ACOUSTIC DESIGN BASED ON MULTI-ASPECT PERFORMANCE ANALYSIS

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ABSTRACT

ACOUSTIC DESIGN BASED ON MULTI-ASPECT PERFORMANCE ANALYSIS

In current architectural practice, architects, due to time and budget constraints do not analyse their designs and evaluate alternatives from the building physics perspective. They expect this analysis to be carried out by engineers. Unfortunately, engineers mostly get involved late in the design process, after many key decisions are already finalized, leaving them powerless to solve problems employing efficient strategies. However, the rapid advances both in computing and engineering have produced various simulation based tools for evaluating building performance that architects themselves can employ in the early design stages. The proliferation of the utilization of these tools throughout the architectural practice and education is necessary for achieving higher performance levels in the built environment. In this study, the main Lecture Hall at Izmir Institute of Technology, Department of Mathematics is diagnosed and documented through measurements and the possibility of predicting this existing level of performance through simulations during the design stage is explored. The brand new Lecture Hall is in urgent need of renovations, with additional costs, in order to improve acoustic, visual and thermal comfort in the space. Architects need to follow a performance based design approach where they consider performance criteria and utilize building simulation tools for design support in order to avoid problems that introduce costs later in the construction and operation of buildings.

ÖZET

ÇOK YÖNLÜ BAŞARIM ÇÖZÜMLEMESİNE DAYALI AKUSTİK TASARIM

Günümüzde mimarlık meslek pratiğinde yapı fiziği konularıyla ilgili ölçütlere bağlı başarım değerlendirmeleri, süreye bağlı kısıtlamalar altında yapılamamakta ve fiziksel çevre kontrolündeki başarım mühendislik projelerinin sorumluluğuna devredilmektedir. Mühendisler ise ana tasarım kararları tamamlandıktan sonra devreye girdiklerinden dolayı verimli olamamaktadırlar. Oysa bilişim teknolojilerindeki hızlı gelişim ile beraber mühendisliğin tüm alanlarında kaydedilen ilerleme; günümüzde mimarların tasarlamakta oldukları yapılı çevrenin fiziksel çevreyle olan etkileşimini benzetimler yoluyla incelemelerini sağlayan çeşitli araçların geliştirilmesini sağlamıştır. Bu tür benzetim araçlarından yararlanılması, binalarda yüksek başarımın elde edilmesinde önemli bir rol oynayacaktır. Bu çalışmada kullanıma yeni açılmış İzmir Yüksek Teknoloji Enstitüsü (İYTE) Matematik Bölümü Amfisindeki mevcut koşullar ölçümler ile belgelenmekte ve mekanın başarım düzeyinin benzetimler aracılığıyla tasarım aşamasında öngörülebilirliği irdelenmektedir. Bu yeni tamamlanmış amfide acil olarak ek maliyetlerle işitsel, görsel ve ısıl konforun sağlanması için yeni düzenlemelerin yapılması gerekmektedir. Mimarların, tasarımlarında başarım ölçütlerini göz önünde bulundurarak kararlarını benzetim sonuçlarına dayandıracakları başarım odaklı bir tasarım yaklaşımı izlemeleri incelenen örnekte olduğu gibi sonradan çözülmesi maliyetli birçok problemden kaçınılmasını sağlayacaktır.

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CHAPTER 1

INTRODUCTION

Today issues related to energy efficiency and environmental sustainability are becoming more and more important in all aspects of our lives. In the construction sector, this is apparent in the growing interest in achieving high-performance buildings. Increasing the energy efficiency of buildings is possible without compromising user comfort while pursuing a harmony between the built and natural environment. Architects at the design stage can achieve this by considering climatic conditions, users' needs and technological options with an appropriate integrated design strategy. However, in current architectural practice, performance analysis of building designs is not done due to time constraints and is left up to the engineers. Architects usually design the building without consulting anyone for heating, cooling, or daylighting. Engineers get involved later in the detailed design stage and are not capable of altering most of the design decisions vital to a building's performance. Löchnert describes that idealised traditional design usually is a linear process which does not allow for design optimisation. A linear process prevents potential improvements in the design.(Treldal 2008).

There is an urgent need to break from this conventional wisdom and move towards an integrated design approach where architects and engineers can collaborate more effectively. A whole new design paradigm is emerging. Terms such as performance-based design or performative design are used to describe a new design approach that does not separate performance evaluation and design generation (Kolarevic et al. 2005). Architects at early design stages need to collaborate with other disciplines. For this, a coordinated working environment is required. (İnan 2006)

With the rapid progress of information technology in all areas of engineering, we now have access to a large number of building performance simulation tools. The use of technology by architects and other disciplines (civil engineer, mechanical engineer, electrical engineer, etc...) provides opportunities for the transmission of digital data faster, more easily and are more economically. Nowadays, almost all projects are in digital formats and with the help of emerging communication technologies, architects can collaborate with other disciplines regardless of time and space. Important decisions are taken with the guidance of experts at early design stages. This provides more reliable results and eleminates the loss of time by retroactive revisions (İnan 2006).

Software such as DesignBuilder, DIALux, Catt, Ecotect, TAS EDSL, Fluent, BEES, GaBi are some examples of simulation tools available to architects. Tools such as EnergyPlus, Radiance and Odeon in fact have become standards in their fields due to the high levels of reliability in their results. However, the use of simulation tools in the design phase is still limited (Hensen et al. 2011). These tools are mostly utilized in big-budget projects with the participation of engineers. To increase their use by architects, many efforts focused on integrating analysis tools and design systems (Ilal 2007). However, more recent studies are being conducted to find out how these tools can be transformed to become more convenient for designers (Attia, et al, 2009). While new tools geared specifically for architects should be developed, current tools are very capable and should be utilized, not ignored. The work presented in this thesis is a case study that demonstrates how, even with available tools, architects can significantly improve their designs.

1.1. Subject and Aim

In this study, a brand new lecture hall in the Department of Mathematics at Izmir Institute of Technology (IYTE) was examined. This building is situated on a hillside on IYTE campus (latitude 38° 19‟; longitude 23° 88‟) (Figure 1). The lecture hall was opened in September 2012 and immediately became the subject of numerous complaints from instructors and students. The Office of Construction at Izmir Institue of Technology requested for an in depth analysis of user comfort conditions in the hall.

Figure 1. Satellite image of the lecture hall
(Source: Google Earth)

In the architectural composition of the building, the cylindirical hall is placed in a privileged location adjacent to the main entrance and is the focal point of the design (Figure 2). Inside, circulation areas surrounding the hall are expanded with gallery spaces. The cylindrical form of the hall is exposed and is easily viewable. The importance of the lecture hall for the building design is stressed. It is the highlight of the design. However, this hall has serious deficiencies in lighting, acoustics and thermal comfort and is unable to perform its function. Visual, auditory and thermal comfort problems are all associated with the glass roof of the space (Figure 3). The design process clearly did not consider any building physics criteria.

The problems of the hall related to building physics could have easily been predicted and prevented if the design team had followed a performance-based design approach and employed basic simulation tools. The main aim of the study is to reveal that architects, without having to input detailed information and adjusting only basic parameters for simulation, can get reliable results with existing tools. For this reason, none of simulation models utilized in this study have been fine tuned or calibrated and none of the advanced settings in the simulation tools have been altered.

Figure 2. External view of the lecture hall

Figure 3. Glass Skylight

1.2. Content and Method

This report is composed of five chapters. The first one is introduction. In this chapter, general concept and aim of study are presented briefly.

In the second chapter, definition of some terms and design strategies related to acoustic, daylighting and heating/cooling performance are clarified.

In the third chapter, the lecture hall is described. Then acoustic, daylighting and heating/cooling performance of the hall are examined. Measurement and simulation result are presented and compared.

In the fourth chapter, proposals to improve user's comfort are presented. The results of simulation are revealed to determine if simulation tools utilized by designers can determine problems early in the design process.

In the last chapter, conclusions are presented.

CHAPTER 2

ACOUSTIC, DAYLIGHTING AND ENERGY EFFICIENCY IN LECTURE HALLS

2.1. Acoustics in Rooms for Speech

Many objective and subjective parameters are available for evaluating the acoustics in spaces. In this chapter sound pressure level (SPL), reverberation time(RT), speech transmission index(STI), articulation index(AI) are defined. The lecture hall is evaluated by referring to these performance indicators in the third chapter. Then the design criteria of rooms for speech are presented. Criteria like; rooms size, shape, surface, orientation, materials, and ambient noise level all have impacts on speech intelligibility.

2.1.1. Sound Pressure Level (SPL)

The sound pressure level is the most commonly used indicator of the acoustic wave strength. It correlates with human perception of loudness (Long 2005). Sound intensity is a measure of the flow of acoustic energy in a sound field. It is also defined as the time average of the net flow of sound energy through a unit area in a direction perpendicular to the area (Jacobsen 2011). The strength of an acoustic source is characterized by its sound power, expressed in Watts (Long 2005).The Leq is an average sound pressure level.

In buildings, sound pressure level depends on attenuation of the speech by distance, orientation of listener and speaker, individual talking, reflections on surfaces like ceiling, walls, windows and furniture, presence of screen and barriers (Moore 1978).

2.1.2. Articulation Index (AI)

Articulation index (AI) is one of methods to measure speech intelligibility. Moore (1978) defines articulation index as a signal-to-noise ratio assessment. AI is measured as a number between 0 and 1.

Table 1 shows ratings of the speech intelligibility and their ranges. AI of less than 0.3 is unsatisfactory, while AI values between 0.3 to 0.5 is marginally satisfactory. For AI values of 0.5 to 0.7 intelligibility is defined good, and above 0.7 speech intelligibility is very good.

AI value is modified by a correction factor presented in Figure 4. The value obtained from this figure is substracted from the calculated AI. Speech intelligibility is improved if there is a clear visual connection between listener and speaker. Figure 5 shows the relation between calculated AI and effective AI when there is a visual connection.

Table 1. Speech Intelligibility and AI
(Source: Mehta, et al. 1999)

AI	Speech Intelligibility
≥0.7	Very Good
0.5-0.7	Good
0.3-0.5	Marginal
‹0.3	Poor

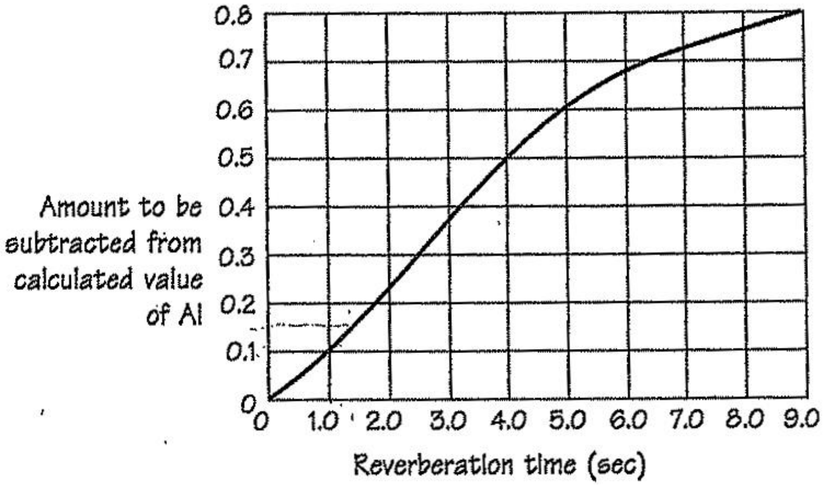

Figure 4. AI Correction factors due to reverberation time (Source: Mehta, et al. 1999)

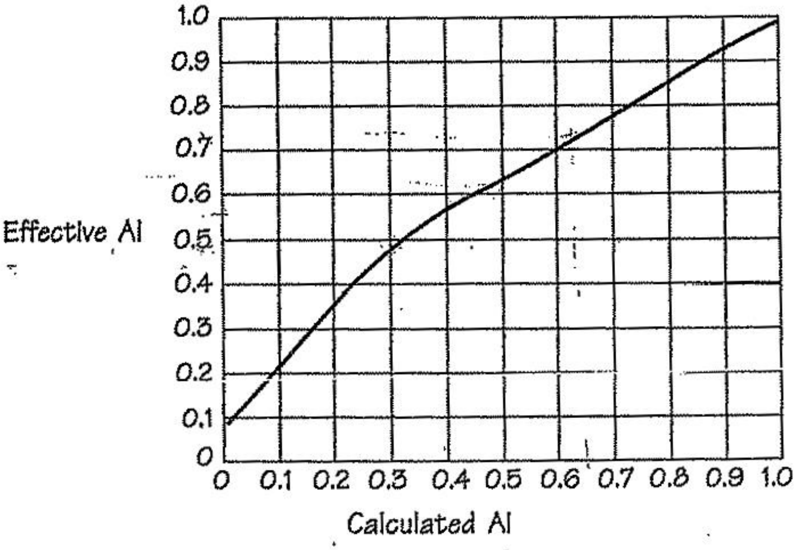

Figure 5.Relation between Calculated and Effective AI when there is a visual connection (Source: Mehta, et al. 1999)

2.1.3. Speech Transmission Index (STI)

Speech transmission index (STI) is a direct measure of speech intelligibility (Long 2005). The speech transmission index (STI) is a tool for predicting speech intelligibility and can be measured on site (Barron 2010).

2.1.4. Reverberation Time (RT)

Reverberation time is the time it takes for the stationary sound pressure level in a room to decay by 60 dB after the source is abruptly switched off. Sabine established the method around the year 1900. According to the Sabine equation, reverberation time is related to the room volume (V) and the total acoustic absorption (A).

Sabine measured the reverberation time, the time it took for the sound level to drop 60 dB (Long 2005). Optimum reverberation times vary on function (Figure 6).

$$T_{60} = 0,161\ V / A \qquad (1)$$

where:

T_{60} = reverberation timeilluminance emerging from the opening

V = volume

A = total absorption of room

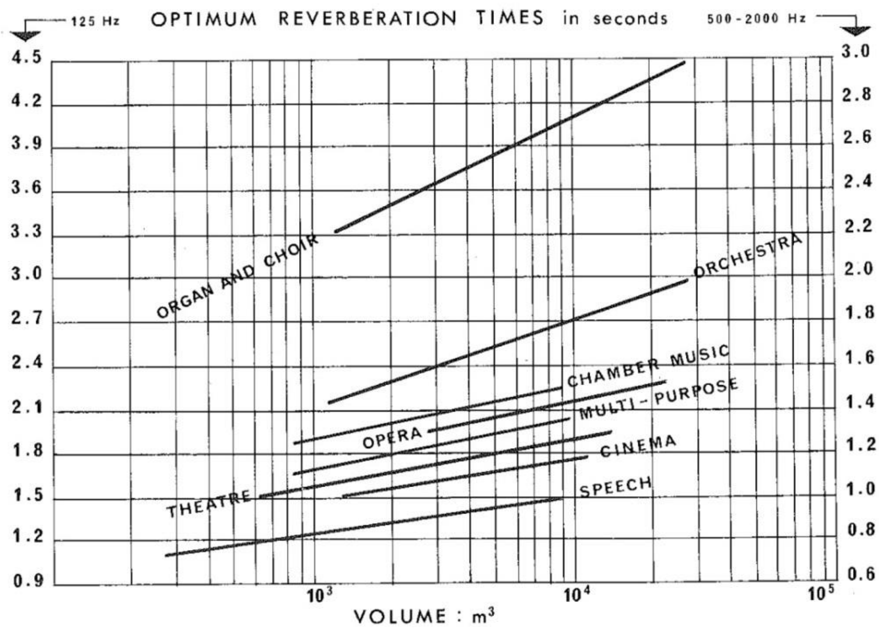

Figure 6. Optimum Reverberation Times for Various Function
(Source: Moore, 1978)

2.2. Design Criteria of Rooms for Speech

Mehta (1999) expresses that speech should be intelligible in spaces like lecture halls. Retaining the natural character of speaker’s voice is the secondary requirement.

