2016)

Table 3 Prior research related to procurement maturity model

No	Model	Reference	Scope				
			G	S	C	Pu	Pr
1	Procurement Alignment Framework	Batenburg and Versendaal (2006)	√	√			√
2	Contract Management Maturity Model (CMMM)	Rendon (2008)			√		√
3	Proc. Maturity, Alignment & Performance Model	Plomp and Batenburg (2009)	√	√			√
4	SKI Model	Møller et al. (2010)	√	√		√	
5	Procurement Maturity Model	Guth (2010)	√	√		√	
6	Purchasing Maturity Assessment Tool	Bemelmans et. al. (2011)	√	√			√
7	MSU Model	Dang (2011)	√	√			√
8	MSU Model +	Johannsen (2013)	√	√			√
9	IPM2	NPPA (2015)	√	√		√	√
10	Procurement Capability Model	Pongsuwan (2016)	√	√			√
11	PCPM	Oktaviani (2018)			√	√	

Notes: G=Goods; S=Service; C=Construction; Pu=Public; Pr=Private

3. Methodology

3.1 Research Approach

This research adopted a mixed research approach and is divided into two parts. The first aspect of the work involved establishing e-compliance maturity assessment criteria for the manual processes. This was sourced from literature and then validated using a focus group discussion with experts comprising of three software developers and one procurement officer with vast knowledge on manual procurement practices. All the members were selected via snowballing to form the team and had not less than five years of experience, except for the procurement officer who was selected purposively. Two among the ICT experts participated in the design of a prototype web-based portal for a reputable public PE in Nigeria. For the procurement expert, he was involved in the focus group discussion to guide the discussion and make sure the discussion is in line with the requirements of the Nigerian public sector procurement. The ICT experts were involved in order to help validating the assessment criteria for e-procurement processes. Four generic processes were identified as the e-compliance maturity assessment criteria for the digitization of the manual procurement processes; Predefined Procedure, Difficulty Level, Nature of Data, and Size of Users. The sub-criteria for the maturity assessment were also established. Each criterion is assessed using a set of sub-criteria as follows: Predefined Procedure - Guidelines and Need for compliance; Difficulty Level - Routine task, Task sensitivity, and Task dependency; Nature of Data - Data Availability and Size & form of data; and Size of Users - User category and Number of users.

The second aspect of the work covers the digital maturity assessment phase. It involved an online questionnaire survey with 79 experts well versed in both manual and electronic public procurement practices. The criteria established from the first part above were used in designing the questionnaire for collecting the data in this second part. About 55% of the respondents also occupy managerial position in their respective organizations and are cooperate members to various professional body.

Table 4 Procurement maturity definition for an indicator.

Levels	Definitions	Rating Scales
Initial (Not Mature)	This level refers to those processes that are mostly ad-hoc in nature with no formal outlined manual procedure as to how it should be carried out. There is no need for any form of digitization at this stage.	0.00-1.00
Developing (improve on manual process)	Processes under this level are defined with well outlined steps, with little need for compliance as its output may not have any significant impact on other process. This stage also may not need any form of digital aid, as the manual procedure is still evolving.	1.01-0.20
Defined (Partially digitize)	Digitization commences at this stage as processes well-structured and the data generated impacts the outcome of the succeeding process. Users begin to realize the need for digitizing, as some form of digital assistance is needed to deliver the required result.	2.01-3.00
Managed (Completely Digitize)	This stage is where complete digitization is required. Processes at this level are well defined and because of the important nature of the data used/generated it have some form of impact on succeeding phases. In most cases, some form of digital aid may be in existence. However, this protocol may not have well-structured and may lack the requisite legal backing as to how they should be carried out for the purpose of uniformity and ease of acceptance.	3.01-4.00
Optimized (Improve)	This level refers to those processes that are have the legal backing with outline structured electronic procedure. The governing law out rightly supports the automation of such processes. Some of these processes may already have existing electronic systems that may only need further improvement.	4.01-5.00

