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Article

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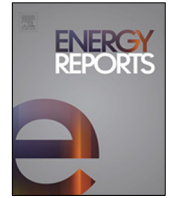
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Research paper

An evaluation process for natural ventilation using a scenario-based multi-criteria and multi-interaction analysis

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ABSTRACT

This study examines natural ventilation with respect to human thermal comfort conditions using a scenario-based, multi-criteria, and multi-interaction analysis. The proposed methodology evaluates the design development process in terms of decisions on building physics and building geometry during the early design stages to maximize human thermal comfort conditions and reduce cooling load requirements. The methodology integrates a detailed three-dimensional (3D) building and computational fluid dynamics (CFD) modeling within a building information modeling (BIM) platform during the design development stage, which is developed and structured to optimize the evaluation process. The operational characteristics of the building in respect of windows and shutters have important effects on natural ventilation, which in turn influences thermal comfort, and cooling load. Thus, the multi-interaction analysis of natural ventilation is considered with operational schemes of enveloping that are integrated into a 3D model of the building, which is further transformed to a CFD model. Then, four scenarios using a manually operated building opening are created using the BIM platform. Thus, multi-interactions are achieved by developing a 3D-building model, that not only include the building's functions and physical specifications but also incorporates the envelope's thermal capacity coupled with openings that have various operational scenarios for natural ventilation. The results show that the correlation between the air temperature and velocity can provide a comfort zone and decrease the cooling load for energy consumption. The numerical results for one scenario 2 show that if the temperature and velocity values are increased together, human sensation as predicted mean vote (PMV) ranges from 0 to 2, which is considered tolerable for summer comfort, whilst the cooling load is reduced by almost 3%.

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1. Introduction

The performance of a building as a complex system of multiple interacting physical processes, is assessed on the basis of several criteria, including energy performance, indoor environment for human comfort and health, environmental degradation and economic aspects (Bandara et al., 2015). This process requires an efficient collaboration of multidisciplinary teams at the beginning of the design stages to obtain sustainable results (Zanni et al., 2017). However, a continuous analysis of sustainability throughout the design process is restricted with the conventional design method due to limited information (Lu et al., 2017). Hence, there are inadequate data to make judgments in order to achieve optimum and sustainable results (Zanni et al., 2017). Consequently, better collaboration and coordination between multidisciplinary design

teams and appropriate data to support design decisions are necessary. *Building information modeling* (BIM) promises a suitable platform with which to solve these issues. In the context of the design stages, BIM supports the addition of multidisciplinary information, thus allowing the data share and assessment to be continuously combined (Lu et al., 2017). BIM design performance can also be validated within its setting, thus allowing designers to make evaluations and select optimal options (Oduyemi and Okoroh, 2016). A prompt and correct comparison of various design possibilities can be attained via BIM, enabling more effective, cost efficient, and sustainable solutions to be obtained (Azhar et al., 2016). In addition, BIM can be utilized to optimize building energy performance.

Building energy usage depends on various factors, such as heating, ventilation, and air conditioning (HVAC) systems, lighting, dweller behavior, climatic conditions, integration of renewables and economics. Among these, HVAC systems are one of the factors with the most impact on building energy usage (Chenari et al., 2016). A crucial factor in HVAC systems is that of ventilation

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to supply proper indoor air temperature (Anon, 0000). Computational fluid dynamics (CFD) programs allow for an exhaustive estimation of thermal comfort and indoor air temperature.

In this study, the design development of a two-story residential building is examined for natural ventilation with particular regard for indoor air temperature and human thermal comfort conditions via a scenario-based multi-criteria and multi-interaction analysis. The scenario-based methodology depends on human control and the integration of 3D and CFD models within the BIM platform. Hence, this methodology offers the opportunity to obtain comfortable conditions in respect of operable openings in the building envelope for natural ventilation.

2. Literature review

CFD usage has been successfully implemented in various building design and analyses such as the examination of building indoor environments and interactivity of the indoor environment and building surface, as well as for investigation of the outdoor environment (Kim, 2013). Recently, some of those studies were also investigated through BIM platform to be able to achieve multiple research motivations.

CFD analysis for natural ventilation in buildings

Respectively, CFD has been used to examine natural ventilation. For instance, full-scale natural ventilation for an atrium that offers a flow pathway along the building, has been analyzed. The outcome showed that open geometry is needed to take advantage of the outdoor environment for proper atrium design (Ray et al., 2014). Building prototypes have also been optimized via CFD, with the three parameters as geometry, orientation, and street height-to-width ratio. This research highlighted the application of CFD simulations to the estimation of natural ventilation for human health and energy efficiency (AbdelRahman et al., 2017). Additionally, the estimation of a whole building's long-term internal air temperature was conducted with CFD simulation. When the simulation results were compared to the real temperature data measured in the building, the simulation results were found to have 92% accuracy (Albatayneh et al., 2018).

In relation to zero-energy buildings, it has been noted that heat flows among the building parts and spaces should be understood, requiring examination of the indoor thermal environment using simulation software. For this, mean radiant temperature maps were calculated with CFD (Naboni et al., 2017). Consequently, because of its multi-objective structure, there have been various investigations into building energy performance. The thermal behavior for particular requirements of a building is modeled via a physical model using CFD, which can implement all kinds of aero-thermal events, including space heating and/or cooling, natural and mechanical ventilation, air conditioning systems, and air, pollutant, and heat dissipation in indoor and/or outdoor building environments.

The utilization of CFD and BIM for buildings

In order to investigate different design objectives and create alternative design alternative forms, climatic and topographic data have been included in the evaluation of building environment performances in a dynamic model containing wind analysis by CFD simulation. The outcomes of this analysis were exported and outlined with BIM software (Chronis et al., 2012). The CFD simulation approach using BIM-based CFD tools has also been suggested for investigation of wind behavior for high-rise buildings. BIM-based analysis for building designs was found to have time-saving benefits with the usage of alternative design and building information in the early design phase (Lee and Song, 2014).

Aiming to create an intelligent control system with automated judgments for supply thermal comfort based on the number

and positions of occupants, a CFD analysis has been utilized to investigate indoor air conditions. BIM has also been employed as a platform combining entire data, implementing space analysis, and helping the evaluation of green building standards for sustainability (Pazhoohesh et al., 2015). Cai and Kang (Li et al., 2016) explained a chilled beam simulation to show how effectively the BIM model could be utilized to generate a CFD model. They mentioned that the definition of space geometry is very time-consuming as it requires many steps for CFD analysis but also that the process for building up CFD input can be accelerated with the help of BIM.

Passive heating and cooling techniques on which studies were conducted using BIM and CFD software have been used to decrease energy usage with desired thermal comfort conditions (Mytafides et al., 2017). A holistic framework based on BIM technology has been suggested for the improvement of high-rise building design in respect of low carbon sustainability. CFD analysis has been combined into a framework for the evaluation of wind influences on indoor air ventilation and thermal temperature (Franke et al., 2004; Soe and Khaing, 2017).

Aims of the study

Whilst there are various goals recorded in the literature when conducting a CFD analysis with BIM platform, there are also some challenges during the implementation process. One of the difficulties is in utilizing multiple software, as this requires the detection of several variables. Additionally, predicting building performance in advance of any system integration is problematic. The objective of this study, therefore, is to integrate a BIM platform into the building design development stage by developing a methodology that includes scenario-based multi-criteria and multi-interaction analysis. The benefit of the proposed methodology is to optimize this multi-interactive and criteria-based evaluation process. Thus, the maximum indoor human thermal comfort conditions with reduced cooling load are evaluated with criteria corresponding to the design decision in terms of structural physics and geometry in the early design phase. The case of indoor thermal comfort conditions for occupants is evaluated by considering air temperature, air velocity, PMV, and predicted percentage of dissatisfied (PPD), while the building energy consumption is evaluated by considering the energy usage of the cooling load. During the evaluation of the developed methodology, the main considerations are as follows:

- **Eliminating the complication of the different software integration:** The 3D building model, which has the specifications of the building's physical conditions, and CFD model, which has specifications related to indoor comfort conditions, are integrated via the BIM platform during the design development stage to identify complications. The process also requires other third-party software integration to maintain geometry information and create an exact simulation domain.
- **Investigation of natural ventilation for manually controlled building openings:** The CFD analysis in the 3D model is developed by utilizing the BIM platform. The different scenarios are managed by occupants operating the building's openings in order to determine indoor thermal comfort conditions. Further design is developed by evaluating cooling and ventilation via the multidisciplinary team. When an occupant feels discomfort from an environment, they act to recreate the comfort zone. This response is called an "adaptive approach". (Fabi et al., 2012). Furthermore, the impact of human behavior on opening or closing windows is not a continuous action, meaning that people tend to control windows only when conditions are uncomfortable (Borgeon and Brager, 2008). Therefore, it is important to analyze the building envelope and its effect on indoor comfort.

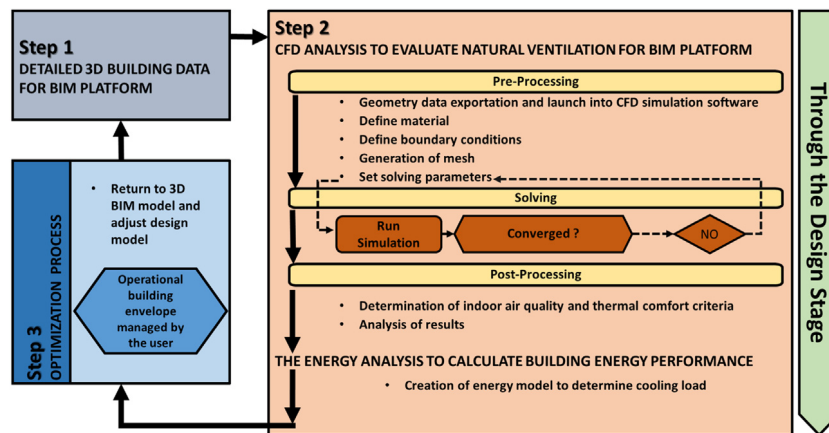


Fig. 1. Methodology.

- **Optimization of building design process:** The optimization of the building design with its physical, thermal, and indoor comfort conditions as a whole can be realized by utilizing the 3D design and CFD model within the BIM platform.
- **Utilizing the multidisciplinary approach through the BIM:** Taking advantage of the CFD approach by using the BIM platform for the design team during the design process can be enabled via linking the building envelope, indoor human thermal comfort as well as projection of the HVAC system. Taking into consideration the CFD analysis outcomes, a suitable cooling and ventilation system can be integrated into the building during the design development stage. This thus requires multidisciplinary approach.