Long (2005) states the requirements in designing rooms for speech,

a. There must be adequate loudness.

b. The sound level must be relatively uniform.

c. The reverberation characteristics of the room must be appropriate.

d. There must be a high signal-to-noise ratio.

e. Background noise levels must be low enough to not interfere with the listening environment.

f. The room must be free from acoustical defects such as long delayed reflections, flutter echoes, focusing, and resonance.

2.2.1. Speaker-Listener Distance

The speech intelligibility decreases with distance. Figure 7 shows how human sound decrease by distance, in an auditorium with 30 seats. The acoustical and visual design strategy is to minimize the speaker-listener distance. Speech intelligibility is also related to seeing speaker, gestures, body movements, etc.

Hearing and seeing should be compatible. The distance between the farthest seat and the stage should be under 25 m (Mehta et al. 1999).

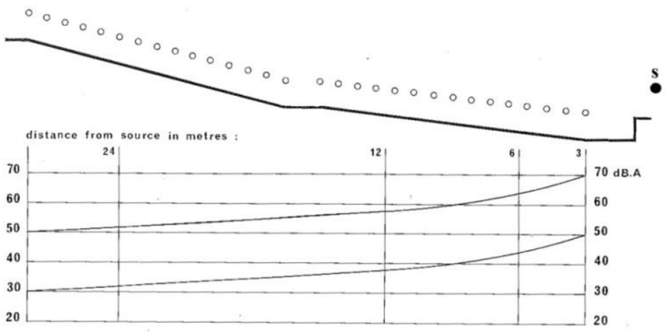

Figure 7. The attenuated human voice by distance
(Source: Moore 1978)

2.2.2. Room Shape

A fan-shape decreases the distance between the audience and the platform. The seating layout should be maximum 125◦ angle if there is a projection screen on the front wall (Long 2005).

The splay of side wall increases the audience capacity. Additionally reflections from side walls are directed toward the rear of the room in fan-shaped room (Mehta et al. 1999). However, speech is not radiated equally in all directions.

In large spaces like lecture halls, the directivity of the speaker’s voice become important. The high frequencies are the most directional because of being most important for intelligibility. (Barron 2010).

The sound pressure is maximum in front of the speaker and decreases on the side of frontal direction. The sound pressure level decrease by angle from the frontal direction.

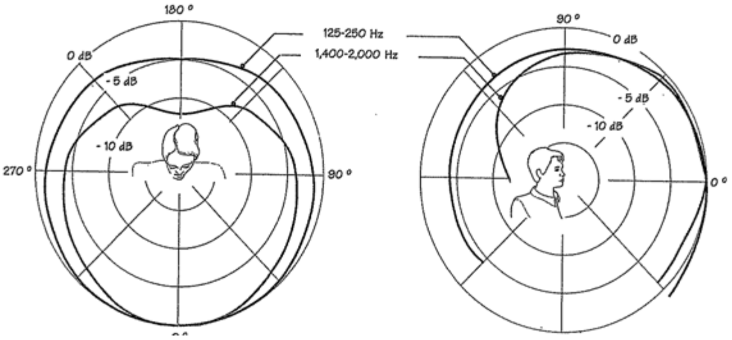

Figure 8. Speech contours with Horizantal and vertical distrubution
(Source: Mehta, et al. 1999)

The maximum side wall splay should be 30° and absolute 65° because of directionality of speech.

2.2.3. Room Volume

Low room volume increases the loudness (Egan 2007). To obtain greater sound energy, smaller volume per seat is required (Mehta et al. 1999).

For a long reverberation time a large volume per seat is needed. Volume/seat value can provide a valuable guideline for acoustic design at the early design stage. (Barron 2010). Recommended area/seat is between 0.55 and 0.7 m² and recommended volume/seat is between 2 and 5 m³ (Mehta et al. 1999).

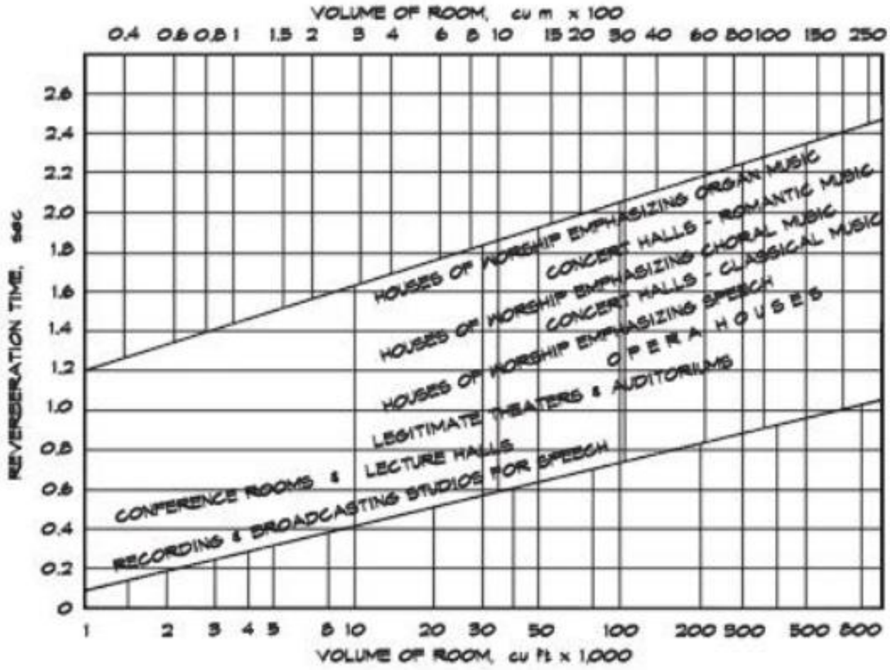

Figure 9. Recommended volume for various functions
(Source: Long 2005)

2.2.4. Reflecting and Absorbing Parts of a Room

Audience provides most of the absorption. If the volume per seat increases, the need to use sound absorption on room surfaces increases as well in order to obtain the required reverberation time. Reverberation times should be less than 0.8 s from 250 to 4000 Hz for classrooms. Long reverberation times reduce the intelligibility of speech and mask speech signals (Egan 2007).

Stage walls should be reflective to send reflected sound over the audience. Absorptive panels should be applied to the rear and side walls of the room to control reverberation and lateral reflections (Long 2005).

The rear wall has the potential to produce echos. Except for small rooms, absorbing materials should be used on the rear wall. Alternatively, the rear wall can be diffusively reflective (Mehta et al. 1999).

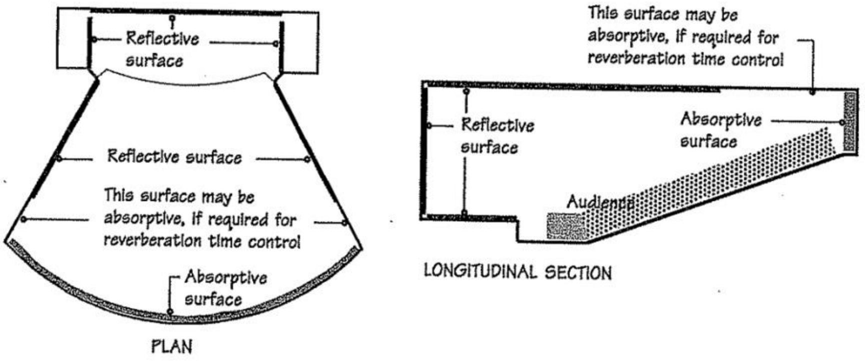

Figure 10. Recommendations for sound reflecting and absorbing parts of a room
(Source: Mehta, et al. 1999)

2.2.5. Floor Rake

A sloped floor provides visual and acoustic comfort. The sloped floor and raised stage increases the direct sound energy over the audience (Mehta et al. 1999). Seating should be greater than 7˚ for visual comfort (Egan 2007). Recommended maximum stage height is 1.05 m. Figure 12 shows that initial sound reaches listeners by decreasing. As sound travels from the first row to rear wall, the heads of listeners provide more absorption in flat halls. (Moore 1978)

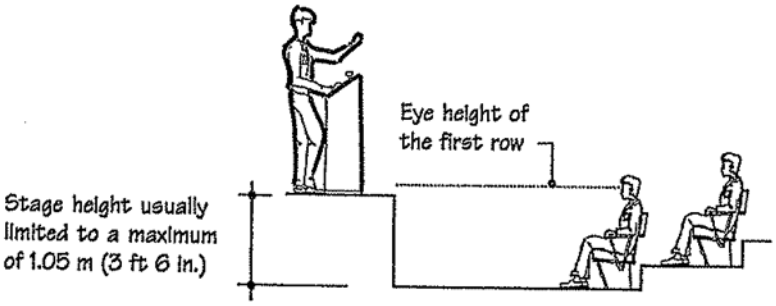

Figure 11. Recommended Raised Stage and the eye level of the first low
(Source: Mehta, et al. 1999)

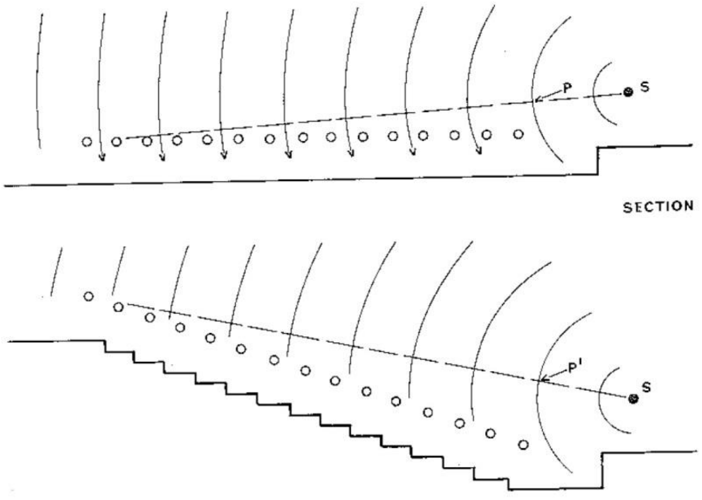

Figure 12. The comparison of Sound Absorption by Audience on Raked and Flat Hall (Source: Moore 1978)

2.2.6. Ceiling Reflections

A reflective ceiling is required for speech. In a large auditorium the ceiling should be profiled to direct sound to the rear parts of the hall.

Suspended panels obscure air conditioning, lighting equipments in the ceiling. Curved reflectors diffuse sound and prevent less acoustical glare especially in multipurpose halls. The recommended size of each reflector is minimum 2.5 m in any one direction. The panels should be chosen to provide high degree of reflection. (Mehta et al. 1999)

2.2.7. Ambient Noise

Conditioning equipments, external noise, footsteps, etc. are the reason of ambient noise. Spaces, such as toilets, foyer, halls, etc. around the hall help to decrease external noise. The carpets also decrease noise (Mehta et al. 1999). Background noise levels should be less than NC 25 and exterior noise than an Leq of 30 dBA (Long 2005).

2.2.8. Sound Reinforcement Systems

A sound system should be included as part of the design and the loudspeakers should be integrated into the appearance of the room (Long 2005).

If seating capacity is greater than 500, sound-reinforcing system is usually required. In small lecture rooms, sound-reinforcing system can be used to help the sof-voiced speakers. The disadvantage of amplified voices is that it –can be harsh and unnatural (Egan 2007).

2.3. Daylighting in Lecture Halls

Daylight provides energy savings for various types of buildings. Buildings such as offices, schools, and industrial facilities can use up to 40 percent of their energy for lighting (Figure 13). Working activities are performed during daylight hours. Architectural design considering daylight usage provides energy savings (Lechner 2009).

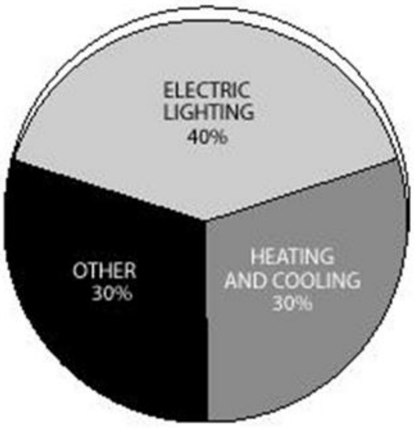

Figure 13. Energy use for various functional buildings
(Source: Lechner 2009)

Daylight improves spatial quality and provides integration between human and nature. It also increases users' satisfaction and thermal comfort (Arpacıoğlu 2012).

The school performance of pupils is related to quality of daylight. The daylight not only has impact on our visual system, but also on our physical and psychological health. It improves productivity and performance of students. Daylight increases student’s performance and provides a better environment for learning and teaching activities (Axarli et al. 2007).

2.4. Variables Affecting Daylighting

2.4.1. Orientation

While planning the location of the building on site, architects should consider maximum usage of natural light. Each architectural programme has its own specific needs of orientation (Phillips 2004).

Lechner expresses rules for orientation:

1. When winter heat is adequate, use of south-facing glazing is needed.

2. When winter heat is not adequate, use of north facing glazing is needed.

3. Without summer overheating glare, avoid east and west glazing is required (Lechner 2009).

Surrounding buildings and vegetation may obstruct the skylight. Designers should consider the daylight potential and daylight availability in their designs. Designers should take into acount the future buildings that will be constructed around their designs. (IEA 2000)

2.4.2. Glass Type

Various types of glass can used in buildings depending on function, cost and aesthetics. Material structure, strength, transparency, etc. determines the selection of glass. Glass has a significant impact on thermal and visual comfort. Philips (2004) mentions the following types of glass.

- Clear glass is basic window glass. It allows direct view to the exterior. It has combinations, such as double or triple glazing.
- Glass blocks can be placed in walls to allow daylight to the interior.
- Laminated glass has internal layers of plastic. Lamination provides strength

with its stratified structure. It can be designed for U/V protection. Low emissivity glass reduces the heat from radiant heat or light by its reflective coating.