Table 5 Established weight the E-compliance Assessment Criteria

Main criteria	Local weights	Sub-criteria	Local weight of sub-criteria
Predefined Procedure – C1	0.59	Guidelines – C5	0.23
		Need for compliance- C6	0.19
Difficulty Level – C2	0.24	Routine task – C7	0.03
		Task sensitivity – C8	0.13
		Task dependency – C9	0.08
Nature of Data - C3	0.12	Data Availability - C10	0.10
		Size & form of data – C11	0.06
Size of Users - C4	0.06	User category – C12	0.13
		Number of users – C13	0.05

Table 6 Maturity Level for Predefined Procedures as stipulated in the NPPA (2007)

Manual Procurement Processes	Mean	SD	Rank	CW	pMW
Advertisement	4.54	0.77	1	0.59	2.68
Tender evaluation	4.10	0.69	2	0.59	2.42
Mobilization (APG verification and payment)	4.06	0.63	3	0.59	2.40
Prequalification	4.00	0.70	4	0.59	2.36
Receipt and opening of tender documents	3.94	0.70	5	0.59	2.32
Debriefing and complaints	3.81	0.86	6	0.59	2.25
Needs Identification	3.80	0.97	7	0.59	2.24
Categorization of disposal	3.51	0.71	8	0.59	2.07
Distribution of tender documents	3.49	0.82	9	0.59	2.06
Tender reporting and award	3.39	0.71	10	0.59	2.00
Contracts review and amendments	3.33	0.90	11	0.59	1.96
Preparation of tender documents	3.32	1.03	12	0.59	1.96
Appointment of consultants and contractors	3.16	0.88	13	0.59	1.86
Selection of procurement method	3.10	0.81	14	0.59	1.83
Setting timelines and key performance indicator	3.09	0.66	15	0.59	1.82
Progress reporting and valuations	3.06	1.05	16	0.59	1.81
Payments	3.00	0.91	17	0.59	1.77
Negotiations	2.91	0.88	18	0.59	1.72
Contract execution (review, signing & sealing)	2.86	0.84	19	0.59	1.69
Reporting and documentation	2.86	0.87	20	0.59	1.69
Selection of disposal method	2.86	1.13	21	0.59	1.69
Cost planning	2.84	0.74	22	0.59	1.68
Monitoring and evaluation	2.82	0.75	23	0.59	1.66
Disposal planning	2.76	0.96	24	0.59	1.63
Appointment of evaluator	2.75	0.76	25	0.59	1.62
Auctioning	2.71	1.20	26	0.59	1.60

Needs prioritization	2.25	0.72	27	0.59	1.33
Contract closeout	2.03	0.80	28	0.59	1.20

Scale used: NA=Not Adequate, SA=Slightly Adequate, MA=Moderately Adequate, A=Adequate and VA=Very Adequate

Table 7 Maturity Level for Task Difficulty Level

Manual Procurement Processes	**Mean**	**SD**	**Rank**	**CW**	**pMW**
Prequalification	3.77	0.75	1	0.24	0.90
Tender evaluation	3.77	0.83	2	0.24	0.90
Needs Identification	3.25	0.65	3	0.24	0.78
Needs prioritization	3.23	1.09	4	0.24	0.78
Cost planning	3.15	0.96	5	0.24	0.76
Progress reporting and valuations	3.15	1.34	6	0.24	0.76
Contracts review and amendments	3.14	1.28	7	0.24	0.75
Reporting and documentation	3.10	1.24	8	0.24	0.74
Negotiations	3.09	1.05	9	0.24	0.74
Mobilization (APG verification and payment)	3.00	1.24	10	0.24	0.72
Preparation of tender documents	2.90	1.18	11	0.24	0.70
Receipt and opening of tender documents	2.86	1.01	12	0.24	0.69
Payments	2.85	1.26	13	0.24	0.68
Disposal planning	2.82	0.89	14	0.24	0.68
Monitoring and evaluation	2.81	1.16	15	0.24	0.67
Categorization of disposal	2.81	0.86	16	0.24	0.67
Auctioning	2.76	1.09	17	0.24	0.66
Tender reporting and award	2.67	1.02	18	0.24	0.64
Debriefing and complaints	2.65	0.99	19	0.24	0.64
Distribution of tender documents	2.59	0.97	20	0.24	0.62
Contract closeout	2.59	1.13	21	0.24	0.62
Advertisement	2.53	1.04	22	0.24	0.61
Appointment of consultants and contractors	2.37	0.92	23	0.24	0.57
Setting timelines and key performance indicator	2.34	0.78	24	0.24	0.56
Selection of procurement method	2.24	0.91	25	0.24	0.54
Contract execution (review, signing & sealing)	2.18	0.69	26	0.24	0.52
Appointment of evaluator	2.18	0.76	27	0.24	0.52
Selection of disposal method	2.09	0.58	28	0.24	0.50