3. Methodology

As shown in Fig. 1, the methodology employed here consists of three main steps to develop the detailed 3D-building model in terms of the building's functions, physical specifications, and envelope thermal capacity coupled with openings that may have different operational scenarios for natural ventilation.

Step 1: Detailed 3D building data for BIM platform

The methodology starts with the generation of a 3D building model that contains information on building geometry, space usage, and materials. This information will also be utilized in further steps.

Step 2: Detailed CFD analysis to evaluate natural ventilation for BIM platform

The sub-step of this section is the CFD analysis to evaluate natural ventilation for the BIM platform and the calculation of the cooling load. The main consideration in this step is the creation of the CFD model and energy model of the building as this is necessary in the examination of natural ventilation by CFD analysis and determination of the response of cooling load via building energy performance simulation. For this, the analysis methods have been not developed. Both the CFD analysis and energy analysis methods were selected and used as found in the simulation programs.

The CFD analysis to evaluate natural ventilation for the BIM platform includes all the CFD simulation steps involved in pre-processing, solving, and post-processing. After the pre-process, which is an important part for preparation of the CFD model, the CFD simulation is initiated and calculations are performed in the background of the CFD simulation program as a solving step. If the simulation solution does not reach convergence, the solving parameters should be checked and then the CFD simulation re-run. In the post-process, the converged solution results are collected

and analyzed to evaluate whether they meet the indoor thermal comfort criteria of the ASHRAE Standards.

- **Geometry data exportation and launch into CFD simulation software:** The building geometry, which was already created with a BIM model, is simplified via extraction of unessential parts according to the simulation aim. Then, outside conditions, such as air volume around the building, are created to consider natural ventilation and wind loads. The created external volume must be dimensional to protect the calculation domain from artificially accelerated flows. The steps of geometry data exportation and launch into CFD simulation software are represented in Fig. 2. The advised dimensions for natural ventilation in the CFD simulation are shown in Fig. 3 (Autodesk, 2018).
- **Define material:** The particular properties, like viscosity, density, temperature, and pressure, of the fluids and the building materials should be defined in the CFD simulation as in the materials data in the BIM model.
- **Define boundary conditions:** Correctly described boundary conditions and initial conditions are important for modeling the CFD in indoor environments (Srebric and Chen, 2002).
- **Generation of mesh:** The turbulence flow and heat transfer models are solved in the CFD with the help of finite intervals that are discretized continuous time and space. The calculations are made at grid points (Srebric and Chen, 2002). Thus, the computational outcome is closely related to the grids used for discretization of the computational domain (Franke et al., 2004). A higher cell count will also increase computation time and the required computer storage capacity. Consequently, the numerical grids should be satisfactory to obtain geometric resolution and expected flow behavior. The mesh should also be precise (Soe and Khaing, 2017).
- **Set solving parameters:** The prediction precision and computational speed for CFD simulations may be affected by a variety of factors, such as numerical method, turbulent model, mesh quality, discretization scheme, and algorithms of pressure and velocity (Wang and John, 1987). It is also necessary to set other solving parameters, such as the physics and control parameters. Before the simulation is run, required result quantity parameters should be adjusted, for instance, the thermal comfort parameters should be determined when it is important to see heat transfer (Anon, 2018a,b). The final step before running the simulation is the placement of monitor points. The monitor points inserted in the model are aimed at examining flow trends and convergence flow throughout the analysis.

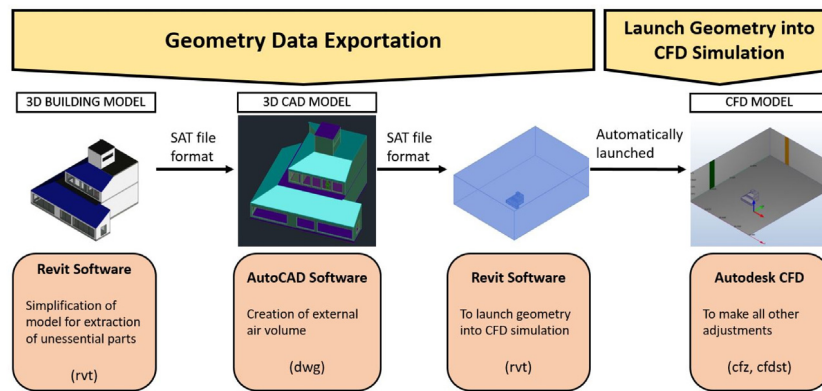


Fig. 2. Geometry data exchange from BIM model to CFD model.

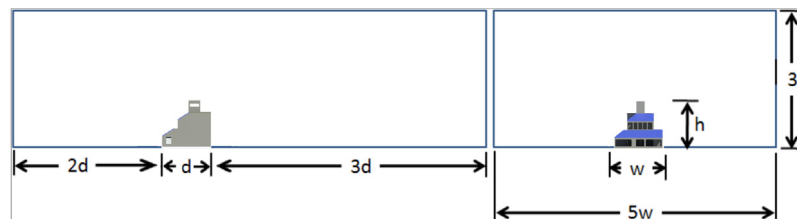


Fig. 3. External volume diameters.

- **Determination of indoor thermal comfort criteria:** The indoor air temperature and velocity were significant here to underline the influence of natural ventilation. The required cooling load would be evaluated according to the indoor air temperature and velocity obtained by natural ventilation. The PMV and PPD values were important for human sensation. The major dependencies aspects of both indoor air temperature and thermal comfort in this study can be considered as temperature, air velocity, and the PMV and PPD values.
- **Analysis of results:** In the post-process stage, the simulation results should be collected in order to check that the indoor air temperature and thermal comfort criteria have been achieved.

Detailed energy analysis to calculate the building energy performance and cooling load

The building energy model is developed to analyze the seasonal building's energy performance. The cooling load is likewise calculated based on the indoor air temperature generated by natural ventilation and is used to determine the annual cooling load.

Step 3: Optimization Process

The optimization process takes place when the collected results from the CFD analysis and energy analysis for annual cooling load do not reach the standard for indoor human thermal comfort conditions.

- **Return BIM model and adjust design model:** Different scenarios can be created with the operable openings on the building envelope. These scenarios are created to optimize the indoor air temperature and velocity obtained by natural ventilation and the cooling load required for indoor air and human thermal comfort conditions.

4. Case study

A hypothetical building was proposed to evaluate the multi-criteria and multi-interaction analysis of natural ventilation on

indoor thermal comfort conditions for occupants and the building energy consumption as cooling load. This building was designed as a free-standing, two-floor family house and located in city called Niğde in Turkey.

4.1. Weather information

Information about temperature, wind, and humidity are crucial for determination of the natural ventilation in terms of indoor thermal comfort of the building. For this case, the average maximum temperature values in Niğde during the summer season were used, which are 26, 29.4, and 29.7 °C for June, July, and August, respectively (Table 1) (Anon, 2018e).

The monthly wind speed range on observed days was mainly between 5 and 19 km/h (Anon, 2018c), while the other hand, the annual wind speed at 10 m is between 5 and 10 km/h (Anon, 2018d). Therefore, the wind speed in the CFD model was assumed as 7 km/h. The annual relative humidity distribution for Niğde is variable, but the main three ranges are 40%–50%, 50%–60%, and 60%–70%. For this study, the maximum value humidity was selected, so 70% (Anon, 2013).

4.2. Application of proposed methodology

The proposed methodology was implemented for the hypothetical building step-by-step as described below.

Step 1: Detailed 3D building data for BIM platform

The hypothetical dwelling has six bedrooms, three bathrooms, one restroom, a kitchen, a living room, and a covered terrace located on the south façade. The living room, on the ground floor, has a gallery for the upper floor, as represented in the plan (Fig. 4).

Operable shutters around the chimney were designed to take advantage of natural ventilation for cooling. The walls of the southern façade and the upper-floor living room together with the roof of the terrace consist of windows to maximize natural lighting. The 3D BIM model images are shown in Fig. 5.

Step 2: Detailed CFD analysis to evaluate natural ventilation for BIM platform

Table 1
Monthly temperature values (centigrade).

Temp.	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Avg. Temperature (°C)	−0.3	0.6	5.2	10.8	15.3	19.7	22.9	22.7	18.2	12.4	6.0	1.7
Avg. Max. Temperature (°C)	4.9	5.9	11.2	16.9	21.5	26.0	29.4	29.7	25.9	19.7	12.5	7.0
Avg. Min. Temperature (°C)	−4.5	−3.8	0	4.8	8.6	12.3	15.2	14.9	10.7	6.4	1.2	−2.5

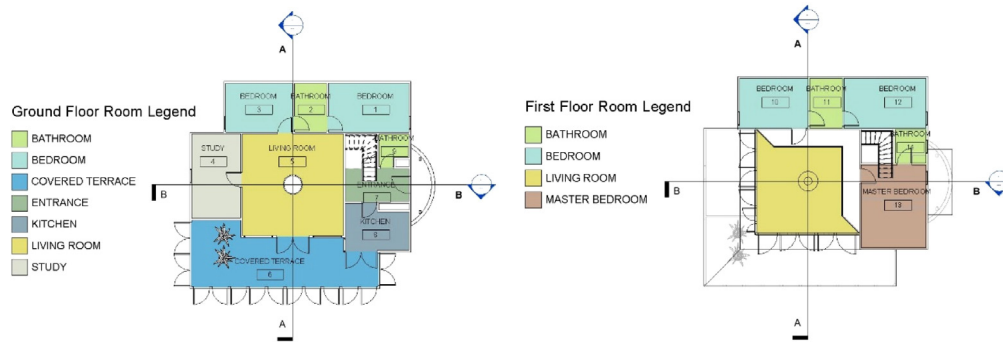


Fig. 4. Ground floor and first floor plan and space usage.

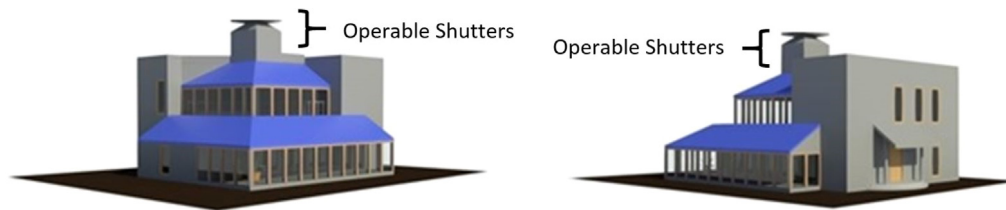


Fig. 5. 3D BIM model of original building.

