

RESEARCH ARTICLE

## MORE ACCURATE COMPUTER SIMULATION FOR INTELLIGENT BUILDINGS: EXPORTING 3D BUILDING MODELS TO DETAILED THERMAL SIMULATION SOFTWARE

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**Keywords:**

Autodesk Ecotect; building 3D modelling; HTB2; human behaviour; intelligent buildings; monitoring; thermal simulation; well-being,

**Abstract:** Intelligent buildings need computer simulation in order to achieve their design targets. However, the majority of detailed simulation software such as HTB2 and Energy Plus do not allow constructing 3D models of the designs; instead buildings are represented in textual format. This significantly discourages architects for using them. This paper investigates the potential of using detailed thermal simulation programs to perform dynamic thermal simulation using 3D models. HTB2 was used as an example of detailed thermal simulation programs and Ecotect was chosen as an example of programs that could be used to quickly build 3D models of the buildings. Ecotect is a user-friendly whole building simulation software that can be easily integrated with the architectural design process. However, it is based on the Chartered Institution of Building Services Engineers Admittance Method and thus inherited its limitations, hence the need for detailed simulation software during the final stages of the design. Five case studies were modelled in Ecotect using several modelling techniques and the internal temperatures were simulated using HTB2. Cases were also monitored for the purpose of model validation. Analysis

of results suggested that a number of necessary measures are necessary to ensure the reliability and accuracy of the results.

## **01. Intelligent buildings and computer simulation**

Intelligent buildings does not necessary have to be complex in organisation, large in size or full of technology. But according to Veitch in her editorial article (Veitch 2009), intelligent buildings must demonstrate: responsiveness, efficiency, and effectiveness. This is to allow them to be able to respond environmental conditions variation, avoid wasting energy through the efficient use of resources, and above all to fit their purpose as any other building. Passive buildings for example will achieve this without or with the use of very little energy. They depend in doing so mainly on their fabric as climatic modifier to moderate the conditions of their internal spaces. They will also use basic design moves including solar orientation, wind orientation, building underground, green roofs etc... to achieve efficiency and responsiveness; to be intelligent. In many cases experience and precedent guide the design process and are sufficient to achieve the aims of a passive designer. Simulation will assist such process and can give a pretty accurate confirmation that the design targets are met. In many case it allows the environmental aspects of the project to become the main design generator. This could mean more intelligent buildings for our society.

Computer simulation of buildings could thus be a very useful tool. The benefits of simulation in predicting the performance of the design at both early and the detailed design stages outweigh the cost of simulation in the majority of cases. This is increasing with the drop in hardware cost, the development of computing power and basic computer components and with the availability of open source simulation tools and plug-ins that allow using for example Energy Plus with Sketchup; a very widely used (by architects) 3D modelling tool. The industry is

heading towards more integrated design practices which more and more architectural firms in the UK employ whole building simulation packages such as Ecotect or IES for the purpose of checking the performance of their designs before even they start communicating with their engineers.

With the pressure being put more on architects to consider the environmental performance of their buildings as early as possible in the design process, we strongly believe that the need for simple to use whole building simulation tools such as Ecotect will be on the rise. Architectural practice will continue to require such architectural friendly (compared to current BIM software) programs that can be used to quickly check the performance of buildings at the early stages of the design such. We also believe that with the government's plan for all new homes in the UK to be zero carbon by 2016, and with the European directive 2002/91/EC with its requirements in relation to energy performance of new and existing buildings, there will still be a need for detailed energy simulation engines and dynamic building simulation programs such as HTB2, Energyplus and EPS-r. The need to programs with no or little cost to learn and that can be acquired for free without having to pay high initial costs or having to pay for upgrades or for online based services such as Autodesk 360 is on the rise.

## **02. Computer simulation and occupant behaviour and well-being**

As discuss earlier, more architects need to quickly and easily check the environmental impact of their designs in order to reduce carbon dioxide emissions and conserve energy and to comply with legislation. Architects and their clients are concerned more than ever with the well-being of their buildings occupants. Despite the difficulty in defining well-being - due to the fact that "issues and people often have feelings and concerns that are not related to a particular

environment” - environmental conditions inside spaces play the greatest role in defining peoples well-being (Clements-Croome 2011).

With all the good intentions building design teams could have, and despite any high performance targets that could be set, a building could still consume more energy than predicted by pre-construction computer simulations. Many factors could cause this to happen such as low quality construction that leads building to perform less than expected. This could also take place due to unanticipated occupancy patterns and behaviour and in many cases could be due to poor facility management. This could happen irrespective of the use of computer simulation in the design process or not.

The behaviour of building users are taken in consideration during computer simulation through specifying space properties such as the number of occupants, their clothing level, metabolic rate, the appliances on/off patterns, and even the open/close patterns of windows and doors. The number of times each space is use and the duration of use are presented as well, usually in the form of schedules. In all validated programs, this is done using deterministic schedules as dictated by the ISO 13790. Whereas probabilistic behaviour models, that can describe the probability of which actions users will tack in the future could be more representative of the real situations being simulated. They could play a very important role in accurately determining for example the heating and cooling load or the electric loads (Baetens and Saelens 2011). Attempts (Yun, Tuohy et al. 2009) over the past few years have been trying for example to develop models using Markov chains to predict the widow state. Others have been trying to use logit distributions, discrete-time Markov process and survival distributions to also predict the window state (Haldi and Robinson 2009).

Another gap with regards to representing user's behaviour in computer simulation programs is the way thermal comfort limits are represented. This is very crucial since "the definition of acceptable indoor climates in buildings is important to the success of a building not only in making it comfortable, but also in deciding its energy consumption and ensuring its sustainability" (Nicol and Humphreys 2001). Determining thermal comfort inside buildings are defined by major standards and guides such as ASHRAE 55, ISO 7730 and CIBSE Guide A (Wei, Buswell et al. 2010). Computer simulation programs subsequently are based on those standards, which are based mainly on Fanger's thermal model developed in 70's.

Fanger's work is based on the assumption that thermal neutrality is best represented by a steady state heat balance (Oosterhuis and Feireiss 2006). He developed his model through conducting a series of experiments in controlled climate chamber employing stationary individuals. This does not take in consideration the normal actions that building users would normally take to make themselves comfort such as changing their clothing level or for example opening a window to cause cooling ventilation. Also Fanger's work determines thermal comfort condition independently from the external outdoor temperature, excluding by such occupants expectations of the environment. This was clearly contested when Fishman and Pimbert found that the clothing level strongly correlate with the outdoor environmental condition and the current season (Fishman and Pimbert 1982).

Recognising this, Ecotect, incorporated the adaptive thermal comfort model that was first suggested by Nicol and Humphreys in 1973 (Nicol and Humphreys 2001). The adaptive thermal comfort model was developed through field studies that gathered "data about the thermal environment and the simultaneous thermal response of subjects in real situations", rather than controlled environments as with Fanger's work (Nicol and Humphreys 2001). The adaptive

approach recognised that human beings are active agents who will take actions to alter their environments or clothing level to maintain their thermal comfort. The model itself relies on the outdoor average air temperature to determine comfortable indoor temperatures. So in Ecotect, simulated internal temperatures are compared to upper and lower thermal comfort temperatures that are calculated using the adaptive thermal comfort model. In theory this should be more representative to the real situation and should be better representing user's behaviour. However, if the calculation of energy consumption is required, then the limits of the thermostat must be specified in order for the program to calculate the total time spent outside the comfortable zone, and hence calculate the amount of energy required to accordingly adjust the indoor temperature to maintain the internal temperature within the comfort zone. This is based on the assumption that building users will unlikely to change the limits of their thermostat except at the beginning of each season, simply because they do not change their wardrobe until then despite the warm spell they could experience during winter for example. Of course many will have experienced times when they had to override the thermostat in an attempt to raise the temperature of the house on a cold night or to lower it during a warm autumn day.

### **03. Computer simulation and Building Information Management**

The building industry including education and research is now experiencing a rise in the use of Building Information Management (BIM) programs that include in many cases the simulation of the environmental performance of the designs. BIM use had gone beyond the design and construction management phases, extending throughout the whole life cycle of the building to include facility management and even up to the demolition phase. BIM models are now valuable to facility managers as they are valuable to design and construction teams. Their value resides in the ability to use them to identify potential problems, automat maintenance jobs, monitor the environmental performance of the building, and potentially find ways to enhance

performance. Real time monitoring data collected by the building's sensors and data from environmental performance simulation could be fed into the BIM model to aid the process of energy optimisation. This will be of a more paramount importance in the future when: a) more architectural firms and practices implement BIM, and b) when the link between BIM models and Building Management Systems is established to allow for more integration between design targets, performance optimization, and the response to conditions. This will open a whole new ways to visualising building management systems in 4D.