Scale used: VE=Very Easy, E=Easy, N=Neutral, D=Difficult and VD=Very Difficult

Table 8 Maturity Level for Nature of Data Used

Manual Procurement Processes	Mean	SD	Rank	CW	pMW
Needs Identification	4.33	1.07	1	0.12	0.52
Prequalification	4.14	0.83	2	0.12	0.50
Receipt and opening of tender documents	4.14	1.02	3	0.12	0.50
Tender evaluation	4.09	1.19	4	0.12	0.49
Advertisement	3.90	0.93	5	0.12	0.47
Tender reporting and award	3.73	1.33	6	0.12	0.45
Distribution of tender documents	3.72	0.73	7	0.12	0.45
Preparation of tender documents	3.61	1.03	8	0.12	0.43
Cost planning	3.22	0.86	9	0.12	0.39
Debriefing and complaints	3.22	0.94	10	0.12	0.39
Progress reporting and valuations	3.22	1.15	11	0.12	0.39
Reporting and documentation	3.08	0.87	12	0.12	0.37
Selection of disposal method	3.08	1.15	13	0.12	0.37
Needs prioritization	3.06	0.90	14	0.12	0.37
Payments	3.06	0.84	15	0.12	0.37
Contracts review and amendments	2.97	1.10	16	0.12	0.36
Mobilization (APG verification and payment)	2.90	1.14	17	0.12	0.35
Disposal planning	2.89	1.13	18	0.12	0.35
Categorization of disposal	2.89	0.95	19	0.12	0.35
Negotiations	2.85	1.00	20	0.12	0.34
Appointment of evaluator	2.77	1.11	21	0.12	0.33
Monitoring and evaluation	2.72	0.95	22	0.12	0.33
Auctioning	2.70	1.03	23	0.12	0.32
Contract execution (review, signing & sealing)	2.68	0.90	24	0.12	0.32
Selection of procurement method	2.63	0.62	25	0.12	0.32
Setting timelines and key performance indicator	2.52	0.62	26	0.12	0.30
Contract closeout	2.27	0.69	27	0.12	0.27
Appointment of consultants and contractors	2.24	0.66	28	0.12	0.27

Scale used: VS=Very Small, S=Small, ML=Moderately Large, L=Large and VL=Very Large

Table 9 Maturity Level for Number of Users Involved

Manual Procurement Processes	Mean	SD	Rank	CW	pMW
Advertisement	4.29	0.87	1	0.06	0.26
Needs Identification	4.16	1.06	2	0.06	0.25
Prequalification	3.96	0.76	3	0.06	0.24
Auctioning	3.87	1.16	4	0.06	0.23
Disposal planning	3.11	1.33	5	0.06	0.19
Monitoring and evaluation	3.03	0.93	6	0.06	0.18