In this step, the CFD model is primarily generated to investigate natural ventilation with respect to indoor thermal comfort conditions for occupants. After the CFD analysis, the energy model is created to examine correlation between natural ventilation and cooling load.

To investigate natural ventilation related to thermal comfort and indoor air temperature in this case, the original building had extensive detailed information. Therefore, some simplification, extraction, and extension of the original 3D building model was conducted. The considerations during preparation of 3D BIM model to CFD model included the following:

- The terrace, living room, and the study are the usage areas most affected by wind; thus, other areas were ignored in the building geometry;
- The topology was also extracted;
- The windows and doors were simplified so as to have no effect on the natural air flow inside the building, with the level of detail for these in the 3D BIM model reduced to LoD 300, which afforded modeling with precise quantities, size, and shape.
- The shutters can be operated by human control to semi- or fully open positions.

The simplified 3D model with its perspective is shown in Fig. 6.

- **Geometry data exportation and launch into CFD simulation program:** The building geometry was simplified using Revit software. A 3D model was exported in the SAT format to convert the external air volume into 3D CAD software. After the creation of dimensional external air volume, the CAD model was imported into Revit as a SAT file format in

order to make final adjustments and launch into the CFD simulation software.

- **Define materials:** To investigate the natural ventilation and heat distribution, air was selected as a variable together with other physical properties, such as density, viscosity, and conductivity. In the same investigation approach, the structural materials as solid class were assigned materials in the CFD database with their physical properties. A solid clay material as a green roof was created and saved in the CFD database. The defined building component materials with properties are shown in Table 2. In order to investigate thermal comfort, a human body was assumed in the building, to represent the occupants. The human body also has to be assigned materials as a solid class with thermo-physical properties.
- **Define boundary conditions:** For the inlet boundary conditions, velocity was specified as normal for the front side of the external domain, and the Cartesian components (V_y) for the top and lateral sides of the external domain (as the dominant air velocity) comprised the Y direction. The air temperature was defined for the inlet flow boundary condition. The applied velocity value, as an inlet flow parameter, was taken from the meteorological wind value. The temperature value, which is the other inlet flow parameter, was taken as the maximum temperature during the summer season. Also, by knowing the temperature differences between day and night, initial indoor temperature was taken based on building' envelop thermal mass capacity. For the outlet boundary condition, static gage pressure was assigned a zero value (0). Total heat generation was applied to the human body as a heat source. Radiation heat

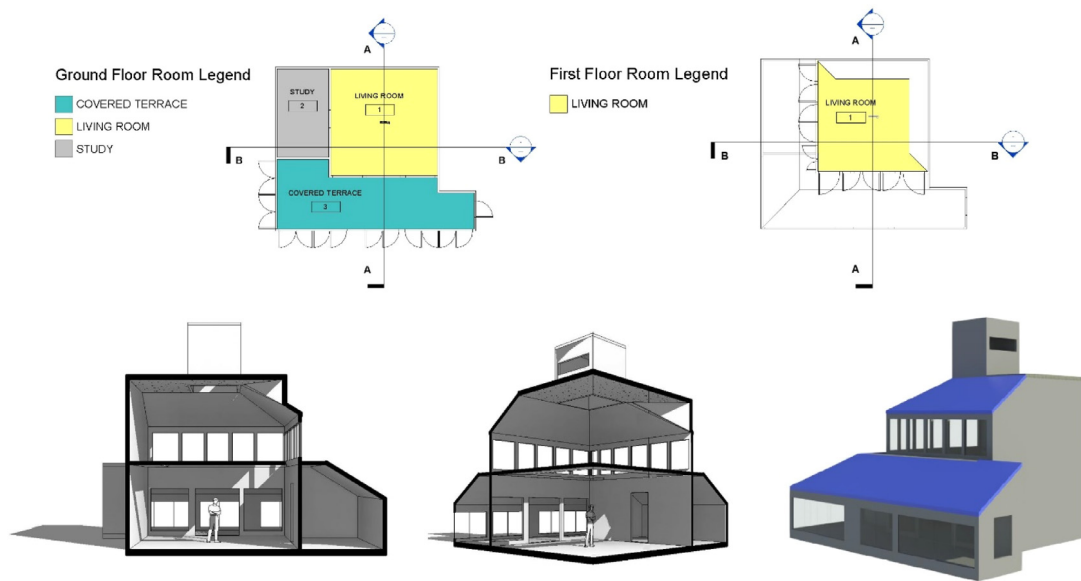


Fig. 6. Simplified building geometry with space usage (above) and simplified building perspectives and 3D BIM model (below).

transfer was considered as the radiation boundary conditions applied to the windows, which comprise the emissivity value of the windows and the value of the outside temperature. To get more convergence and reduce computing time, the initial conditions for building components were determined. When assigning initial conditions to building components, the temperature values for all the building materials were related to the summer weather conditions. All applied boundary conditions and initial conditions with values are shown in Fig. 7.

- Generation of mesh:** During mesh creation, mesh was firstly generated automatically, which means that mesh distribution in the model was examined at all edges, surfaces, and volumes (Vanderberg and Tschappat, 2015). In order to improve automatically created mesh, small edges and surface were diagnosed by CFD simulation software. The problematic surfaces were first identified and then refined from the model. The benefit mesh creation using this method is that a quicker and more efficient mesh distribution was produced. Fig. 8 represents the generated mesh distribution respectively for the CFD model, building, and inside of the building. For the unstructured grid mesh, the total nodes and elements were almost 2.5 k and 12.4 k, respectively.
- Set solving parameters:** The Autodesk CFD program was used to observe natural air movement, indoor air temperature, and velocity, along with human sensation as PMV and PPD values in the building. For these purposes, the parameters must be selected in the CFD model. Wall function was not considered due to the importance of heat transfer, which was considered as conduction, convection, and radiation. The $k-\epsilon$ turbulence model was selected. When determining the flow properties, internal flows enter and pass along a solid structure, and external flows with an immersed body inflow and flow move according to the solid body. For this natural ventilation simulation model, the flow properties selected were internal and external incompressible flow. The finite element method is used in CFD simulation program, due to its ability to model any geometric shape. There are two problems with flow governing equations when considering computational fluid dynamics. One of them is dispersion error, which is caused by inappropriate modeling of advection or inertia terms (Anon, 2017). To

overcoming this, alternative discretization techniques have been introduced over years (Schnipke, 1986). Here, Modified Petrov–Galerkin was used as a discretization scheme. The other significant problem when governing partial differential equations with computational fluid dynamics is the lack of an explicit pressure equation for incompressible flows (Anon, 2017). To deal with this, the semi-implicit method, called SIMPLE (and its variations), is regarded as the most appropriate method for pressure-linked equations. Here, the SIMPLE-R technique was used (Anon, 2017). It was important to see the air movement and behavior with time for this study, so the solution mode was selected as transient. Therefore, the parameters for transient analysis were determined as time step, stop time, and inner iteration. Consequently, all selected solving parameters for the analysis were determined (Table 3).

In order to observe the behaviors of trends and convergence, the monitor points were placed in the model before running the analysis. The exact locations were determined with Cartesian coordinates for monitoring points inside the building (Fig. 9). After all the solving parameters were set, the CFD simulation was run. During the CFD simulation, when the program is running, the calculation steps use the segregated solution method, which separately solves all governing equations with an explicit pressure equation, and the iteration technique, which assumes only one unknown for each equation and solves in a repeating cycle unless all equations are met (Anon, 2018a).

- Determination of indoor thermal comfort criteria:** In this study, the major dependency aspects of both indoor thermal comfort can be considered as temperature, air velocity, and the values of PMV and PPD.
- Analysis of results:** Collecting the analysis data, the X–Y Plots were generally used to see air velocity magnitude, indoor air distribution, and PMV. The vector plots were used to obtain a more detailed understanding of air velocity direction. Besides temperature, velocity, and PMV, the analysis data reports and outputs at monitor points were collected.

Detailed energy analysis to calculate the building energy performance and cooling load

The annual cooling load was calculated via eQUEST© (Anon, 2019), which is a building energy performance simulation tool.

Table 2
Defined materials with physical properties.

Building components	Materials	Type	Physical properties					
			Density (kg/m ³)	Specific heat (J/kg K)	Conductivity (W/mK)	Emissivity	Transmissivity	Electrical resistivity (Ω-m)
Wall	Concrete	Fixed Solid	2306	837	1.1	0.92	0	0
Floor	Concrete	Fixed Solid	2306	837	1.1	0.92	0	0
Top roof	Brick	Fixed Solid	1600	890	0.14	0.92	0	0
Roof of atrium and terrace	Window Solar	Fixed Solid	2700	840	0.78	0.92	Solar window	5e+07
Windows	Window Solar	Fixed Solid	2700	840	0.78	0.92	Solar window	5e+07
External and internal volume	Materials	Type	Physical properties					
			Density (kg/m ³)	Specific heat (J/kg K)	Conductivity (W/mK)	Emissivity	Viscosity (Pa-s)	Compressibility (Cp/Cv)
	Air	Variable Fluid	1.1644	1004	0.02563	1	1.817e−05	1.4
Occupant	Materials	Type	Physical Properties					
			Density (kg/m ³)	Specific heat (J/kg K)	Conductivity (W/mK)	Emissivity	Transmissivity	Electrical resistivity (Ω-m)
	Human body	Fixed Solid	998	4182	50	0.98	0	0

