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Improving Indoor Air Quality with Natural Ventilation Methods: A Simulation Study

Caner Yetiş*
Merve Tuna Kayılı**

Abstract
In modern life, strategies developed in line with the increasing energy demand cause many environmental problems on a global scale. One of the most important of these problems is inadequate indoor air quality. The most critical parameters affecting indoor air quality during the design phase are selecting wrong and unhealthy building products, insufficient window sizes, and unplanned natural ventilation. This study investigates whether indoor air quality can be improved only by effective natural ventilation methods, without compromising thermal comfort, through small changes that can be applied to buildings. For this purpose, simulation studies were carried out to reveal whether indoor air quality could be improved without compromising thermal comfort in a library building. As a result, when evaluating the improvement recommendations, the thermal comfort range for the cross-ventilation and chimney effect ventilation recommendations is 'comfortable' in winter and 'comfortable-partially comfortable' in summer. For the ventilation recommendations with roof wings, skylights and wind towers, the thermal comfort range for summer and winter remained in the "comfortable" range due to the high natural ventilation performance.

Keywords:
Buildings with atriums, Improvement proposals, Indoor air quality, Natural ventilation, Thermal comfort, Simulation software, IDA ICE

*Vocational School of Technical Sciences, Bitlis Eren University, Bitlis, Turkey. (*Corresponding author*)

E-mail: cyetis@beu.edu.tr

**Başak Cengiz Faculty of Architecture, Karabük University, Karabük, Turkey.

E-mail: mervetunakayili@karabuk.edu.tr

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INTRODUCTION

Since the beginning of the 20th century, the time spent indoors has increased due to changing living standards, and this situation has led individuals to need a more comfortable indoor space. Therefore, in the literature, in addition to air pollution, the effects of indoor air pollution on human health have also been investigated (Klepeis et al., 2001; De Giuli et al., 2012; Odeh & Hussein, 2016; Rivera-Rios et al., 2021; Li & Ma, 2021; Wang & Norbäck, 2022). It has been observed that due to the worldwide energy crisis emerging, especially in the 1970s, and the high insulation level in buildings, the air permeability between the indoor and outdoor environment of buildings has been prevented. As a result of this, short- and long-term health problems as well as other disorders related to the living environment, such as Sick Building Syndrome and Tight Building Syndrome, have emerged in individuals (Vural, 2004; Persily & Emmerich, 2011; Güler, 2012). Wrong design decisions and the production of buildings with high impermeability and artificial building materials cause a decrease in indoor air quality due to the ineffective use of natural ventilation. The most important reasons of the decrease in indoor air quality are the infiltration of industrial gases originating from the outside environment, CO_2 and particulate matter arising from human activities, and volatile organic compounds (VOCs) included in bitumen-based building products, cleaning materials, and furniture (Abt et al., 2000; Chao & Cheng, 2002; Cattaneo et al., 2011; Salma et al., 2013; Luengas et al., 2015; Lei et al., 2019; Shrubsole et al., 2019; Sun et al., 2019; Kozielska et al., 2020; Abdel-Salam, 2021; Gonzalez-Martin et al., 2021). It is known that this pollution in the indoor air causes psychological and physiological effects on people using buildings. These effects have led to the need to determine indoor air pollution levels and to develop effective methods for solving problems (Mendell et al., 2013; Mendes &Teixeira, 2014; Fernández-Agüera et al., 2019; Kapola et al., 2020; Ao et al., 2021).

Adequate ventilation is one of the most effective ways to remove building-based pollutants, which reduce indoor air quality, from a building (Gonzalez-Martin et al., 2021; Etheridge, 2011; Jin et al., 2014; Kumar et al., 2021). In the context of sustainable building design criteria, it is vital to make decisions for adequate and effective natural ventilation during the design process of the building in order to create healthy interior spaces by using low energy (Heiselberg, 2004; Omrani et al., 2017; Wang & Malkawi, 2019; Utkucu & Sözer, 2020). Artificial building materials, the disproportion between the number of users and the size of the space, and the lack of adequate natural ventilation openings are some of the reasons that reduce indoor air quality. In such cases, indoor air quality can be improved by mechanical ventilation, which requires additional equipment and energy (Emmerich, 2006; Wright et al., 2009; Kovesi et al., 2009; Park et al., 2014; Francisco et al., 2017; Huang et al., 2020; Zhang et al., 2021). On the other hand, buildings are responsible for a large part of global energy consumption. The energy needed for heating,

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cooling, air conditioning, and clean air causes resource consumption. The energy needed for building ventilation constitutes half or more than half of the total building energy consumption (Cui et al., 2020). Therefore, reducing the energy needed in buildings is as important as the indoor air quality. Thus, indoor air quality and energy performance must be achieved together (Zhang et al., 2021).

The purpose of this study was to investigate whether the indoor air quality of a building can be improved without compromising on the thermal comfort of the building and increasing energy consumption by applying only the principles of controlled natural ventilation. The study also aimed to develop recommendations for natural ventilation based on on-site measurements and simulation results. Within the scope of the research, on-site measurements were carried out in the building for five days. The results obtained through on-site measurements were verified by the simulation program, and natural ventilation recommendations were developed based on simulation results. It is expected that this study, which underlines that indoor air quality can be improved with the effective design of natural ventilation methods, will guide works aiming to build constructions with low energy consumption. The study will also contribute to the literature in the fields of economics and sustainability.

MATERIALS AND METHODS

Case Study

The adequate provision of indoor comfort conditions and natural ventilation strategies is directly related to the natural and artificial environment in the nearby area, as well as the physical characteristics of the building. At this stage, it is essential to identify the areas causing pollution near the building and determine the direction of possible air currents in the environment.

In the context of the study, to be able to improve indoor air quality by only natural ventilation designs without compromising thermal comfort, a university library building with an atrium and many users was chosen. The building is located in Karabük, which is a city in Turkey's Western Black Sea region. The campus where the library is located is on the southern slope of the valley shaped by Araç Stream and in the center of the sloping topography. There are iron and steel rolling mills on the northwest line of the building and agricultural and forest areas along the east and south facades (Figure 1). As seen in Figure 2 (a and b), air currents formed around the building are in two primary forms: the air currents formed in the prevailing wind direction and the air currents formed due to the slope developing depending on the topography. While there are no structures in the area facing the northern facade of the building, there is the laboratory building of the university in the area facing the southern facade of the building. The southwest facade of the building leads to the low-rise sports complex, and the northwest facade leads to the R&D building (Figure 3a). The library with two floors has a rectangular plan of 25 m-37.5 m and is located in the northwest-southeast direction. A double-winged automatic door provides entrances to the building from the southeast and northwest facades. The atrium area, which defines the entrance axis in the planning scheme, is 10.5 m-8.4 m in size and is located in the center of the building circulation axis. The circulation axis formed by the atrium covered with a steel carrier glass cover system is a glass curtain wall, while the other facades of the building are composite curtain walls. The eastern and western parts of the atrium consist of symmetrical study areas and bookshelves. There are a total of six group study rooms, three of which are on the ground floor and three on the 1st floor (Figure 3b, c). These rooms are located next to the stairs and elevator block on the northeast facade of both floors.

