SIMULATION MODEL FOR ENERGY PERFORMANCE AND USER COMFORT EVALUATION OF ATRIUM BUILDINGS

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ABSTRACT

In recent years highly glazed spaces and atriums are seen as a sign of advanced technology. An atrium is the social center of a building where people gather for social activities and also is a significant element of passive building systems if designed properly to provide user requirements. Estimation of energy use and thermal performance is difficult because of the complex thermal phenomena occurred at the atrium space due to its large size and high solar gains through the fenestration. It is not easy to obtain comprehensive results for evaluating the performance of the atrium building with a single simulation program. This paper introduces a performance based model for energy use and user comfort evaluation of atrium buildings with the use of multiple building performance simulation tools; Window 5.2, EnergyPlus, Comis, Delight, Gambit and Fluent and the resulting outputs which support the methodology.

INTRODUCTION

An atrium performs impressive spaces, revives the indoor space by admitting daylight, maximizes the benefit from direct solar gain, maintains solutions for natural ventilation and acclimatization, increases interaction and socialization of the people. It acts as a filter of undesirable effects of outdoor environment factors such as rain, snow or wind, and retains the desirable effects of outdoor such as sunshine, fresh air and visual circumstances (Bryn 1993; Bednar 1986; Saxon 1986). Energy saving potential of an atrium is associated with the provision of daylight into the occupied spaces, forming a buffer zone between indoor and outdoor environment and providing natural ventilation with the help of the stack effect.

Despite these advantages, large glazing surfaces of atrium cause excessive solar heat gain in summer and heat loss in winter and also air stratification especially in summer that affect user comfort and energy performance of atrium buildings.

It is not easy to estimate thermal and energy performance of an atrium building because of the complex thermal phenomena and air stratification. The structures and features of the existing building simulation programs are not capable of solving complex air flow and stratification problems of an atrium since these tools were developed mostly for conventional buildings. Large size of the atrium space, large area fenestration and three dimensional buoyancy-driven flows resulting from solar heat and internal gains such as equipments, lighting and people cause air stratification at the atrium space. Solar radiation penetrating the atrium through the fenestration is transmitted and reflected from the adjacent surfaces. Since the calculation of transmitted and reflected solar radiation from surfaces is complicated, accurate and comprehensive methodologies incorporated with sophisticated computer tools are required for determining the air stratification and air flow pattern occurred in an atrium (Laouadi et al 1999; 2002). As an alternate, computational fluid dynamics (CFD) program can calculate and demonstrate air flow patterns and air stratification but it takes more time and requires more powerful hardware computers.

This paper introduces a performance based model to determine if the performance of the designed atrium building is adequate to maintain energy and comfort standards. In the study, for performance evaluation of an atrium building, total energy use, air stratification and air flow structure were computed with the interaction of the different simulation programs EnergyPlus and Fluent, as well as the auxiliary tools that support them. Finally, an application was presented in order to substantiate that the methodology was working.

SIMULATION TOOLS

The tools used in the simulation model are:

- Window 5.2 for determining the thermal and optical properties of transparent component of building;
- Comis for calculating the air flow patterns between zones;
- Delight for calculating the total initial contribution of daylight in the zones;
- EnergyPlus for computing total building energy loads and providing input data for the other programs;
- Gambit for specifying the geometrical data of the atrium building;
- Fluent for comprehensive calculations of environmental conditions of the occupied zones and air stratification of the atrium.

EnergyPlus, a new generation of building energy simulation software, was conducted to estimate the energy use of an atrium building. EnergyPlus simulates building energy flows based on an input file containing a detailed description of the building construction, HVAC systems and their controls and calculates total (lighting, cooling and heating) energy use of the building. EnergyPlus accepts a window description file from Window 5.2 as the input data so that exactly the same window can be exported to EnergyPlus for energy analysis.

Air flow pattern of the atrium can be calculated with an integrated Comis air flow model. Direct solar heat gain through the glazed roof of the atrium, thermal effect of transmitted sun light or adjacent spaces can be calculated by specifying solar distribution systems. EnergyPlus was also used to obtain daylight illuminance levels and glare index at the occupancy zones. Because of the solar gain and airflow interaction, a uniform air temperature distribution does not occur in atrium. Nevertheless EnergyPlus is not capable of determining air stratification in the atrium zone since it assumes a constant mean air temperature for the calculations (EnergyPlus Version 2.1.03 Input and Output References 2005).