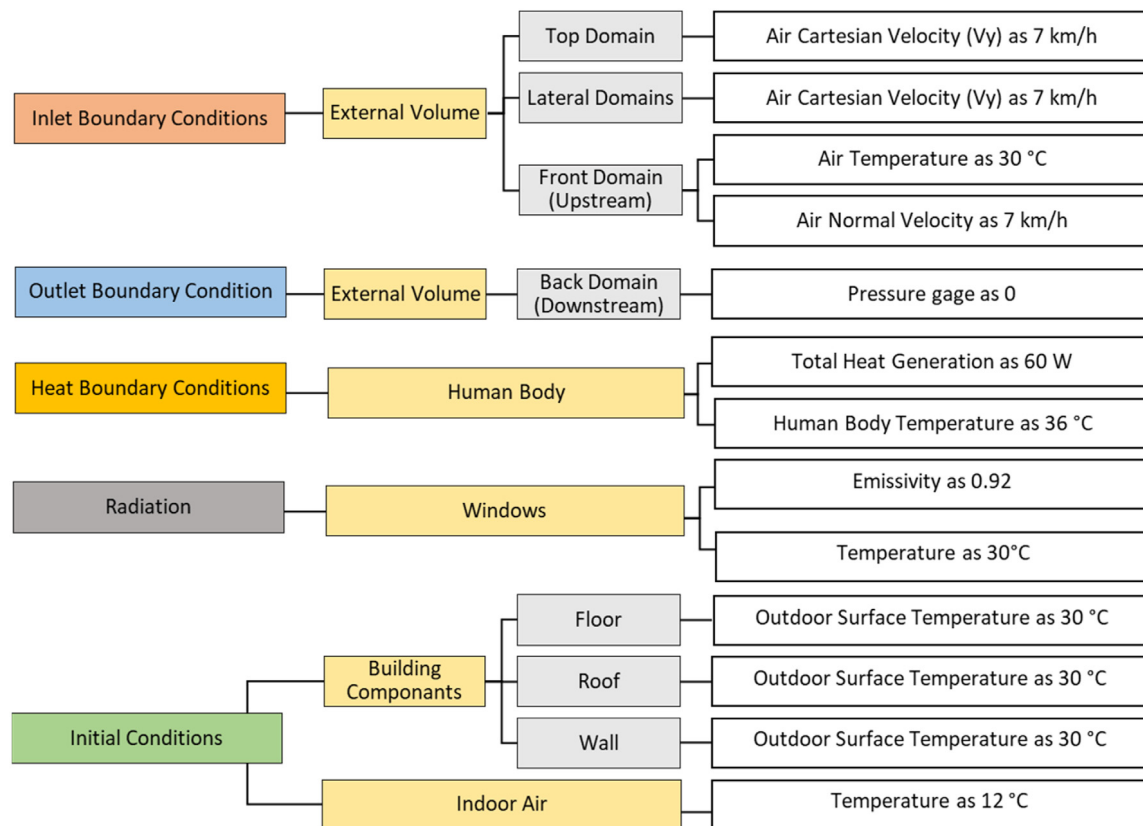


Fig. 7. Applied boundary and initial conditions.

This tool was selected because it is easy to use for this type of analysis and provides accurate and detailed results (Crawley et al.). During the creation of the energy model, the main inputs were building geometry, weather data, cooling systems, and

other HVAC components with related parameters. The building geometry and space usage were represented in Fig. 4. The thermal and physical properties for the building envelope were the same as those used for the CFD model. The split cooling system was

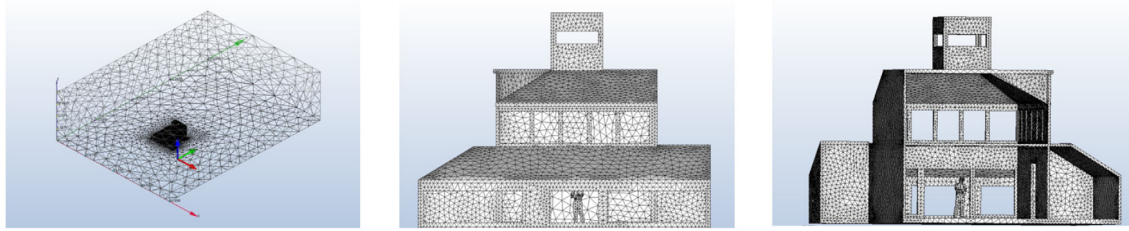


Fig. 8. Mesh distribution for CFD model, on building, and into building.

Table 3

All selected solving parameters for analysis.

Solve physics parameters		Solve control parameters	
Parameters	Selected value	Parameters	Selected value
Flow	Select	Solution mode	Transient
Turbulence	Selected as turbulent	Time step size	2
Turbulence model	k- ϵ model	Stop time	10 800
Compressibility	Incompressible	Inner iterations	1
Heat	Select	Solver computer	Cloud
Gravity method	Earth	Thermal comfort	Selected
Gravity direction	0,0,-1	Metabolic rate	60 W/m ²
Max. wall distance	13	Clothing	0.5 clo
Discretization method	Finite element method	Humidity	76%
Discretization schemes	ADV 5 (Modified Petrov- Galerkin)		
Discretization scheme order	2 < order < 3		
Algorithm	SIMPLE-R		

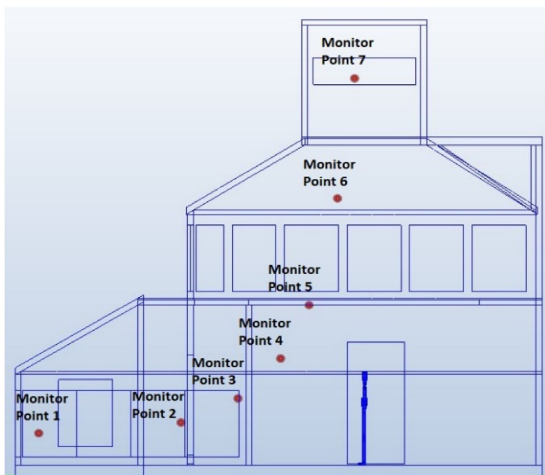


Fig. 9. Monitor point in building.

designed to have adaptive cooling system. Cooling design temperatures were provided from CFD analysis since the indoor air temperature is very sensitive for calculating the cooling load.

In this CFD analysis, the main force on the wind was pressure differences, so outside temperature difference according to time was not considered. The CFD analysis was conducted at a specific time to examine the natural ventilation influences on indoor air temperature and air velocity. The reason for implementation of the CFD analysis at a specific time was to determine the indoor temperature when the outside temperature was at its maximum. However, the energy analysis was conducted annually depending on the weather file. The purpose of the energy analysis was to calculate the annual response of the cooling load according to the indoor air temperature obtained by natural ventilation. In summary, maximum moments were calculated by CFD analysis and the temperature of the indoor air was determined. The annual

cooling load requirement for this maximum value was calculated by energy analysis.

Step 3: Optimization Process

After the determination of outcomes for the CFD and energy analyses, building design was evaluated in terms of building physics and geometry. If the indoor human thermal comfort conditions, and responding cooling load were not satisfactory, possible scenarios would be generated depending on operable openings on the building envelope. The possible scenarios thus depending on the operable openings were created by returning to the BIM model and making adjustments to the design model.

- **Return to BIM model and adjust design model:** The possible scenarios could be created with the dependencies of operable openings on the building façade. In this context, four scenarios were generated, as follows:

- **Scenario 1:** all windows on the ground and second floors were opened, and the shutters were semi-opened (two sides);
- **Scenario 2:** all windows on the ground and second floors were opened, and the shutters were also fully opened (four sides);
- **Scenario 3:** the second-floor windows were closed, the ground-floor windows were opened, and the shutters were semi-opened (two sides);
- **Scenario 4:** the second-floor windows were closed, the ground-floor windows were opened, and the shutters were fully opened (four sides).

5. Results and analysis

During the application of the proposed methodology, various tools were used, model transferring was carried out, and a multi-tool analysis conducted. The chief difficulty of model transferring between Revit as the BIM tool and the CFD analysis was losing data during transportation. Since only the geometry transfer was made from the 3D model, the materials of the building components had to be defined again in the CFD program. Another

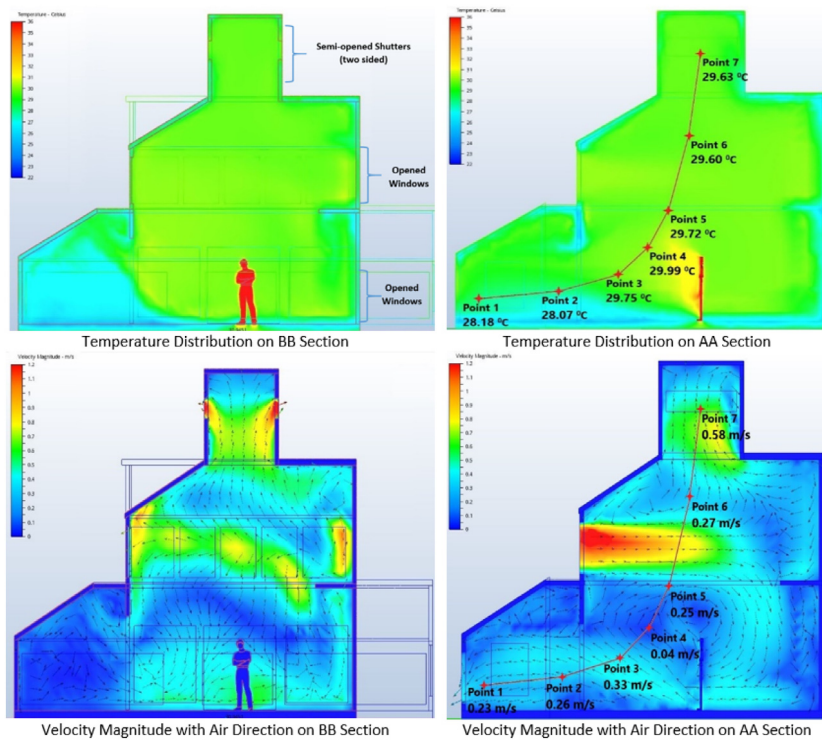


Fig. 10. Temperature distribution and velocity magnitude with air direction on BB and AA section for Scenario 1.

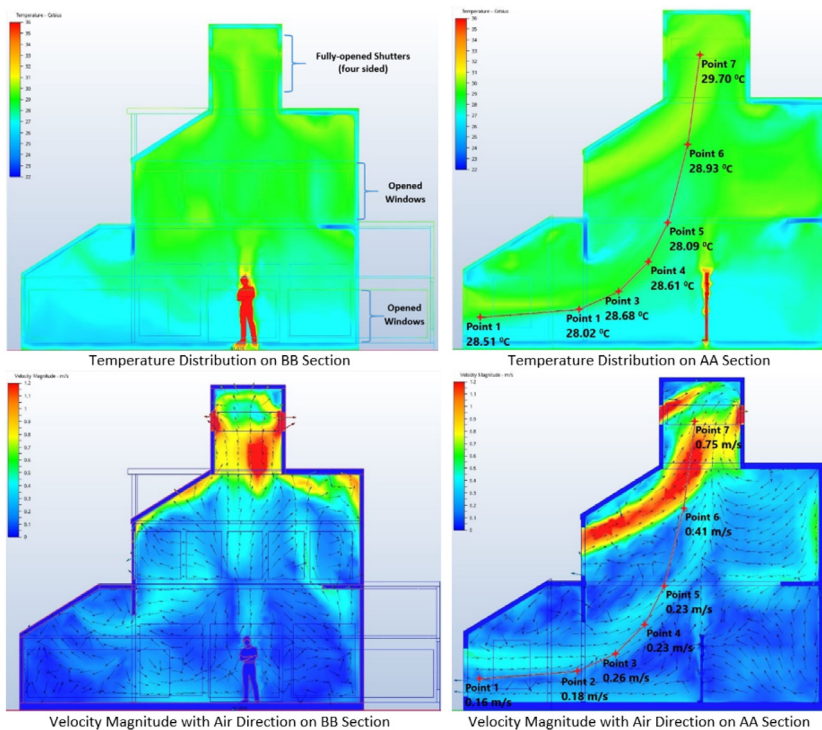


Fig. 11. Temperature distribution and velocity magnitude with air direction on BB and AA Section for Scenario 2.

difficulty involved the requirements of extra data for the CFD analysis model, namely, external air volume. Generation of these required a third party computer-aided design (CAD) tool. Thus, this model transferring process could be seen as time-consuming.