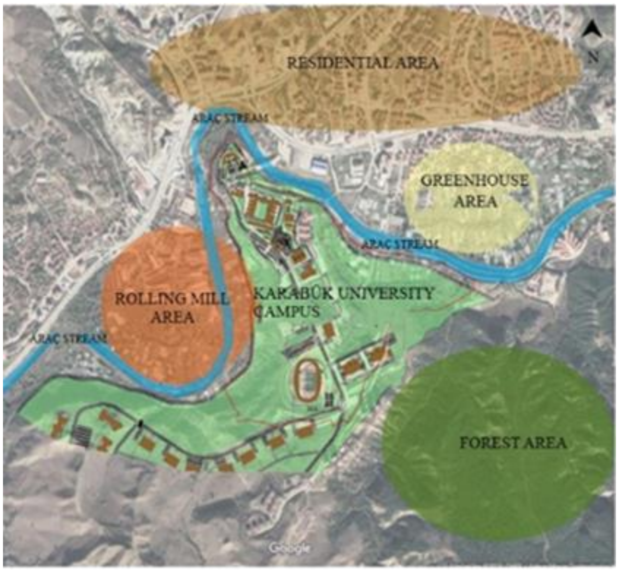

Figure 1. Analysis of the close environment of the library

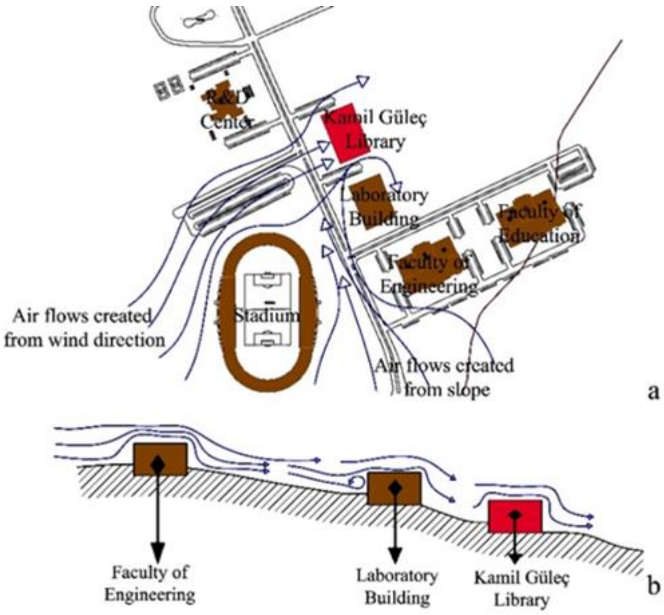

Figure 2. a) Air currents formed in the vicinity of the building **b)** Air currents formed from the slope

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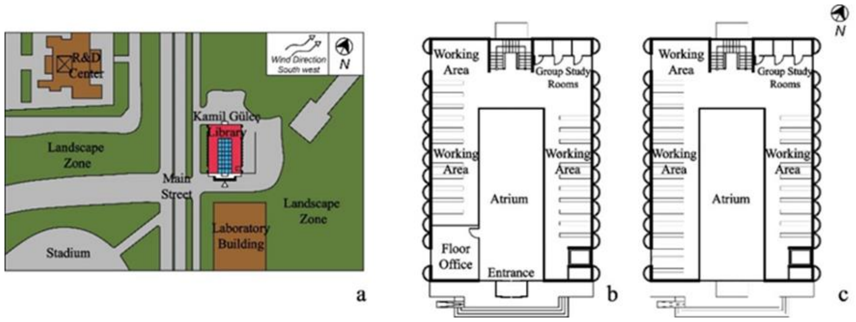

Figure 3. a) Site plan of the library **b)** Ground floor plan of the library **c)** 1st floor plan of the library

Simulation Software

In the study, the IDA ICE (IDA Indoor Climate and Energy) software was used to determine the thermal comfort of the building and to analyze the improvement proposals. IDA ICE is a simulation software that provides outputs related to indoor comfort by simulating indoor energy consumption, thermal comfort conditions, lighting, heating and cooling loads, CO_2 amount, humidity amount, and PMV-PPD (predictive mean vote-predicted percentage of dissatisfied) calculations. The IDA ICE software has been used in many studies related to indoor comfort, and it is stated that this software is suitable for determining indoor climatic comfort (Mateo & Aranaz, 2011; Soleimani-Mohseni et al., 2016; Hilliaho et al., 2015; Karlsen et al., 2015). The software offers an infrastructure where meteorological data and all data related to the building and its environment can be evaluated together. In addition to the IDA ICE's modeling capability, IFC models created by Archicad, Revit, Autocad, and Magicad-based programs can also be loaded. Data related to regional heat and energy balances, air and surface temperatures, amount of daylight and illumination level, results related to building occupancy rate, heat and mass transfer, and results for indoor air quality, PPD, PMV comfort indices, and energy demand are the outputs reported by the software.

Determination of the Thermal Comfort and Indoor Air Quality

In order to determine the current indoor air quality of the library and to validate the simulation software to be used in the presentation of improvement proposals, indoor thermal comfort and air quality should be determined. In this context, temperature, humidity CO_2, and TVOCs (total volatile organic compounds) measurements were performed using the devices detailed in Table 1.

Table 1. Devices used in measurement process and their features.

Measuring Device	Function	Technical Features
Extech CO250	CO_2, humidity, and temperature	Measuring range: 0-9.999 ppm (Sensitivity: 1 ppm)
Extech VFM200	TVOCs	Measuring range: 0.00-9.99 ppm (Sensitivity: 1 ppm)

For measurements, three different points on each floor, which were far from each other and where there was no airflow, were determined

(Figure 4a, b). While deciding the measurement times, considering that the library would be used more during the exam periods, the interval of 12.30.2019-01.03.2020 was determined for the winter period. During the winter, the measurements were performed by repeating each of them three times at 30-minute intervals for five days between 10:00-19:00 when the library was the busiest. The mean values were determined by calculating the arithmetic mean of the three measurements. The data obtained for each indoor pollutant were analyzed based on the threshold values determined by international institutions and organizations (US-EPA, WHO, WSHD, ASHRAE, HONG-KONG) (Table 2).

Figure 4. a) Ground floor measurement points **b)** 1st floor measurement points

Table 2. Threshold limit values determined for indoor thermal comfort and indoor air quality (CO_2 and TVOCs) according to international institutions

Parameters	EPA	WHO	WSHD	ASHRAE	HONG-KONG
CO_2 (ppm)	1000	1000	1000	1000	800
TVOCs (ppm)	3	1-3	1-3	2	-
Temp. (°C)	22.5-25.5	22.5-25.5	22.5-25.5	22.5-25.5	22.5-25.5
Hum. (%)	<70	<70	40-70	30-60	40-70

Determination of the improvement proposals and decision-making process

Natural and mechanical ventilation methods can ensure the removal of pollutants detected indoors. However, taking into account the hypothesis that “it is possible to achieve a sustainable and healthy building by following the right design strategies without increasing the energy needs of the building", it was aimed to improve the building only with natural ventilation. When examining the design of the building at this stage, the presence of an atrium space was a guide in natural ventilation scenarios.