- Patterned glass has potential to provide variety of patterns which diffuse the light.
- Photochromic glass responds to heat and light. It darkens under high levels of light and become transparent in low levels of light in a short period.
- Prismatic panels are formed to redirect daylight or reduce glare. Panels are made of acrylic, polycarbonate, etc. in various patterns and thicknesses.
- Tinted glass is generally designed for exterior of buildings and automobile windows in different materials, various colors. The glasses provide solar radiant heat transmission.
- Wired glass with a wire mesh are used for security and fire resistance to high temperatures (Phillips 2004).

2.4.3. Shading Systems

Shading is an effective strategy to improve thermal comfort and visual comfort especially in the summer. The ideal shading prevents solar radiation as much as possible while allowing views to the exterior. The ideal shading systems can reduce the effect of heat gain from the sun, sun glare through the windows and provide privacy.

The type, size, and location of a shading system depends on the level of direct, diffuse, and reflected components of the total solar load.

External shading acts like a barrier against the sun and has implications on the aesthetics of a building (Lechner 2009).

In comparison to using air-conditioning systems, passive shading strategies are both cheaper and more sustainable. Shading systems can be internal and external. To control the heat gain, external shading can be effective and economic in long term (Phillips 2004).

2.4.4. Windows

The window is an opening in a wall or side of a building and allows light and air to the interior. Windows have two main types, first on the side walls of a building, and second on the roof (Phillips 2004). Windows determine the distribution of daylight to a space. Horizontal openings provide more light than vertical openings (Lechner 2009).

2.4.5. Building Form

The form of the building determines vertical and horizontal openings. It also determines the amount of area that will have access to daylighting. In multistory buildings a 4.5 m perimeter zone can be fully daylit and another 4.5 m can be partially daylit (Lechner 2009).

2.4.6. Color

Light colors reflect more light into the building and farther into the interior and diffuse the light at the same time. Light-colored interiors reflect light farther into the building and diffuse it to reduce dark shadows, glare, and excessive-brightness ratios (Lechner 2009).

2.5. Design Principles of Skylights

Strategies for diffuse skylight can be designed for sky conditions. These strategies are related to direct sunlight.

In general designers aim to control solar shading and glare protection. Solar shading is not only related with thermal function, but also related with obstructing direct sunlight, and glare protection for visual functions. Additionaly solar shading systems can protect skylight and reflected sunlight (IEA 2000).

Lechner (2009) mentions the following skylight strategies:

a. Skylight spacing should provide uniform lighting. If there are no windows, the skylights should be spaced, as shown in Figure 14.

b. The sloped walls around skylights provide better light distribution and less glare.

c. The skylight sould be placed high in a space. This provides opportunity to diffuse light before reaching the floor.

d. Skylights should be placed near walls.

e. Interior reflectors should be used to diffuse the sunlight.

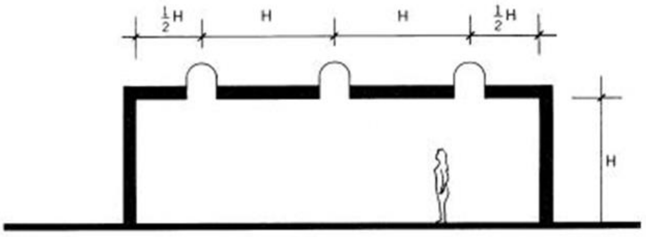

Figure 14. Recommended spacing for skylights without windows as a function of ceiling height (Source: Lechner 2009)

f. Exterior shades and reflectors are used for the summer and winter. While shading should obstruct the summer sun, reflectors should collect the winter sun for the skylight.

g. Horizontal skylights collect more light and heat in summer. Skylights steeply sloped by the north or south provide more uniform light.

2.6. Energy Efficiency in Buildings

IEA (International Energy Agency) indicates that energy consumption in buildings account for about 40% of the world’s total use of energy. Energy is used in buildings for heating and cooling, ventilation, lighting, etc.

An efficient building should minimize heat loss or gain depending on the season and its internal features. Architects’ consideration in solar use, control, air movement, etc. determines occupants’ thermal comfort (Bainbridge 2011).

Thermal comfort is one of the main goals of building design and is necessary to provide a base for comfortable living. During the design stage architects should consider human factors, climatic factors and building factors.

2.6.1. Concepts of Thermodynamics

Thermodynamics is a first definition of heat. The discipline divides the world into systems and environments (Hens 2012).

The first law of thermodynamics is the principle of conservation of energy. Energy cannot be created or destroyed but only converted from one form to another. The second law of thermodynamics is that heat (or energy) transfer can only transfer from a hotter to a cooler surface (Szokolay 2008)

Heat flow means end energy consumption. Keeping the convenient temperature in buildings is the main target of thermal comfort. Temperature has an impact on comfort and durability (Hens 2012).

Heat flow from a high to a low temperature zone can take place in three forms: conduction, convection and radiation.

Thermal conduction is a heat transfer period in solids or static fluids (von Bèockh 2012). Conductivity is related to material properties, regardless of its shape or size. Transmittance, or U-value includes the surface effects and it is the most commonly used value for measurement (Szokolay 2008).

The heat transfer between a solid wall and a fluid is defined as convective heat transfer or commonly convection. Transfer occurs as free convection or forced convection. In free convection the fluid flow is driven by gravity on account of the density difference. In forced convection the flow happens due to an external pressure difference (von Bèockh 2012).

Heat transfer by thermal radiation is carried by electromagnetic waves (von Bèockh 2012). The material affect radiation by interacting in particular the surface of the material (Lechner 2009).

Buildings can have a series of heat inputs and outputs: internal heat gain (Qi), conduction heat gain or loss(Qc) , solar heat gain (Qs), ventilation heat gain or loss (Qv), evaporative heat loss. (Qe). Szokolay defines these inputs and outputs as follows:

Internal heat gain (Qi) can be affected only by separating any heat emitting functions from spaces or dissipating the generated heat at or near the source.

Solar heat gain (Qs) is a result of windows mostly. Window size, orientation, glazing material and shading devices affect solar heat gain.

Conduction heat flow (Qc) is influenced by the shape of the building, the surface-to-volume ratio and the thermal insulating features of the envelope.

Ventilation heat flow (Qv) is affected by the fenestration and other openings, the wind direction, wind permeability of the envelope.

Evaporative cooling (Qe) is a method used in hot-dry conditions by mechanical equipment (Szokolay 2004).

2.6.2. Passive Solar Design

Architects in early design stage should consider the potential of the site and determine their design approach by the features of the site. When opportunities offered by the site are properly taken advantage of, the requirements on mechanical equipment can be reduced. At the same time, this passive design approach reduces costs over the lifetime of the building. Bainbridge and Haggard (2011) defines passive building design as an integrated design approach that uses on-site energy sources and admits to the interior by architectural more than mechanical systems. A passive building uses energy from the sun and climate of the site.

The solar heat input can overheat the interior, this may cause discomfort. The roof of the examined hall is designed with a reflective glass cover. In spite of the reflective glass, cooling and heating loads adversely affect the users' thermal comfort. Window size and placement decisions are the most important decisions in passive solar design approach. In this study, properties of various glass types are considered for improving thermal performance. Windows let through sunlight, indoor heat and solar radiation from the building envelope. Therefore most of heat losses in winter, solar heat gains in summer are result of windows (NREL 2001).

A window's heat transmittance is measured by U-factor. A smaller U-factor provides more insulating value than a larger one. To improve energy-efficiency, some glasses are coated with a very thin layer of material that is engineered to transmit or reject certain frequencies of radiation. This coated glass is called low-emissivity (low-e) glass (NREL 2001).

Glass's transmittance is measured by solar heat gain coefficient (SHGC), which is a decimal number less than one. The low U-value windows also reject most solar gains (low SHGC) (NREL 2001). G-value is the coefficient to measure the solar energy transmittance of glass. G-value is used generally in Europe. While SHGC considers the complete window assembly including frames, G-value is a property of glass alone.

CHAPTER 3

EVALUATION OF THE LECTURE HALL

In this chapter, first, the lecture hall is described, then acoustic, daylighting and thermal performance of the hall are examined. Measurements and simulation results are presented.

The lecture hall in Izmir Institute of Technology Department of Mathematics opened in the fall semester of 2012-2013 academic years. The hall has a seating capacity of 220 people arranged in a circular plan within a cylindrical mass. Cylinder diameter is 14.60 m. Ceiling height at the back of the hall above the back row is 7 m. Ceiling height above the stage is 11.75 m.

Reflective glass is used to cover the whole roof. Concrete beams carry the weight of the roof with a structural grid of 3.5 m. x 3.5 m. The four squares in the center are used as a large (~40m^2 total) skylight. The rest of the roof has thermal insulation and suspended ceiling underneath the reflective glass cover.

The walls of the hall are plastered aerated concrete blocks. The floor is covered with natural stone. The desks are made of wood (Figure 15). The hall is placed along the northeast-southwest axis, the plane of the roof slopes down approximately 8 degrees to the southwest. The plan and section of the hall is shown in Figure 16.

Figure 15. Interior of the lecture hall

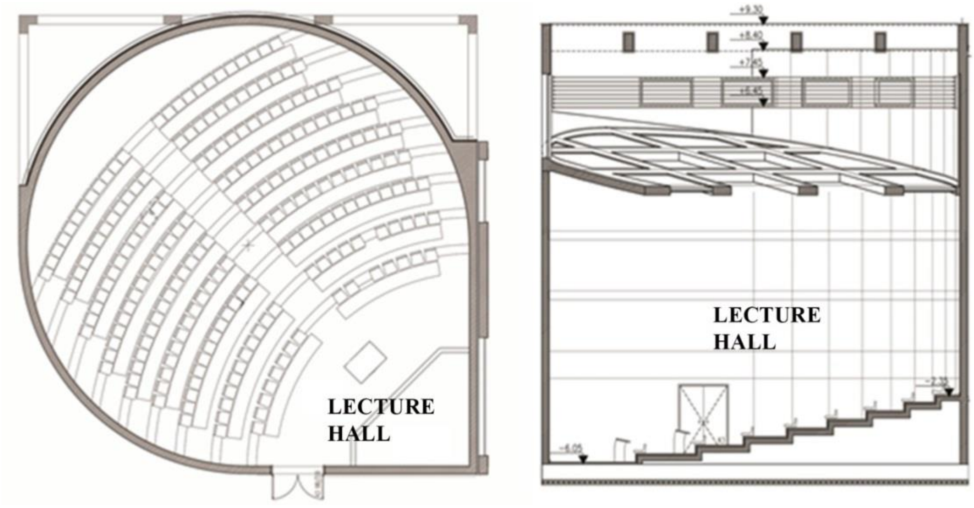

Figure 16. Plan and section of the lecture hall

3.1. Acoustic Analysis

3.1.1 Measurements

Over the years, a number of different methods for measuring the reverberation time have been developed and implemented, the most common being: the interrupted noise method, the integrated impulse response method, the method of recording the room response to an impulsive source, the burst method. (Jambrosic, et al. 2008) The interrupted noise method is chosen for measurements.

Acoustic measurements were conducted in April 2012. Reverberation times were measured by Brüel + Kjaer 4296 OmniPower sound source, 2716 amplifier and 2260 Sound Measuring Equipment (Figure 17).

In particular the following experimental procedure was used:

a. Start the measurement and recording of data, in order to estimate the background noise level;

b Switch on the source, by remote control, so that the acoustical field can go in a stable state;

c. Switch off the source, so that the acoustical field starts its decay;

d. Stop the measurement and data recording (Quartieri et al. 2010).

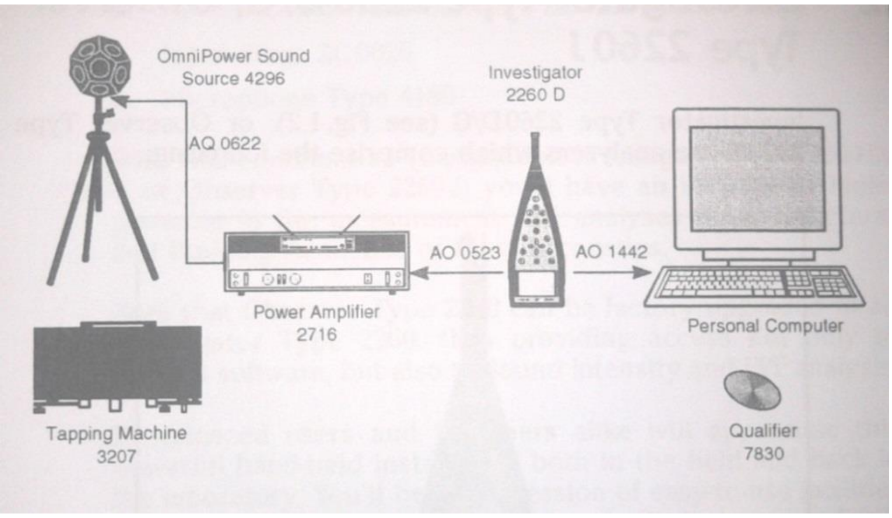

Figure 17. Brüel + Kjaer system for measurements and analyses of Building Acoustics (Source: Brüel + Kjaer 2260 Manual)

Twenty four points was chosen in order to achieve appropriate coverage in the room. Four main points are referenced for analysis. Reverberation time was measured from 100 Hz to 3.15 kHz. The points where reverberation times were measured are shown in the Figure 18.

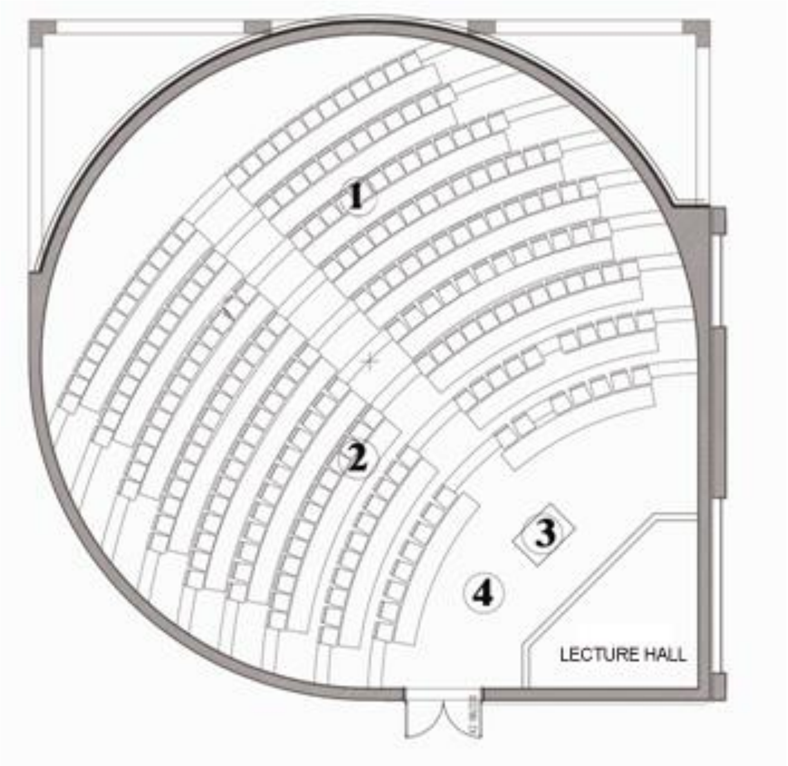

Figure 18. Reverberation time measurement points

Measurements were taken while the hall was empty and the background noise was 23.6 dB (Leq (A), 30s).

