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Assessing the thermal response of a multi-zone ventilated building using TRNSYS

Azeldin El-sawi [1], Suliman Alfarawi [2 *], Hossin Omar [3]
[1,2,3] Department of Mechanical Engineering, Faculty of Engineering, University of Benghazi, Benghazi, Libya

تقييم الاستجابة الحرارية لمبنى متعدد الغرف ذي تهوية باستخدام برنامج *TRNSYS*

عز الدين الصاوي [1]، سليمان الفاراوي [2 *]، حسين عمر [3]
[1،2،3] قسم الهندسة الميكانيكية، كلية الهندسة، جامعة بنغازي، بنغازي، ليبيا

[*]*Corresponding author:* *suliman.alfarawi@uob.edu.ly*

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Abstract
This work is aimed to provide a design model of a multi-zone building. The thermal response of a ventilated zone is calculated in conjunction with hourly change of outdoor air temperatures. Numerical simulations are carried out to investigate the effect of outdoor weather conditions on the indoor air temperatures. A simulation tool is developed to analyze the thermal performance of a multi-zone building's envelope. The numerical solution is conducted using the commercial software package, TRNSYS. To evaluate the dynamic thermal performance of the residential apartment during the summer season, the first three days of June were selected as a time-simulated period. Based on an annual climatic profile weather record data, selected time-simulated periods characterized by high and low thermal conditions were further considered in order to perform a more detailed thermal analysis of the building performance. We found that the thermal response of building's envelope in conjunction with insulation layer has a significant effect on reducing the variations of indoor air-temperature compared with only implementing ventilation system. The reduction of the indoor air-temperature is found to be in the range of 2-3 °C.

Keywords: HVAC systems, Building, Simulation, Transient.

الملخص
يهدف هذا العمل إلى تقديم نموذج تصميمي لمبنى متعدد الغرف. تم حساب الاستجابة الحرارية لمنطقة التهوية بالتزامن مع التغيرات الساعية في درجات حرارة الهواء الخارجي. أُجريت محاكاة عددية لدراسة تأثير الظروف الجوية الخارجية على درجات حرارة الهواء الداخلي. طُوّرت أداة محاكاة لتحليل الأداء الحراري لغلاف المبنى متعدد الغرف. تم تنفيذ الحل العددي باستخدام حزمة البرامج التجارية.TRNSYS
لتقييم الأداء الحراري الديناميكي للشقة السكنية خلال فصل الصيف، تم اختيار الأيام الثلاثة الأولى من شهر يونيو كفترة محاكاة زمنية. استنادًا إلى بيانات سجل الطقس السنوي، تم اختيار فترات محاكاة زمنية أخرى تتميز بظروف حرارية مرتفعة ومنخفضة لإجراء تحليل حراري أكثر تفصيلًا لأداء المبنى. وجدنا أن الاستجابة الحرارية لغلاف المبنى، بالإضافة إلى طبقة العزل، لها تأثير كبير في تقليل تقلبات درجة حرارة الهواء الداخلي مقارنةً بتطبيق نظام التهوية فقط. وُجد أن انخفاض درجة حرارة الهواء الداخلي يتراوح بين 2 و3 درجات مئوية.

الكلمات المفتاحية: أنظمة التدفئة والتهوية وتكييف الهواء، المباني، المحاكاة، العابر.

Introduction

Conventional cooling systems require a considerable amount of primary energy resulting in an increase of building operation cost. As a result, the greenhouse gas (GHG) emissions are accordingly boosting. It was reported that the building sector in developed nations uses about 40% of the world-wide total energy and contribute up-to 40% of GHG [1]. Hasan [2] used life cycle cost analysis to determine optimum insulation thicknesses in a building. The results showed that for rock wool as an insulation, 10 years is the saving lifetime with 21$/m^2. He reported payback periods of 1-1.7 years for rock wool and 1.3-2.3 years for polystyrene insulation depending on the type the wall structure.

Abdulgalil [3] studied the cooling load profile of an office building to determine appropriate thermal energy storage strategies. The dynamic thermal analysis is demonstrated as peak ambient temperatures reported to reach up to 46 °C, leading to significant thermal loads on building walls and roofs. Therefore energy consumption consequently increased to maintain indoor thermal comfort. The study further indicated that peak cooling loads typically occur during late afternoon hours due to the combined effects of elevated outdoor temperatures, internal heat gains, and the Urban Heat Island (UHI) phenomenon in dense urban environments.