Since the introduction of the idea of BIM in the 70's by Van Nederveen (Nederveen and Tolman 1992), it was not popularly used until perhaps the introduction of Revit by Autodesk in 2002 [ref] following the publication of Autodesk's white paper; Building Information Modelling (Autodesk 2002), many years after Graphisoft had already started introducing the concept in ArchiCAD in the late 80's. Few other tools were born and almost died such as the German Ribcon. Well established computer based thermal simulation packages as for example EnergyPlus, IES, ESP, HTB2 and Ecotect have been under development in parallel to BIM roughly also since the 70's. However, they are relatively much more developed and widely used by engineering practitioners and academia. Revit and ArchiCAD had started for some time now to integrate energy evaluation functionality; Revit uses VE (Virtual Environment) developed by IES (integrated environmental solutions) and ArchiCAD uses VIP-energy application developed by StruSoft. Yet, we still believe than none of these solutions are as promising to be integrated in the early stages of the architecture design process by architects as Ecotect despite how powerful VE and VIP-energy are.

It is anticipated that sustainability features of BIM, plus more seamless workflow, more effective collaboration across multidisciplinary teams, on and off sites, will mean that BIM will

grow more in the future. The growth of cloud-based services and more powerful computers and handheld tablets will contribute to BIM being used by more members of the design team on and off building sites, and will hopefully make BIM's energy evaluation modules more accessible for architects. Meanwhile, we strongly believe that Ecotect is the only low cost, easy to learn and user-friendly programme on the market that can fit easily with the design process.

#### **04. Research background and previous work**

Computer simulation can allow architecture practitioners, researchers and students to predict the energy efficiency and environmental behaviour of buildings. There are a wide range of detailed thermal simulation software available such as HTB2<sup>1</sup>, DEROB-LTH<sup>2</sup>, DOE-2, EnergyPlus<sup>3</sup> and ESP-r<sup>4</sup>. The interfaces of those packages are complicated and they require an extensive experience in computer simulation and involve substantial time to master. It is relatively difficult to input building geometry to these software tools as well as to interpolate the simulation results. The model has to be introduced in textual format leading in some cases to inaccuracy due to human error during data input, consumes time and requires knowledge of computer programming. In addition, this also does not fit with the mode of thinking in architectural practice and education. All those factors limit the integration of such software programs within the architectural design process. Whole building simulation such as IES<sup>5</sup> and Autodesk Ecotect<sup>6</sup> allow the drawing 3D models of the building allowing more effective understanding of the issues involved in the quantification of the environmental performance of buildings. Geometric data are introduced to those tools either from CAD programs or directly

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<sup>1</sup> <http://www.cardiff.ac.uk/archi/ComputerModelling.php>

<sup>2</sup> <http://www.derob.se>

<sup>3</sup> <http://www.eere.energy.gov/buildings/energyplus>

<sup>4</sup> <http://www.esru.strath.ac.uk/Programs/ESP-r.htm>

<sup>5</sup> <http://www.iesve.com>

<sup>6</sup> <http://www.ecotect.com>

using their 3D-based interfaces. Flexibility and ease of building 3D models varies from one tool to another.

Autodesk Ecotect has a very user-friendly interface that allows building and manipulating 3D models easily. User can import 3D computer models in \*.3ds or \*.dxf formats from the widely used computer aided design software such as AutoCAD, 3D Studio, Rhinoceros or Sketchup. Autodesk Ecotect version 5.6 and over is able to import and export gbXML as well. This facilitates more flexible communication with ArchiCAD and several other simulation and modelling tools (Marsh 2006).

One of the main shortfalls of Autodesk Ecotect is its inability to simulate the dynamic nature of thermal performance of buildings. This is perhaps not an issue in case of parametric studies that aims to investigate the relative effectiveness of design options, but hinders the use of Ecotect in research and practice, when thermal performance detailed analysis is required. Ecotect inherited this limitation from the CIBSE Admittance Method it uses. Autodesk Ecotect uses this method to calculate internal temperatures and heat loads. Admittance Method is a pseudo-dynamic method based on variation about the mean value. It also has the disadvantage of not taking in consideration the effect of solar radiation when it enters the space. Solar radiation is considered a space load the moment it hits a window and is not traced to check which internal surface it hits and accordingly heats up. Equally important, Autodesk Ecotect can not calculate thermal lag for composite elements that are not included in its library. This either prevents the representation of certain cases or forces approximation leading to in accuracy in simulation. To this end a detailed thermal simulation tools should be used in later stages of the design process or research projects.

Autodesk Ecotect model can be exported to a wide range of well established detailed thermal modelling software such as ESP-r, EnergyPlus, DOE-2 and HTB2. The following is a brief discussion of the advantages and disadvantages of each tool.

ESP-r is an integrated energy modelling software for the simulation of the thermal, visual and acoustic performance of buildings and can also perform computer fluid dynamics (CFD) analysis. It can predict the energy consumption and the associated gaseous emissions associated with the environmental control systems. It was developed at the Energy Systems Research Unit of the University of Strathclyde in the 1970's. ESP-r thermal simulation engine uses a finite volume conservation method. It was subjected to a substantial number of validation studies including inter-model comparisons and comparisons with monitored data (Strachan 2000). ESP-r is designed for UNIX operating system but can now run under OSX 10.5 and 10.6 or on Windows in the Cygwin environment. Buildings can be graphically represented in EPS-r. However, it clearly very user unfriendly and thus it is unlikely to be used during architectural design.

EnergyPlus is mainly a thermal simulation software that can model heating, cooling, lighting, ventilation but can also simulate water use in buildings. It was developed by the U.S Department of Energy. It is a cross platform tool that runs on Windows, Macintosh and Linux. It is based on DOE2 that was developed by James J. Hirsch & Associates in collaboration with Lawrence Berkeley National Laboratory. Buildings are introduced to EnergyPlus using input text files. This had hindered its use in architecture practice. However, lately it can be used with SketchUp - 3D modelling software widely used in architecture practices - through the use of Legacy OpenStudio plug-in which allows the user to create and edit EnergyPlus zones and surfaces without leaving SketchUp. This is a huge step that is expected to encourage the use of

EnergyPlus in architecture practice; however, expertise in using EnergyPlus at the text level is still required. Another main limitation for EnergyPlus is its inability to accept more than four sided thermal zones. Although this is not a prohibitive problem in the majority of cases, it makes it impossible to use EnergyPlus to study non-rectangular forms.

HTB2 is a general purpose dynamic energy and environmental performance simulation tool. It is based on a simple Finite Difference Heat transport model (ECOTECH 2008), and can calculate internal temperature and energy use. It is “an example of a Detailed Simulation Programme or DSP. As such it is complex software and can require a considerable learning effort to achieve its full potential” (Alexander, Hassan et al. 1997). It generates its own heat flow coefficients and response factors from the detailed information of the layers making up composite building materials. This overcomes Autodesk Ecotect’s inability to calculate thermal time lag of composite materials. However, the main disadvantages of HTB2 are: a) the inability to handle complex occupancy profiles, and b) the inability to handle complex glazing and shading systems. In Previous work, Alexander et al (Alexander, Mylona et al. 2005) looked into developing HTB2 algorithms to be able to handle calculating the effect of glazing and shading options such as slatted blinds. They modified the algorithm to be capable of predicting total solar transmission of glazing with mid-pane shading combinations. HTB2 can be linked to several software tools such as Autodesk Ecotect and the air-conditioning system simulation program BECON. The later could be used in conjunction with HTB2 to assess the electricity consumption for air-conditioning systems. This was used for example by Yik et al (YIK F. W. H., JONES P. et al. 2008) to assess the electricity consumption for air-conditioning in high-rise buildings in Hong Kong.

In computer simulation, it is necessary to strike a balance between accuracy, simplicity and flexibility of the simulation process. Being able to easily, quickly and accurately represent a design case is an important factor in any simulation study. To this end Autodesk and HTB2 are considered in this work as a suitable combination of tools that could be used to perform detailed thermal simulation.