In order to create natural ventilation scenarios, indoor air circulation was discussed first. As seen in Figure 5, the currents coming from the prevailing wind direction and the slope reach the interior space through the existing windows in the northwest and southeast on the ground floor and the first floor and the main entrance door on the ground floor. Air currents formed in the prevailing wind direction are directed depending on the landscape elements lined up along the road, and air vortices are formed here and there. It can be said that the effect of the air currents

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reaching the building is limited due to the short stature of the trees positioned along the facade and their arrangement along the sloping land.

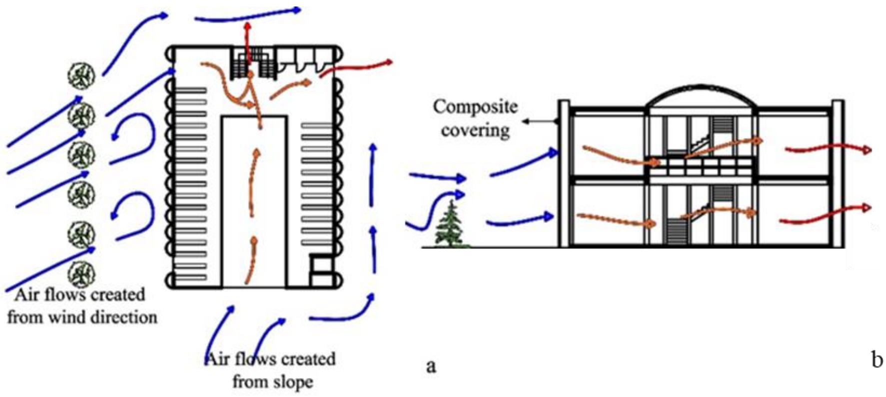

Figure 5. a) Plan diagram of air currents in the building **b)** Section diagram of air currents in the building

In the first stage, a simulation was carried out by taking into account the indoor and outdoor air movements and using the existing openings of the structure. For the simulation, it was assumed that the existing windows in the building remained open for ten minutes every two hours. As a result of the simulation, by providing fresh air to the building from the southwest, which is the prevailing wind direction, the CO_2 level was in line with the threshold values. However, the temperature and humidity values were 3-4 ℃ and 20% higher than the threshold values, respectively. It was determined that thermal comfort could not be provided due to the small size of the windows (Figure 6). The large size of the existing windows and their negative effects on thermal comfort, especially in winter, necessitate insulated culverts with smaller dimensions. Therefore, within the scope of the study, insulated culverts with a size of 30*30 and a relatively low thermal permeability coefficient were preferred (Table 3). In addition, since the humidity value was much lower than it should be, a steam humidifier with a special control feature was included in the system to improve humidity values.

Table 3. Technical specifications of the insulated grille.

Parameters	**Value**
Width (cm)	30
Height (cm)	30
Material	Aluminum
Solar heat gain coefficient	0.78
Heat conduction coefficient W/(m^2.K)	3.688
Thermal resistance (m^2.K)/W	0.271

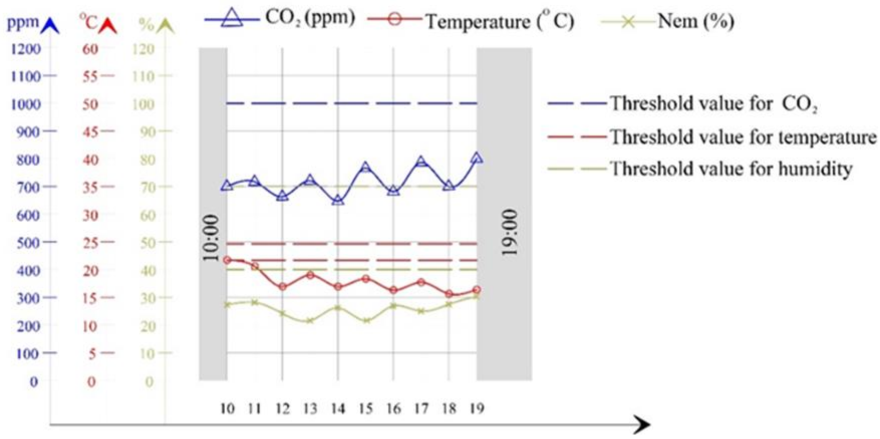

Figure 6. The effect of natural ventilation planned using existing structural openings on indoor thermal comfort and air quality

Based on the literature review (Kuesters & Woods, 2012; Jomezadeh et al., 2020; Haw et al., 2012; Acret & Hunt, 2014; Escombe et al., 2019; Carbonari et al., 2006) conducted considering the atrium space, it was decided that it would be the correct way to develop improvement scenarios in the context of the principles of cross-ventilation, chimney effect ventilation, roof wing ventilation, skylight ventilation, and wind tower ventilation. In each scenario created by considering each ventilation method, the prevailing wind direction (the southwest) was taken into account, and the air currents were planned to enter through the vents to be opened in these areas. In order to evacuate the polluted air, culverts in the southeast direction were considered. Height differences were created between the inlet and outlet vents to provide adequate natural ventilation in each scenario. The primary and visual characteristics of these proposed systems are presented in detail in Table 4 and Figure 7.

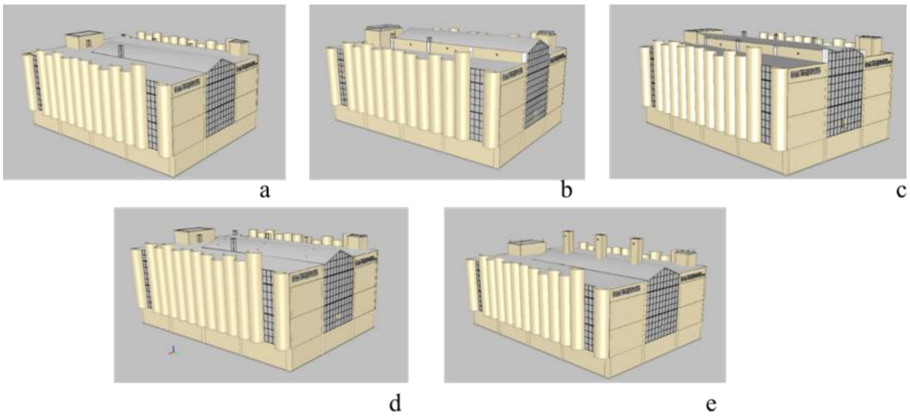

Figure 7. a) Simulation model for cross ventilation proposal, **b)** Simulation model for stack ventilation proposal, **c)** Simulation model for roof wing ventilation proposal, **d)** Simulation model for skylight ventilation proposal, **e)** Simulation model for wind tower ventilation proposal