Frédéric [4] studied the effect of using PCM (phase change material) incorporated inside buildings envelope. Type 260 model transfer has been developed to simulate the thermal behaviour of PCM on the thermal comfort inside the buildings. Previous research has highlighted the importance of dynamic thermal modeling in understanding how residential buildings respond to external climatic conditions, particularly in dense urban environments affected by the Urban Heat Island (UHI) phenomenon. Studies show that accurate prediction of indoor environmental conditions requires solving detailed thermal balance equations that account for conduction, convection, and radiation simultaneously. This approach allows researchers to capture the complex interactions between the building envelope and the surrounding microclimate, which is essential for improving energy efficiency and ensuring thermal comfort. In parallel, the literature identifies TRNSYS as one of the most advanced tools for transient thermal simulation. Its modular structure and components—such as the well-established Type 56—enable detailed modeling of multi-zone buildings and the dynamic behavior of internal and external heat sources. Previous studies demonstrate that TRNSYS effectively represents real weather-driven fluctuations in indoor temperature and humidity, making it highly suitable for developing reliable predictive models in residential applications.

Chen [5] investigated cooling load distribution in large-space buildings by dividing the building into multiple thermal zones to evaluate temperature and cooling load variations across different orientations and locations. The methodology was based on multi-zone thermal simulation, where the building was segmented into external, medial, and internal zones to capture spatial thermal differences under summer and winter conditions. Seasonal simulations were carried out with and without HVAC operation to compare multi-zone thermal responses. The results demonstrated highly uneven temperature and cooling load distributions, with external zones experiencing significantly higher thermal loads than internal zones due to solar exposure and envelope effects. The study emphasized that uniform cooling load assumptions may lead to inefficient HVAC design and energy waste. However, the research acknowledged that simulation accuracy depended heavily on zone detail and simplifying assumptions, which may differ from real building behavior.

Rashad [6] performed a comprehensive year-round dynamic energy analysis of a detached residential building using TRNSYS to assess heating demand, cooling demand, and thermal comfort under multiple operational scenarios. Their methodology involved constructing a three-zone building model using Google SketchUp with TRNSYS 3D, then importing it into TRNBuild (Type 56). Seven progressive simulation scenarios were analyzed, including geometry definition, ideal HVAC, internal gains, occupancy schedules, infiltration rates, and thermal comfort parameters. Hourly simulations were conducted to examine annual and peak energy demand variations. The findings revealed that building envelope characteristics, occupancy assumptions, and infiltration rates dramatically influenced thermal performance, with total annual heating and cooling demand varying by 70.16% across scenarios. The study confirmed TRNSYS as a powerful tool for detailed residential energy analysis. Nevertheless, domestic hot water demand, advanced HVAC control, and broader climatic applicability were not included.

Ebaid [7] examined the feasibility of integrating a solar-assisted adsorption cooling system into an industrial textile building in Cairo using TRNSYS 18. The methodology involved developing a detailed industrial building model in Type 65/TRNBuild, incorporating meteo-norm weather data, equipment heat gains, solar collector arrays, adsorption chiller performance, storage tank systems, and auxiliary boiler support. A full-year simulation (8760 hours) with 1-minute intervals was conducted, and parametric optimization was performed by varying collector area and storage tank capacity. The study identified optimal system parameters that reduced conventional cooling energy consumption while achieving favorable economic and environmental performance. The obtained results demonstrated that solar-assisted cooling can significantly enhance industrial HVAC sustainability in hot climates. However, system complexity, space requirements, and advanced operational control challenges were identified as major implementation limitations.

Bhaskoro [8] investigated the transient cooling load characteristics of an academic building located in a hot and humid climate using TRNSYS. The methodology involved developing a dynamic simulation model of the building, in which the building envelope, occupancy schedule, and HVAC operation were incorporated to evaluate annual cooling load characteristics. Three alternative air-conditioning strategies were subsequently assessed to identify the most effective approach for reducing cooling energy consumption. The results revealed that heat gain through the building envelope was the dominant contributor to the annual cooling load, accounting for 52.57% of the total cooling demand. In addition, approximately 50% of the annual cooling energy was consumed during part-load and off-peak operating conditions. Among the investigated strategies, increasing the indoor temperature set point proved to be the most effective, reducing the annual cooling load by 27.4%. However, the study was limited to a single academic building located in a hot and humid climate, and therefore its findings may not be directly applicable to buildings with different occupancy characteristics or climatic conditions.