No previous work was found to investigate introducing Autodesk Ecotect 3D models to HTB2. Only Marsh and Al-Oraier (Marsh and Al-Oraier 2005) employed Autodesk Ecotect in a previous work to build a model of a traditional adobe dwelling and exported it to HTB2 and Energy plus. They studied the issues associated with creating a base computer model in Autodesk Ecotect that is fully compatible with HTB2 and EnergyPlus simulation tools. They then compared the two outputs to the monitored data. They found reasonably close agreement between the simulated and monitored data. However, in some cases they found significant variation between the results of the two software tools and the measured data and between the results of the two software tools themselves. This close agreement between the simulated results and the measured data was unsupported quantitatively. Moreover, this work did not discuss the methods and constraints associated with exporting the model from Autodesk Ecotect to HTB2. Gado (Gado 2001) had used Ecotect version 5 to build a 3D model of a walk up housing block and exported it to HTB2. Initial simulation runs produced very odd results. This work had lead Ecotec's developer at that time; Dr. Andrew Marsh to revisit HTB2 exporting facility in Ecotect and several changes were made. However, the model was not validated and the accuracy of the simulation result not investigated.

## 05. Modelling for Autodesk Ecotect simulation

There are several methods of building a 3D model in Autodesk Ecotect. The choice depends mainly on the stage of the design process and the types of analysis required. Models could be directly built on Ecotect. Alternatively they can be exported from other software such as Sketchup, AutoCAD, 3D Max or Rhinoceros in DXF or 3ds format. However, this results in a very large Ecotect file, which will be very difficult to handle and will affect the simulation time. In other cases, doing so will result in a very complex Ecotect model, which will be very difficult to edit and navigate through and will not be suitable for running thermal simulation in the first

□ In case of lighting analysis, the user has to model the building in greater details. For example all light shelves, wide window sills and external shading devices have to be drawn. External building lighting analysis expected to affect the building design should be modelled. However, only the space which the lighting analysis is interested in could be built in isolation of the rest of the building, as long as there are no parts of the building expected to overshadow the windows.

Another way to introduce the building to Ecotect is to trace over a scanned hand drawn or a computer sketch using either the centre line of the walls or the internal boundaries of spaces to define the thermal zones. This method is expected to be very popular in architectural context as it allows checking a wide range of design options very early on during the design process and even before any of the designs are drawn on the computer. If a model is drawn in Autodesk Ecotect properly, the thermal simulation will run smoothly. However, not every Autodesk Ecotect model will successfully be exported to and simulated by HTB2. Hence, the importance of this work.

## 06. Modelling for exporting to HTB2

There are several rules that must be followed when building a model in Autodesk Ecotect for the purpose of exporting it to HTB2. According to Autodesk Ecotect documentation (ECOTECT 2008) these are:

1. The number of windows in a model being exported to HTB2 must not exceed 100. HTB2 is a FORTRAN program and all its array sizes are predefined. This means that HTB2 can only store 100 shading masks hence the limitation on the number of windows. If the model contains more than 100 windows, HTB2 file can be edited manually to use the same shading masks for the windows facing the same orientation. Another approach would be to amalgamate several separate windows in the same wall into a single window as shown in Figure 5; **(insert Figure 5)**
2. In addition, HTB2 documentations adds the following limitations:
  - a. 100 modelled and 3 un-modelled spaces;
  - b. 25 construction types, using a total of 100 parts;
  - c. 25 window types and 100 shading masks;
  - d. 600 elements, with 9000 fabric nodes;
  - e. 100 heating systems.
3. Each window must be assigned to the object onto which any direct solar radiation will fall. By default Autodesk Ecotect assigns this to the floor of the zone in which the window is located. If Autodesk Ecotect is unable to find an associated floor object, it will choose another zone object and generate a warning message;
4. HTB2 does not use the thermal properties of composite elements that Autodesk Ecotect generates. Instead it generates its own heat flow coefficients and response factors from the detailed layers information. If the properties of any layer used to build up a material

in Autodesk Ecotect are not accurate or not specified, HTB2 will generate an error message and the exporting process will be aborted;

## **07. Research aims**

This paper aims to investigate the techniques and precautions required when building and exporting Autodesk Ecotect 3D models to HTB2. The reliability of the HTB2 simulation results depends on: 1) the accuracy of the data input; this includes the building geometry, material specification and weather data, and 2) the method by which the Autodesk Ecotect model is built. The later is the focus of the work presented in this paper.

## **08. Research methodology**

Five classrooms of three primary schools built in al-Minya Governorate (Omer ebn al-Khatab school, Al-Lamaty school and Al-Shaheed school) of the Arab Republic of Egypt (refer to Figure 1) were employed as a vehicle for the investigation. All classrooms are rectilinear in shape with internal dimension of 8000mm x 5000mm (refer to Figures 3 and 4). **(insert Figure 1)**

The three schools employed vary in size; form and orientation as shown in Figure 2. **(insert Figure 2)**. However, all schools used the same structural and construction systems. **(insert Figure 3 and Figure 4)**

Egypt is situated in the northeast corner of Africa (27 00N and 30 00E). According to Köppen-Geiger climate classification system, Egypt lies in the warm desert climatic zone. The country is further divided into seven climatic design regions. Al-Minya lies in the desert climatic design zone. This zone is the largest among the seven regions. It is characterised by large diurnal variation with typical average outdoor day air temperatures of 4°C and typical night average air

temperature of 20.5°C in August, and typical average low outdoor air temperature of 4°C in winter.

The internal air temperatures inside the classrooms were monitored during May 2007; the hottest month of the academic year in Egypt. 3D models of the classrooms were built on Autodesk Ecotect using different techniques and to different levels of complexity. The models were then introduced to HTB2 and the simulation outputs were compared to the corresponding monitored data graphically and statistically using Mann-Whitney test to quantify the strength of the closeness between both the monitored and simulated data for each level of detail in each case.

Hobo U12 data loggers were used to monitor the internal air temperature inside the case studies. External weather data during the monitoring period were logged using a Hobo weather station to create a weather file that was later used in the thermal simulation. Outdoor temperature ranged between 43.42°C and 15.62°C. Relative humidity ranged between 72.25% and 6.75%.

In order for Autodesk Ecotect to recognize the orientation of each surface, especially in very complex models, the normals of all surfaces must point outwards (Marsh 2006; ECOTECT 2008). The effect of 13 modelling and exporting conventions and rules provided by Autodesk Ecotect developer Dr. Andrew Marsh (Marsh 2006; ECOTECT 2008) on the reliability of the simulation were investigated. Those conventions can be summarised as:

1. Each zone must be drawn as an enclosed three dimensional prism with planar surfaces on all sides. In other words, each zone must be 'air tight' volume. Autodesk Ecotect will only consider a volume of space as a thermal zone if its surfaces fully enclose the entire volume;

2. Two zones are considered to be adjacent if they are parallel to each other and less than a specified distance apart known as adjacency tolerance. This must be adjusted to accommodate the separation distance as appropriate depending on the modelling technique applied;
3. All the types of elements and materials used have to be specified;
4. Each space of the building under investigation must be drawn as a separate zone;
5. If a space is adjacent to or includes another secondary space that exchange air with, then the secondary space could be added to the primary zone;
6. A large open-plan space with windows in several sides must be divided into several sub-zones;
7. The shared elements between two adjacent zones must be adjacent and overlapping;
8. External shading systems must be placed on a non-thermal zone so as not to contribute to the thermal zone;

Further three modelling attributes were varied: a) the model size, b) method of void construction, and c) the wall construction detailing level. Internal air temperatures were simulated and were then compared to the monitored internal air temperatures.

## **09. Results and discussions**

Mann-Whitney test was used to compare the monitored data with the simulated internal air temperatures. Results showed a significant difference ( $p < 0.05$ ) suggesting by such that the level of the model detail has a significant effect on the simulation accuracy. Several levels of model details were then used and the level of details that yielded internal air temperatures closest to the monitored data was further used in the investigation.

To investigate the collective effect of all the modelling methods and particularly the effect of the proposed level of model detail, the other four classrooms were modelled using all rules listed above. Once again, the internal air temperatures of the classrooms were simulated using HTB2 and the results were compared statistically to the monitored data. Applying Mann-Whitney test on the simulated and the monitored temperatures suggested that the difference in all cases was not significant ( $p > 0.05$ ).