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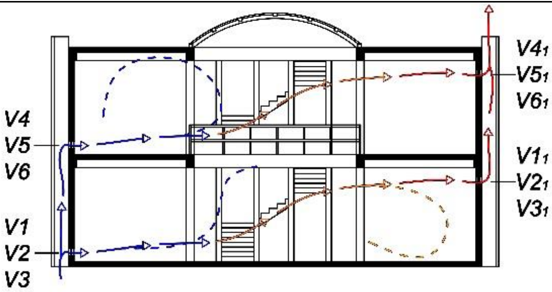
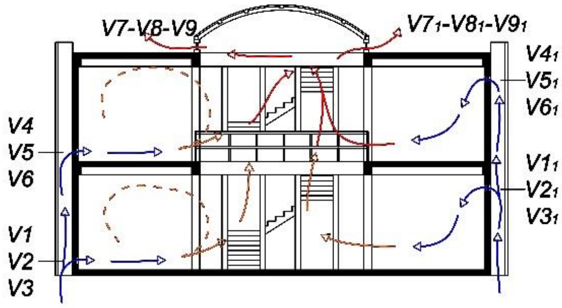
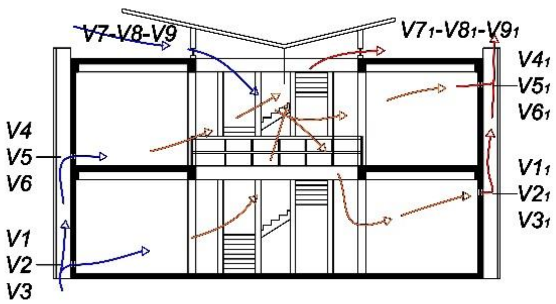
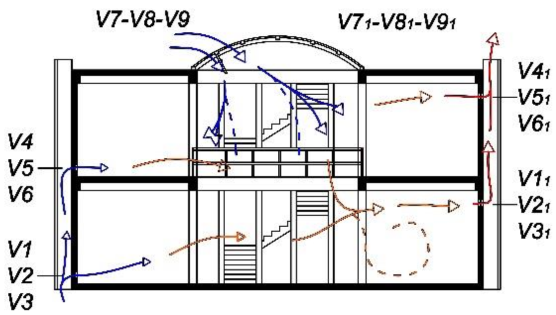
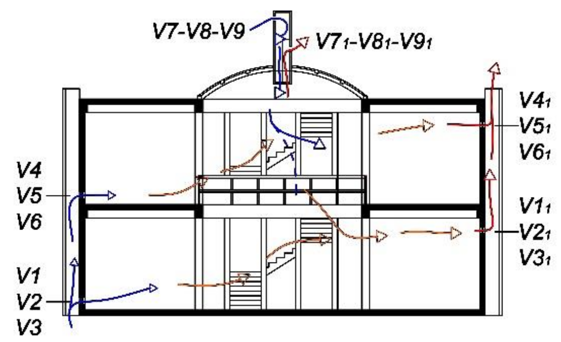
Table 4. Decisions on improvement proposals and their features.

Cross Ventilation (12 vents)	
Location of vent	**Section schemas**
Ground floor; southwest façade +1.10 altitude; V1, V2 and V3, southeast façade +3.50 altitude; $V1_1$, $V2_1$ and $V3_1$ 1st floor; southwest façade +4.60 altitude; V4, V5 and V6, southeast façade +8.00 altitude; $V4_1$, $V5_1$ and $V6_1$	
Stack Ventilation (18 vents)	
Location of vent	**Section schemas**
Ground floor; southwest façade +1.10 altitude; V1, V2 and V3, southeast façade +3.50 altitude; $V1_1$, $V2_1$ and $V3_1$ 1st floor; southwest façade +4.60 altitude; V4, V5 and V6, southeast façade +8.00 altitude; $V4_1$, $V5_1$ and $V6_1$ Atrium ceiling height; southwest façade +10.20 altitude; V7, V8 and V9, southeast façade +10.20 altitude; $V7_1$, $V8_1$ and $V9_1$	
Roof Wing Ventilation (18 vents)	
Location of vent	**Section schemas**
Ground floor; southwest façade +1.10 altitude; V1, V2 and V3, southeast façade +3.50 altitude; $V1_1$, $V2_1$ and $V3_1$ 1st floor; southwest façade +4.60 altitude; V4, V5 and V6, southeast façade +8.00 altitude; $V4_1$, $V5_1$ and $V6_1$ Atrium ceiling height; southwest façade +10.20 altitude; V7, V8 and V9, southeast façade +10.20 altitude; $V7_1$, $V8_1$ and $V9_1$	
Skylight Ventilation (18 vents)	
Location of vent	**Section schemas**
Ground floor; southwest façade +1.10 altitude; V1, V2 and V3, southeast façade +3.50 altitude; $V1_1$, $V2_1$ and $V3_1$ 1st floor; southwest façade +4.60 altitude; V4, V5 and V6, southeast façade +8.00 altitude; $V4_1$, $V5_1$ and $V6_1$ Atrium ceiling height; southwest façade +10.20 altitude; V7, V8 and V9, southeast façade +10.20 altitude; $V7_1$, $V8_1$ and $V9_1$	

Wind Tower Ventilation (18 vents)	
Location of vent	**Section schemas**
<u>Ground floor;</u> southwest façade +1.10 altitude; V1, V2 and V3, southeast façade +3.50 altitude; $V1_1$, $V2_1$ and $V3_1$ 1st <u>floor;</u> southwest façade +4.60 altitude; V4, V5 and V6, southeast façade +8.00 altitude; $V4_1$, $V5_1$ and $V6_1$ <u>Atrium ceiling height;</u> southwest façade +10.20 altitude; V7, V8 and V9, southeast façade +13.20 altitude; $V7_1$, $V8_1$ and $V9_1$	

RESULTS

Thermal comfort and indoor air quality

It is observed that the library ground floor temperature values tend to increase in the process from morning hours to noon and show a slight decrease in the evening hours and proceed in a stable course. It is possible to say that this increase between morning and noon is related to the increase in the number of people and the outdoor temperature. The fact that the temperature on the 1st floor is higher than the temperature on the ground floor can be explained by the constant inflow of cold air into the interior due to the main entrance door on the ground floor, the high number of users on the 1st floor, and the fact that the heated air reaches the upper levels by rising. As seen in Figure 8, the temperature values varying between 22℃ and 24.3℃ throughout the day are in line with the threshold values (22.5℃ to 25.5℃) determined by the US-EPA, WHO, WSHD, ASHRAE, and HONG-KONG institutions.