While conducting the measurements, the ISO Standard 3382-1: 2009, Acoustics-Measurement of room acoustic parameters was considered.

The ISO Standard requires that:

a. The positions of microphones must be at least half wave length far from each other, a minimum distance of about 2 m for the common frequency range;

b. The distance between each position and the nearer reflecting surface, including the floor, must be at least one quarter of wave length, generally about 1 m ;

c. The microphones must not be too close to a source position, in order to avoid influence from direct sound.

d. For measurements in octave bands the bandwidth of the signal shall be greater than one octave and for measurements in one-third octave bands the bandwidth of the signal shall be greater than one-third octave.

e. The impulse source shall be able to produce a peak sound pressure level sufficient to ensure a decay curve starting at least 45 dB above the background noise in the corresponding frequency band. If only T20 is to be measured it is sufficient to create a level at least 35 dB above the background level.

f. It is preferable to measure reverberation times in octave bands from 63 Hz to 4 kHz in concert halls and rooms for speech.

The recommended maximum volume for a lecture hall for 220 people is 1100 m^3. The ceiling, in order for the cylinder to be expressed in the street facade, is designed too high for the lecture hall. As a result the volume of the hall is 1875 m^3. Moreover, the only sound absorbing material is the suspended ceiling tiles. For these reasons, reverberation time is too long. The recommended reverberation time is between 0.7s – 0.9s. However, actual reverberation times are between 3.0s – 5.9s. Measured reverberation times are shown in Table 3.

3.1.2. Simulations

Building energy simulation is step by step process and involves one or several of the following steps (Harputligil, 2007):

- An analysis in order to determine the the problem or requirements for design,
- Selecting the appropriate simulation software,
- Creating the model of building with relevant elements and attributes,
- Calibration of the model,
- Arrangement of conditions (indoor comfort conditions, climate data, etc..)
- Evaluation of the simulation results,
- Evaluation of results for the design.

Acoustic, visual and thermal performance of the lecture hall are evaluated for analysing the current conditions and the proposals to improve users' comfort in the light of results obtained simulation results by referencing the simulation process.

For the acoustic simulation of sound in large rooms there are two classical geometrical methods, namely the Ray Tracing method and the Image Source method.

The Ray Tracing method uses a large number of particles, which are emitted in various directions from a source point. The particles are traced around the room loosing energy at each reflection according to the absorption coefficient of the surface. The Image Source method is based on the principle, that a specular reflection can be constructed geometrically by mirroring the source in the plane of the reflecting surface. The advantage of the image source method is that it is very accurate, but if the room is not a simple rectangular box there is a problem (Rindel 2000).

The disadvantages of the two classical methods have led to development of hybrid models, which combine the best features of both methods. One method, which has proven to be efficient, is the 'secondary source' method used in the ODEON program (Rindel 2000).

The lecture hall is modeled and simulated in ODEON software. Acoustical analysis of the hall is conducted in ODEON through a four stage process: Modeling, placement of source, material assignments and simulation evalution. ODEON model is created by importing a surface model prepared in AutoCAD and saved as a DXF file. Odeon uses planar surfaces for models (Kara 2009). The circular walls of the hall are modeled as 29 surfaces. Figure 19 shows the internal perspectives of lecture hall model.

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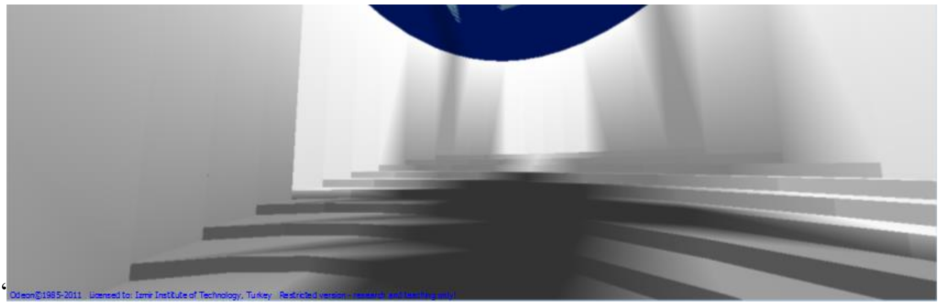

Figure 19. Internal perspective of ODEON model

Odeon library includes materials having absorption factors from 63 to 8000 Hz octave band. (Kara 2009) Surfaces are assigned materials that already exist in ODEON library and results are obtained without fine tuning and without using advanced settings. Just like architects could have employed this simulation during the early design stage. The source is defined as the omnidirectional point source, at a height of 1,5 meters. Figure 20 and Table 2 shows the estimated reverberation times by ODEON.

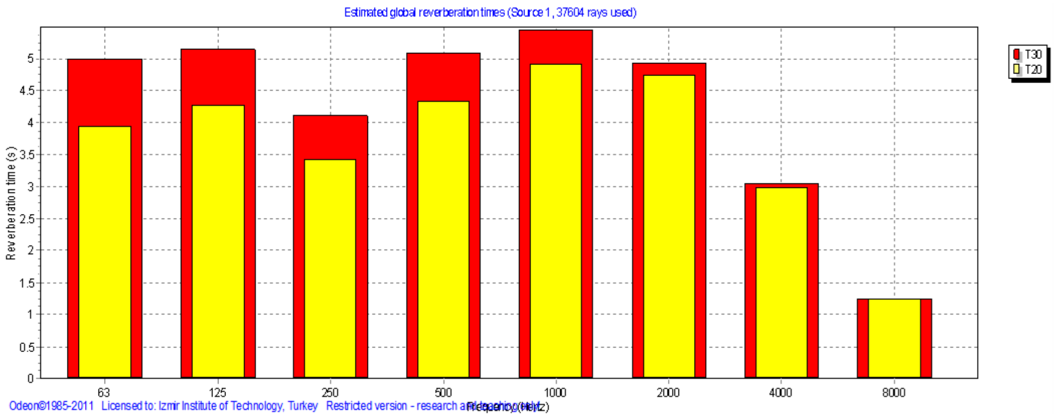

Figure 20. Estimated reverbertion times by ODEON software

Table 2. Estimated reverbertion times by ODEON software

T30 estimates

Hz	63	125	250	500	1000	2000	4000	8000
[s]	4.99800	5.14800	4.11000	5.07600	5.44200	4.93200	3.04200	1.24800

T20 estimates

Hz	63	125	250	500	1000	2000	4000	8000
[s]	3.94200	4.27500	3.42000	4.32000	4.91400	4.73400	2.97900	1.24200

ODEON simulation and actual measurement results are very close. Only at 125 Hz ODEON estimates a higher reverberation time. Table 3 and Figure 21 present the comparison of measured reverberation times to ODEON results. As a result of such long reverberation times, it is very difficult to conduct lectures in this hall.

Table 3. Measured reverberation times and ODEON results [s]

Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**
Point 1	3.3	3.94	5.09	5.71	5.12
Point 2	3.09	3.34	4.99	5.7	5.13
Point 3	3.11	3.69	4.98	5.86	5.14
Point 4	3.75	3.8	5.03	5.57	5.18
Measurement average	3.31	3.69	5.02	5.71	5.14
Odeon	5.15	4.11	5.08	5.44	4.93

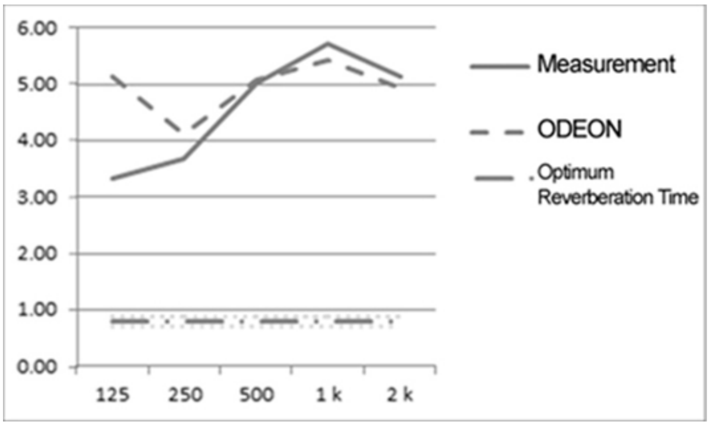

Figure 21. Measured reverberation times and ODEON results [s]

3.1.3. Calculation of Articulation Index

Articulation index is calculated for the lecture hall to examine speech intelligibility. The reverberation time measurement Point 1 and 2 are referenced for calculation. These points are presented in Figure 22.

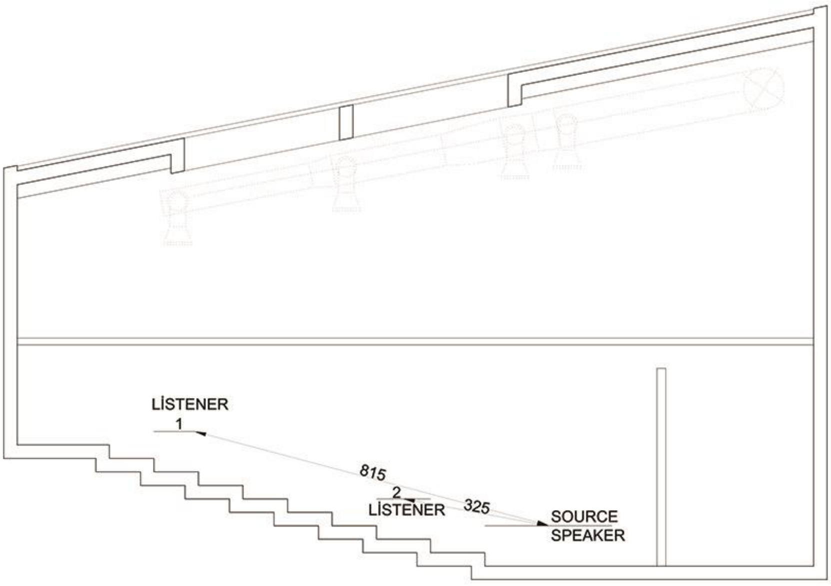

Figure 22. Reference points for Articulation Index Calculation

Articulation Index is calculated by:

$$AI = \sum WF \times (S\text{-}N) \tag{2}$$

Where:

AI = Articulation Index

WF = Weighting Factor for respective one-third octave band

S-N = Signal-to-Noise ratio for respective one-third octave band (Mehta et al. 1999).

Sound pressure level decreases by distance. The reduction is calculated using equation 3.

$$\Delta L = 20 \log(distance) \tag{3}$$

Noise rating levels used in calculation are presented in Table 4. Table5 and Table 6 show the calculation for Point 1 and 2.

Table 4. Noise Rating Values used in Calculation of AI
(Source: ISO/R 1996:1971)

Maximum Sound Pressure Level (dB)								
Noise Rating - NR - Curve	Octave band mid-frequency (Hz)							
	62.5	125	250	500	1000	2000	4000	8000
NR 30	59	48	40	34	30	27	25	23

Table 5. The Calculation of Articulation Index for Point 1

Frequency (Hz)	SPL at 1 m	Direct SPL for Point 1(8.15 m away)	Noise level(dB) from NR 30	S-N Ratio	WF	AI=(S-N)*WF (Point 1)
250	78.5	60.28	40	20.28	0.0024	0.049
500	80	61.78	34	27.78	0.0048	0.133
1000	74	55.78	30	25.78	0.0074	0.191
2000	68	49.78	27	22.78	0.0109	0.248
4000	63	44.78	25	19.78	0.0078	0.154

AI=0.049+0.133+0.191+0.248+0.154=0.775

Table 6. The Calculation of Articulation Index for Point 2

Frequency (Hz)	SPL at 1 m	Direct SPL for Point 2(3.25 m away)	Noise level(dB) from NR 30	S-N Ratio	WF	(S-N)*WF (Point 2)
250	78.5	68.26	40	28.26	0.0024	0.068
500	80	69.76	34	35.76	0.0048	0.172
1000	74	63.76	30	33.76	0.0074	0.250
2000	68	57.76	27	30.76	0.0109	0.335
4000	63	52.76	25	27.76	0.0078	0.217

AI=0.068+0.172+0.250+0.335+0.217=1.041

Reverberation time for the hall is 4.57 s. The value to substract is determined as 0.55 using Figure 4. Calculated AI is 0.225 and 0.491 for point 1 and point 2, respectively. Since the speaker can easily be seen by the students, Effective AI is determined using Figure 5. Effective AI values are 0.4 for Point 1 and 0.6 for Point 2. The corresponding ratings are ‘marginal’ for Point 1 and only ‘good’ for Point 2. These ratings suggest that improvements for speech intelligibility in this lecture hall are required.

3.2. Daylighting Analysis

3.2.1 Measurements

The skylight provides opportunity to maximize the use of natural light. The main advantage of top lighting is the uniform and high illumination levels possible. Unfortunately, top lighting also presents some potential glare problems (Lechner 2009). In the lecture hall, there are no shading devices and the abundance of daylight has a negative impact on projection systems. Also, the stage and the whiteboards are placed in the northeast corner and the roof slopes down towards the southeast. As a consequence, direct sunlight shines on the whiteboards causing glare. Additionally, the exposed ventilation ducts in the ceiling creates dark shadows and high contrast under direct sunlight.

Daylight levels were measured on December 20, 2012 at 12:00, 14:00, and 16:00. During the measurements light levels outside the building was measured at 1048 lux (12:00), 3092 lux (14:00) and 569 lux (16:00). The 23 measurement points are indicated in Figure 23. The daylight levels are plotted in Figure 24, Figure 25 and Figure 26.