One case study - Omar ebn al-Khatab - was modelled in Autodesk Ecotect taking in consideration all previously mentioned conventions. On exporting the model to HTB2, numerous errors were generated, and the exporting process was forcibly aborted. The error messages in most cases did not provide enough guidance on how to fix the faults in the model. For example, when an Autodesk Ecotect model including a curved surface drawn as an arch was exported to HTB2, the process was stopped, and the following error message was displayed: “*ERROR: RDLAY: inappropriate surface area has been specified*”. It was not clear from this message which surface caused the error, and why it was inappropriate. Accordingly a parametric analysis was conducted to pinpoint the cause of error. Two reasons were found: a) model size, and b) the method of voids construction. Each of those points are discussed below:

**Model size.** In most cases, it is difficult not to exceed the limitations on the total number of the Ecotect model elements. The model of a multi-storey building for example could easily exceed this limit if built to a reasonable level of details. The current work proposes several recommendations to reduce the total number of elements while maintaining a fair level of accuracy. Those recommendations could be summarised as follows:

1. It is important to include the overshadowing effect due to surrounding buildings.

However, modelling the surrounding buildings could substantially increase the total

number of elements in the model. To avoid this it is proposed to reduce the details of the surrounding buildings by representing several adjacent blocks as one zone as shown in Figure 6 (**insert Figure 6**);

2. Reduce the details of the adjacent zones by using larger non-thermal zones as shown in Figure 7. Ecotect “will make any surface that is adjacent to one or more planar objects on a non-thermal zone into an *adiabatic surface* i.e. has no heat flow through it” (Autodesk Ecotect, 2008a). This is valid in the case of, for example, a terraced house or a multi-storey building. In these cases the heat flow from adjacent zones could be ignored assuming that the temperatures inside all houses will be roughly the same as the model under investigation (**insert Figure 7**);
3. Every partition is created with a construction line to allow the manipulation of its shape. These lines become of no use after completing the model and unnecessarily double the number of partitions in the model. Therefore, it is advised to delete those lines before exporting the model to HTB2.

***Voids construction.*** In two of the case studies, the classrooms are arranged on a linear single sided corridor exposed from one side to the elements as shown in Figure 3. One way of modelling this in Autodesk Ecotect is to construct a zone representing the corridor and then insert a void in the external walls as shown in Figure 8a. HTB2 requires the detailed layer information of each object. Since void is not built up of layers, HTB2 could not handle it. Hence, an error message saying that there is an unknown source for the void layer was displayed when the model was exported from Autodesk Ecotect to HTB2. To overcome this problem it is proposed to delete the wall and build the solid parts around the void using a single plane as shown in Figure 8b. It is to be noted that this plane must be in the same zone and should be assigned a wall material. (**insert Figure 8**)

Using all the recommendation discussed above, an Autodesk Ecotect model of the case study was built and was successfully exported to HTB2 and the thermal simulation was conducted. In order to validate the simulation results, the hourly simulated and monitored data were compared as shown Figure 9 (Figure 9). Applying Mann-Whitney test on the data revealed a significant difference ( $p < 0.05$ ), despite the two sets of data trends being consistent. One reason for this could be the fact that walls are constructed of different materials of different thicknesses as shown in Figure 10. Further work was conducted to investigate the effect of the model level of details on the accuracy of the simulation results.

**(insert Figure 10)**

## **10. Effect of model details on the simulation accuracy**

In order to investigate the effect of the model details on the simulation accuracy, a parametric analysis was conducted. The aim is to optimize the level of details without jeopardizing the accuracy of the results. The first case study was modelled using the following methods:

**Method 1.** All walls of all zones are drawn in full details. Every part of the wall is drawn as a single plain or partition and is specified a specific material;

**Method 2.** Only walls of the zone under investigation are drawn in full details with the rest of the building's walls drawn in a simple manner. The later was achieved by drawing the wall as a one element using the material properties of its largest section;

**Method 3.** Only the zone under investigation is drawn in a simple form with the rest of the building drawn in full details;

**Method 4.** All zones are drawn in simple form.

Figure 11 presents the HTB2 simulated internal air temperatures inside the classroom generated using the four modelling techniques. The simulated temperatures were then compared to the monitored data. Applying one way ANOVA test ( $F=205.39$ ) on the data revealed that the mean internal air temperatures inside the four cases are significantly different ( $p<0.05$ ). Applying Post Hoc LSD test on the data revealed that there is a significant difference ( $p<0.05$ ) between the simulated internal air temperature and the monitored temperature in all cases except in case of using the second modelling technique.

**(insert Figure 11)**

## **11. Results validation**

In order to validate the proposed conventions and rules in terms of simulation results accuracy, the other four case studies were modelled using the technique that yielded internal air temperatures that is statistically closest to the monitored temperatures. Models were then exported to HTB2 and the thermal simulation was performed successfully in all cases. The simulation results were compared statistically to the monitored data using Mann-Whitney test. Analysis of results suggested that the difference between the simulated and the monitored air temperatures in all cases is not significant ( $p>0.05$ ) as shown in Table 2. Figures 12-16 graphically present a comparison between the simulated and monitored data inside the four case studies. They indicate a consistent trend of both sets of data.

**( insert Figures 12-16 )**

## **12. Conclusion**

Although this work main focus was not the investigation of the case studies, the authors believe that the data presented here are very useful for further studies concerning itself with the performance of schools in hot arid climates. This is important as “a (large) number of studies have sought to establish a relationship between the nature and quality of the physical environment in which students learn and the learning outcomes” (Cardellino, Leiringer et al. 2011).

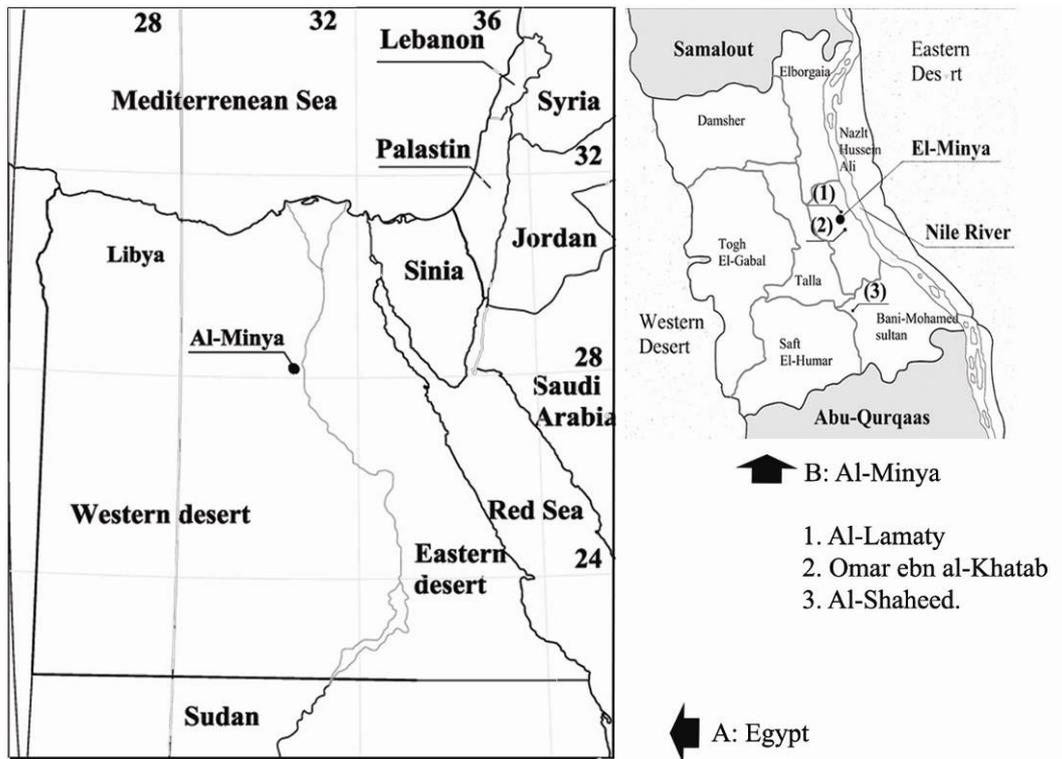
The main focus of this paper was the investigation into the techniques and precautions required when exporting 3D model generated by the whole building analysis software tool Autodesk Ecotect to the detailed thermal simulation software HTB2. It was found that there are fifteen precautions and techniques required to guarantee the accuracy of the thermal simulation in HTB2 using an Ecotect model (refer to sections 3-5). This conclusion was validated through monitoring five different case studies and the simulated temperatures were statistically compared with the monitored data (refer to section 6).