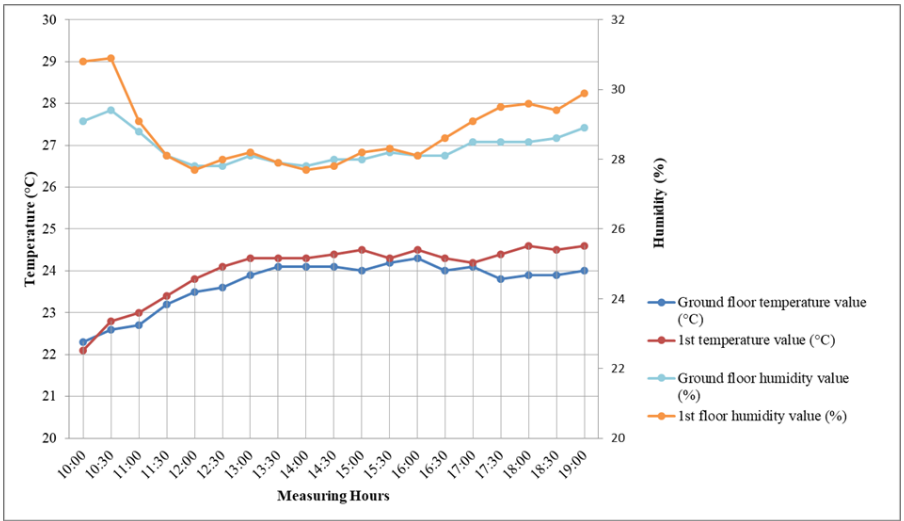


Figure 8. 5-day average temperature-relative humidity graph for the ground floor and 1st floor

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It is observed that the ground and first-floor relative humidity values tend to decrease sharply towards the noon hours and tend to increase sharply towards the evening hours. The fact that the humidity is lower between 12:00 and 16:30 compared to morning and evening hours can be explained by the decrease in the relative humidity due to the increase in indoor temperature. It is believed that the reason why the humidity value of the first floor is lower and fluctuates between 12:00 and 16:30 compared to the ground floor is that the temperature level on the 1st floor is higher than the ground floor. The humidity measured on both floors follows the limit values determined by the US-EPA (<70%) and WHO (<70%) institutions; WSHD (40%-70%), ASHRAE (30%-60%), and HONG-KONG (40%-70%) were determined not to comply with the lower limit values determined by the institutions (Figure 8). In the context of the average indoor temperature (23.8℃-24.2℃), relative humidity (27.4%-29.2%), air movement velocity (0.02 m/s), activity level (1 met), clothing condition (1 clo) data, and ASHRAE 55-2017, the obtained PMV value was found to be 0.02 and 0.14 (i.e., “Neutral”) for the ground floor and 1st floor, respectively. The PPD value, which expresses the percentage of people dissatisfied with the interior thermal comfort, was determined as 5% for each floor. Based on the thermal comfort ranges determined by ASHRAE 55-2004, the thermal comfort range of the interior was determined as “partially comfortable” (Figure 9).

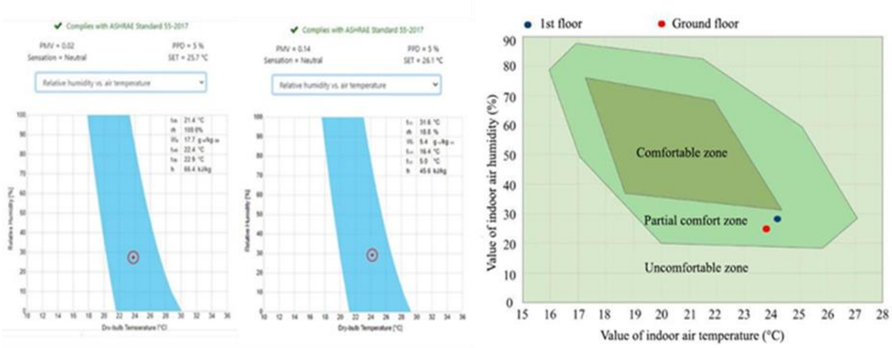

Figure 9. Thermal comfort graph (ASHRAE 55-2017) and comfort zones of Ground and 1st Floor

As seen in Figure 10, while CO_2 values on the ground floor were determined between 800 ppm and 1200 ppm, these values were between 800 ppm and 1250 ppm on the 1st floor. These values were 2-3 times the amount of CO_2 (423 ppm) measured outdoors. It was determined that since the morning hours, the CO_2 values for both floors were above the threshold values determined by the HONG-KONG (800 ppm) institution. At noon, in parallel with the increase in the number of people, the CO_2 concentration in the environment increased sharply and exceeded the threshold value determined by the US-EPA, WHO, WSHD, and ASHRAE (1000 ppm) institutions (Figure 10).

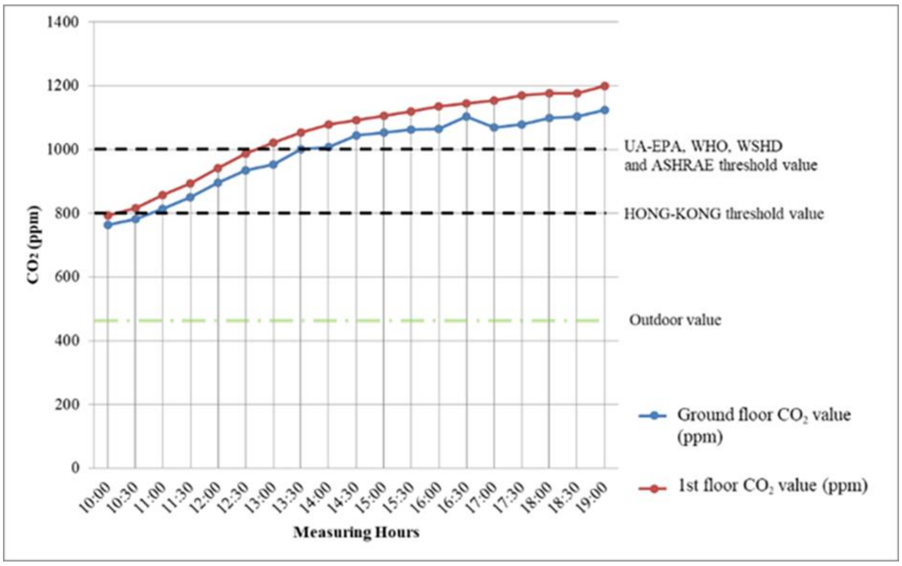

Figure 10. Average CO_2 value graph for ground floor and 1st floor for 5 days

The amount of TVOCs measured within the scope of the study represents the total amount of all VOC types in the environment. It was observed that the total TVOCs concentration measured in the ground and first floor was around 1.5 ppm throughout the day (Figure 11). This value was below the threshold values determined by US-EPA (3 ppm) and ASHRAE (2 ppm) and above the threshold values determined by WHO and WSHD (1 ppm). It was also observed that with the start of the cleaning process in the space as of 16:00, there was an increase in the amount of TVOCs in the space due to the chemical used in this process (Figure 11).