Asim [9] investigated the feasibility of a solar-powered cooling system for residential buildings located in the hot climate of Pakistan using TRNSYS. The methodology involved developing a complete dynamic simulation model integrating an absorption chiller, an evacuated tube solar collector, a hot water storage tank, and a conditioned building. Local weather data representing the climatic conditions of Lahore, Pakistan, were incorporated into the simulation to evaluate system performance throughout the cooling season. Several design parameters, particularly the collector area and thermal storage capacity, were analyzed to determine the optimum system configuration. The results demonstrated that an evacuated tube solar collector with an area of 12 m^2, combined with a stratified hot water storage tank, was capable of maintaining the indoor air temperature at or below 26°C during the cooling season. The study further confirmed the capability of TRNSYS to accurately simulate solar-assisted cooling systems and highlighted the significant potential of solar energy for reducing electricity consumption in hot climatic regions. However, the research was limited to the climatic conditions of Pakistan and mainly focused on the performance of the solar cooling system without considering detailed cooling load estimation, economic analysis, long-term operational performance, or experimental validation.

Building Description and Simulation Assumptions

In this study, the TRNSYS software is employed to perform all calculations related to indoor air temperature, as well as heating and cooling loads. The program enables the simulation of building performance and the estimation of energy consumption over various time scales, including hourly, monthly, and annual periods.

TRNSYS is recognized as a robust and flexible tool for the simulation of thermal systems, particularly for multi-zone buildings. It is widely utilized by engineers and researchers to analyze the impact of different factors, such as HVAC operation, occupant behavior, and the integration of renewable energy sources, including solar energy.

For the purpose of this study, the building is modeled as a Libyan apartment consisting of eight thermal zones as illustrated in Figure 1. These zones represent different functional spaces within the apartment, including bedrooms, living areas, kitchen, bathroom, and circulation spaces. The multi-zone configuration allows a realistic representation of heat transfer processes and thermal interactions within the building. The following assumptions are adopted in the simulation model:

1. The apartment geometry, construction materials, and envelope characteristics are modeled according to the actual building specifications implemented in the TRNSYS environment.
2. Weather data obtained from the National Climate Data and Information Archive in Libya are used as the climatic boundary conditions. The outdoor air temperature variations are recorded on an hourly basis.
3. The air change function is scheduled to provide an air change rate of 5 ACH during the period from 6:00 AM to 19:00 PM, while an air change rate of 2 ACH is maintained during the remaining hours of the day.
4. To satisfy indoor thermal comfort requirements, the indoor air temperature is maintained at a set-point temperature of 24°C throughout the simulation period.