## **13. Further work**

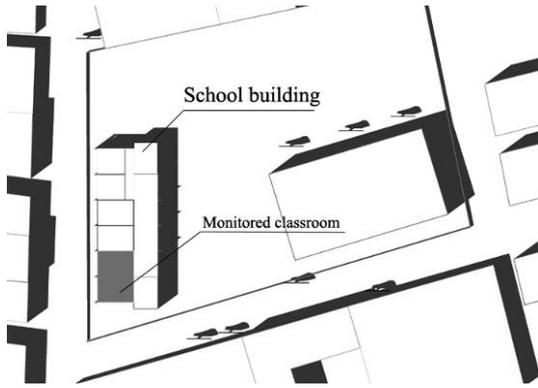
During the course of this work, four main gaps in the knowledge were identified for further work. These are:

1. The role of computer simulation in the design process of intelligent buildings seems to be underestimated. Further work that looks into the ways of how computer simulation could be used to achieve more intelligent buildings is needed.
2. Exploring the effect of weather files type (on-site monitored weather data, typical metrological year or synthesized) used by Ecotect or HTB2 on the accuracy of the thermal simulation;

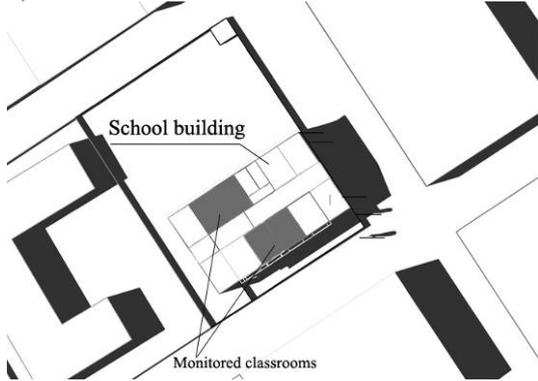
3. Finding out how to generate Ecotect weather file from monitored outdoor data logged on site for the purpose of simulating a specific condition;
4. Studying the effect of modelling techniques and computer processing powers on the duration of simulation in both Ecotect and HTB2;
5. Investigating the effect of the simulation algorithm (admittance method verses Finite Difference Heat transport model) on the thermal simulation accuracy.



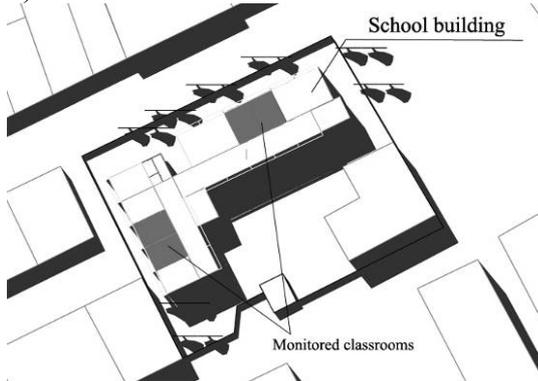
**Figure 1:** a) Map of Egypt with the location of al-Minya and Belbas, b) Skem school location in Beblas, c) Case studies location in al-Minya: 1- al-Lamaty 2 – Omar ebn al-Khatab 3- al-Shaheed



a)

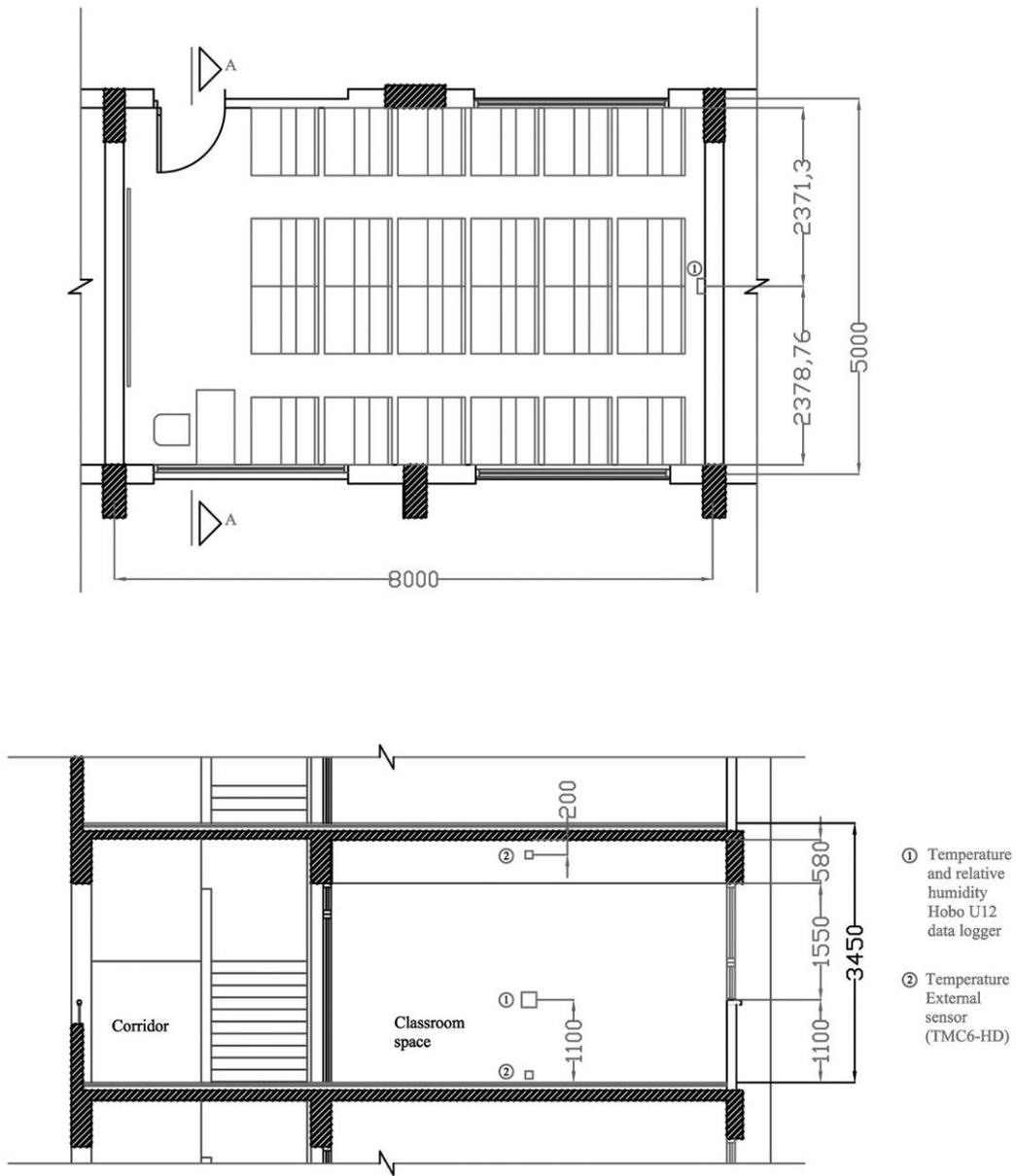


b)



c)

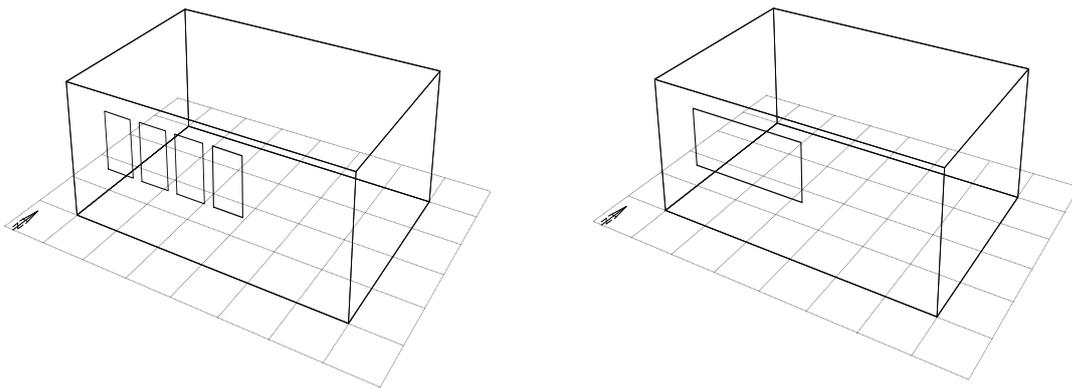
**Figure 2:** a) Omar ebn al-khatab, b) Al-Lamaty, c) Al-Shaheed.