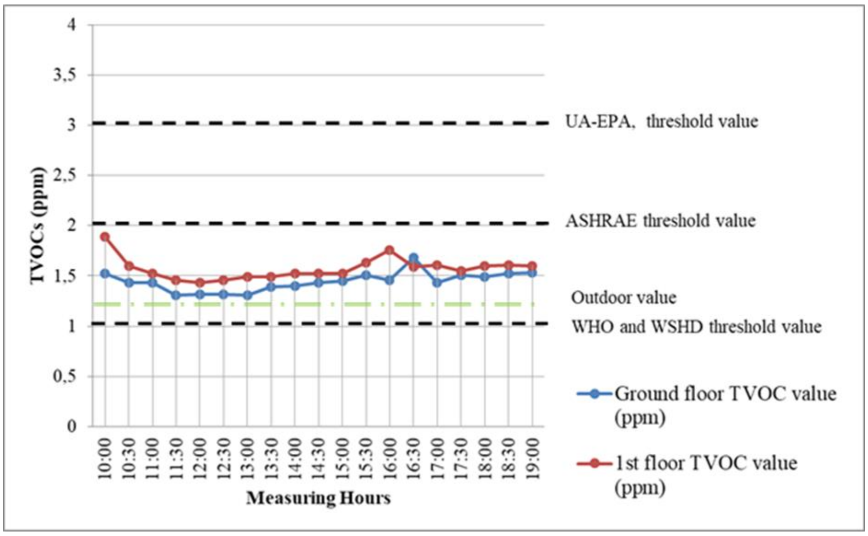

Figure 11. Graph of 5-day average TVOCs for ground and 1st floor

Calibration of the Simulation Data

After the indoor air quality level was determined by on-site measurements performed in the library, the current situation was simulated with the IDA ICE simulation program, and the margin of error was determined by comparing the obtained results with each other. At this stage, physical data such as the current state of the building, the

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density and number of users on the measurement days, and weather conditions were entered into the simulation program, and attention was paid to ensure that all conditions were the same. The graph of 5-day CO_2, humidity, and temperature values obtained from simulation results and on-site measurements is given in Figure 12.

Root mean square deviation (RMSE/Root-Mean-Square-Deviation) and mean crossover error (MBE/Mean Bias Error) were determined for the deviation of CO_2, humidity, and temperature values obtained as a result of simulation studies and on-site measurements, and these are presented in Table 5. In order to verify simulation results based on the ASHRAE 14-2002 standard, RMSE and MBE values are expected to be within 30% and 10%, respectively. As seen in Table 5, RMSE and MBE values were found to be much lower than the accepted upper limit values, and it was determined that the simulation program was appropriate for use in determining improvement proposals.

Table 5. The deviation values determined between the simulation program and on-site measurement values

		Day 1		**Day 2**		**Day 3**		**Day 4**		**Day 5**	
		CV (RMSE)	**NMBE**	**CV (RMSE)**	**NMBE**	**CV (RMSE)**	**NMBE**	**CV (RMSE)**	**NMBE**	**CV (RMSE)**	**NMBE**
G	Temp	0.01	0.32	0.01	0.24	0.01	0.04	0.01	1.03	0.01	0.82
	Hum	0.09	6.5	0.06	3	0.11	12	0.05	3.4	0.12	6.4
	CO_2	0.01	0.23	0.03	0.32	0.03	1.30	0.02	0.73	0.02	0.83
1	Temp	0.01	0.2	0.01	0.51	0.01	0.97	0.01	0.08	0.01	0.24
	Hum	0.06	0.8	0.03	0.87	0.09	7.3	0.02	0.13	0.06	1.88
	CO_2	0.75	7.8	0.33	2.6	0.06	0.7	0.12	1.4	0.03	0.06

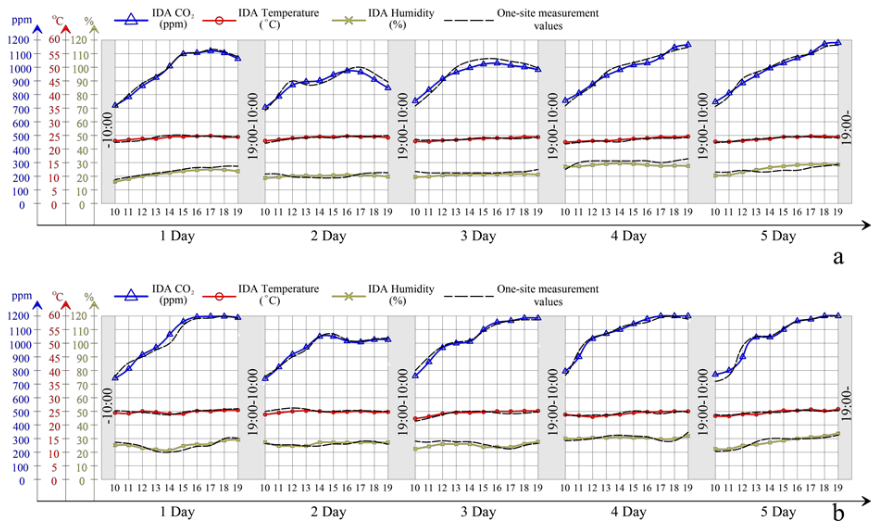

Figure 12. Daily CO_2, temperature, and humidity verification graphs of **a**) the ground floor and **b**) the 1st floor

Results of the Improvement Proposals

For the cross-ventilation proposal, it was planned to install 12 vents. Results revealed that the air quality of the space could be improved without compromising thermal comfort. The average CO_2 level was 838.5 ppm, while the average temperature and humidity were 22.1 ℃ and

50.9%, respectively. Based on this proposal, it can be recommend that the vents should be kept open for 10 minutes at intervals of 30 minutes during the summer season and for 10 minutes at intervals of 120 minutes during the winter season when the library is in use (Table 6).

For the proposal on chimney effect ventilation, 18 vents were planned. Results related to this proposal showed that the air quality of the space could be improved without compromising thermal comfort. The average CO_2 level was 812.5 ppm, and the average temperature and humidity were 22.3°C and 52%, respectively. Based on this ventilation proposal, it can be recommended that the vents should be kept open for 10 minutes with an interval of 45 minutes during the summer season and for 10 minutes with an interval of 180 minutes during the winter season when the library is in use (see Figure 13). Chimney effect ventilation is more effective than cross-ventilation in terms of natural ventilation performance because it incorporates both the principles of cross-ventilation and the additional ventilation provided by the additional vents located at the roof level (Table 6).