CFD simulations integrated into BIM platform provide a better understanding of air movements within already developed building architecture. All the physical conditions of the building,

which included conductivity level of the building envelope and thickness as well as openings working skin were introduced into the architectural model utilized directly for the CFD. With the concern of detail being airflow simulation, the Autodesk CFD tool could not be considered. For natural ventilation inside the building, however, it is very beneficial for combination of the natural

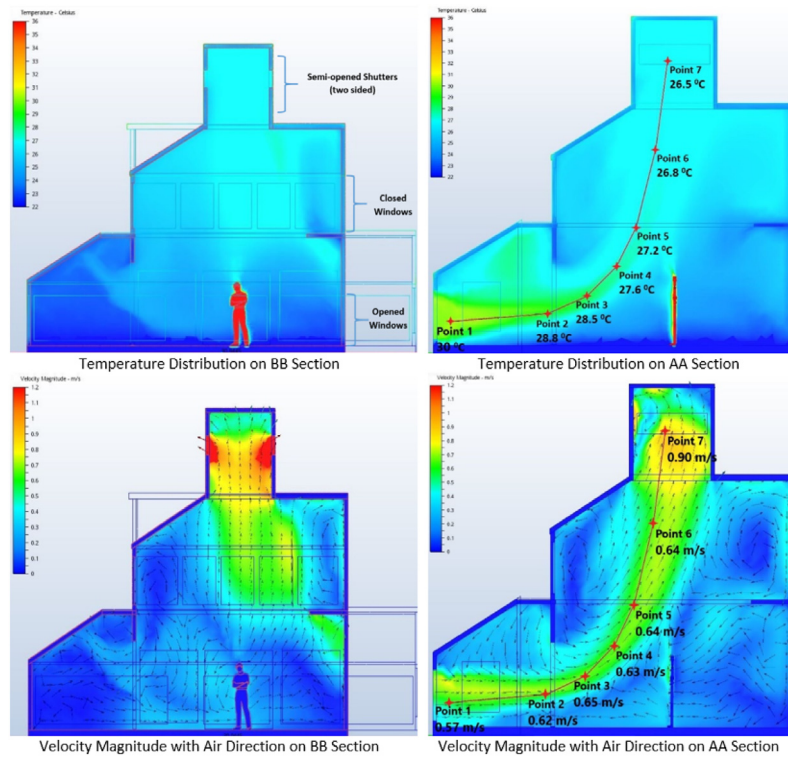


Fig. 12. Temperature distribution and velocity magnitude with air direction on BB and AA section for Scenario 3.

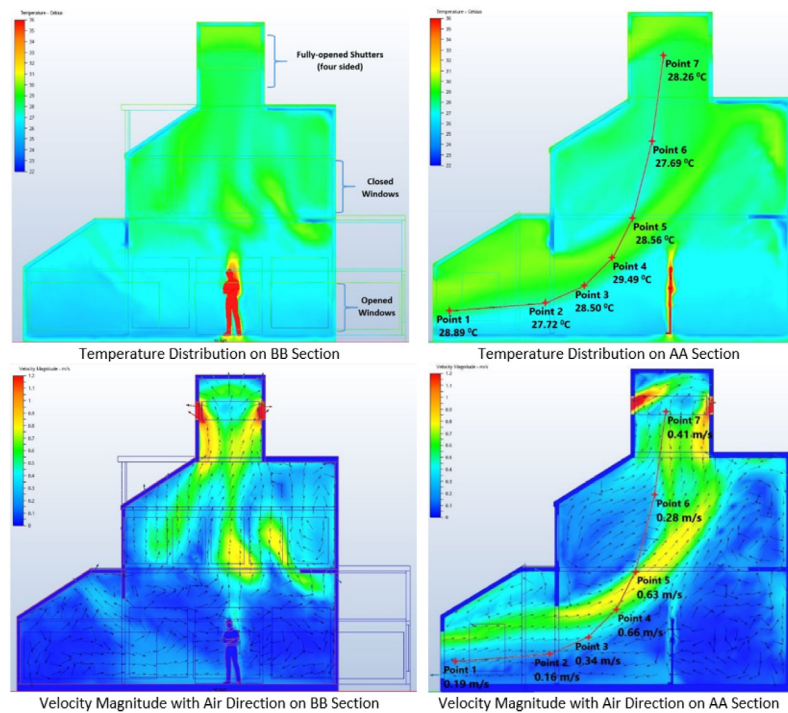


Fig. 13. Temperature distribution and velocity magnitude with air direction on BB and AA section for Scenario 4.

ventilation with building conditions to achieve more realistic results. Natural ventilation could be interpreted with air movement, temperature, and velocity as well as human sensation (PMV and PPD) values. Thus, CFD simulation results were achieved for the four scenarios.

Scenario 1 The mean temperature value was 30.87 °C. The mean velocity magnitude was 0.26 m/s. With the air passing through

the second floor windows openings, air velocity decreased. The air movement entered dominantly from the second floor and left from the ground floor and shutter openings. Therefore, the air was circulated inside the building. The temperature distribution and velocity magnitude with air direction on the AA and BB sections are shown in Fig. 10. In addition to temperature and velocity

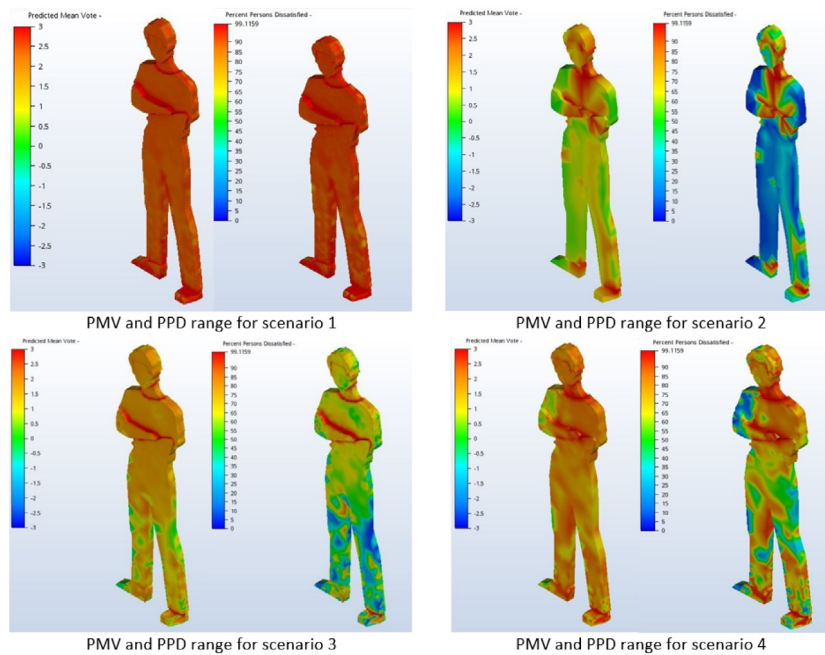


Fig. 14. PMV and PPD ranges for all scenarios.

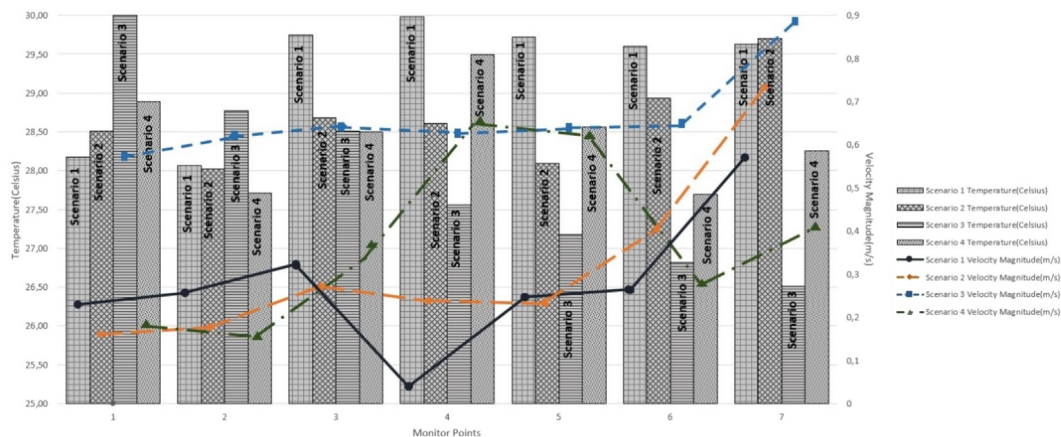


Fig. 15. Temperature and velocity magnitude at all monitor points for all scenarios.

distribution inside building, the distribution of these parameters for each scenario also shown with external domain in [Appendix](#).

In Scenario 1, Monitor Points 1 and 2 had lower temperature values than others, and the air movement around these two monitor points tended to go from the inside to outside. Hence, the air temperature was lower in the terrace than living room. According to the temperature and velocity magnitude, the PMV value for this scenario was between 2 and 3, which means that the human sensation was warm-to-hot. The PMV and PPD ranges are shown in [Fig. 14](#). To sum up, when considered at 30 °C outside temperature, the inside of the building on the ground level had a temperature drop on average of 1.5 °C to almost 28 °C with air velocity reaching 0.33 m/s in the living room. This was not favorable.

Scenario 2 The mean temperature for the second scenario was 28.18 °C, which was lower than in the first scenario. The mean velocity magnitude was 0.45 m/s. When investigated, the temperature distributions and air velocity were in sections, as represented in [Fig. 11](#). The air entered from both the ground and second-floor window openings and left through the shutter openings on the four sides of the chimney.

Table 4

Mean temperature and mean velocity values for all scenarios.