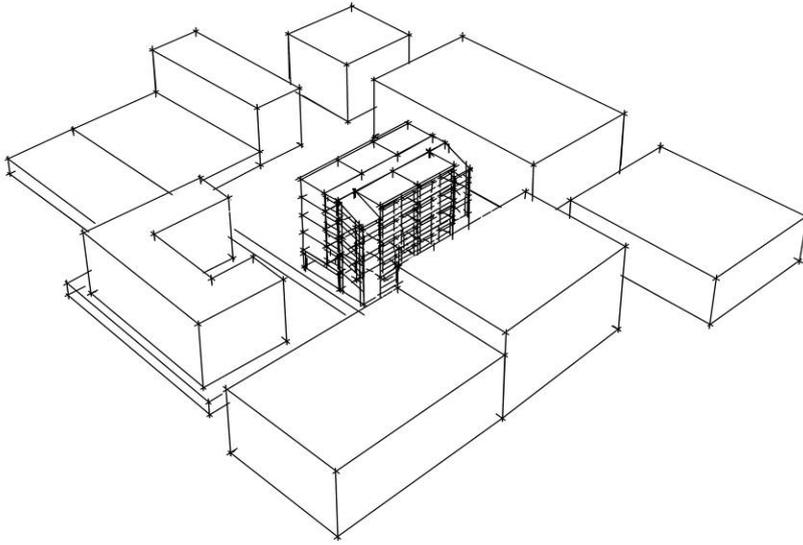
**Figure 3:** Typical plan and section of the governmental primary schools built by GAEB including the location of the temperature and humidity data loggers and sensors.



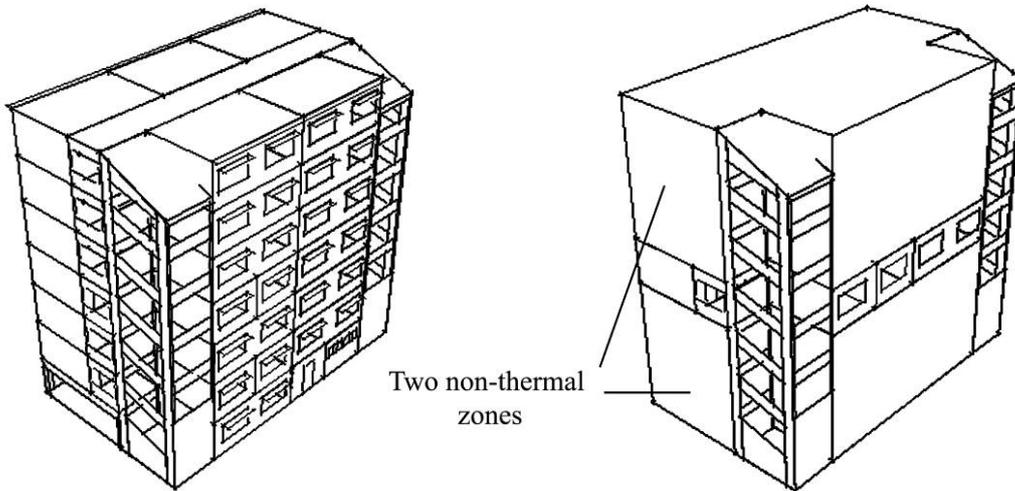
**Figure 4:** External and internal views of El-Lamaty primary school.



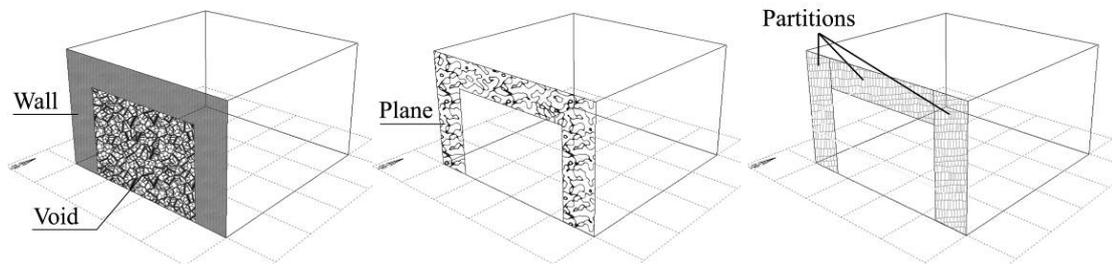
**Figure 5:** Replacing several windows on the same wall with a single window of the same combined area.



*Figure 6: Surrounding buildings drawn in Autodesk Ecotect as single non-thermal zones.*