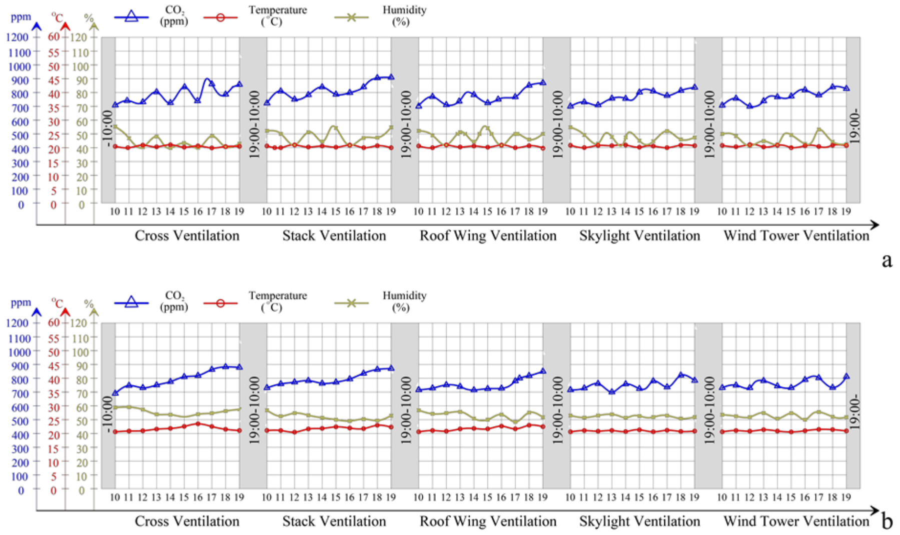

Figure 13. a) Winter period simulation results for improvement proposals, **b)** Summer period simulation results for improvement proposals

In the proposal of roof wing ventilation, the grilles were open for 10 minutes with 60-minute intervals in summer and 10 minutes with 180-minute intervals in winter. In addition, the CO_2 content was kept at an average value of 783 ppm. In the skylight ventilation proposal, the grilles were open for 10 minutes with 45-minute intervals in summer and 10 minutes with 150-minute intervals in winter. The results revealed that the roof wing provided better ventilation performance than the skylight due to its ability to direct wind towards the prevailing wind direction (Table 6 and Figure 13).

For the wind tower ventilation proposal, it was planned to install 18 vents. Results showed that the air quality of the space could be improved without compromising thermal comfort. The average CO_2 level was measured at 785 ppm, while the average temperature and humidity were 21.9 °C and 50.5%, respectively. Based on this ventilation proposal, it can

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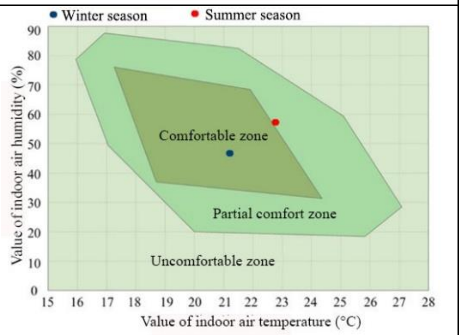
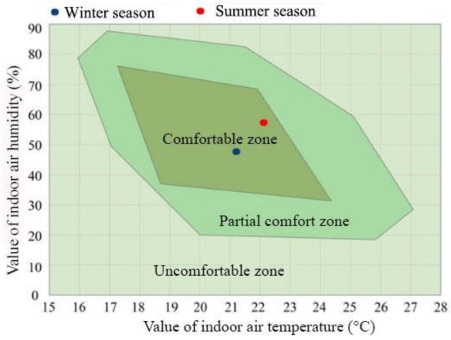
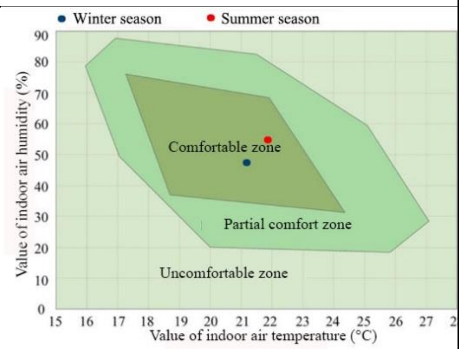
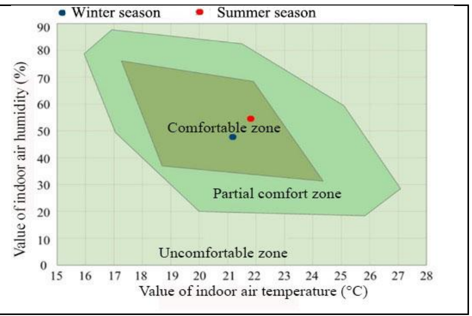
be recommended that the vents should be kept open for 10 minutes at 30-minute intervals during the summer season and for 10 minutes at 150-minute intervals during the winter season when the library is in use. As seen in Table 6 and Figure 13, the natural ventilation performance of this proposal is lower than that of the chimney effect, roof wing, and skylight proposals during the summer season, while it is lower than the chimney effect and roof wing ventilation proposals during the winter season, and equivalent to the skylight proposal.

Table 6. Thermal comfort and indoor air quality results for improvement proposals

	Window opening periods	**Average values**	**Comfort charts**
Cross V.	Summer season; 10 min every 30 min Winter season; 10 min every 120 min	Temp.; 22.1 Hum.; 50.9 CO_2; 838.5	
Stack V.	Summer season; 10 min every 45 min Winter season; 10 min every 180 min	Temp.; 22.3 Hum.; 52 CO_2; 812.5	
Roof Wing V.	Summer season; 10 min every 60 min Winter season; 10 min every 180 min	Temp.; 22.1 Hum.; 52.6 CO_2; 783	
Skylight V.	Summer season; 10 min every 45 min Winter season; 10 min every 150 min	Temp.; 22.1 Hum.; 51.5 CO_2; 780	

Wind Tower V.	Summer season; 10 min every 30 min Winter season; 10 min every 150 min	Temp.; 21.9 Hum.; 50.5 CO_2; 785	

DISCUSSION

Results of the study revealed that in terms of indoor air quality, skylights (780 ppm), roof wings (783 ppm), and wind towers (785 ppm) had the lowest average CO_2 values, while cross-ventilation (838.5 ppm) and chimney-effect ventilation (812.5 ppm) had the highest CO_2 values. Based on the analyses related to the effects of the proposed improvements on thermal comfort, it can be said that the winter season's thermal comfort range remains within the "comfortable" range. For the summer season, the cross and chimney effect ventilation proposals that offer the minimum open periods necessary to ensure thermal comfort and air quality result in a "comfortable-partially comfortable" range. The ventilation proposals, which include a roof wing, skylight, and wind tower, maintain a comfortable thermal range during both summer and winter seasons due to their high natural ventilation performance. These findings provide an answer to the research question by demonstrating the consistency of natural ventilation systems in improving indoor air quality without compromising thermal comfort.

The research findings showed that all five proposed systems offered comfortable space during the winter season. However, only cross-ventilation and chimney effect ventilation provided partially comfortable space during summer. Literature studies have shown that systems developed using atrium spaces provided suitable conditions for the summer season but not for the winter season (Sokkar & Alibaba, 2020). The reason for this is the decrease in outdoor temperature during winter and the restriction of natural ventilation conditions as a result. It is important to note that this evaluation is objective and based on empirical evidence. Furthermore, the position of the building, climatic conditions, type and size of the atrium, and the material used for the atrium's top covering can contribute to varying outcomes in both summer and winter. It should be noted that in such studies, the combination of multiple variables can result in diverse findings. In the study, solutions for both summer and winter seasons were examined taking into account all relevant factors for the winter season due to the building's location in a cold climate zone. In addition to atrium ventilation, composite facades of the building act as a chimney carrying outdoor air to the interior in a warmer manner. Based on the evaluation of these proposed solutions and the various factors, it is believed that the results of this study are consistent with the existing literature and offer a unique perspective.