For an accurate and realistic modeling, determining air stratification at the atrium was included in the simulation model. A general purpose commercial CFD package Fluent was conducted for the prediction of surface temperatures and air stratification at the atrium zone. The software employs a body-fitted coordinate system for accurate representation of a flow domain with irregular geometries such as atria (www.fluent.com). Gambit software was used for specifying the geometrical data of the atrium building. The data; mean air temperature, air flow rate, heat transfer coefficients and inside/ outside surface temperatures calculated with EnergyPlus are used as boundary condition data for the Fluent simulations.

PERFORMANCE BASED MODEL

The main aim of the model is to demonstrate the integration of various simulation tools for performance evaluation of atrium buildings associated with performance approach. Modeling process includes the evaluation of the energy performance and user comfort analyzes of the atrium building considering multi-criteria. The performance-based conceptual model includes input/output data, simulation model, data transferring, comparison and evaluation of the atrium building according to the criteria concerning the thermal and visual comfort issues and energy consumption. The conceptial model was presented in Figure 1.

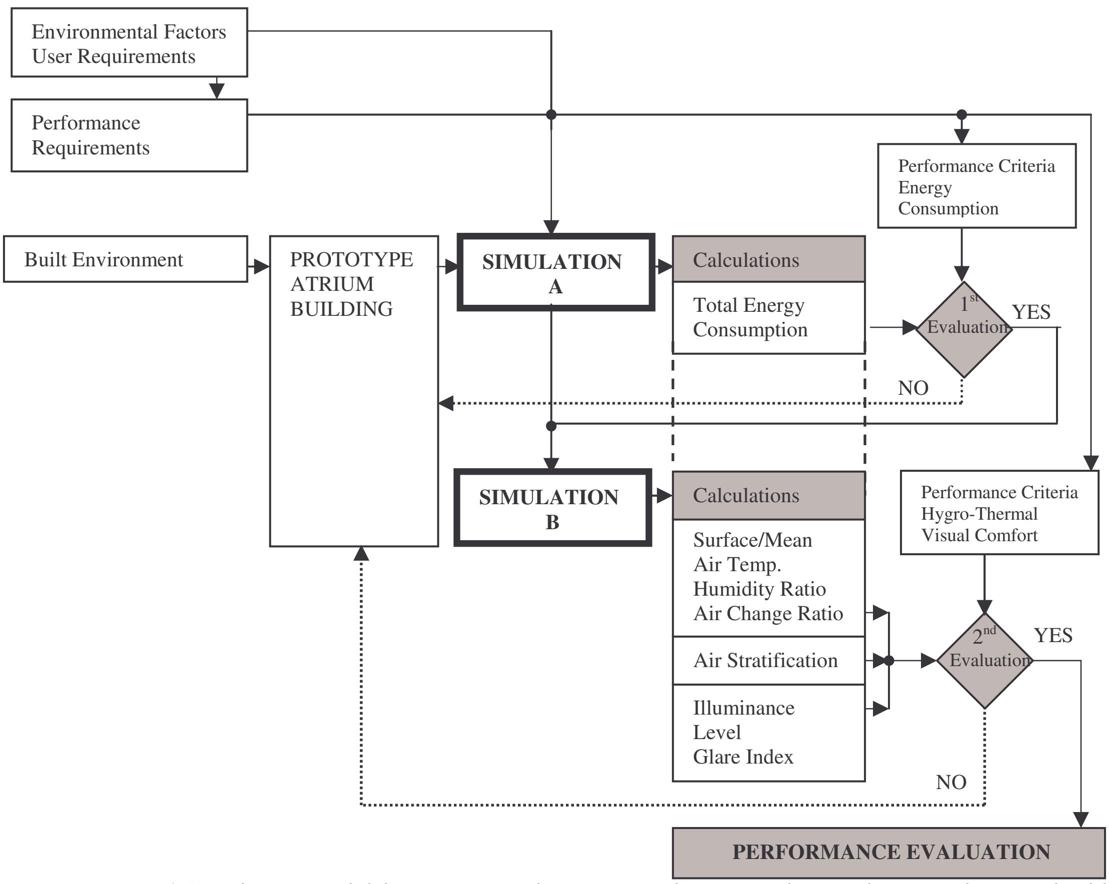


Figure 1 Simulation model for energy performance and user comfort evaluation of atrium buildings

As the initial step of the model, performance criteria were determined for the evaluation by considering the issues related with atrium buildings. Information was given on the performance requirements complied with natural environmental factors and user requirements according to performance concept.