*Figure 7: Reducing the number of elements of a multi-storey building.*

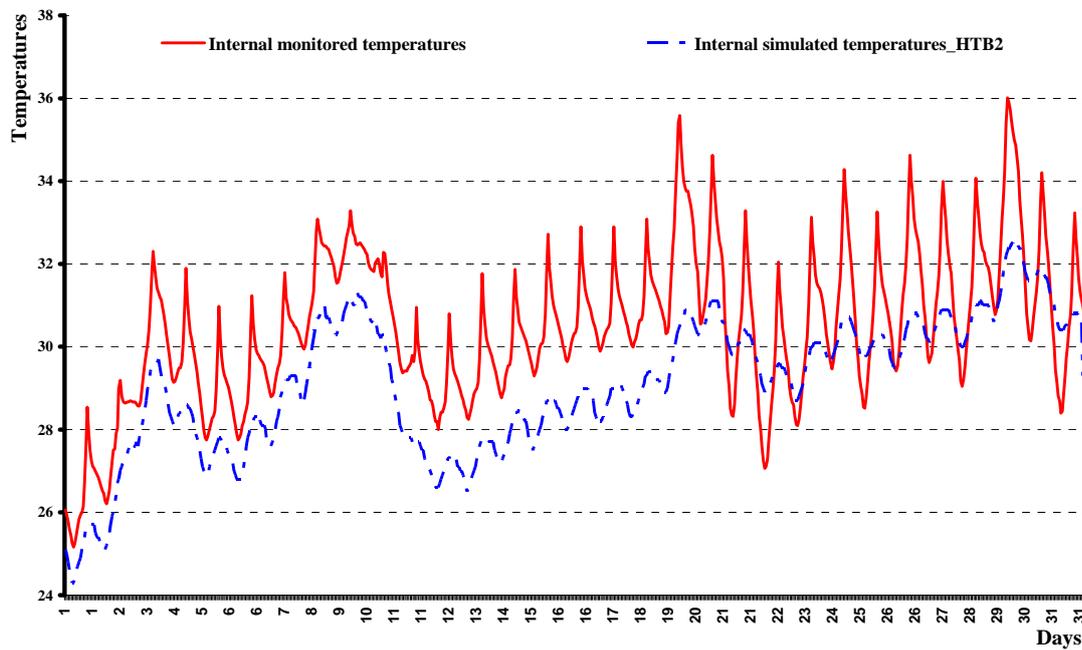


a. Void in a wall

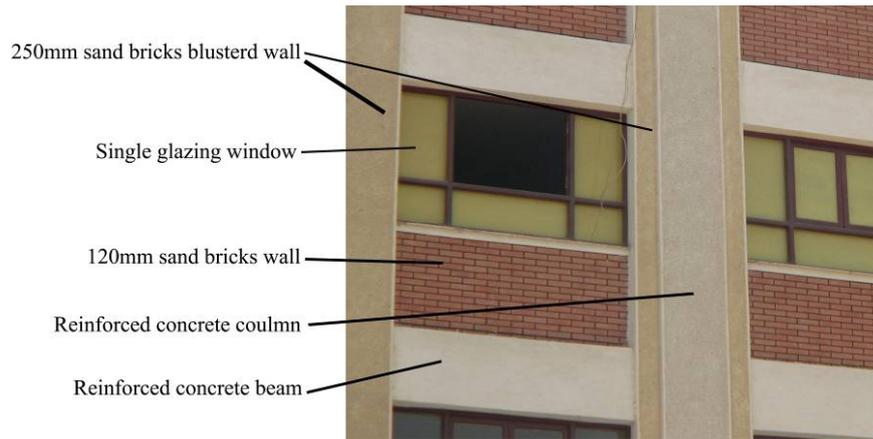
b. Solid part as a single Plane

c. Solid parts as several partition

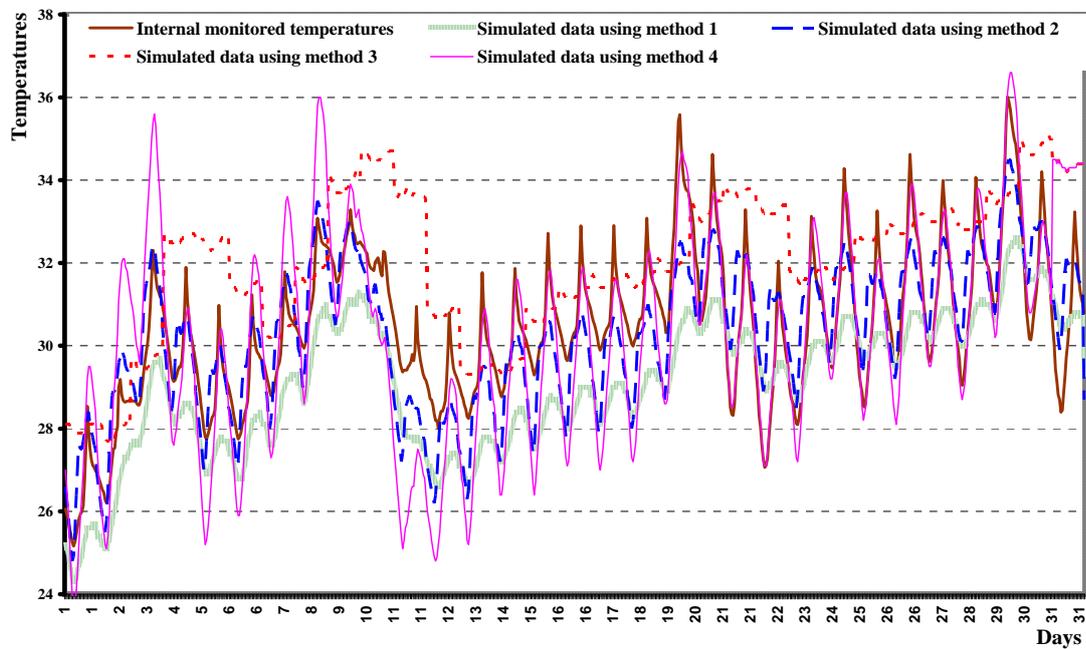
**Figure 8:** Techniques of building a void in Autodesk Ecotect.



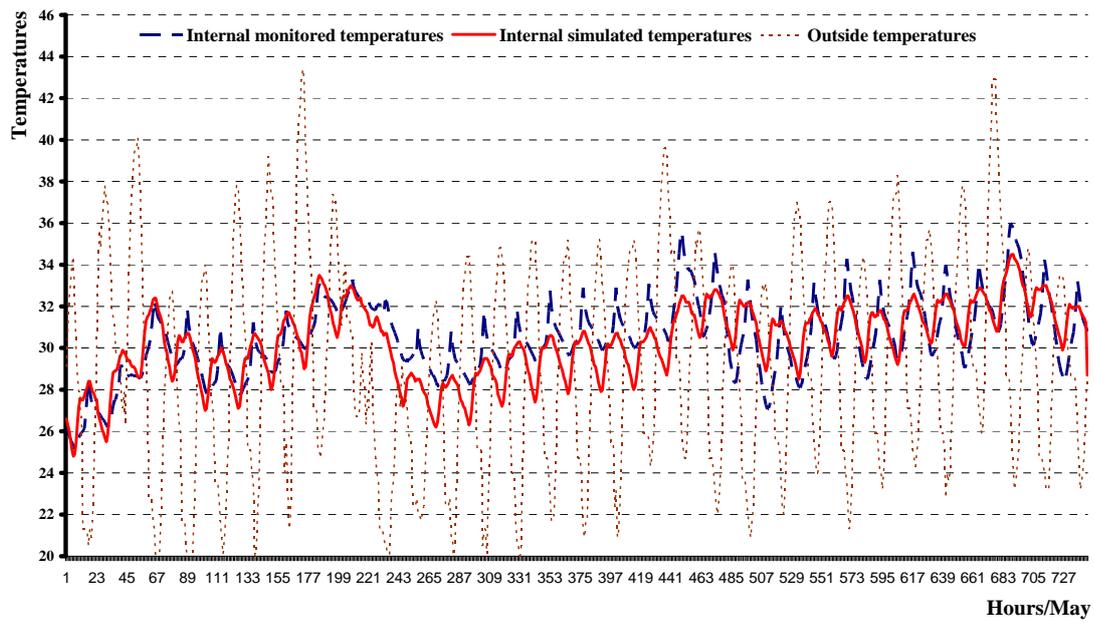
**Figure 9:** The internal monitored air temperatures compared to the HTB2 simulated air temperatures.



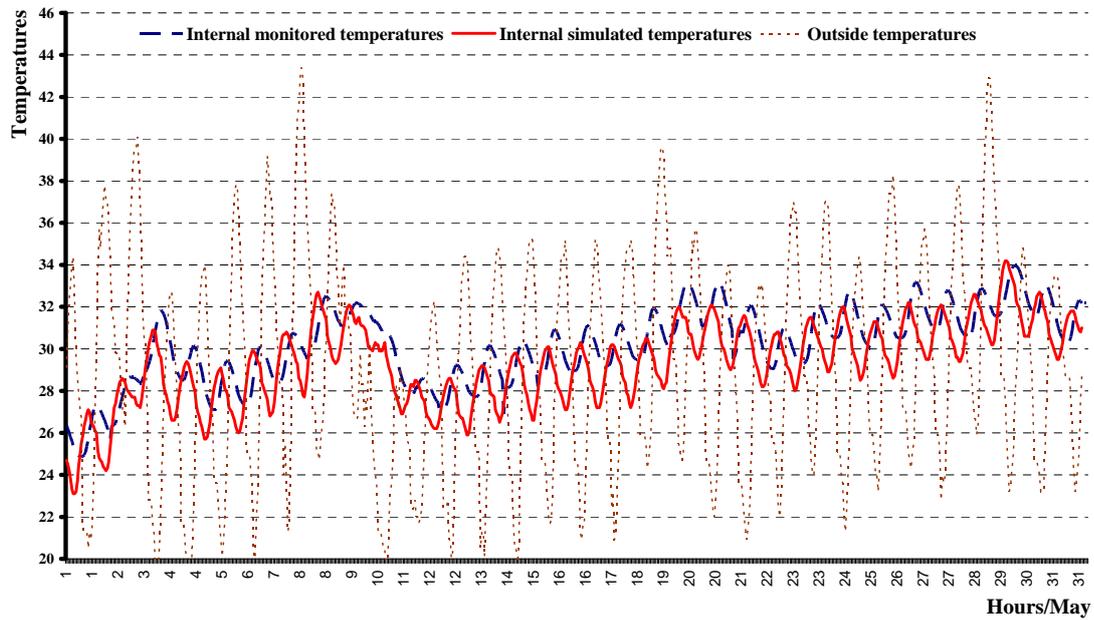
*Figure 10: Different materials used in the external wall, after Mohamed.*