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Many studies on natural ventilation proposals for buildings with atriums take into account window elevation differences, compliance with the prevailing wind direction, and the amount of airflow (Li et al., 2013; Ghafar & Moosavi, 2015; Hijleh & Vethanayagan, 2019; Mahmoud et al., 2019; Sokkar & Alibaba, 2020). In this study, these factors were also considered because they are supported by the literature.

Cost is a major issue in proposals for natural ventilation. The economic burden of interventions to existing structures is a key factor that needs to be addressed. In the study, five proposals were also analyzed in terms of their economic impact. Cross-ventilation, chimney-effect ventilation, and skylight ventilation were designed to open only vents without intervening in the structure. Therefore, the economic problems in these systems are limited. However, interventions to the top cover of the building may cause economic problems in the proposals of roof-wing ventilation and wind-tower ventilation. The study shows that all five proposed systems improve thermal comfort and indoor air quality with no significant differences between them. Therefore, considering economic issues, it can be recommended to use the systems that require the least structural intervention first. When using systems that require building intervention, practical solutions can be achieved by using inexpensive and removable panels.

In the literature on natural ventilation in buildings with atriums, extensive research has been conducted to determine the most efficient atrium size, height, and form (Li et al., 2010; Aldawoud, 2012; Hussain & Oosthuizen, 2012; Acred & Hunt, 2014). This current study aimed to emphasize the significance of design decisions by highlighting interventions made to the atrium space in an existing layout. It is expected that the systems proposed in the context of this study will enhance the literature and reinforce the study's originality. Furthermore, evaluating an atrium space in a heavily used environment where mental activities occur and its role in natural ventilation are viewed as factors that bolster the study's impact on user health and sustainability.

CONCLUSION

In this study, five natural ventilation proposals designed to improve the indoor air quality of a library by only natural ventilation without compromising on thermal comfort were created taking into account the natural ventilation principles that can come to the fore in buildings with atriums. In the proposals, it was assumed that insulated grilles were integrated into the structure as required by cross-ventilation, chimney-effect ventilation, roof-wing ventilation, skylight ventilation, and wind-tower ventilation. In the context of each proposal, the minimum open periods that can be applied to the culverts in terms of providing thermal comfort and air quality for the summer and winter seasons were determined by numerous simulations. It was revealed that the indoor air quality could be improved without compromising thermal comfort in the building by determining the appropriate culvert open times for each of

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the five proposals. However, not all improvement methods played a role in the ventilation of the building with the same degree of effectiveness as expected. The chimney ventilation was more effective than the cross-ventilation regarding natural ventilation performance. It can be said that the reason for this is the cross-ventilation principles and the additional ventilation provided by additional vents on the roof level. In addition, the ventilation efficiency obtained with the roof wing was higher than that provided by the skylight due to the large wind volume obtained by directing the roof wing to the prevailing wind direction. However, it can be said that the wind-tower ventilation efficiency is lower than the efficiencies of chimney-effect, roof wing, and skylight ventilation methods for the summer season, it is lower than the efficiencies of chimney-effect and roof-wing ventilation methods for the winter season, and it has the same performance with the roof-window ventilation (Figure 14).

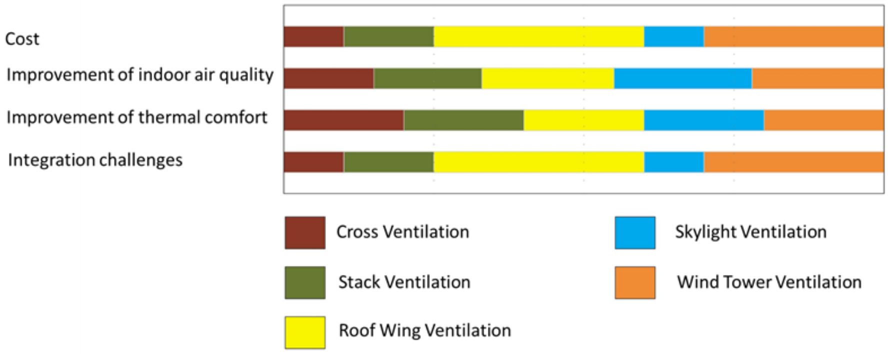

Figure 14. Performance analyses of natural ventilation proposals

On the other hand, in terms of cost-effectiveness, it can be said that there are costs of only 12 grilles and application costs in the cross ventilation proposal. In comparison, there are costs of 18 grilles and application costs in the chimney-effect ventilation proposal. Even though the roof wing proposal has higher ventilation performance than the ventilation proposals with the roof wing, skylight, and wind tower, which have the cost of 18 culverts, it is costlier than other proposals because it requires the integration of the proposed roof wing to the structure by completely replacing the covering system in the atrium.

In conclusion, solutions to improve indoor air quality should include pollutant source control and natural and mechanical ventilation. In addition, to provide the indoor air control of a building effectively and sustainably and provide adequate natural ventilation, the land characteristics, prevailing wind direction, and the analysis of climatic data are the criteria that should be taken into account during the design process of the building. If these criteria are not considered sufficiently during the design process, the systems proposed to be integrated into the building may cause both time and economic losses (Figure 14). In this context, it is believed that this study, in which the hypothesis of “indoor air quality of a building can be ensured by natural ventilation methods without compromising the thermal comfort” was confirmed, will shed

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light on new improvement proposals to be developed for atrium structures and natural ventilation methods to be considered in the design phase of these structures.

This study highlights the significance of decision-making during the design phase and proper management of atrium spaces within a building. Due to the dependence of natural ventilation on various parameters, design decisions are limited to the structural scale. Improving this situation was the primary objective of this study. Furthermore, future studies should aim to develop a comprehensive model encompassing all buildings by incorporating the spatial elements and criteria discussed in the current study.

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Resume

Caner YETİŞ graduated from Karabük University Department of Architecture in 2018. He started his master's degree at Karabük University in 2019 and completed his master's degree in 2021 with a dissertation titled Determination of indoor air quality and suggestions for improvement in atrium buildings: Example of Kamil Güleç library' and completed his master's degree in 2021. In the same year, he started his doctoral education and his doctoral education continues. He continues his studies in the fields of energy, indoor air quality, building materials and sustainability.

Merve TUNA KAYILI graduated from Karabük University Department of Architecture in 2008. She started her master's degree at Gazi University in 2008 and completed her master's degree in 2010. Between 2011-2016, she worked as a researcher at Delft Technical University while doing her doctorate. In 2023, she received the title of Associate Professor and continues her studies in the fields of energy efficient building design, building materials and sustainability.

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