Setting timelines and key performance indicator	3.01	1.02	7	0.06	0.18
Distribution of tender documents	2.95	1.14	8	0.06	0.18
Needs prioritization	2.94	1.02	9	0.06	0.18
Tender reporting and award	2.87	0.82	10	0.06	0.17
Appointment of evaluator	2.84	1.17	11	0.06	0.17
Selection of procurement method	2.78	1.05	12	0.06	0.17
Receipt and opening of tender documents	2.72	0.78	13	0.06	0.16
Appointment of consultants and contractors	2.54	0.95	14	0.06	0.15
Progress reporting and valuations	2.54	0.80	15	0.06	0.15
Cost planning	2.49	0.88	16	0.06	0.15
Receipt and opening of tender documents	2.46	0.73	17	0.06	0.15
Selection of disposal method	2.44	0.83	18	0.06	0.15
Contracts review and amendments	2.39	0.71	19	0.06	0.14
Categorization of disposal	2.37	0.77	20	0.06	0.14
Payments	2.33	1.17	21	0.06	0.14
Preparation of tender documents	2.15	0.80	22	0.06	0.13
Contract execution (review, signing & sealing)	2.14	0.97	23	0.06	0.13
Reporting and documentation	2.14	1.12	24	0.06	0.13
Contract closeout	1.99	0.65	25	0.06	0.12
Negotiations	1.82	0.71	26	0.06	0.11
Mobilization (APG verification and payment)	1.80	1.06	27	0.06	0.11
Debriefing and complaints	1.75	0.63	28	0.06	0.11

Scale used: VS=Very Small, S=Small, A=Average, L=Large and VL=Very Large

Table 10. E-compliance Maturity Level for the Manual Procurement Lifecycle in Nigeria

Manual Procurement Process	**Overall Maturity Weight**	**Maturity Level**
Advertisement	4.29	0.87
Advertisement	4.01	Optimized
Prequalification	4.00	Managed
Tender evaluation	3.98	Managed
Needs Identification	3.79	Managed
Receipt and opening of tender documents	3.66	Managed
Mobilization (APG verification and payment)	3.57	Managed
Debriefing and complaints	3.38	Managed
Distribution of tender documents	3.30	Managed
Tender reporting and award	3.26	Managed
Categorization of disposal	3.23	Managed
Contracts review and amendments	3.22	Managed
Preparation of tender documents	3.22	Managed

Progress reporting and valuations	3.10	Managed
Cost planning	2.97	Defined
Payments	2.96	Defined
Reporting and documentation	2.93	Defined
Negotiations	2.91	Defined
Setting timelines and key performance indicator	2.87	Defined
Appointment of consultants and contractors	2.85	Defined
Selection of procurement method	2.85	Defined
Monitoring and evaluation	2.85	Defined
Disposal planning	2.84	Defined
Auctioning	2.82	Defined
Selection of disposal method	2.71	Defined
Contract execution (review, signing & sealing)	2.66	Defined
Appointment of evaluator	2.65	Defined
Needs prioritization	2.65	Defined

3.2 Establishing the Digital Maturity Assessment Criteria

Since there is no existing literature on e-compliance maturity assessment for evaluating the manual procurement process in the context of this study, it becomes imperative to develop maturity criteria and assessment. So, a generic set of criteria was first identified from literature. They were further ranked in order of priority weight using the Best-Worst Method (BWM) developed by Rezaei (2016), as a more reliable and consistent alternative to the common Analytical Hierarchy Process (AHP). Using the BWM approach the following procedures was followed;

Step 1: Determine the digital maturity criteria.

Step 2: Establishing the best criterion (the most important criterion - B) and the worst criterion (the poorest criterion - W) using experts from the focus group.

Step 3: The best decision criterion (B) is determined to be superior to other determined criteria. A 9-point scale is used for this procedure. Numbers 1 to 9 are used on this scale, and 1: B is equally important for j; 9: B is much more important than j. As a result of the process, the best case (BO) vector is obtained according to other criteria.

This vector is defined as follows;

AB = (aB1, aB2, aB3, …… aBn),

(aBj, indicates the superiority of B over j, and aBB is equal to 1)

Step 4: The superiority of all decision criteria over the worst decision (W) criteria was determined. A 9-point scale is used for this procedure. This scale uses numbers 1 to 9 and 1: W is equally important for j; 9: W is much more important than j. At the end of the process, the status (OW) vector of other criteria is obtained according to the worst criteria. This vector is defined as follows;

Step 5: Determine criteria optimum weights (w*1, w*2, …, w*n).