Natural environmental factors and user requirements

Environmental factors affecting energy performance and user comfort requirements can be separated into the parameters related with climatic and geographical factors, which were specified as the input data in the simulations for characterizing the outdoor environment. User requirements are the conditions that users need to perform their activities depending on the factors affecting the performance of the atrium (Figure 2). In this study, hygro-thermal and visual comfort were considered as the basic user requirements.

Performance requirements / criteria

Definition of the performance concept is essential in order to describe the properties and criteria related with the building. Performance of the building can be defined as the attitudes of the components of the building system under natural and artificial effects in time.

In this study building energy performance was evaluated according to the building energy use. The building energy performance gives an opinion about energy use sources and alternative proposals. The factor and the relationships that affect the performance requirements and criteria are given in Figure 2.

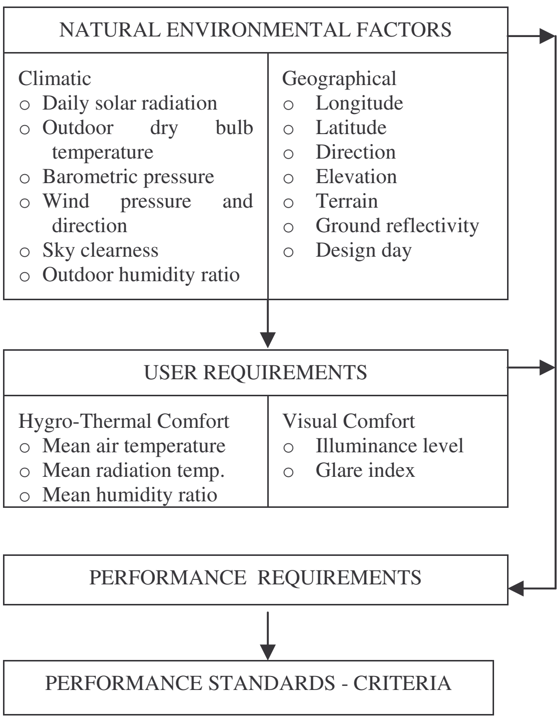


Figure 2 Performance standards and criteria

Objectives and constraints determined from rules, standards and regulations are in relation with the natural environmental factors and user requirements. They have a direct impact on the evaluation of the performance of a building. Since regulations and standards developed in Turkey are not sufficient, the assumptions were made by taking the previous studies into account (IEA 1994).

Built environment

The built environmental factors that affect energy and user comfort performance of building are given in Figure 3. Each of these factors can be determined to set their impact on the performance of the atrium building. All the sub-factors of built environment were modeled according to building management program. Each of these factors can be determined to set their impact on the performance of the atrium building.

BUILT ENVIRONMENT	
Near surroundings Position and size of the exterior obstacles' ○ solar radiation reflectivity of the surrounding surfaces	Users ○ Numbers ○ Activity level ○ Clothes' thermal insulation value ○ Schedule of building
General properties of the building ○ Volume, size and orientation ○ Function ○ Using schedule ○ Air movement/temp/humidity ○ HVAC system schedule	Building components ○ Opaque ○ Transparent Thermal/optical properties

Figure 3 Built environment factors

In specifying the building components two sub-evaluation phases were proposed in order to verify the thermal and optical properties of the components in accordance with the standards and regulations.