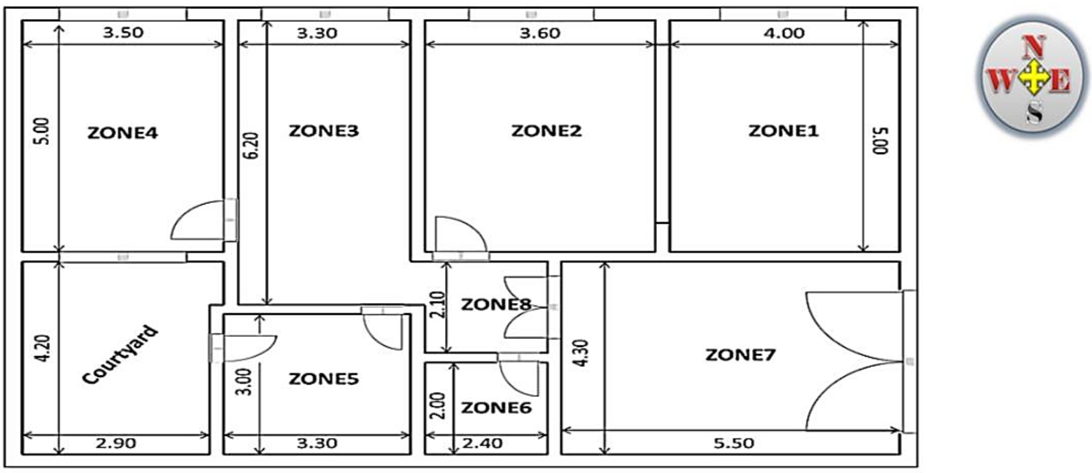


Figure 1: Simplified Layout of the Modeled Building

Building Envelope Characteristics and Model Description

Although the apartment is modeled as a multi-zone building consisting of eight thermal zones, the present study focuses on Zone 3 for the detailed thermal analysis. The selection of Zone 3 was based on its location within the apartment, where it is surrounded by adjacent zones and therefore experiences thermal interactions from neighboring spaces. As a result, its thermal response can be considered representative of the average thermal behavior of the building as a whole. Furthermore, Zone 3 reflects the combined effects of heat transfer through the building envelope, internal heat gains, ventilation, and inter-zonal heat exchange. Therefore, it was selected as the reference zone for evaluating the thermal performance of the conventional and insulated building envelopes under the climatic conditions of Benghazi, Libya.

The building envelope defines the physical and thermal boundary between the indoor and outdoor environments. It consists of walls, roof, floor, windows, and doors, all of which influence heat transfer and overall energy performance. In this study, the envelope components are described in terms of their dimensions, construction layers, and material properties, as summarized in the following tables (1,2,3).

The thermal building response is simulated used TRNSYS for multi-zone model. The model is an apartment with dimensions of 6.2m×3.3m×2.76m. Each wall of the apartment is divided in several layers of materials, which forms a composite wall, more details are provided in Table 1. Floor area is having a dimension of 6.2m×3.3m. Exterior walls, façade (2.69m×2.76m) are facing north directions. In the west side, there is one door and one corridor access through the zone8 in east side. Two adjacent zones are in vicinity of the considered model on west-east directions.

Table 1 Details of wall components in a traditional building.

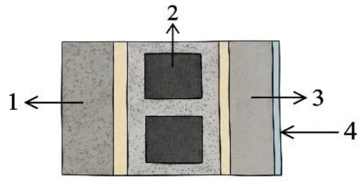
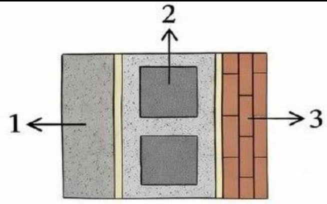
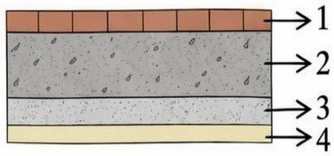
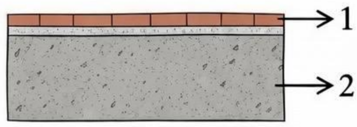
Wall Type	Description	Wall Layer
External and Internal walls Zone number (1,2,3,4,7,8)		1.cement-out 2.hollow block 3.cement-in 4.paint-in
Kitchen and Bathroom Walls Zone number (5,6)		1.cement-out 2.hollow block 3.ceramics
Roof Zone Number (1,2,3,4,5,6,7,8)		1.ceramics 2.reinforced concrete slab 3.cement-in 4.paint-in
Floor Zone number (1,2)		1.ceramics 2.plain concrete slab

Table 2 Description of window and door types in a traditional house

Type	Shape	Area (m^2)	Width (m)	Height (m)
Window 1	Single glass	1.2 m^2	1 m	1.2 m
Window 2	Single glass	0.64 m^2	0.80 m	0.80 m
Door (room)	Spruce-pin	2.20 m^2	1 m	2.20 m
Door (kit., bat)	Spruce-pin	1.98 m^2	0.9 m	2.20 m
Door (main entrance)	Spruce-pin	7.50 m^2	3 m	2.50 m
Door (house enter)	Spruce-pin	3.08 m^2	1.40 m	2.20 m

Table 3 Description of thermal properties of different layer types of a traditional building.