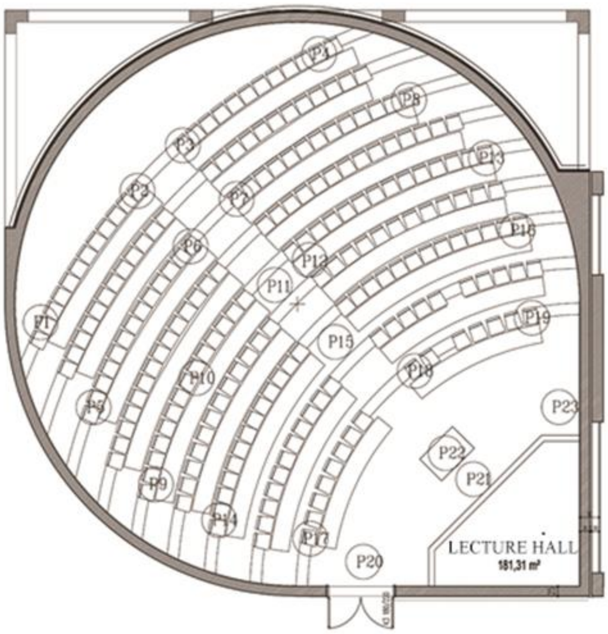

Figure 23. Measurement points for daylight

3.2.2. Simulation

Daylight in the hall is simulated in 3ds Max Design software. After modeling the hall, materials have been assigned and location, date and weather settings are entered. Daylight illuminance levels are estimated for the measurement points and compared with measurement results in Figure 24, Figure 25 and Figure 26. Measured values are on average higher than simulated estimates. This is related to material selections in simulation and more importantly the difference between the actual sky conditions and the simulation settings. Surface materials and texture features are entered by considering natural characteristics of materials. Colors of materials are determined with Photoshop by transferring average RGB values taken from the photos of surfaces. Approximate reflection, refraction of the surface materials are entered to the material. Properties of materials used in simulation are presented in Table 7.

Table 7. Properties of materials used in 3ds Max.

	Material	Colour	Reflection Level	Diffuse Level	IOR (Index of Refraction)
Wall	Plastered Aerated Concrete Blocks	RGB(183,177,179)	30%	65%	3
Floor	Natural Stone	RGB(119,134,153	60%	25%	3
Desk	Wood	RGB(159,135,125)	30%	25%	3
Roof	Reflective Glass	RGB(254,254,254)	20%	5%	1,5
Whiteboard	Film Laminate	RGB(120,132,144)	70%	75%	5

Daylight level distributions are very similar between measured and simulated values. The values 3ds Max Design provides without any calibration or fine tuning have the following relative mean square percentage errors (Equation 4): 29.5% for 12:00, 28.6% for 14:00 and 41.8% for 16:00. Slightly higher deviations are observed at points near the white boards that were not modeled in the simulation tool. CIBSE (The Chartered Institution of Building Services Engineers) recommends 500 lux for lecture halls (CIBSE, 1999). Both measurement results and simulated estimates are much higher than the recommended values around noon.

However, in the afternoon, the light levels fall below required levels. Adjustable shading elements are recommended to ensure compliance with different sky conditions throughout the day.

$$RMSPE = 100 * \sqrt{\frac{\sum_{1}^{n} \left(\frac{y_{estimated} - y_{measured}}{y_{measured}}\right)^2}{n}} \qquad (4)$$

Duration of direct sunlight incidence on the whiteboard and the projection screen can be determined by almost every computer-aided architectural design tool. The sunlight incidence on the wall is shown for March 21 at 15:30 in Figure 27. 3ds Max Daylight Analysis tool also reveals the direct sunlight hitting the whiteboard and the projection screen all year long (Figure 28). Analysis with Ecotect software clearly shows that direct sunlight hits the whiteboard and the projection screen between February and October (Table 9). It is assumed that the hall operates 9:00 to 17:00 on weekdays. Direct sunlight hits the whiteboard during approximately 30% of all lecture hours. Shading devices are necessary for all afternoon classes held in this lecture hall.

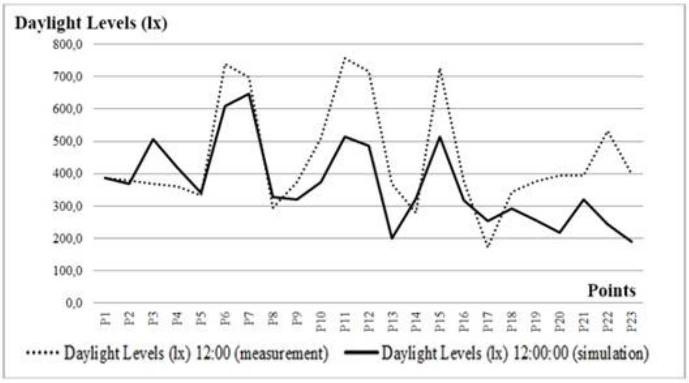

Figure 24. Daylight levels (12:00) – comparison of measurement and simulation

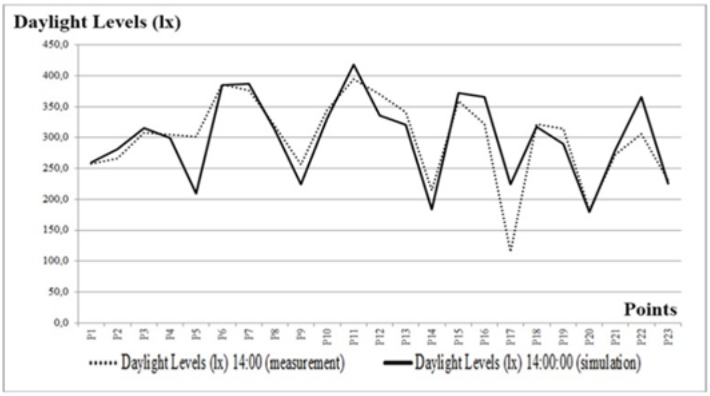

Figure 25. Daylight levels (14:00) – comparison of measurement and simulation

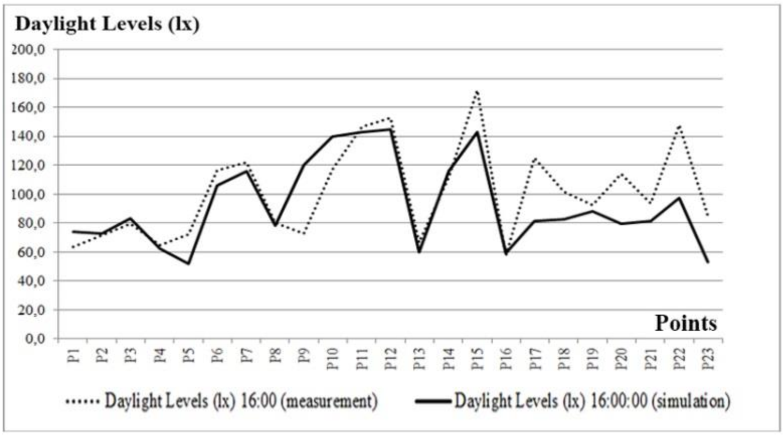

Figure 26. Daylight levels (16:00) – comparison of measurement and simulation

Table 8. Daylight levels measurement and simulation results

	Measurement (December 20, 2012)			**Simulation**		
	12:00	**14:00**	**16:00**	**12:00**	**14:00**	**16:00**
P1	386	257	64	387	266	64
P2	380	266	72	369	256	63
P3	368	308	80	507	347	95
P4	360	305	65	419	287	72
P5	332	301	72	341	235	58
P6	739	386	117	609	419	104
P7	699	377	122	646	445	111
P8	295	318	80	328	220	54
P9	375	257	73	321	220	60
P10	510	345	117	374	253	69
P11	757	394	147	514	357	90
P12	715	371	153	486	335	83
P13	370	342	66	200	135	38
P14	279	214	112	322	222	56
P15	725	359	172	513	352	90
P16	377	322	58	318	215	53
P17	174	116	125	253	177	42
P18	343	322	102	292	200	49
P19	376	314	92	257	175	45
P20	393	183	114	218	149	38
P21	395	272	94	321	219	53
P22	533	306	148	243	168	40
P23	400	231	85	189	128	30

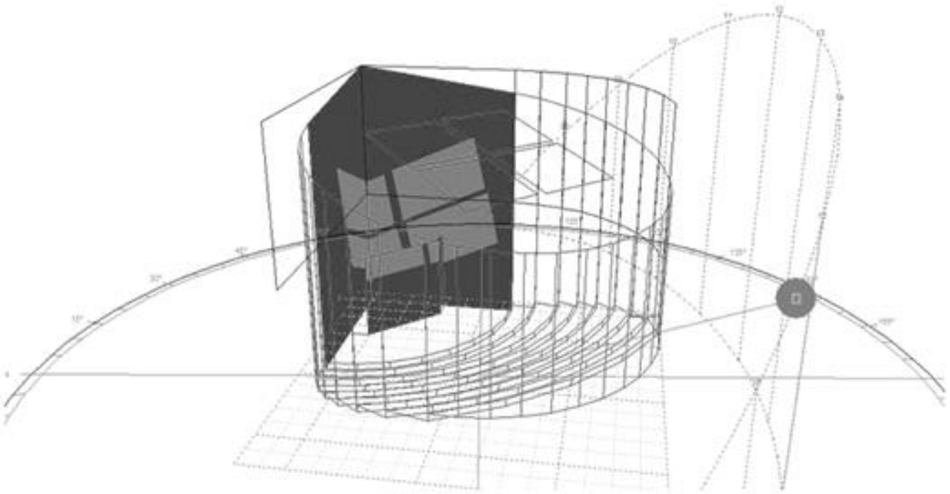

Figure 27. Daylight incidence on the whiteboard / projection screen by Ecotect (March 21, 15:30)

Table 9. Duration of daylight incidence on the whiteboard/ projection screen

February	12:30 - 15:00
March	12:00 - 16:00
April	12:30 - 16:30
May	13:00 - 17:00
June	13:00 - 17:30
July	13:00 - 17:00
August	12:30 - 16:30
September	12:00 - 16:00
October	12:30 - 15:00

Figure 28. Daylight incidence on the whiteboard / projection screen by 3ds Max Daylight Analysis Tool (March 21, 15:30)

3.3. Energy Efficiency

3.3.1 Simulation

The roof is designed with a reflective glass cover. This leads to increased cooling and heating loads in Izmir which has a Mediterranean climate with daily averages of 29°C in July and 9°C in January.

Long term measurements in the hall have not been conducted. However, the implications of designing a roof surface with a skylight oriented to southwest in Izmir have been explored with Ecotect software. Monthly heating and cooling loads have been estimated for the current situation with a skylight using reflective glass, as well as the alternative which is a closed concrete roof with standard insulation. It is assumed that the hall operates 9:00 to 17:00 on weekdays for 100 users. Results are presented in Table 10 and Table 11. Ecotect simulation estimates that the total annual heating and cooling loads are increased by 52% because of the skylight.

Table 10. Monthly heating and cooling loads comparison with Closed concrete roof with standard insulation

	Closed concrete roof with standard insulation		
	HEATING	COOLING	TOTAL
Month	(kWh)	(kWh)	(kWh)
January	179.4	0.0	179.4
February	218.2	0.0	218.2
March	97.1	0.0	97.1
Apri	15.6	215.3	231.0
May	0.0	1188.0	1188.0
June	0.0	1684.7	1684.7
July	0.0	1881.1	1881.1
August	0.0	1811.2	1811.2
September	0.0	1331.3	1331.3
October	0.0	665.0	665.0
November	64.9	0.0	64.9
December	168.8	0.0	168.8
TOTAL	743.9	8776.7	9520.7
Per m² (179,4 m²)	4.1	48.9	53.1

Table 11. Monthly heating and cooling loads comparison with roof with skylight

	Roof with skylight		
	HEATING	COOLING	TOTAL
Month	(kWh)	(kWh)	(kWh)
January	159.1	0	159.1
February	196.6	0	196.6
March	58.6	0	58.6
April	6	254.9	260.9
May	0	1907.6	1907.6
June	0	2759.6	2759.6
July	0	3043.2	3043.2
August	0	2932.5	2932.5
September	0	2132.1	2132.1
October	0	859.7	859.7
November	38	0	38
December	172.2	0	172.2
TOTAL	630.5	13889.5	14520.1
Per m^2 (179.4 m^2)	3.5	77.4	80.9

CHAPTER 4

PROPOSALS AND DISCUSSION

4.1. Proposals for Improving Comfort Conditions in the Lecture Hall

Acoustic, visual and thermal performance of the lecture hall needs to be improved. This chapter presents the proposals to improve users' comfort in the light of results obtained from field measurements and simulation results.

Unfortunately due to severe budget constraints, external shading devices could not be considered. However, movable shades respond to variations in daylighting. To reduce heat gain, interior shades should be highly reflective, while darker colors can be acceptable outdoors. Shading is much more effective when placed outside the glazing (Lechner 2009)

Use of a rolling roof system over the skylight would have been an effective design option to improve visual and thermal comfort. The motorized system performs folding and sliding movement. Louvres turning around its axis obstruct the direct sunlight and reduce solar heat gain. Louvres can move by wheels and the skylight can be completely closed allowing the use of projection systems.

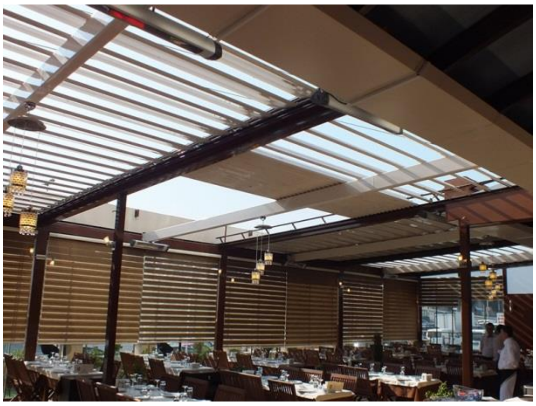

Figure 29. Rolling roof system
(Source: http://www.makrowin.com)

To improve the acoustics, a series of acoustic baffles are proposed for placement under the skylight (Figure 29). Baffles have glass wool structure and provide high absorption. The energy hitting the surface of sound blocking panel is converted into heat energy due to the friction in the pores of the panel and the sound energy reflected from the surface decreases.

Figure 30. Acoustic baffles
(Source: http://aktav.com.tr)

Also acoustic fiberglass panels with 95 kg/m³ density are proposed for mounting on the rear wall (behind the audience). The semi-rigid panels are mounted with concealed vertical profiles that fit channels in the panels. Both the baffles and the acoustic panels have 40mm thickness.

Sound absorption is defined as the ratio of absorbed sound energy to total incident sound energy (Moore 1978). Baffles have a porous structure. The absorption coefficients of porous absorbers increase with frequency (Mehta et al. 1999). Figure 31 shows the sound absorption coefficients of the wall panels. Note that values exceeding 1.0 are due to testing procedures and are rounded to 1.0 for simulation.