The opaque components of the building were designated to satisfy the regulations before the simulations to prevent redundant calculations. The building components were designed to meet the Turkish Standard code 825 in the sub-evaluation phase. Window 5.2 program was used to get sub evaluation data for the transparent components. Sub-evaluation procedure was proposed for verifying the fundamental window performance indicators such as Heat Transmission Coefficient (U value), SHGC (Solar Heat Gain Coefficient) and Tvis (Visible Transmittance) that fulfill the performance standards or criteria at the component level. The output data obtained from Window 5.2 was used in EnergyPlus as input data files for identifying thermal and optical properties of glazing systems (Winkelmann 2001). The properties of building components that were effective in energy calculations such as dimension, position, joint, color and material were taken into consideration in design and selection stages.

SIMULATION MODEL

Since sophisticated software tools are required to understand the complex phenomena in an atrium, various simulation programs were used for the comprehensive analysis of an atrium building. The interaction of the different tools was explained by considering the inputs, outputs, processes, mechanisms and controls.

Heating, cooling, lighting energy load calculations with EnergyPlus

Heating and cooling energy load calculations can be estimated by determining heat gain and losses that are listed below (Çetiner, Ozkan 2005):

- gain and losses resulting from heat transmission;
- gain and losses from solar radiation;
- gain and losses resulting from air infiltration;
- gain and losses resulting from mass effect;
- gain resulting from internal heat gains.

These calculations were performed by using EnergyPlus, which is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources.

At the first evaluation phase, total energy use was considered as the performance indicator for energy performance evaluation of the atrium building. Total annual energy use per square meter of the building was computed. If the results were under the accepted limits, then the calculations were repeated until the accepted level was achieved.

User comfort and calculations of environmental conditions with EnergyPlus and Fluent

In the simulation model the atrium building was separated into office and atrium zones. Each zone differed from the others according to its orientation, function, occupancy and heating/cooling temperatures. Energy performance analysis was performed at the building level including the atrium and occupied zones. Air stratification analysis was performed for the atrium zone while the user comfort analysis was performed for the occupied zones.

The following output data for hygro-thermal comfort which was based on the humidity ratio and the operative temperature was accepted within the region shown in ASHRAE Standard 55-2004 given below.

	Air temperature (^oC)	Humidity Ratio (kg/kg)
Winter	19.6/23.9	0.012
	26.3/21.7	0
Summer	23.6/26.8	0.012
	28.3/25.1	0

For these outputs the operative temperature was simplified to be the average of the air temperature and the mean radiant temperature (EnergyPlus Engineering Reference Manual 2005).

Visual comfort is influenced by (Anon 2001);

- illuminance level of space
- glare index
- spatial distribution of daylight

At the second evaluation phase, humidity ratio calculated with EnergyPlus, inside surface and mean air temperatures calculated with Fluent. The results were used for the comparison of the environment of the hygro-thermal comfort conditions given in ASHRAE 55-2004 standards.

Illuminance level and glare index calculated with EnergyPlus were used for the visual comfort evaluations based on the limits. If the user comfort values reached the required levels, then the evaluation process continued.

Air stratification with Fluent

Air stratification in the atrium was calculated by using Fluent simulation program with the output data obtained from EnergyPlus simulations. This program typically require surface temperatures, heat transfer coefficient or heat fluxes as input, and the model suggests to get these data from hourly calculations of Energyplus. Mean air temperature, surface temperature, inside and outside temperatures, heat transfer coefficients between the surfaces and the adjacent air were the output data of EnergyPlus. These were used as the input data to specify boundary conditions of the surfaces for the CFD calculations with the program.

Solar load and radiation models of the program were used in simulating the air stratification. The radiation effects were included in the calculations to solve the problem.

The standard k-ε turbulence model was used to simulate the effect of turbulence of air flow. The model for predicting air flow consisted of the conservation equations for mass, momentum, enthalpy, turbulent kinetic energy and its dissipation (Gan, Riffat 2004).

The effect of buoyancy in the momentum equation was simulated using the Boussinesq model in which the fluid density was taken as a function of temperature. In order to calculate radiative heat transfer between atrium and adjacent zones, the discrete transfer radiation model was used. However the radiation model was included in the calculation to evaluate the effect of radiant heat exchange between the internal surfaces.

For all opaque materials, the absorptivity for the infrared and visible bands, and for transparent materials absorptivity and transmissivity for infrared and visible bands were recorded.