Layer Type	Thickness (cm)	Conductivity $\frac{kJ}{hr.m.K}$	Capacity $\frac{kJ}{Kg.K}$	Density $\frac{kg}{m^3}$.
Cement-out	1	2.592	0.840	1762
Hollow concrete block	20	2.592	0.835	2083
Cement-in	1	2.592	0.840	1762
Paint-in	0.5	0.13	2.09	40
Ceramics	3	0.6117	0.980	280
Reinforced concrete slab	30	6.09	0.840	2000
Plain concrete slab	10	0.648	1	704

Proposed building envelope

The scenario investigated involves the integration of high-performance insulation boards within the building's thermal envelope to enhance energy efficiency. Specifically, Rockwool (Mineral Wool) boards are applied to the interior surfaces of walls exposed to direct solar irradiation and rain, as well as the roofing system across all zones. This strategic placement aims to minimize heat gain and stabilize the indoor thermal environment.

The following table details the thermal and physical properties of the proposed insulation material, which are essential for the numerical simulation and the assessment of the building's overall energy performance.

Rock wool is considered one of the most effective thermal insulation materials used in residential and commercial buildings due to its high efficiency in reducing heat transfer and improving indoor energy performance. It is manufactured from natural volcanic rocks such as basalt and dolomite, which are melted at very high temperatures and then spun into fine fibers to form rigid insulation boards or blanket insulation with excellent thermal and acoustic properties.

In this graduation project, rock wool was selected as the thermal insulation material for walls and roofs because of its strong resistance to heat transfer, excellent fire resistance, and long service life. The selected insulation material has a thermal conductivity of 0.045 W/m·K, a density of 200 kg/m^3, and a specific heat capacity of 0.84 kJ/kg·K, which represent suitable engineering properties for reducing thermal loads and maintaining indoor thermal stability.

The application of rock wool insulation contributes significantly to reducing cooling and heating demands, improving occupant thermal comfort, and minimizing electrical energy consumption. Therefore, it is considered an efficient and sustainable solution in modern building envelope design and energy-efficient engineering applications.

Table 4 Description of layer types and their thermal properties used in the proposed envelope

Layer Type	Thickness (cm)	Conductivity $\frac{kJ}{hr.m.K}$	Capacity $\frac{kJ}{kg.K}$	Density $\frac{kg}{m^3}$
Cement-out	1	2.592	0.840	1762
Hallow concrete block	20	2.592	0.835	2083
Cement-in	1	2.592	0.840	1762
Paint-in	0.5	0.13	2.09	40
Ceramics	3	0.6117	0.980	280
Reinforced concrete slab	30	6.09	0.840	2000
Insulation-in (Rockwool Board)	(5 – 7)	0.045	0.84	200

Results and Discussion
This chapter presents and discusses the simulation results obtained using the TRNSYS software for the selected residential apartment located in Benghazi, Libya. The analysis evaluates the indoor thermal performance, hourly air temperature variations, and the associated heating and cooling loads under the influence of local urban climatic conditions. Hourly weather data for the entire year were incorporated into the simulation model in order to reproduce realistic environmental conditions and accurately represent the transient thermal behavior of the building.
Furthermore, a comprehensive comparative analysis is carried out between the conventional building envelope and the proposed thermally insulated envelope using Rockwool insulation. The comparison demonstrates the significant effect of thermal insulation in reducing energy consumption, minimizing peak thermal loads, and improving indoor thermal comfort for occupants. Figure 2 illustrates the annual variation of outdoor air temperature based on hourly weather data imported into the TRNSYS simulation environment for the city of Benghazi.