	Mean temperature (C)	Mean velocity magnitude (m/s)
Scenario 1	30.87	0.26
Scenario 2	28.18	0.45
Scenario 3	27.66	0.48
Scenario 4	28.18	0.40

Until the last two monitor points, the temperature was around 28 °C. At Monitor Point 6, the temperature increased to 29 °C, and the final monitor point it was almost 30 °C. The velocity value was 0.16 m/s as minimum at the first monitor point, and 0.75 m/s as maximum at the final monitor point. Providing a lower temperature and velocity magnitude in ground floor, the human sensation for the second scenario was more adequate than for the first. The PMV value of Scenario 2 was between 0 and 3; thus, the PPD value range was dominantly between 0 and 40 ([Fig. 14](#)). Consequently, temperature and air velocity were distributed evenly inside of house, the temperature dropped 2 °C to almost 28 °C and air velocity reached 0.26 m/s on the ground

Table 5
Temperature and velocity magnitude at each monitor point.

Monitor points	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Temperature (C)	Velocity magnitude (m/s)	Temperature (C)	Velocity magnitude (m/s)	Temperature (C)	Velocity magnitude (m/s)	Temperature (C)	Velocity magnitude (m/s)
1	28.18	0.23	28.51	0.16	30.00	0.57	28.89	0.19
2	28.07	0.26	28.02	0.18	28.78	0.62	27.72	0.16
3	29.75	0.33	28.68	0.26	28.51	0.65	28.50	0.34
4	29.99	0.04	28.61	0.23	27.56	0.63	29.49	0.66
5	29.72	0.25	28.09	0.23	27.18	0.64	28.56	0.63
6	29.60	0.27	28.93	0.41	26.82	0.64	27.69	0.28
7	29.63	0.58	29.70	0.75	26.51	0.90	28.26	0.41

Table 6
Monthly electricity consumption for cooling.

Electricity consumption (kWh)		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Scenario 1	Space Cool	0	0	10	70	240	720	650	1210	420	140	0	0	3460
Scenario 2	Space Cool	0	0	10	60	230	700	640	1190	410	130	0	0	3370
Scenario 3	Space Cool	0	0	10	60	230	700	640	1180	410	130	0	0	3360
Scenario 4	Space Cool	0	0	10	60	230	700	640	1190	410	130	0	0	3370

Table 7
Annual electricity consumption for cooling and its comparison.

Annual electricity consumption for cooling (kWh)	Comparison of cooling consumption (%)
Scenario 1	3460
Scenario 2	3370
Scenario 3	3360
Scenario 4	3370
	0
	-2.60
	-2.89
	-2.60

floor and 0.4 m/s on the first floor. Because of the balanced air temperature and velocity distribution, the PMV level achieved was acceptable.

Scenario 3 The mean temperature value was 27.66 °C. In the third scenario, hot outdoor air only entered from the ground floor windows, at 30 °C, and the temperature reached its peak value in the terrace. This behavior could be explained by the fact that the hot outdoor air stayed in the terrace room as it moved through the building, which would mean that the terrace acted as a temperature buffer zone. The mean velocity magnitude was 0.48 m/s. The only entrance for air was the ground floor windows openings, and the only exit was through the shutter openings located on two sides of the chimney in this scenario. The velocity magnitude with air direction and temperature distribution are shown in sections (Fig. 12).

In these sections, the temperature and velocity ranges were larger, so the temperature and velocity values at the monitor points indicated more specific results. The temperature was lower at each monitor point. However, the velocity values and the PMV range were varied in the third scenario. The PMV range was from 0 to 3, and the PPD range was similarly affected (Fig. 14). Briefly, in this scenario, the temperature dropped by an average of 3 °C, reaching almost 27 °C in the living room and 26 °C on the second floor, while velocity reached 0.64 m/s evenly on both floors. Therefore, the PMV level was in the tolerable range.

Scenario 4 The mean temperature was 28.18 °C. The outdoor air entered largely from the ground floor windows and slightly from shutter openings and exited through the four shutter sides. While the hot air passed from the terrace to the atrium, the temperature

decreased. However, when the air rose to the chimney, it would cross the hot outside air again. The mean velocity magnitude for the final scenario was 0.40 m/s (Fig. 13).

The PMV range was from -0.5 to 3. The lowest value was at the feet and the highest value at the arms and neck. Due to this larger range for PMV, the PPD had also various values (Fig. 14). In brief, the temperature drops reached almost 3 °C on the terrace while coming back to an average of 1 °C in the living room. Velocity also had a variable distribution, from 0.67 m/s to 0.66 m/s. The PMV level was tolerable.

Summarizing, the mean temperature and velocity values for all scenarios, as displayed in Table 4, show that Scenario 1 had the maximum mean temperature value and Scenario 3 the minimum. The mean temperature values for Scenarios 2 and 4 were the same. However, their standard deviations of temperature were different, at 1.76 for Scenario 2 and 2.20 for Scenario 4. This means that the standard deviation gave information about the distribution of values, which for Scenario 4 were more inconsistent than for Scenario 2. The maximum mean velocity magnitude was observed in Scenario 3 and the minimum velocity magnitude in Scenario 1.

In Table 5, the temperature and velocity magnitudes are summarized for each monitor point of each scenario. There were no clear trends except in Scenario 3, where the temperature decreased. The most consistent value was observed in Scenario 2, where the temperature was around 28 °C. The velocity magnitudes at Monitor Point 7 were higher for all scenarios because the monitor at there was located at the chimney openings, so this acted as an air exit place. Scenarios 2 and 3 had no dramatic monitor point changes except at Point 7. The velocity magnitude

for Scenarios 2 and 3 were changed by around 0.2 and 0.6 m/s, respectively. The maximum velocity magnitude was observed in Scenario 3 due to the velocity value at around 0.6 m/s; the most drastic decrease was observed in Scenario 1 at Monitor Point 4, while the largest increase was in Scenario 4 at Monitor Points 4 and 5.

To understand the relationship between temperature and air velocity, the literature was investigated. For this purpose, the activity level with a suggested clothing have already defined in TS EN ISO 7730. Accordingly, if the operative temperature and relative air velocity increase together and the PMV becomes closer to zero (TSE, 2017). Also, it was found that if the velocity increases, there is more heat transfer and skin temperature decreases over time (Atmaca and Yiğlit, 2011). Acceptable air movement levels were given as 0.4 m/s and 0.9 m/s air velocities where the temperatures were 26 °C and 30 °C, respectively (Cândido et al., 2010). Thus, it could have expected that temperature and velocity value should tend to increase together.

In this study, that direct trend was not observed in all four scenarios. Therefore, to more clearly see the relationship between temperature and velocity, all scenarios values were represented graphically in Fig. 15.

After the evaluation of CFD analysis outcomes, the energy analysis results for cooling load were collected. The cooling need started at March and lasted until October, but the dominant period for cooling is during the summer season.

By taking advantage of natural ventilation for each scenario, to be able to keep indoor comfort level, adaptive cooling is needed. Therefore, electricity consumption of the cooling system is evaluated. The monthly electricity consumption responding to the cooling load for each scenario is represented in Table 6.

The highest electricity consumption was observed in Scenario 1 because it had the highest indoor temperature (30.87 °C). For the same reason, Scenario 3 showed the lowest electricity consumption, while Scenarios 2 and 4 had the same indoor temperature and electricity consumption values. The highest electricity consumption was set as a base point to compare each scenario's cooling load variations. Therefore, Scenario 1 was used as the baseline and the cooling load variation for other scenarios set accordingly. As Table 7 shows, the cooling load was reduced 2.6% in Scenarios 2 and 4, while in Scenario 3, this reduction reached almost 2.9%.

The aim of the scenario-based multi-criteria and multi-interacting analysis of natural ventilation is for the optimization process to maximize building energy performance and conditions for human comfort. For this purpose, the indoor air temperature, air velocity magnitude, PMV, PPD, and electricity consumption responding to cooling load ought to be considered together. When comparing the results of the temperature and velocity distribution, the acceptable levels in Scenarios 2 and 3 (and even Scenario 4) exhibit both temperature drops and tolerable air velocity through the employment of the design strategy. The cooling load reduction is observed in Scenarios 2, 3, and 4. Further to these, air velocity magnitude influences human sensation, here, as PMV and PPD. Thus, when PMV level inside the living room is considered, Scenario 2 attains an acceptable level and can thus be adjudged overall as the best of the four.

6. Conclusion

The aim of this study was to optimize the evaluation process through a scenario-based multi-criteria and multi-interaction analysis of natural ventilation. Thus, the methodology employed, which aimed to maximize indoor human thermal comfort conditions, and reduce requirement of cooling load, was applied to a hypothetical building. The design criteria applied were air

temperature, air velocity, PMV, PPD, and energy performance as electricity consumption. During the evaluation, various considerations led to the following advantages and weaknesses.

- The advantage of the integrating the 3D building model and CFD model within the BIM platform was to share common data for creating and exporting the geometry. Three different programs were used, enabling data exchange to be employed between these programs during the creation of the building geometry. The 3D model was developed by Revit, adding external volume around the model by CAD, and simplification of the model to analyze the CFD was achieved by Autodesk. The Revit-based BIM platform provided greater ease and speed during the process. However, since only the geometry transfer was made from the 3D model, the building component materials had to be redefined in the CFD program. Although this process seems time-consuming, the CFD program includes its own materials database from which the additions, edits, or recreations can be easily made. Since the new materials are stored in the database, it is not difficult to reassign materials to all scenarios. On the other hand, if the geometry and material assignments are carried out together, the BIM-based CFD program can be fully utilized. The combination of geometry and materials assignments from the BIM-based CFD program may thus be further enhanced.
- The optimization of the building design with its physical, thermal, and indoor comfort conditions as a whole was achieved by utilizing the CFD analysis within the BIM platform. The process involved a scenario-based, multi-criteria, and multi-interaction analysis of natural ventilation. Regarding the multi-criteria, each criterion might require a different expertise, such as building design specifications including not only architectural features but also physical characteristics, and specifications about indoor thermal comfort conditions and air temperature as well as appropriate methods to be applied for natural ventilation calculation.
- Four different scenarios were created for investigation of the natural ventilation. These were employed for a case study of adequate conditions for indoor thermal movement. In addition to the four scenarios, more options with different combinations of building openings could also have been created.

This study has thus demonstrated the combination of an architectural structure and computational fluid mechanics for analysis of indoor thermal comfort conditions via natural ventilation at the early design stage level. Such a combination also has great potential for further design stages in respect of HVAC systems. This could help to optimize building energy performance through the coordination and collaboration of multidisciplinary design teams. In this case study, the outcomes from Scenario 2 represent the best thermal comfort regard to PMV and PPD values. On the other hand Scenario 3 represent the best energy efficiency.