Performance evaluation

The final performance evaluation of the atrium building is provided by the results obtained from the first and second evaluation phases.

The first evaluation phase takes into account the total energy consumption (heating, cooling and ligting) of the building calculated by EnergyPlus. The total annual energy use was considered as the performance indicator in evaluating energy efficiency of the building. If the building energy use satisfies the specified performance criteria, it can be said that the building is energy consious.

The second evaluation phase aimed to criticize the performance that provides the user comfort of the building. The second evaluation phase includes user hygro-thermal and visual comfort according to the values obtained from EnergyPlus and Fluent output data. The required performance indicators were window surface temperature, mean air temperature and humidity ratio for hygro-thermal comfort; illuminance level and glare index for visual comfort at zones. The output data, illuminance level and glare index, obtained from EnergyPlus calculations were closed to realistic results. Hence in evaluation process these values could be taken into consideration.

EnergyPlus assumes a uniform air temperature distribution in atrium and is not capable of determining air stratification. Hence the mean air and surface temperatures were computed with Fluent to obtain the modified data which include the effect of air stratification for the evaluation of the hygro-thermal comfort in the occupied zones of the atrium building.

If the values meet the performance criteria, it can be said that building is respond to the comfort conditions. Otherwise the building had to be remodeled according to a new set of assumptions and variables to achieve the intended performance level (Figure 4).

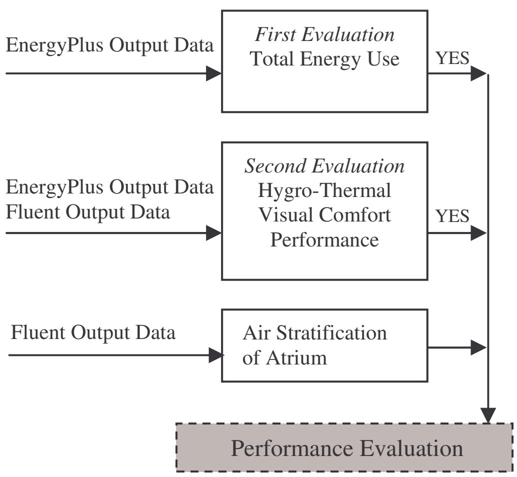


Figure 4 Performance evaluation of atrium

APPLICATION

Description of the building

Three storey office building was designed for the simulation studies (Figure 5, 6). Three sided atrium office building was designed in order to consider the effect of the vertical and horizontal surfaces of the atrium on the thermal performance of the building. The atrium space was assumed only for circulation between the adjacent zones and south external wall was designed as the entrance of the building.

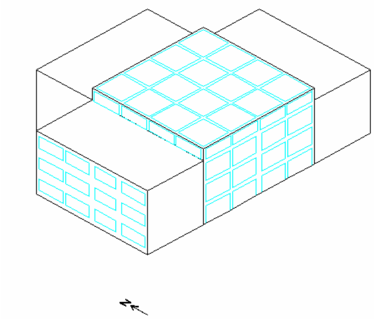


Figure 5 Perspective of the office building

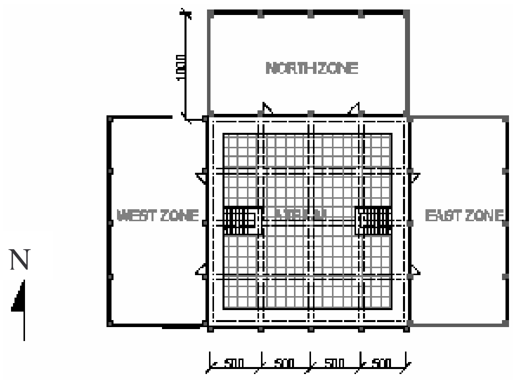


Figure 6 Plan of the office building

The physical properties of the building elements of the office building are as follows:

Thermal characteristics:

- Roof: U= 0.3 W/m^{2}K
- Ground floor: U= 0.32 W/m^{2}K
- Intermediate floor: U=4.5 W/m^{2}K (considered as adiabatic)
- Opaque part of facades (walls): U= 0.32 W/m^{2}K (without glazed part)
- Internal walls: U= 5.2 W/m^{2}K (between zones and atrium)
- Glazing system: U= 2.6 W/m^{2}K, SHGC, 0.75 and Tvis, 0.74.