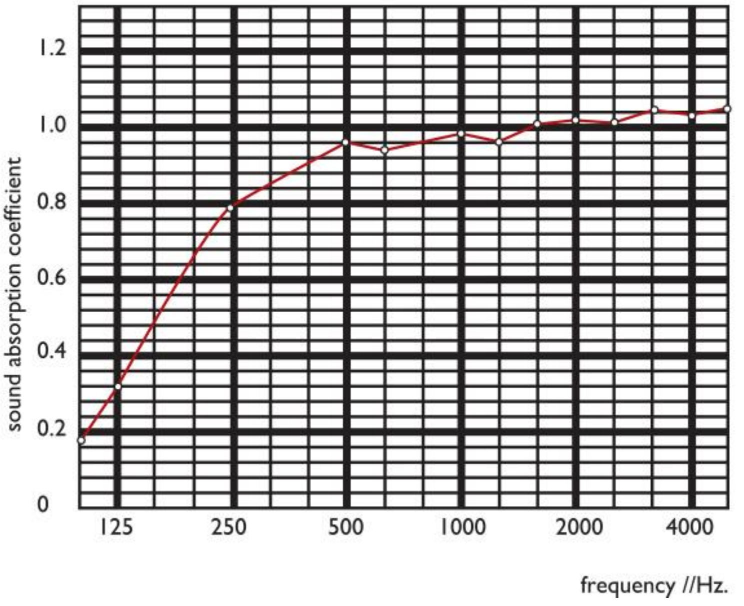

Figure 31. Sound absorption coefficient of wall panel
(Source: http://aktav.com.tr/)

ODEON simulations indicated that 130 m² of absorbing surface provided by the baffles was insufficient and more absorption was required. 53 baffles (81 m²) with size of 90x170 cm are proposed on the ceiling with grid profiles carriers. 65 sound-absorbing panel (78 m²) with size of 60x 200 cm are envisaged on the rear wall coverings with U profiles carriers. Absorbent surface with approximately 159 m² are obtained. The improvements in performance were predicted by ODEON. Reverberation time estimates for the treated hall is given in Table 12. The values obtained by ODEON are close to optimum values. The plan and section of the proposal are seen in Figure 32 and Figure 33.

Table 12. Reverberation times for proposed improvements (s)

Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**
Odeon	1.41	0.98	0.73	0.77	0.89

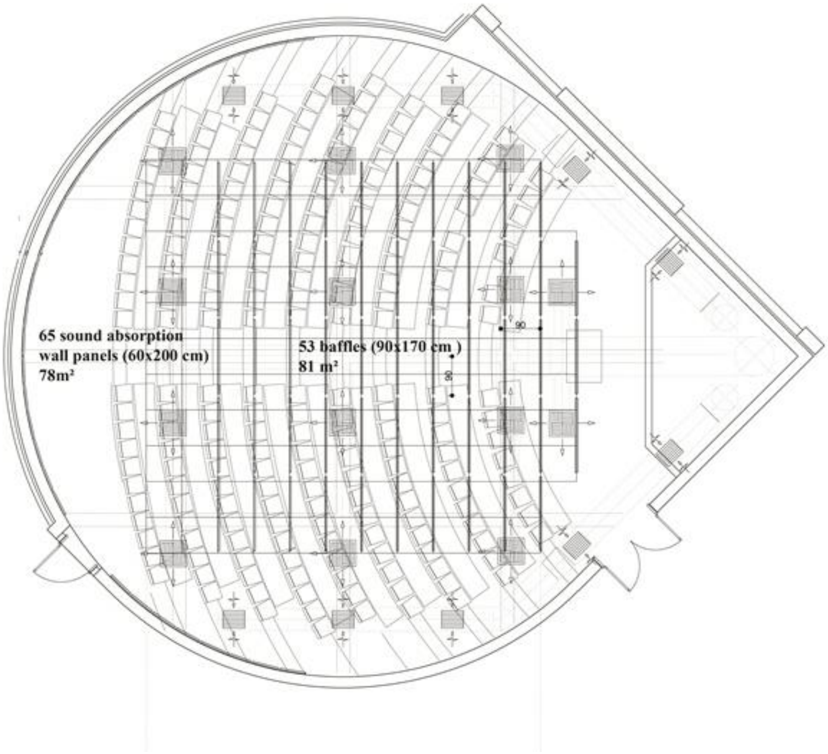

Figure 32. Plan of the arrangement of sound absorption panels

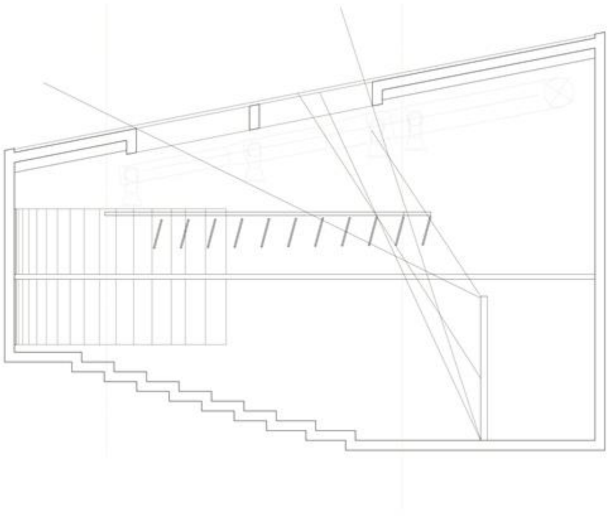

Figure 33. Section of the arrangement of sound absorption panels

The proposal’s improvent in speech intelligibility is also predicted using AI values. The average reverberation time after improvements is predicted as 0.956 s. Figure 4 provides the value of 0.09 to substract for this reverberation time. Thus calculated AI is 0.685 for Point 1 and 0.951 for Point 2. Effective AI becomes 0.75 for Point 1 and 0.95 for Point 2. Predicted AI ratings are ‘very good’ for both points after proposed improvements.

Top lighting presents some potential glare problems. To improve visual comfort the baffles are designed as a series of louvers that will act as shading devices to prevent direct sunlight from reaching the whiteboard and projection screen surfaces. Figure 34 show that the system of baffles controls glare and veiling reflections. Wireframe and three-dimensional model of the hall showing the arrangement of baffles and sound-absorbing panels in the hall are shown in Figure 35 and Figure 36.

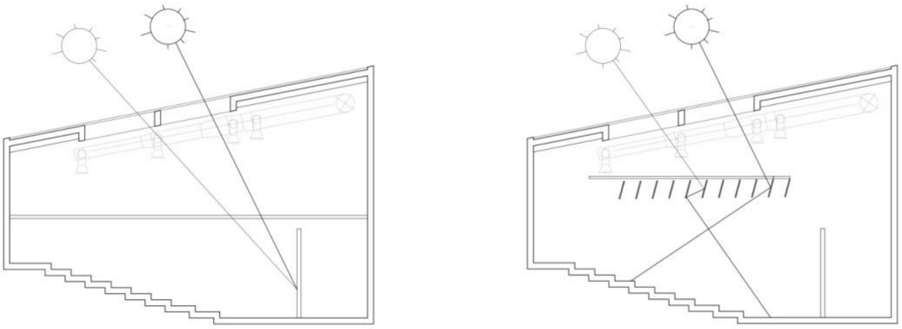

Figure 34. The system of baffles control direct glare and veiling reflections

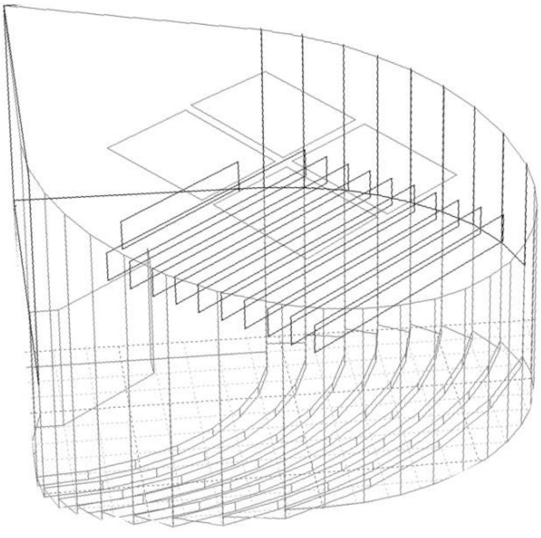

Figure 35. The proposed acoustic baffles under the skylight

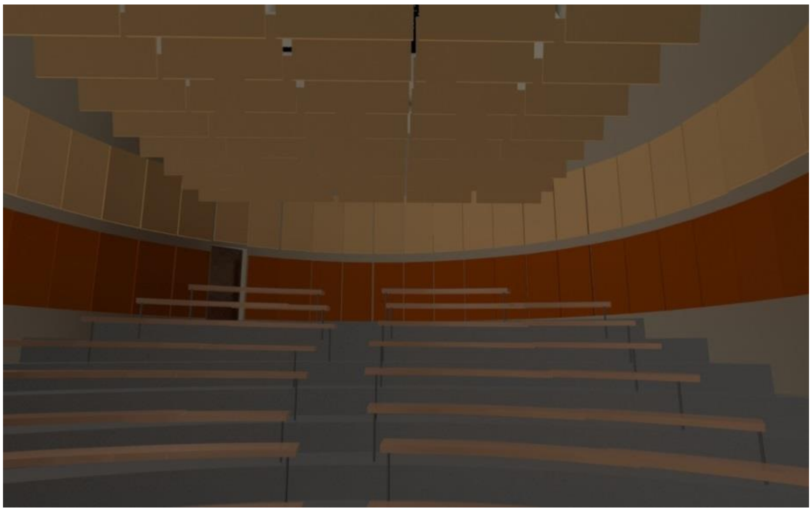

Figure 36. Three-dimensional model showing the arrangement of sound-absorbing panels and baffles in the hall

Analysis with Ecotect software reveals that the baffles shorten the period of direct sunlight glare on the whiteboard. The period of glare is related to angle of the baffles. The proposal is simulated with various angles in Ecotect. Sunlight incidence on the wall is shown for March 21 at 15:30 in Figure 37 with the proposal. 3ds Max Daylight Analysis tool also provides a similar result (Figure 38). It is revealed that proposal decreases the period of direct sunlight on the whiteboard. The direct sunlight causes glare 17% (with 0˚), 15% (with 5), 12% (with 15˚) and 11% (with 30˚) of lecture hours all around the year. Direct sunlight is prevented in months the hall is used extensively between October and February. Direct sunlight hits the whiteboards from March to September. Durations of daylight incidence on the whiteboard are shown in Table 13. Unfourtunately, the daylight levels decrease with the use of baffles. Figure 39, Figure 40 and Figure 41 present simulation results of current situation and the hall with the proposal. These figures reveal the decrease in the daylight levels with the proposed baffles. Especially in the afternoon hours daylight levels are low.

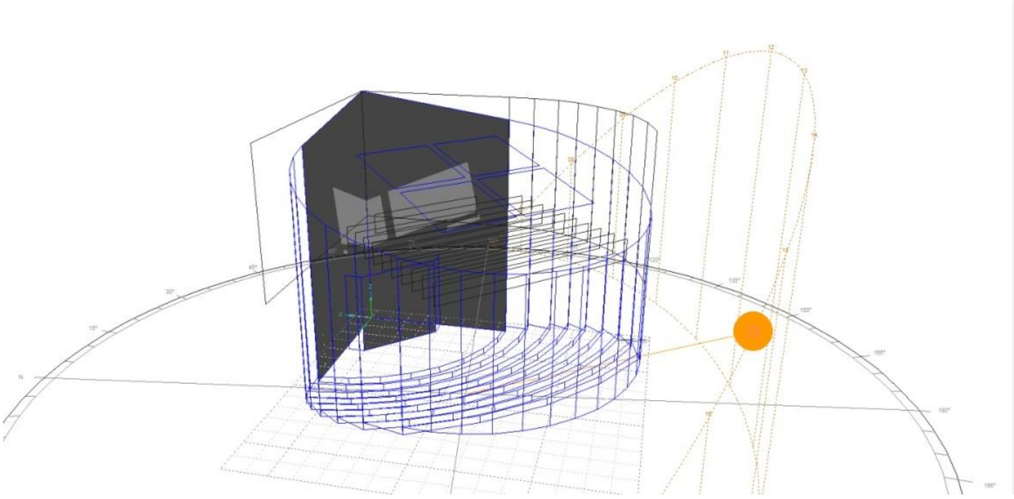

Figure 37. Daylight incidence on the whiteboard / projection screen by Ecotect with the Proposal(March 21, 15:30)

Figure 38.Daylight incidence on the whiteboard / projection screen by 3ds Max Daylight Analysis Tool with the Proposal (March 21, 15:30)

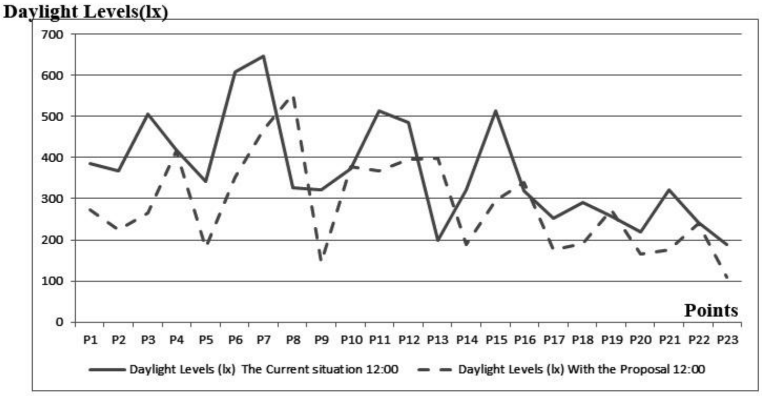

Figure 39. Daylight levels (12:00) – Comparison of Simulation Results of the Current Situation and with the Proposal

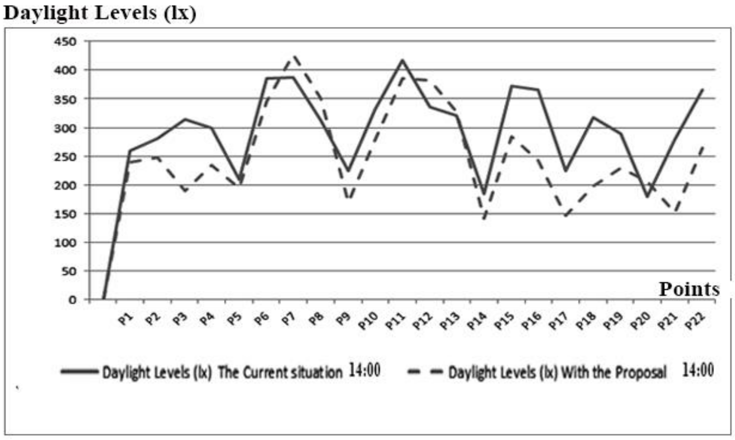

Figure 40. Daylight levels (14:00) – Comparison of Simulation Results of the Current Situation and with the Proposal

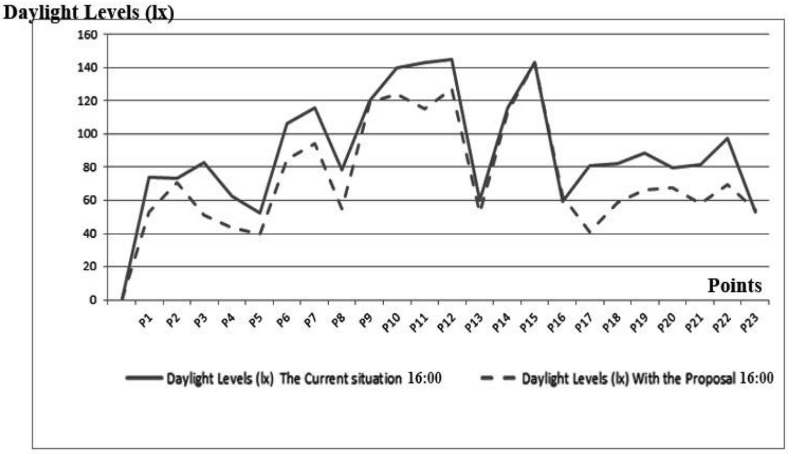

Figure 41. Daylight levels (16:00) – Comparison of Simulation Results of the Current situation and with the Proposal

Table 13. Duration of daylight incidence on the whiteboard/ projection screen with the proposal related to angle of baffles

	With 0°angle	With 5° angle	With 15°angle	With 30° angle
March	12:30 -14:00	12:30 - 13:30	12:30 - 13:30	12:30 - 13:00
April	12:30 -14:30	12:30 - 14:00	13:00 - 14:00	12:00 - 13:00
May	13:00 -15:00	13:00 - 14:30	13:00 - 14:30	13:00 - 14:30
June	13:00 -15:30	13:00 - 15:00	13:00 - 15:00	13:00 - 15:00
July	13:00 -15:00	13:00 - 14:30	13:00 - 14:30	13:00 - 14:30
August	12:30 -14:30	12:30 - 14:00	13:00 - 14:00	12:30 - 13:00
September	12:30 -14:00	12:30 - 13:30	12:30 - 13:30	12:30 - 13:00

In climatic conditions of Turkey, glass solutions providing optimum balance between energy efficiency and comfort are required. Especially in Mediterranean and Aegean coasts with long, hot summers, use of air conditioning is common. High performance low-e glass reduces cooling energy consumption, providing energy savings. In winter it reduces the loss of heat.