There must be maximum absolute diameters to find optimum weights [$\left| wB - aBjwj \right|$, $\left| wj - ajwwww \right|$] minimized for all js.

$$min\ maxj\ [\left| wB - aBjwj \right|,\ \left| wj - ajwwww \right|]$$

s.t.

$$\sum_j wj = 1$$

Wj ≥ 0, for all J's.

The equation above can also be expressed with the linear problem below;

min ʒL , for all j's

s.t.

$\left| wB - aBjwj \right| \leq$ ʒL , for all j's

$\left| wj - ajwwww \right| \leq$ ʒL , for all j's

$$\sum_j wj = 1$$

Wj ≥ 0, for all J's

3.3 The Maturity Assessment

For the second aspect of the work the data analysis used were mean, standard deviation. The Criteria Weights (CW) was from the BMW analysis, while the process Maturity Weight (pmw) was arrived at by multiplying CW by the mean score of each process.

In order to adequately evaluate the e-compliance maturity level of the various processes within the manual procurement lifecycle, a five (5) level e-compliance maturity categorization

was adopted as shown in Table 4. With 4.01-5.00 was considered to be the most matured process, while those within 0.00 – 1.00 were considered the least matured.

4. Results and Discussion

The validation exercise outcome presented 13 variables which are grouped into 4 criteria and 9 sub-criteria as presented in Table 5.

Predefined procedure (C1) was identified to be the most important criteria that affect procurement process e-compliance maturity, followed by Difficulty level (C2), then Nature of data (C3) and Size of users (C4) was considered as the least important. On the other hand, for the sub-criteria Guidelines, Need for compliance, Task sensitivity and User category returned as the most important, while Data availability, Dependency and size & Form of data are the least important sub-criteria. In line with this output, the result was also evaluated in terms of consistency rate and it was checked whether this value was below 0.25 in accordance with the Best Worst method. A ksi* of 0.12 for the main criteria and 0.16 for the sub criteria, implying that the result of this finding is consistent.

4.1 *E-compliance Maturity Assessment*

Result for the first category assessment as shown in Table 6, presents Advertisement, Prequalification, Mobilization, Prequalification and Receipt and Opening of tender as the highest ranked when it comes to the level of details and procedural guide. Reference to their criteria weights (CW) for the group, the process maturity weights (pMW) for these top processes are 2.68, 2.42, 2.40, 2.36 and 2.32 respectively. Also, the least defined processes are Monitoring and evaluation, Disposal planning, Appointment of evaluator, Auctioning, Needs prioritization and Contract closeout with pMW of 1.66, 1.63, 1.62, 1.60, 1.33, and 1.20 respectively. This result portrays those processes that are mature with respect to the first class of the e-compliance maturity assessment. The result tallies with findings of studies like that of Betts et al. (2006) and Fong and Yan (2009) that pointed out advertisement as one of the earliest developments in e-procurement. This only suggests its development over the years, leading to its high maturity as part of a predefined process.

The findings in Table 7 identified Prequalification and Tender Evaluation as the most difficult task with the same mean score of 3.77 and pMW of 0.90. Needs identification, Needs prioritization and Cost planning were ranked 3rd, 4th and 5th with a pMW of 0.78, 0.78, and 0.76 respectively. The least difficult task identified include; Appointment of consultants and contractors, setting timelines and key performance indicator, selection of procurement method, contract execution (review, signing & sealing), appointment of evaluator and selection of disposal method. The result is pointing towards the attention received by bidder prequalification and tender evaluation as a difficult task especially due to its subjectivity. This result is in line with recent efforts to digitise bidder prequalification and tender evaluation by Abdullahi et al. (2019a, b, c).

In Table 8, Needs Assessment emerged with the highest mean score of 4.33 and 0.52 as the pMW was found to require some reasonable amount of data from the various units within the procuring entity. Prequalification and receipt & opening of tender documents were also among the top ranked processes in this stage they both had 0.50 as pMW. Another critical process identified at this stage was Tender evaluation which involves the analysis of the various tenders received towards identifying the lowest responsive bids. It has a pMW of 0.49 and is line with the findings from the process validation exercise. The findings are supported by Abdullahi et al. (2019a, b, c) who has demonstrated that the processes can be digitised.