The frame and the dividers were made up of aluminum with thermal break and U value of the frame was 5.68 W/m^{2}K. The fenestration of the office zone was placed longitudinally on the facade and 50% of the external wall area was glazed.

Since the atrium was considered as a circulation area, it was not continuously occupied. There were

18 people in each occupied office zone. The office zones were totally occupied during working hours between 9.00-12.00 and 13.00-18.00 while half of the workers were assumed to be working during 8.00-9.00 and 12.00-13.00. Moreover the building was occupied only five working days in a week.

For the official activities, user activity level was assumed to be 150 W/person and user clothe type was considered to be 1 clo in winter, 0.5 clo in summer and 0.85 clo in transient seasons (ASHRAE Standards 2001).

The thermostat set points of the heating and cooling systems for the office zones were specified as 15-30°C between 0.00-7.00 hours; 23-25°C between 7.00-17.00 hours and 15-30°C between 17.00-24.00 hours. The thermostat set points the heating system for the atrium zone was specified as 10°C between 0.00-7.00 hours; 15°C between 7.00-17.00 hours and 10°C between 17.00-24.00 hours during heating season.

The atrium zone was considered to be cooled with natural ventilation so that no cooling thermostat set point was specified. The atrium space was connected with its adjacent spaces via operable windows/doors in each zone that remained closed and opened when the zone temperature was higher than the ventilation temperature and the outside temperature. The ventilation temperature was set as 19ºC. Venting opening factor was set between 5-10ºC. Operable skylight windows provide air flow and reduce the stratification problem during the peak periods in summer. The windows were modeled with the same venting strategy.

With daylighting controls, the office zone electric lights were dimmed linearly so as to provide 500 lux at the two reference points which were located 4.50 m and 1.50 m from the external and internal window wall respectively, centered on the window and at a height of 0.76 m above the floor. Illuminance level of working plane and maximum allowable discomfort glare index were specified as 500 lm/m^2 and 22 for the office zones, respectively (EnergyPlus Input Output Reference 2005).

Recessed fluorescent lighting was modeled with a lighting power density (LPD) of 0.11 W/m^2. Full LPD levels were modified by the occupancy schedule (e.g., at 8:00-9.00, 50% of full LPD was on, at 9:00-17.00, 100% of full LPD was on, at the remained hours and off days 5% of full LPD was on) in combination with daylighting controls. Heat was apportioned to the interior space (42%) as thermal radiation, (18%) as visible radiation and (40%) as convection (Lighting Handbook: Reference & Application 1993).

The heat equipment load was specified 160 W/person assuming that each worker was using one PC. Equipments were switched on based on the same schedule of the occupancies. No other equipment was defined.

Annual Heating, Cooling and Lighting Loads

The annual heating and cooling energy consumptions of the each zone is given in Figure 7-8 respectively. According to the simulation results, the cooling and heating energy consumptions and mean air temperatures of the intermediate floor were lower than the other floors.

Because of the solar gain and lower heating set-point, lowest heating energy use was maintained at the atrium zone in accordance with the total floors of each zone. Maximum heating energy load is recorded as 5187 kWh at the north zone, 3331 kWh at the east zone and 2769 kWh at the west zone (Figure 7).

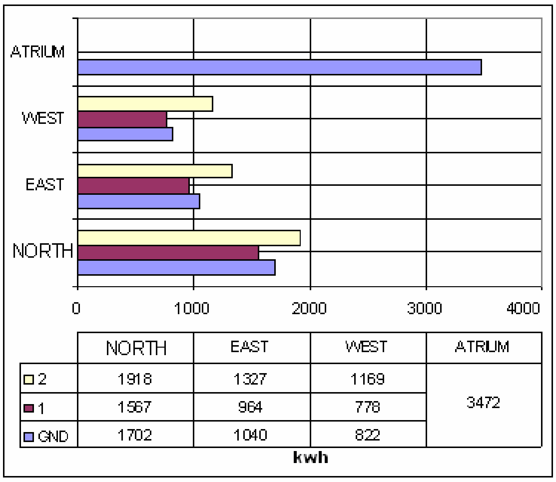


Figure 7 Annual heating energy use of the zones in kWh

Cooling energy loads of the zones were given in Figure 8.