For improving thermal performance the only option at this stage where the building is completed is to replace the reflective glass with a high performance low-e glass with solar heat gain coefficient (SHGC) of 0.46 and U-value of 1.3 W/m^{2}K. Ecotect estimates a savings of 22% over the existing conditions. The monthly loads results are given in Table 14.

Replacing glass with a high performance glass, causes a higher decrease in cooling energy loads than heating. The cooling loads decreases by %24. The solar gains are decresed by 47% with the proposed glass. Comparison of solar gains with current situation and the proposal are shown in Table 15. Cooling loads are mostly result of solar gains through the skylight.

Table 14. Monthly heating and cooling loads with the proposed high performance

	Skylight with high performance glass		
	HEATING	COOLING	TOTAL
Month	*(kWh)*	*(kWh)*	*(kWh)*
January	179.5	0	179.5
February	215.2	0	215.2
March	81.4	0	81.4
April	9. 5	189. 9	199.3
May	0	1433.3	1433.3
June	0	2071.2	2071.2
July	0	2300.6	2300.6
August	0	2215.6	2215.6
September	0	1617.5	1617.5
October	0	676.4	676.4
November	55.8	0	55.8
December	180.0	0	180.0
TOTAL	721.3	10504.6	11225.9
Per m^2 (179.4 m^2)	4.0	58.5	62.6

Table 15.Comparison of solar gains with current situation and the proposal

	Current	With Proposal
Month	Direct Solar Gains- Qg *(KWh)*	Direct Solar Gains - Qg *(KWh)*
January	11.30	5.98
February	16.80	8.89
March	25.14	13.30
April	28.14	14.89
May	40.85	21.61
June	52.25	27.64
July	52.40	27.72
August	47.58	25.18
September	39.30	20.79
October	24.37	12.90
November	15.34	8.12
December	8.29	4.38
TOTAL	361.76	191.40
Per m^2 (179.4 m^2)	2.02	1.07

4.2. Discussion

Traditionally architects are rarely trained in using these analysis tools and relegate performance analysis to engineers and specialists. Since simulation studies are both costly and require time, these engineers and specialists are called in to conduct simulations mostly for big-budget projects.

However, simulation tools like Energy Plus, Radiance and Odeon provide reliable results and have become standards in their fields. Their interfaces have improved and are able to accommodate novice users. Technological advances especially in the area of Building Information Modeling (BIM) are providing solutions to the long standing problem of interoperability. Simulation tools are now more capable in exchanging data with architectural design environments. Today, architects have simulation tools that they can use on their own during early design. Yet, architects are still reluctant to consider building physics issues while they design and view building physics as an engineering problem that should be dealt with after the design is complete. Architectural education needs to emphasize the importance of interdisciplinary approaches (İnan, 2006). Following integrated design principles and producing high performance buildings is required for a more sustainable future.

In this study, a new lecture hall in the Department of Mathematics at Izmir Institute of Technology (IYTE) was examined. The complaints of students and instructors pointed to acoustic problems that were severe. Instructors chose to move their lectures to other spaces. However, acoustics in the space was not the only problem with regard to user comfort. Daylighting problems caused glare on the screen and whiteboard. The skylight caused overheating in the hall.

In exploring solutions to the acoustic comfort problems that required immediate resolution, a multi-aspect performance analysis was carried out in order to improve the overall user comfort. The skylight and the high roof were the early design decisions which the architect had taken without considering its effect on the indoor environment.

This study aims to reveal, in a retroactive manner, if the designer would have been able to identify the severity of the conditions in the hall with simulation tools during the early design stage. Therefore, in this study simulations are carried out with mostly default values without detailed design information. Only tools that are commonly introduced to architects at most universities are used. The only exception might be considered to be ODEON, which is both expensive and geared for the expert acoustician. 3ds Max Design is a common modeling and animation package that architects enjoy using. Ecotect is a multi-aspect simulation tool that integrates thermal, lighting and acoustic capabilities.

CHAPTER 5

CONCLUSIONS

The skylight oriented towards the southeast is clearly the most important feature that adversely affects user comfort. The roof with the large skylight was clearly designed as an attractive feature to add to the quality of the space. However, because design was not evaluated with a building physics perspective, the skylight turned into a feature that is the cause of dissatisfaction. Problems exist in visual comfort, acoustics as well as energy efficiency. Throughout the year, in the afternoons, direct sunlight is able to fall onto the whiteboard and the projection screen and cause glare. Also the lack of a shading device makes using the projection system difficult especially on a bright day. The acoustics in the hall is especially problematic. Very little absorption exists in a volume that is too large (1.7 times larger than recommended size) for a lecture hall. As a result, reverberation times are more than four times the optimum values, severely reducing speech intelligibility. Moreover, the glass roof naturally creates additional heating and cooling loads. Ecotect simulations estimate an additional 52% in total loads. If a performance-based design approach had been followed and simulation tools employed, all of the above problems would have been foreseen and prevented. Most probably designers would have choosen not to go with the skylight option. However, unfortunately today, improvement strategies with additional costs have to be formulated in order for the brand new building to function as it was intended.

Two reasons are offered to explain why architects do not utilize simulation tools in their design process: The first is that numerous problems exist with data transfer (interoperability) from CAD tools to analysis tools; and the second is that the time required for evaluation of alternatives using simulation tools extends the design process (Attia, et al, 2009). Especially in the early stages of the design phase, many design decisions are not finalized and architects cannot provide detailed simulation data. For this reason, in this study detailed models are not prepared only simplified models are created. Also, only basic simulation settings are entered. None of the advanced simulation settings are adjusted. The aim has been to obtain results quickly without too much effort. The results obtained demonstrate that existing tools can be utilized to unveil major problems in design without much effort. Even “quick and dirty” simulations provide good estimates.

Another obstacle that hinders the utilization of building simulation software is the architects’ tendency to relegate the responsibility to evaluate building performance to engineers and specialists. However, this case study shows that exploring design alternatives should be carried out by designers early in the design process and existing tools can provide invaluable results even to the novice user.

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APPENDIX A

CONFERENCE PAPER

Title:	"Renovating a lecture hall with a glass roof: A case study for performance based design"
Authors:	E.Atça, M.E. İlal, T. Başaran, T. Kazanasmaz and Z Durmuş Arsan
Conference:	presented at the 2nd Central European Symposium on Building Physics in Vienna, Austria

Renovating a lecture hall with a glass roof: A case study for performance based design

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ABSTRACT: In current architectural practice, architects, due to time and budget constraints do not analyze their designs and evaluate alternatives from the building physics perspective. They expect this analysis to be carried out by engineers. Unfortunately, engineers mostly get involved late in the design process, after many key decisions are already finalized, leaving them powerless to solve problems employing efficient strategies. However, the rapid advances both in computing and engineering have produced various simulation based tools for evaluating building performance that architects themselves can employ in the early design stages. The proliferation of the utilization of these tools throughout the architectural practice and education is necessary for achieving higher performance levels in the built environment.

In this study, the main Lecture Hall at Izmir Institute of Technology, Department of Mathematics is diagnosed and documented through measurements and the possibility of predicting this existing level of performance through simulations during the design stage is explored. The brand new Lecture Hall is in urgent need of renovations, with additional costs, in order to improve acoustic, visual and thermal comfort in the space. Architects need to follow a performance based design approach where they consider performance criteria and utilize building simulation tools for design support in order to avoid problems that introduce costs later in the construction and operation of buildings.

Key Words: Performance based design, Simulation, Building performance

INTRODUCTION

Today issues related to energy efficiency and environmental sustainability are becoming more and more important in all aspects of our lives. In the construction sector, this is apparent in the growing interest in achieving high-performance buildings. Increasing the energy efficiency of buildings is possible without compromising user comfort while pursuing a harmony between the built and natural environment. Architects at the design stage can achieve this by considering climatic conditions, users' needs and technological options with an appropriate integrated design strategy. However, in current architectural practice, performance analysis of building designs is not done due to time constraints and is left up to the engineers. Engineers get involved later in the detailed design stage and are not capable of altering most of the design decisions vital to a building's performance. There is an urgent need to break from this conventional wisdom and move towards an integrated design approach where architects and engineers can collaborate more effectively. A whole new design paradigm is emerging. Terms such as *Performance-based Design* or *Performative Design* are used to describe a new design approach that does not separate performance evaluation and design generation (Malkawi, 2005; Shea, Aish, & Gourtovaia, 2005).

With the rapid progress of information technology in all areas of engineering, we now have access to a large number of building performance simulation tools. Software such as DesignBuilder, DIALux, Catt, Ecotect, TAS EDSL, Fluent, BEES, GaBi are some examples. Tools such as EnergyPlus, Radiance and Odeon in fact have become standards in their fields due to the high levels of reliability in their results. However, the use of simulation tools in the design phase is still limited. (Hensen & Lamberts, 2011) These tools are mostly utilized in big-budget projects with the participation of engineers. To increase their use by architects, many efforts focused on integrating analysis tools and design systems (İlal, 2007; Oxman, 2008). However, more recent studies are being conducted to find out how these tools can be transformed to become more convenient for designers (Attia, Beltrán, De Herde, & Hensen, 2009; Weytjens & Verbeeck, 2010).

While new tools geared specifically for architects should be developed, current tools are very capable and should be utilized not ignored. The work presented in this paper is a case study that demonstrates how, even with available tools, architects can significantly improve their designs.

In this study, a brand new lecture hall in the Department of Mathematics at Izmir Institute of Technology will be examined. The lecture hall was opened in September 2012 and immediately became the subject of numerous complaints from instructors and students. These problems could have easily been predicted and prevented if the design team had followed a performance-based design approach and employed basic simulation tools. The main aim of the study is to reveal that architects, without having to input detailed information and adjusting only basic parameters for simulation, can get reliable results with existing tools. For this reason, none of simulation models utilized in this study have been fine tuned or calibrated and none of the advanced settings in the simulation tools have been altered.

In this paper, first, the lecture hall is described, then acoustic, daylighting and heating/cooling performance of the hall will be examined. Measurements and simulation results will be compared to determine if simulation tools utilized by designers can determine problems early in the design process.

THE LECTURE HALL

The lecture hall under investigation has a cylindrical mass. In the architectural composition of the building, it is placed in a privileged location adjacent to the main entrance and is the focal point of the design (Fig. 1). Inside, circulation areas surrounding the hall are expanded with gallery spaces. The cylindrical form of the hall is exposed and is easily viewable. The importance of the lecture hall for the building design is stressed. It is the highlight of the design. However, this hall has serious deficiencies in lighting, acoustics and thermal comfort and is unable to perform its function. Visual, auditory and thermal comfort problems are all associated with the glass roof of the space (Fig. 2).The design process clearly did not consider any building physics criteria.

The lecture hall in Izmir Institute of Technology Department of Mathematics opened in the fall semester of 2012-2013 academic year. The hall has a seating capacity of 220 people arranged in a circular plan within a cylindrical mass. Cylinder diameter is 14.60 m. Ceiling height at the back of the hall above the back row is 7 m. Ceiling height above the stage is 11.75 m (Figs. 3- 4).

Figure 1.External view of the lecture hall roof.

Figure 2.Glass skylight.

Reflective glass is used to cover the whole roof. Concrete beams carry the weight of the roof with a structural grid of 3.5 m. x 3.5 m. The four squares in the center are used as a large (40m^2 total) skylight. The rest of the roof has thermal insulation and suspended ceiling underneath the reflective glass cover (Fig. 2).

The walls of the hall are plastered aerated concrete blocks. The floor is covered with natural stone. The desks are made of wood. The hall is placed along the northeast-southwest axis, the plane of the roof slopes down approximately 8 degrees to the southwest (Figs. 3-5).

Figure 3.Interior of the lecture hall.

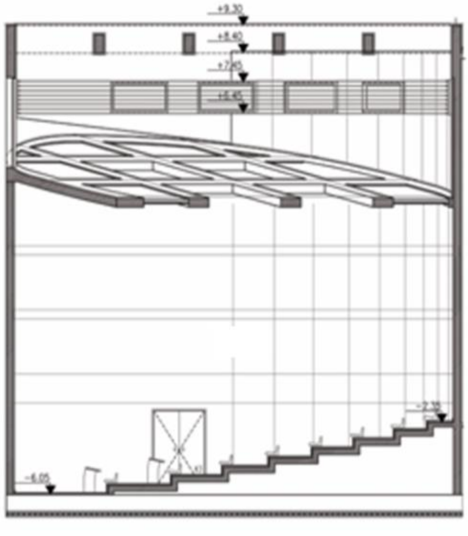

Figure 4.Section of the lecture hall

ACOUSTIC ANALYSIS

Acoustic measurements were conducted in April 2012. Reverberation times were measured by Brüel + Kjaer 4296 OmniPower sound source, 2716 amplifier and 2260 Sound Measuring Equipment. The four points where reverberation times were measured are shown in Figure 6.