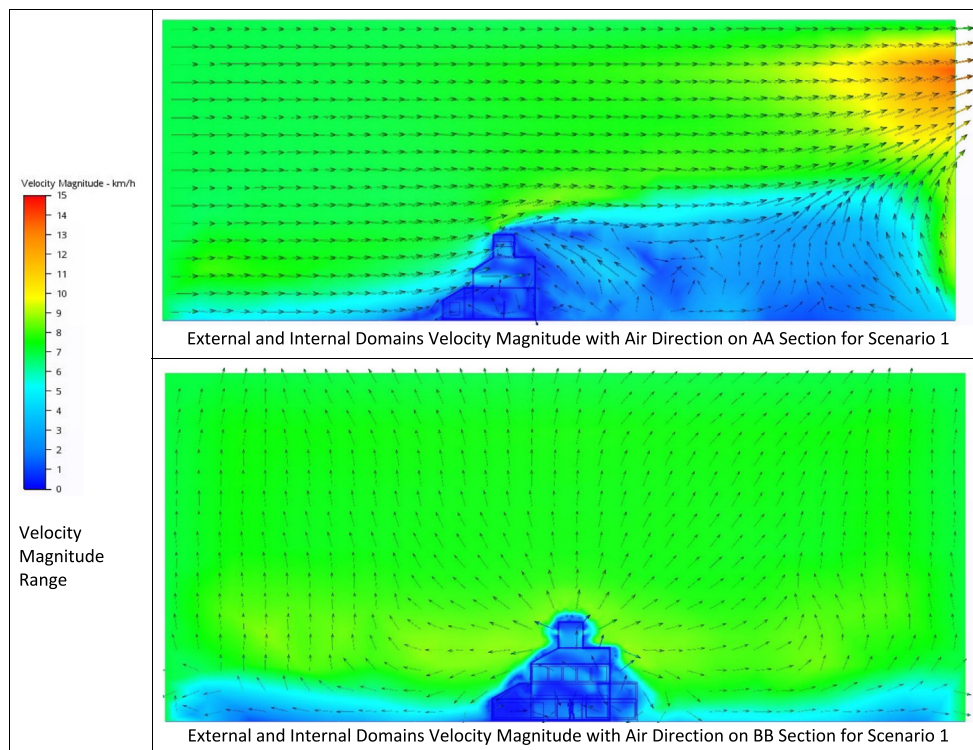
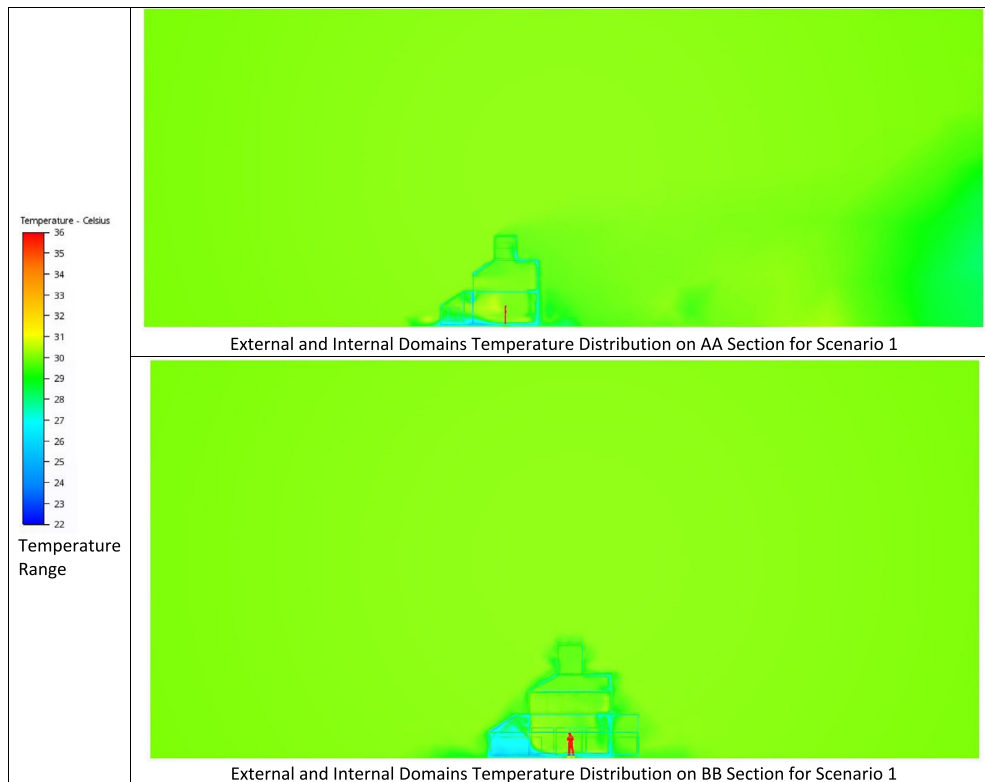
Declaration of competing interest

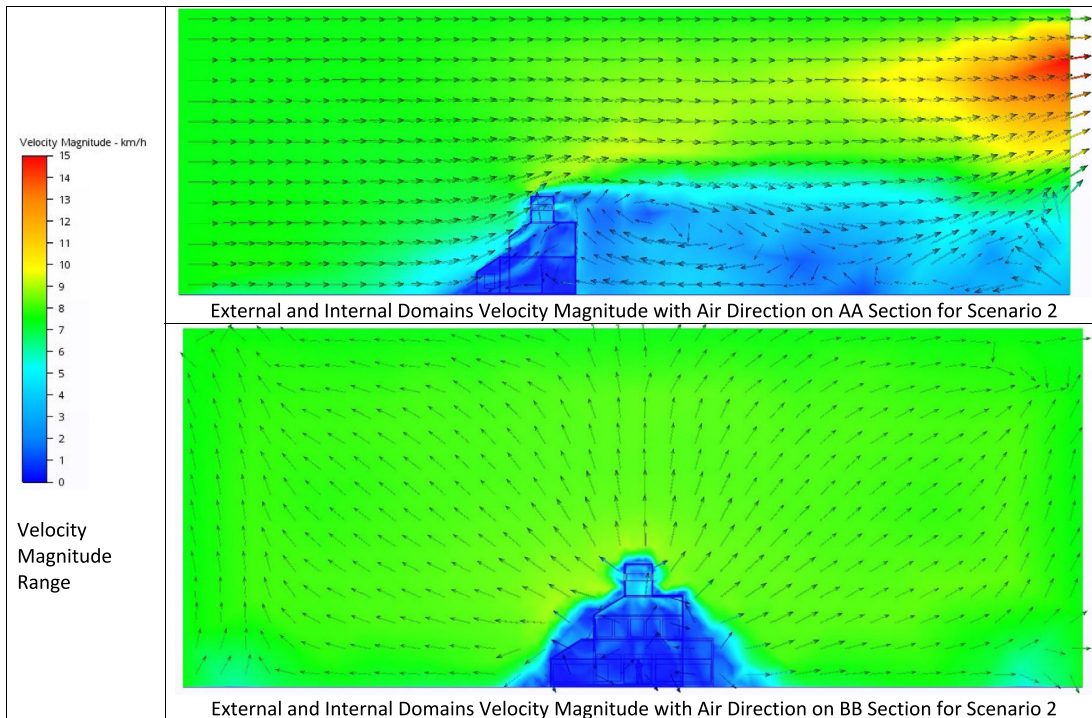
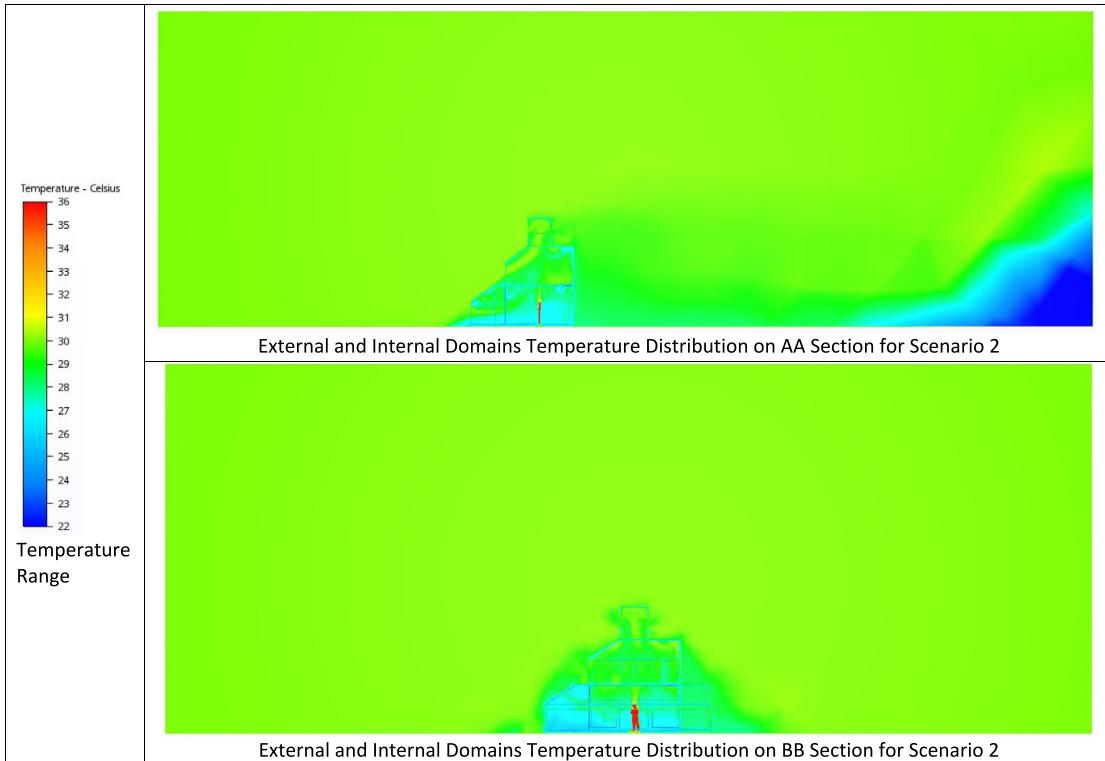
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