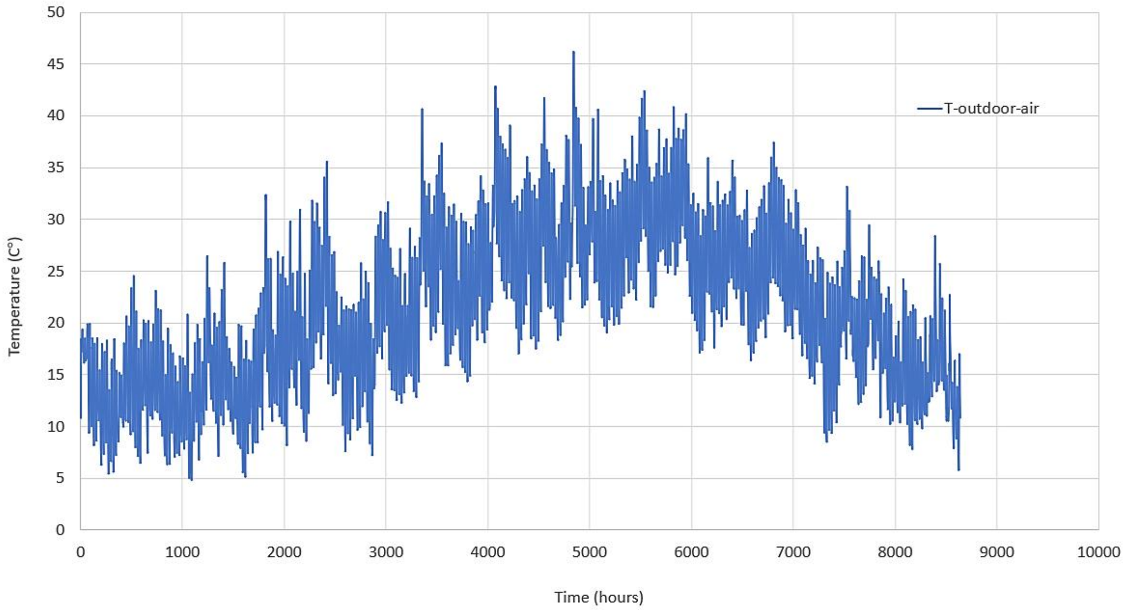


Figure 2: Annual Outdoor Air Temperature Variation

The figure 2 demonstrates the continuous fluctuation of ambient temperature throughout the year due to daily and seasonal climatic changes.
Based on this annual climatic profile, selected time-simulated periods characterized by high and low thermal conditions were further considered in order to perform a more detailed thermal analysis of the building performance.
To evaluate the dynamic thermal performance of the residential apartment during the summer season, the first three days of June were selected as a time-simulated period. This section analyzes the hourly indoor air temperature variations for both the uninsulated and insulated configurations against the outdoor ambient air temperature. As shown in figure 3, the indoor air temperatures of the uninsulated spaces highly fluctuate and closely follow the outdoor ambient air temperature profile during period of summer days. Due to the high thermal conductivity of the conventional concrete block walls and the lack of insulation, heat flows through the walls of the building's envelope. This causes an increase of indoor air temperatures during peak hours, which properly reduces indoor thermal comfort and increases the cooling demand.

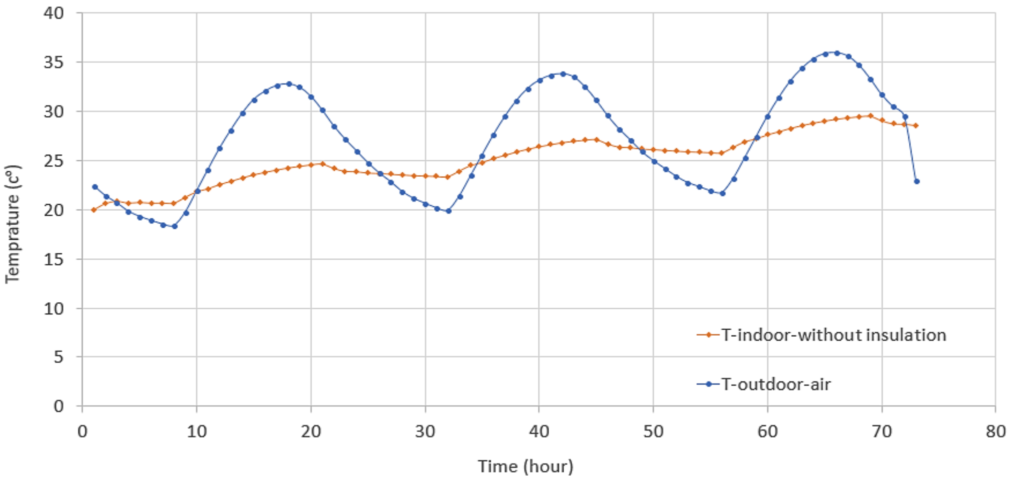


Figure 3: indoor temperature variations for the uninsulated building envelope

Figure 4 demonstrates the thermal behavior when the proposed Rockwool insulation layer is added during the same period of summer days. The indoor air temperatures of the insulated zones remain remarkably stable and smooth throughout the three days, showing a very narrow fluctuation range. The insulation layer successfully decouples the indoor spaces from the harsh outdoor summer conditions, keeping the indoor environment cooler and more comfortable.