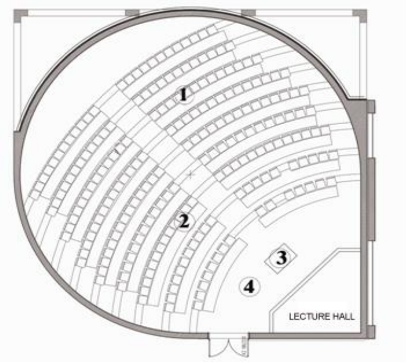

Figure 5.Reverberation time measurement points.

Measurements were taken while the hall was empty and the background noise was 23.6 dB (Leq (A), 30s). The recommended maximum volume for a lecture hall for 220 people is 1100 m3. The ceiling, in order for the cylinder to be expressed in the street facade, is designed too high for a lecture hall. As a result the volume of the hall is 1875 m3.

Moreover, the only sound absorbing material is the suspended ceiling tiles. For these reasons, reverberation time is too long.The recommended reverberation time is between 0.7s – 0.9s. However, actual reverberation times are between 3.0s – 5.9s. Measured reverberation times are shown in Table 1. The reverberation times are also plotted in Figure 7. As a result of such long reverberation times, it is very difficult to conduct lectures in this hall.

The acoustics is modeled and simulated in ODEON software. The estimated reverberation times are presented in Table 1 and plotted in Figure 7. ODEON and measurement results are very close. Only in the lowest frequency (125 Hz) the ODEON estimate is much higher. ODEON model is created by importing a surface model prepared in AutoCAD and saved as a DXF file. Surfaces are assigned materials that exist in ODEON library and results are obtained without fine tuning and using advanced settings.

Table 1.Measured reverberation times and ODEON results [s]

Frequency [Hz]	**25**	**50**	**00**	**000**	**000**
Point 1	3.3	3.94	5.09	5.71	5.12
Point 2	3.09	3.34	4.99	5.7	5.13
Point 3	3.11	3.69	4.98	5.86	5.14
Point 4	3.75	3.8	5.03	5.57	5.18
Measurement average	3.31	3.69	5.02	5.71	5.14
Odeon	5.15	4.11	5.08	5.44	4.93

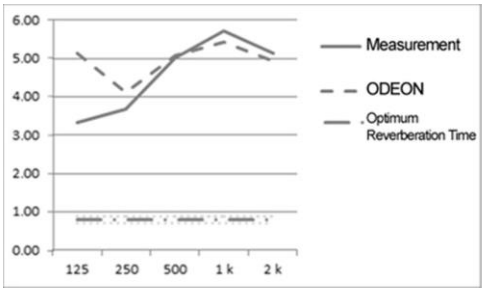

Figure 6.Reverberation times [s]

DAYLIGHTING ANALYSIS

The skylight provides opportunity to maximize the use of natural light. However, there are no shading devices and the abundance of daylight has a negative impact on projection systems. Also, the stage and the whiteboards are place in the northeast corner and the roof slopes down towards the southeast. As a consequence, direct sunlight shines on the whiteboards causing glare. Additionally, the exposed ventilation ducts in the ceiling creates dark shadows under direct sunlight.

Daylight levels were measured on December 20, 2012 at 12:00, 14:00, and 16:00. During the measurements light levels outside the building was measured at 1048 lux (12:00), 3092 lux (14:00) and 569 lux (16:00). The 23 measurement points are indicated in Figure 8. The measurement results are presented in Table 2. The daylight levels are plotted in Figure 9-11.

Daylight in the hall is simulated in 3ds Max Design software. After modeling the hall, materials have been assigned and location, date and weather settings are entered. Daylight illuminance levels are estimated for the measurement points (Table 2) and compared with measurement results in Figures9-11. Measured values are on average higher than simulated estimates. This is related to material selections in simulation and more importantly the difference between the actual sky conditions and the simulation settings.

Daylight level distributions are very similar between measured and simulated values. The values 3ds Max Design provides without any calibration or fine tuning have the following relative mean square percentage errors (Equation 1.): 29.5% for 12:00, 28.6% for 14:00 and 41.8% for the 16:00. Slightly higher deviations are observed at points near the white boards that were not modeled in the simulation tool. CIBSE (The Chartered Institution of Building Services

Engineers) recommends 500 lux for lecture halls (CIBSE, 1999). Both measurement results and simulated estimates are much higher than the recommended values around noon. However, in the afternoon, the light levels fall below required levels. Adjustable shading elements are recommended to ensure compliance with different sky conditions throughout the day.

$$RMSPE = 100 * \sqrt{\frac{\sum_1^n \left(\frac{y_{estimated} - y_{measured}}{y_{measured}}\right)^2}{n}} \quad (1)$$

Duration of direct sunlight incidence on the whiteboard and the projection screen can be determined by almost every computer-aided architectural design tool. The sunlight incidence on the wall is shown for March 21 at 15:30 in Figure 12. Analysis with Ecotect software clearly shows that direct sunlight hits the whiteboard and the projection screen all year long (Table 3). Shading devices are necessary for all afternoon classes held in this lecture hall.

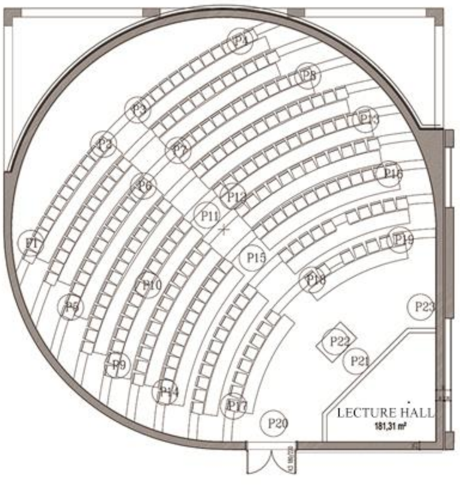

Figure 7.Measurement points for daylight levels.

Table 2. Daylight levels measurement and simulation results. [lux]

	Measurement (December 20, 2012)			Simulation		
	12:00	14:00	16:00	12:00	14:00	16:00
P1	386	257	64	387	266	64
P2	380	266	72	369	256	63
P3	368	308	80	507	347	95
P4	360	305	65	419	287	72
P5	332	301	72	341	235	58
P6	739	386	117	609	419	104
P7	699	377	122	646	445	111
P8	295	318	80	328	220	54
P9	375	257	73	321	220	60
P10	510	345	117	374	253	69
P11	757	394	147	514	357	90
P12	715	371	153	486	335	83
P13	370	342	66	200	135	38
P14	279	214	112	322	222	56
P15	725	359	172	513	352	90
P16	377	322	58	318	215	53
P17	174	116	125	253	177	42
P18	343	322	102	292	200	49
P19	376	314	92	257	175	45
P20	393	183	114	218	149	38
P21	395	272	94	321	219	53
P22	533	306	148	243	168	40
P23	400	231	85	189	128	30

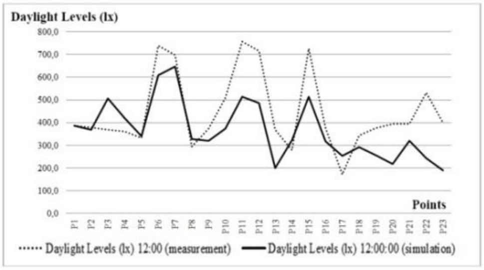

Figure 8.Daylight levels (12:00) – comparison of measurement and simulation

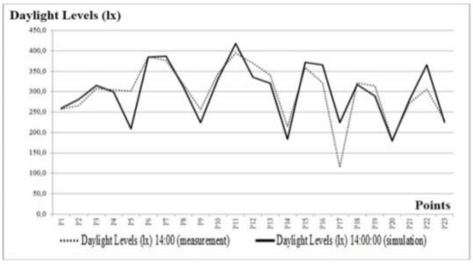

Figure 9.Daylight levels (14:00) – comparison of measurement and simulation

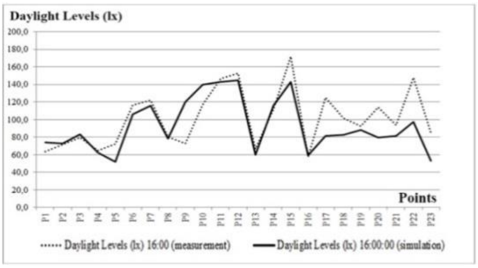

Figure 10.Daylight levels (16:00) – comparison of measurement and simulation.

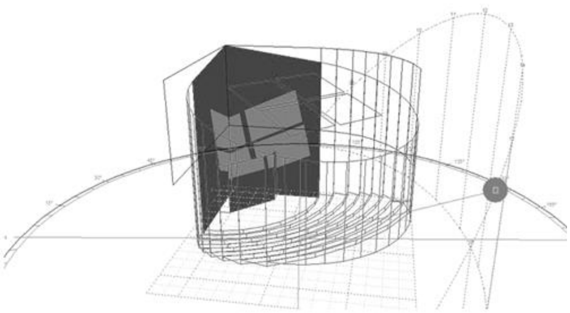

Figure 11.Daylight incidence on the whiteboard / projection screen (March 21, 15:30).

Table 3.Duration of daylight incidence on the whiteboard / projection screen.

December	12:30 - 16:00
January/November	12:30 - 16:30
February/October	12:00 - 17:00
March/September	11:30 - 17:30
April/August	12:00 - 18:00
May/July	12:15 - 18:15
June	12:30 - 18:30

Table 4. Monthly heating and cooling loads comparison

	Roof with skylight		
	HEATING	COOLING	TOTAL
Month	*(kWh)*	*(kWh)*	*(kWh)*
January	159.1	0	159.1
February	196.6	0	196.6
March	58.6	0	58.6
April	6	254.9	260.9
May	0	1907.6	1907.6
June	0	2759.6	2759.6
July	0	3043.2	3043.2
August	0	2932.5	2932.5
September	0	2132.1	2132.1
October	0	859.7	859.7
November	38	0	38
December	172.2	0	172.2
TOTAL	630.5	13889.5	14520.1
Per m^2 (179.4 m^2)	3.5	77.4	80.9

ENERGY EFFICIENCY

The roof is designed with a reflective glass cover. This leads to increased cooling and heating loads in Izmir which has a Mediterranean climate with daily averages of 29°C in July and 9°C in January. Long term measurements in the hall have not been completed. However, the implications of designing a roof surface with a skylight oriented to southwest in Izmir have been explored with Ecotect software. Monthly heating and cooling loads have been estimated for the current situation with a reflective glass skylight, as well as the alternative which is a closed concrete roof with standard insulation. It is assumed that the hall operates 9:00 to 17:00 on weekdays for 100 users. Results are presented in Table 4. Ecotect simulation estimates that the total annual heating and cooling loads are increased by 52% because of the skylight. Reliability of these results will be determined after long term measurements are completed in February 2014.

PROPOSAL FOR RENOVATION

Acoustic, visual and thermal performance of the lecture hall needs to be improved. It should be noted that due to severe budget constraints, external shading devices were not allowed. To improve the acoustics, a series of acoustic baffles are proposed to be placed under the skylight (Fig. 13). ODEON simulations indicated that the 130 m^2 of absorbing surface provided by the baffles was insufficient and more absorption was required. The final proposal includes 150 m^2 of wood panels mounted on studs with rock wool backing on the rear wall (behind the audience). Reverberation time estimates for the treated hall is given in Table 5.

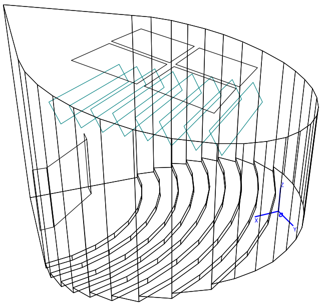

Figure 12.The proposed acoustic baffles under the skylight.

Table.5.Reverberation times for proposed improvements [s]

Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**
Odeon	1.41	0.98	0.73	0.77	0.89

To improve visual comfort the baffles are designed as a series of louvers that will act as shading devices to prevent direct sunlight to reach the whiteboard and projection screen surfaces. For improving thermal performance the only option at this stage where the building is completed is to replace the reflective glass with a high performance low-e glass with solar heat gain coefficient (SHGC) of 0.46 and U-value of 1.3 W/m^{2}K. Ecotect estimates a savings of 22% over the existing skylight. The monthly loads results are given in Table 6.

Table 6.Monthly heating and cooling loads with the proposed high performance glass

	Skylight with high performance glass		
	HEATING	COOLING	TOTAL
Month	(kWh)	(kWh)	(kWh)
January	179.5	0	179.5
February	215.2	0	215.2
March	81.4	0	81.4
April	9. 5	189. 9	199.3
May	0	1433.3	1433.3
June	0	2071.2	2071.2
July	0	2300.6	2300.6
August	0	2215.6	2215.6
September	0	1617.5	1617.5
October	0	676.4	676.4
November	55.8	0	55.8
December	180.0	0	180.0
TOTAL	721.3	10504.6	11225.9
Per m^2 (179.4 m^2)	4.0	58.5	62.6

CONCLUSION

The skylight oriented towards the southeast is clearly the most important feature that adversely affects user comfort. The roof with the large skylight was clearly designed as an attractive feature to add to the quality of the space. However, because design was not evaluated with a building physics perspective, the skylight turned into a feature that is the cause of dissatisfaction. Problems exist in visual comfort, acoustics as well as energy efficiency. Throughout the year, in the afternoons, direct sunlight is able to fall onto the whiteboard and the projection screen and cause glare. Also the lack of a shading device makes using the projection system difficult especially on a bright day. The acoustics in the hall is especially problematic. Very little absorption exists in a volume that is too large (1.7 times larger than recommended size) for a lecture hall. As a result, reverberation times are more than four times the optimum values, severely reducing speech intelligibility. Moreover, the glass roof naturally creates an additional heating and cooling load. Ecotect simulations estimate an additional 52% in total loads. If a performance-based design approach had been followed and simulation tools employed, all of the above problems would have been foreseen and prevented by most probably not choosing to go with the skylight option. However, unfortunately today, improvement strategies with additional costs have to be formulated in order for the brand new building to function as it was intended.

Two reasons are offered to explain why architects do not utilize simulation tools in their design process: 1) numerous problems exist with data transfer (interoperability) from CAD tools to analysis tools; and 2) the time required for evaluation of alternatives using simulation tools extends the design process (Attia, et al., 2009). Especially in the early stages of the design phase, many design decisions are not finalized and architects cannot provide detailed simulation data. For this reason, in this study detailed models are not prepared only simplified models are created. Also, only basic simulation settings are entered none of the advanced simulation settings are adjusted. The aim has been to obtain results quickly without too much effort. The results obtained demonstrate that existing tools can be utilized to unveil major problems in design without much effort. Even “quick and dirty” simulations provide good estimates.

Another obstacle that hinders the utilization of building simulation software is the architects’ tendency to relegate the responsibility to evaluate building performance to engineers and specialists. However, this case study shows that exploring design alternatives should be carried out by designers early in the design process and existing tools can provide invaluable results even to the novice user.

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