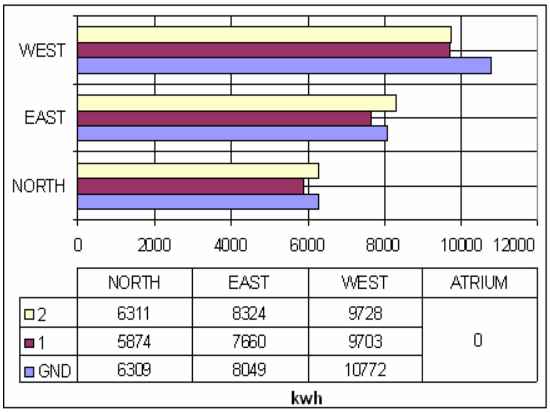
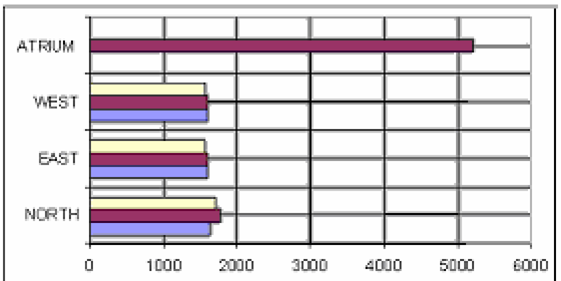


Figure 8 Annual cooling energy consumption of each zone in kWh

When heating and cooling loads were compared, it is seen that cooling load has the biggest part of the energy consumption. The highest cooling energy use is calculated in the west zone as 50.3 kWh/m^2. This result shows the requirement of solar shading devices and proper glazing system design in order to prevent high excessive solar heat gains.

Lighting energy loads of each zone was given in Figure 9. The highest lighting load was calculated at the north zone.



	NORTH	EAST	WEST	ATRIUM
2	1705	1550	1552	
1	1774	1602	1596	5215
GND	1628	1608	1600	

kwh

Figure 9 Annual lighting energy consumption of the zones in kWh

According to the first evaluation phase of the model, the heating, cooling and lighting energy consumption of the each zone was controlled and the highest use energy was recorded at the west zone as 62.8 kWh/m^2, 53.5 kWh/m^2 at the east zone and 47.9 kWh/m^2 at the north zone.

The application of the model was limited up to the second evaluation phase.

CONCLUSION

In this paper, a model which aimed to evaluate energy and user comfort performance of an atrium building by using multiple simulation tools, was introduced.

The simulation model includes the following phases:

- Evaluation at the component level: Performance evaluations of the opaque and transparent component.
- Evaluation at the building level: Performance criteria used were total energy use of the whole building including the atrium and other thermal zones.
- Evaluation at the zonal level: The performance criteria used for evaluating the hygro-thermal comfort were window surface temperature, humidity ratio, illuminance level and glare index at the office zone and air change rates and air stratification at the atrium zone.

In the proposed simulation model, evaluation mechanisms were suggested from the beginning of the construction of the atrium building, sub evaluations are suggested in order to make sure if the performance standards and criteria were met or not. Building component alternatives (opaque and transparent) were selected according to the standards. Hence, the excessive energy consumption and discomfort conditions could be prevented.

User comfort was analyzed considering hygro-thermal and visual comfort conditions. The EnergyPlus output data - illuminance level and glare index- were used without modifications for the evaluation of the visual comfort. Since the EnergyPlus output data - mean radiant and air temperature - were insufficient for evaluating the thermal comfort conditions of the atrium buildings, comprehensive computing efforts were done with Fluent. Thus, the effects of the air stratification on the adjacent surfaces of the occupied zones from lower to upper levels could be determined.

By the help of the simulation model, both energy performance and user comfort condition of the atrium building can be evaluated to make the building energy consious and responsive to the user comfort requirements. The goal is to reach atrium building design that lower the total energy consumption and provide comfortable environments.

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