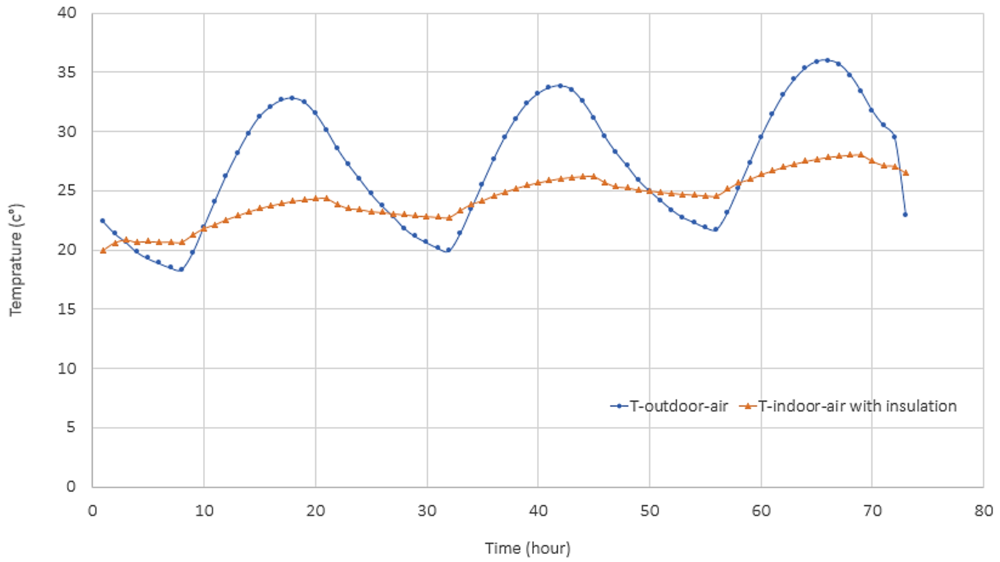


Figure 4: Temperature Variations for the Insulated Building Envelope.

The figure 5 illustrates the effect of adding thermal insulation (rock wool boards) on the indoor air temperature compared to a conventional uninsulated building, during an extended period at the beginning of June, where outdoor air temperatures record high values during the daytime. In the case of the uninsulated building, the indoor air temperature rises notably, being significantly influenced by the external climatic conditions, which reflects the low thermal resistance of the building envelope. In the case where thermal insulation layer is added, the indoor air temperature is lowered by about 2 to 3 degrees Celsius. This difference proves the efficiency of thermal insulation in reducing heat gain from the outdoors, as the insulation acts as a barrier that slows down heat transfer through the walls and roof, thereby improving indoor thermal comfort and reducing dependence on cooling systems. Thus, the addition of insulation represents an effective solution to cope with the hot climate and achieves the project's objective of improving thermal performance and reducing energy consumption.

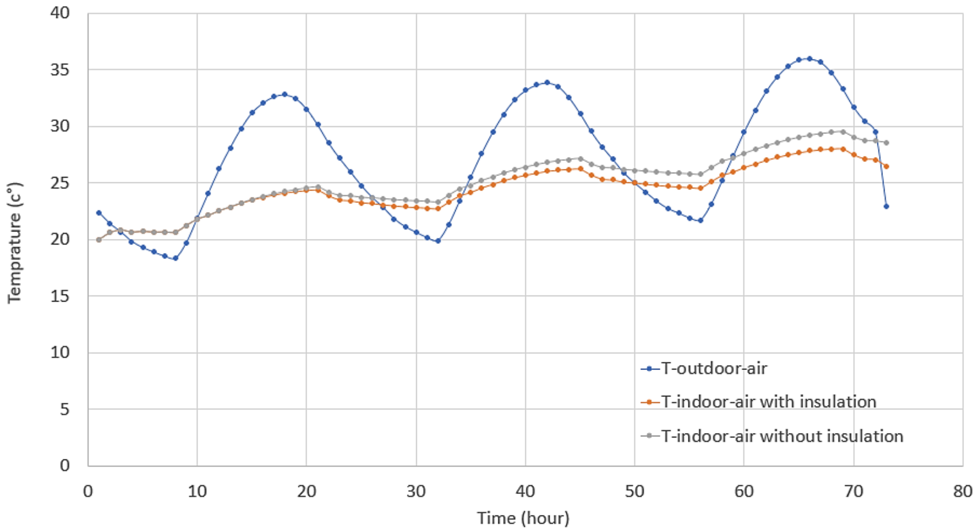


Figure 5: Indoor air temperature response with and without thermal insulation.