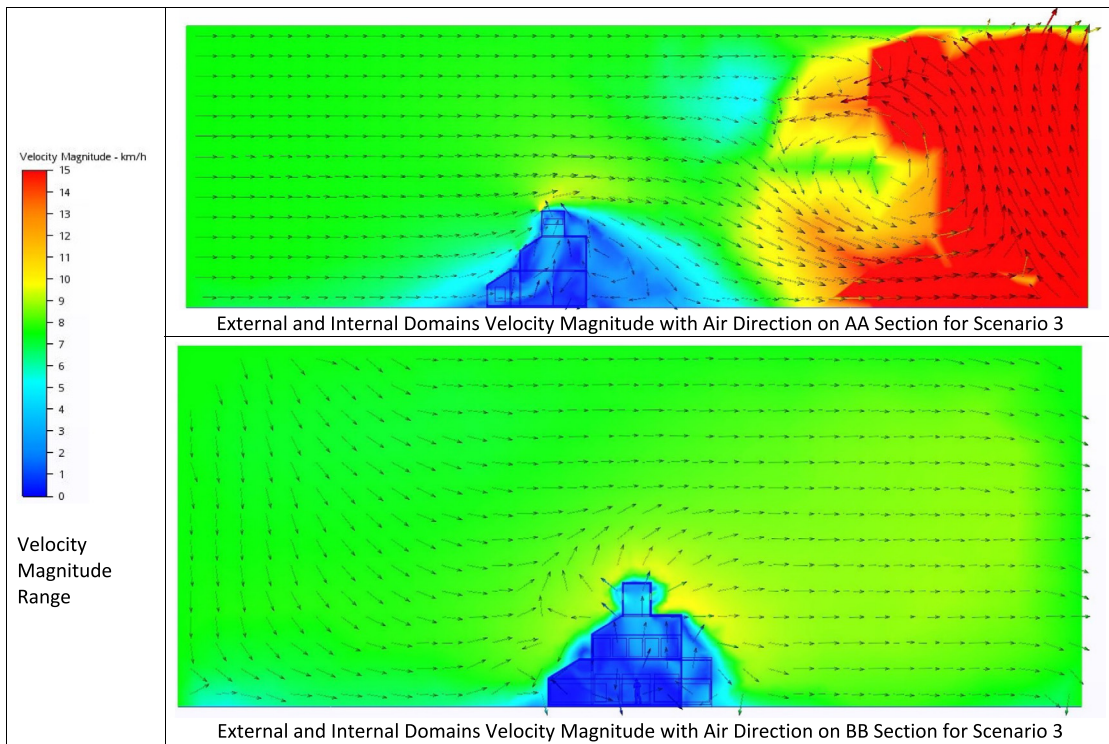
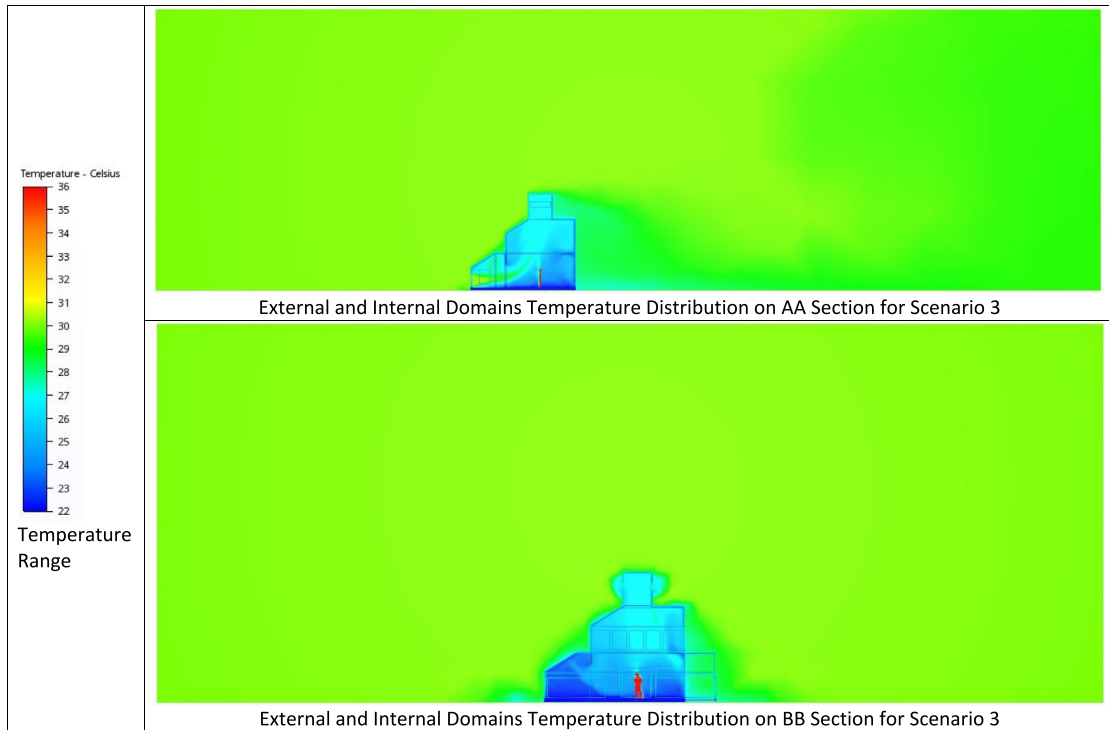
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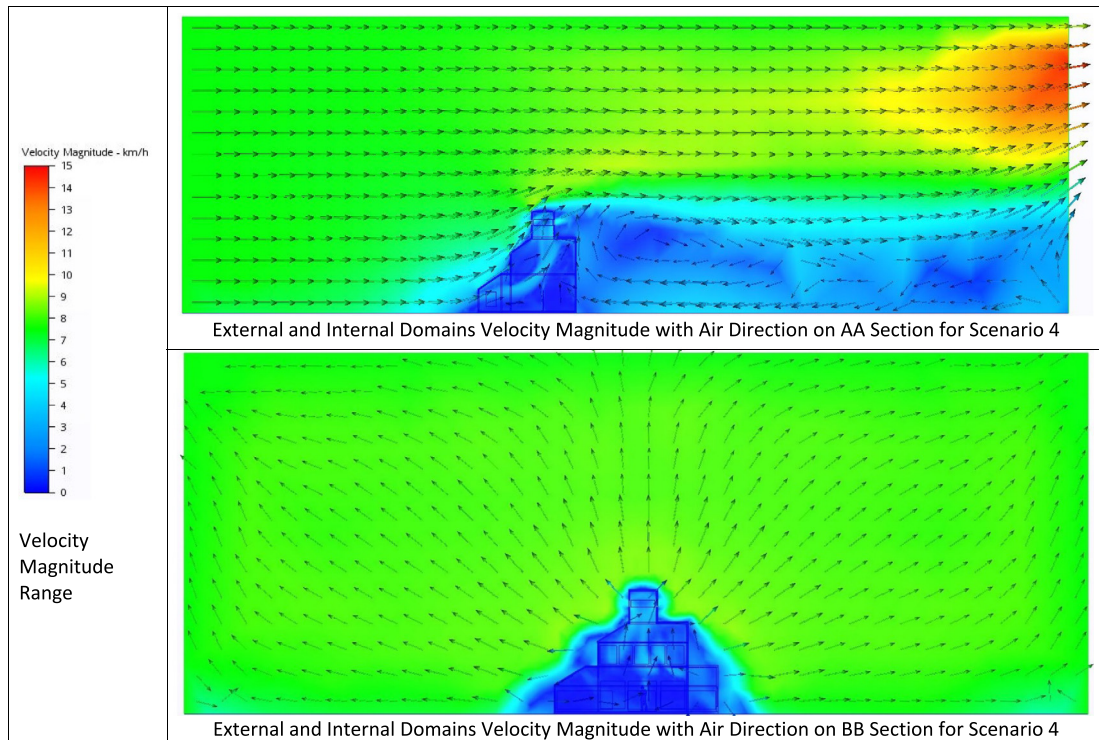
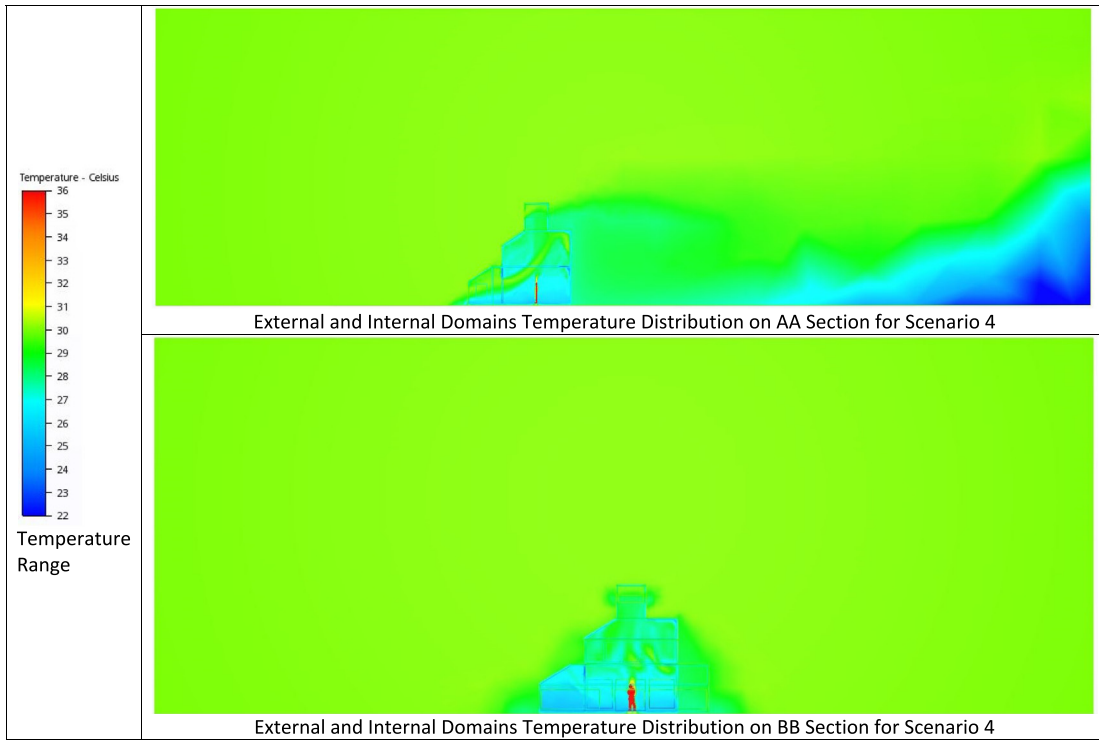
Duygu Utkucu: Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Hatice Sözer:** Conceptualization, Validation, Resources, Data curation, Writing - review & editing, Supervision.

Appendix









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