Apart from the top ranked processes, some of the least ranked processes and their pMW include; Selection of procurement method (0.32), Setting timelines and key performance indicator (0.30), Contract closeout (0.27) and Appointment of consultants and contractors (0.27), as they require very little information to come to a decision at the end of each process.
The result from the survey identified captured in Table 9 shows Advertisement with a pMW of 0.26 to be the most matured process at this stage of the assessment. Other processes include Needs identification (0.25) and Prequalification (0.24). The findings are supported by Abdullahi et al. (2019a, b, c) who has demonstrated that the processes can be digitised.

Finally, the final result for the maturity level of the manual procurement processes as contained in Table 10 shows the aggregation of the responses from the four-maturity assessment class.

Advertisement returned as the most matured manual process ready for full automation with an overall maturity weight (OMW) of 4.01 and also being the only process within the Optimised (Improve) level. This means that amongst the 28 manual processes, advertisement is the only processes is fully e-compliance matured. The second process is prequalification with an OMW of 4.00 slightly outside the Manage (completely digitize), it has well defined procedures however lacks any standards as to how this should be carried out in a digitise environment. While the next 3 processes and their OMW are Tender evaluation = 3.98, Needs identification = 3.79 and Receipt & opening of tender = 3.66 respectively but on the manage category (completely digitise). Works by Abdullahi et al. (2019a, 2019b, 2019c), have reported similar findings for the tendering stage of the procurement circle.

The subsequent processes are within the defined category (partially digitise) and their OMW are as follows: Cost planning = 2.97, Payments = 2.96, Reporting and documentation = 2.93, Negotiations = 2.91, Setting of timeline and key performance indicators = 2.87, while for the least matured processes are Auctioning = 2.82, Selection of disposal method =2.71, Contract execution = 2.66, Appointment of evaluator = 2.65, Need prioritization = 2.65 and Contract close out =2.21 and are also within the Defined Category. Most of these processes still have key aspect being carried out manually as they still require some form of human reasoning in coming to a

decision. However, this is a deviation to existing e-procurement best practices as outlined in the reports on by KPPS (2016) as processes like payment, auctioning, and negotiations already have existing e-compliance equivalent in operation in Korea and other affiliate countries.

5. Conclusion

In conclusion, the manual procurement circle is mature for digitizing as most of the critical processes that affect that affect the effective delivery of projects are within the Optimized (Improve) and Managed (completely digitize) maturity levels. The identified process areas that are readily mature for the deployment of e-compliant equivalent include Advertisement, Prequalification, Tender evaluation, Needs identification, Preparations of tender document, Receipt and Opening of tender. Most of these findings are in line with the works on tendering by Abdullahi et. al., (2019a, 2019b, 2019c). However, this study indicates that the other processes overlooked in the digitization of the Nigerian public procurement processes are mature for deployment. The study therefore presents a useful basis for going beyond the Tendering Phase in the development of a more robust e-procurement system in Nigeria. The maturity assessment was only for the processes. Hence, further research can be conducted to assess readiness of the public procuring entities and other available technologies like machine learning for deployment of semi-autonomous systems.

The implication of this study reveals the avenue for Nigerian public procuring entities in harnessing information and communications technology and World Wide Web to improve the public procurement sector. Hence, public procuring entities in Nigeria should are endeavor to adopt digital procurement processes. Also, the regulatory body of the Nigerian public procurement sector, the Bureau of Public Procurement, should enforce this effort.

A major limitation of this study is that it is conducted using the public procurement regulatory guide of Nigeria, the Nigerian Public Procurement Act (NPPA, 2007). As such, its applicability is limited to the country of development. However, lessons could be drawn given that the 1966 United Nations Commission on International Trade Law (UNCITRAL) is the basis of government procurement laws in most.

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