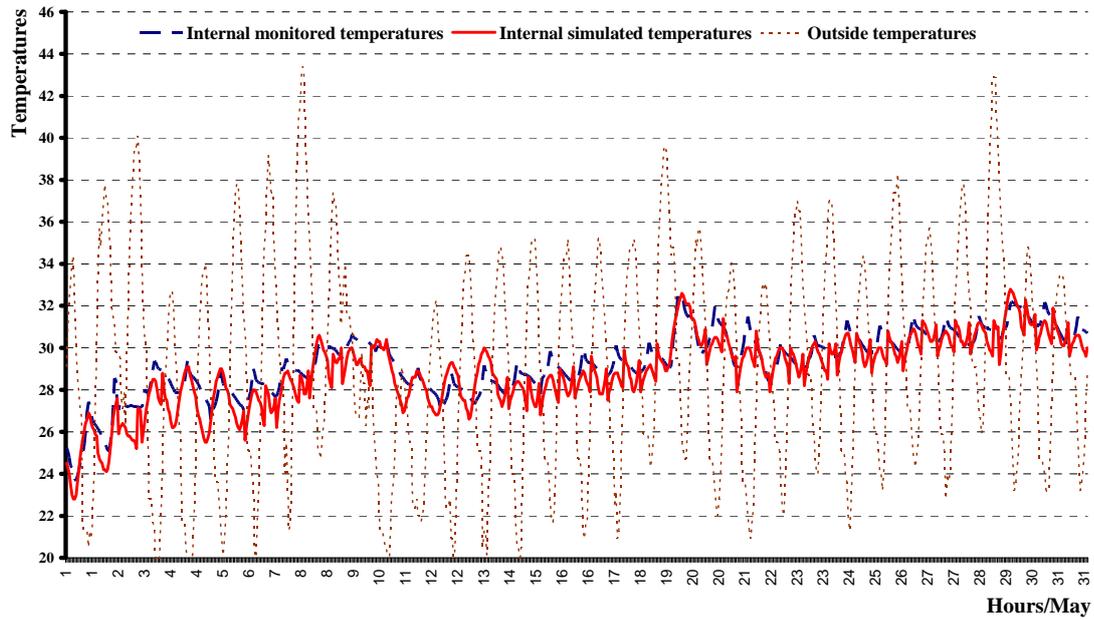
*Figure 11: Internal simulated air temperature generated using all wall modelling techniques compared to the monitored internal air temperature inside Omar ebn al-Khatib classroom.*



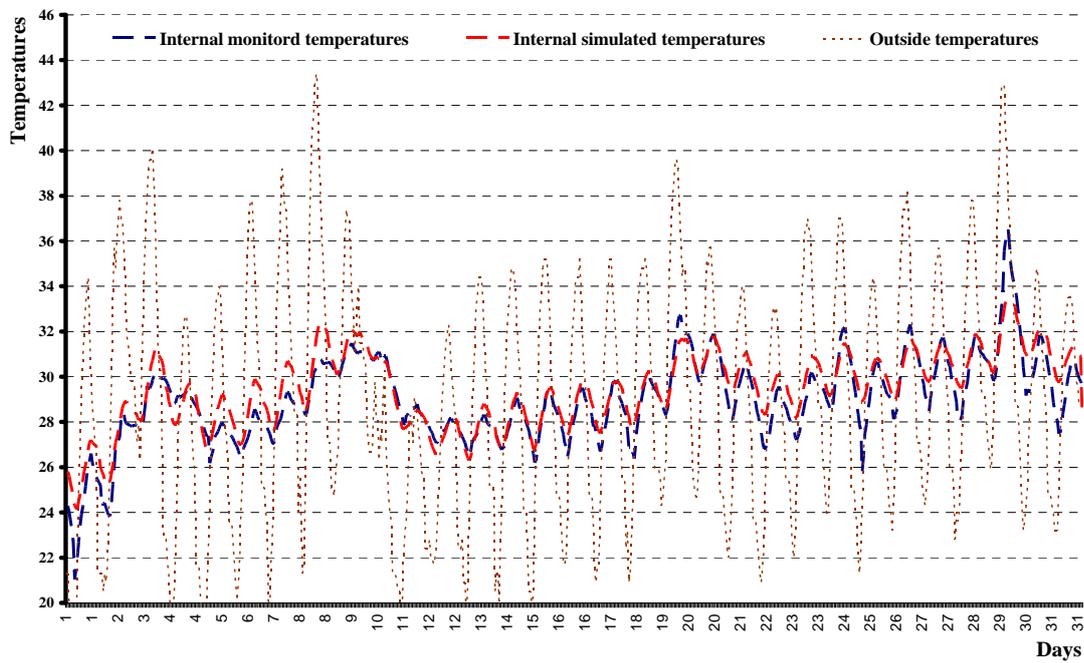
**Figure 12:** Internal simulated air temperature generated using the proposed wall modelling technique compared to the monitored internal air temperature inside Omar ebn al-Khatab (Classroom 1).



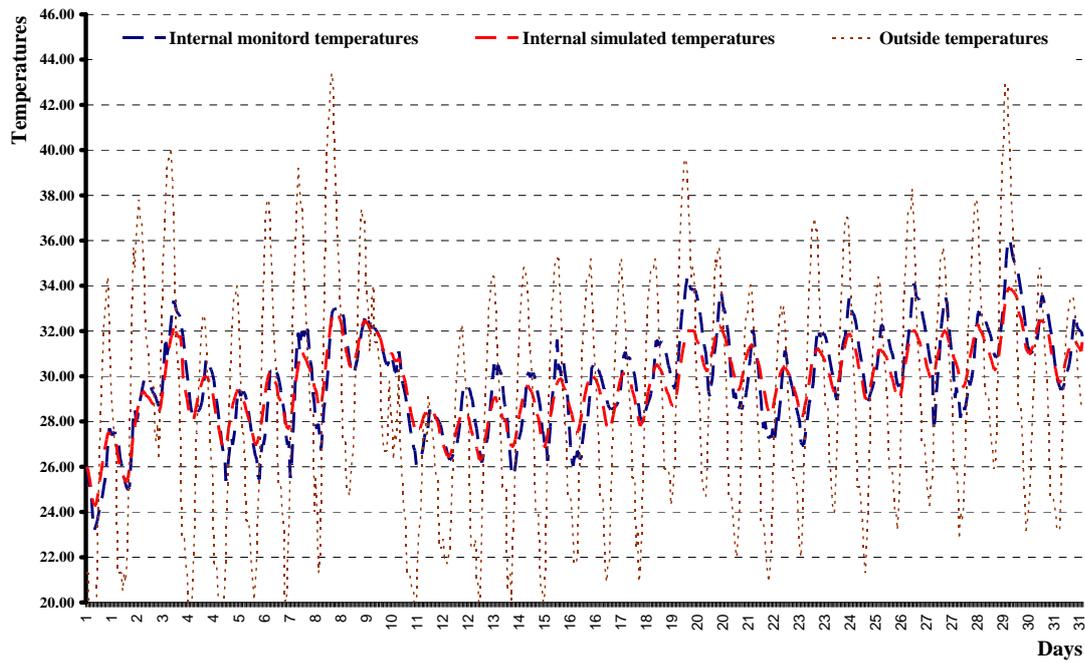
**Figure 13:** Internal simulated air temperature generated using the proposed wall modelling technique compared to the monitored internal air temperature inside al-Shaheed School (Classroom 2).



**Figure 14:** Internal simulated air temperature generated using the proposed wall modelling technique compared to the monitored internal air temperature inside al-Shaheed School (Classroom 3).



**Figure 15:** Internal simulated air temperature generated using the proposed wall modelling technique compared to the monitored internal air temperature inside al-Lamaty School (Classroom 4).



**Figure 16:** Internal simulated air temperature generated using the proposed wall modelling technique compared to the monitored internal air temperature inside al-Lamaty School (Classroom 5).

**Table 1:** The effect of wall modelling techniques on the accuracy of the simulated internal air temperature.

Internal air temperature					
	Monitored	Simulated using method 1	Simulated using method 2	Simulated using method 3	Simulated using method 4
Mean	30.47	29.10	30.28	31.98	30.25
SD	1.84	1.64	1.78	1.78	2.57
ANOVA	F=205.389, P=0.005 Significant				

**Table 2:** Validation of the all conventions and rules.

Primary schools employed as case studies										
Classroom	Omar ebn al-Khatab		Al-Lamaty				Al-Shaheed			
	Classroom 1	Classroom 1	Classroom 2	Classroom 2	Classroom 3	Classroom 3	Classroom 4	Classroom 4	Classroom 5	Classroom 5
M=Monitored temp. S=Simulated temp.	M	S	M	S	M	S	M	S	M	S
Mean internal temp.	30.47	30.28	29.75	29.67	28.99	29.43	29.26	27.75	30.17	29.31
SD	1.84	1.78	2.38	1.74	1.91	1.66	1.50	2.08	1.81	1.92
Mann-Whitney test	P=0.22		P=0.06		P=0.10		P=0.39		P=0.06	
The difference between the monitored and simulated internal air temperature	ns		ns		ns		ns		ns	

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