Figure 6 shows the hourly calculated indoor air temperature, the measured outdoor air temperatures, and the cooling load. The ventilation load required to regulate the indoor air temperature is estimated for two cases: 1) with a normal building's envelope, and 2) applying the insulation to building's envelope to assess its potential to stabilize the indoor air temperature.

Eq. (6) was used to calculate the cooling energy during the daytime. Calculations were performed when the indoor air temperature exceeded the target temperature of 24°C, T_{set}.

$$Q_{cooling} = \rho c \dot{V}(T_{Air} - T_{set}) \qquad (6)$$

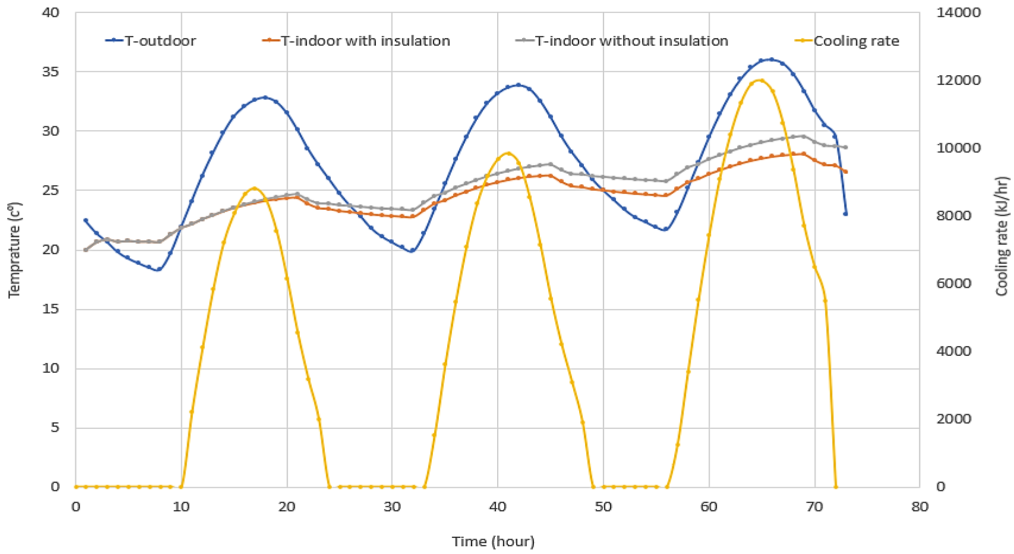


Figure 6: Variations of indoor air temperatures with and without thermal insulation along with cooling energy for hourly outdoor air temperature changes on June 1st.

Conclusion

TRNSYS is a dynamic simulation software for building energy calculations to analyze the thermal performance of building thermal response model. The building model is described as a Type 56 and its visual interface given as (TRNBuild).

The thermal performance of ventilated zone system is assessed using hourly inlet air data obtained from the national climate data and information archive, Libya for summer months. The mechanical ventilation system is

integrated into a multi building zone with an advanced control unit through a suitable set point for meeting the thermal comfort requirement. Thus, the swing of indoor air temperature is stabilized during the day-time.
The control strategy for a ventilated room is applied to allow that the indoor air temperature did not exceed 24 °C. The daily ambient outdoor air-temperature variations are recorded based on hourly changes.
To analyze the effect of building's envelope system with and without the insulation layer, three days of June are chosen from the summer season. The thermal response of building's envelope in conjunction with insulation layer has a significant effect on reducing the variations of indoor air-temperature compared with only implementing ventilation system. The reduction of the indoor air-temperature is found to be in the range of 2-3 °C.
The cooling load was calculated when both the indoor air temperatures were higher than the set point. The potential cooling load, $Q_{cooling}$, for a typical day is calculated hourly and reported. The indoor air temperature and heating load are quantified. The results demonstrate the effectiveness of the proposed building model in improving thermal stability, enhancing indoor comfort, and flatting the heating the outdoor air temperature during winter conditions.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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