TOOL FOR DESIGN DECISION MAKING: ZERO ENERGY RESIDENTIAL BUILDINGS IN HOT HUMID CLIMATE

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ABSTRACT

Informed decision-making is the basis for the design of Net Zero Energy Buildings (NZEBs). This paper investigates the use of building performance simulation tools as a method of informing the design decision of NZEBs. The aim of this study was to develop a design decision making tool, ZEBO, for zero energy residential buildings in hot climates and to evaluate the effect of a simulation-based decision aid, on informed decision-making using sensitivity analysis. An assessment of the role of the BPS tools used in informing the decision-making was ascertained through cases studies, usability testing and several self-reported metrics. The paper provides results that shed light on the effectiveness of sensitivity analysis as an approach for informing the design decisions of NZEBs

.INTRODUCTION

The Net Zero Energy Buildings (NZEBs) objective has raised the bar of building performance and will change the way building are designed and constructed. During the coming years the building design community at large will be triggered by mandatory codes and standards that aim to reach neutral or zero energy built environments (IEA 2009). In the same time, lessons from practice shows that designing a robust NZEB is a complex, costly and tedious task. In order to design such buildings it is important to assure informed decision making during the early design phases for NZEBs. This includes the integration of building performance simulation (BPS) tools early on in the design process (Hensen 2002). BPS is ideal to lower those barriers. BPS opens the door to other mainstream specialism including architect and smaller practices during earlier design phases (Fig. 1).

However, the integration of BPS in the design of NZEB is challenging and requires making informed design decisions and strategic analysis of many design solutions and parameter ranges and simulates their performance. A recent study by Attia has shown that architects most important selection criteria for BPS tools is its intelligence and ability of guidance to inform the decision-making. (Attia 2011a).

Ensuring the best guidance is available during critical decision making of NZEB design. Designers'

decisions to design NZEBs should be informed. This paper presents a method and decision support building simulation program that can be used as an proactive guide in the early design stages of residential NZEB design in hot climates. The paper proposes a parametric approach. The idea of this tool is to provide better guidance of design decision to deliver NZEB in hot climates. This is achieved through enabling sensitivity analysis to inform the decision-making and allow a variety of alternatives to be created in short time.
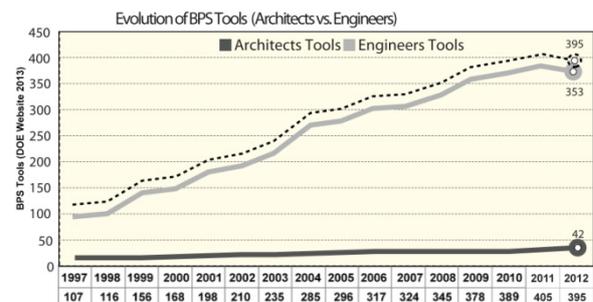

Figure 1: Evolution of BPS tools in the last 10 years

DESIGN PROCESS & TOOLS OF NZEBS

A building delivery process has traditionally been a discrete and sequential set of activities (Mahdavi 1993). Designers start with rules of thumb to create a design, and then model it to verify its compliance with the performance goals. If the proposed design did not meet, the goals the designers would go back and start again. This tedious trial and error approach continues until finding the design that meets the performance conditions. However, the "net zero" objective is an energy performance-based design goal that embraces the integration of energy-performance goals early in the design process. Architects are forced to expand their scope of responsibility beyond function and aesthetics. The design process of small scale NZEBs, with no energy specialist on board, shows that the design is not intuitive and energy performance requirements must be determined in the early design stages. Therefore, BPS tools are a fundamental part of the design process (Hayter et al. 2001, Athienitis, et al. 2010, Donn et al. 2009). During early design phases, 20% of the design decisions taken subsequently influence 80% of all design decisions (Bogenstätter, 2000). In order to

apply simulation during early design phases it is better to understand the current building design and delivery process of NZEBs, because the effectiveness of tools are affected by the process. This section elaborates on previous attempts at solving integration issues related to the NZEB design delivery process and the use of simulation tools.

NZEB design approaches

A NZEB is a grid-connected and energy-efficient building that balances its total annual energy needs by on-site generation (Marzal 2011). The main concern of NZEBs design is robustness through the Metric-based Design or the Performance-based Design (PBD) approaches. As formulated by Kalay and Torcellini, the PBD approach emphasises the design decision making in relation to performance (Kalay 1999). Experience with constructed NZEBs shows that their design process is based on performance-based decision making that effectively integrates, early on, all aspects of passive building design, energy efficiency, daylight autonomy, comfort levels, renewable energy installations, HVAC solutions, in addition to innovative solutions and technologies (Hayter 2001, Athienitis et al. 2010, Molenaar 2009). Thus, evaluating different design combinations and parameters based on their performance became an additional activity during the early design stages of NZEBs. To put the design process of NZEBs in perspective, designers have to meet with successive layering constraints with a performance-based objective, where "form follows performance". Designers have to define their work in a set of performance criteria, rather than work out the design traditionally in a prescriptive objective.

Conceptual early design stages of NZEBs

The process of NZEBs design can be described as a successive layering of constraints on a building. Every new added decision, every defined parameters, is just one more constraint on the designer. At the start of the NZEBs design process the designer has many decisions and a relatively open set of goals. By the end, the building is sharply defined and heavily constrained. For NZEBs high constraints are imposed due to environmental and energetic requirements. The constraints provide useful anchor for ideas. Conceptual early design stages of NZEBs can be divided into five sub-stages: (1) Specifying Performance Criteria, (2) Generating Ideas, (3) Zones-Layout Design, (4) Preliminary Conceptual Design, and (5) Detailed Conceptual Design. Sub-stages 2 to 5 do not always follow a sequential linear order. The design process goes into a cyclic progression between those sub-stages in which each sub-stage elaborates upon previous constraints.

Barriers to integrating BPS during early phases

Experience with post occupancy evaluation of constructed NZEBs shows that the design of high-performance buildings is not intuitive, and that BPS tools are a fundamental part of the design process.

The nature of the aggressive goals of NZEBs requires the early creation of energy models during pre-conceptual and conceptual design phases. Recent studies on current barriers that face the integration of BPS tools into NZEBs design are summarised below (Athienitis 2010). Figure 2 illustrates the barriers of decision making during early design stages of NZEBs design.

(1) Geometry representation, (2) Filling input, (3) Informative support for decision making (guidance), (4) Evaluative performance comparisons, (5) Interpretation of results and (5) Informed iteration
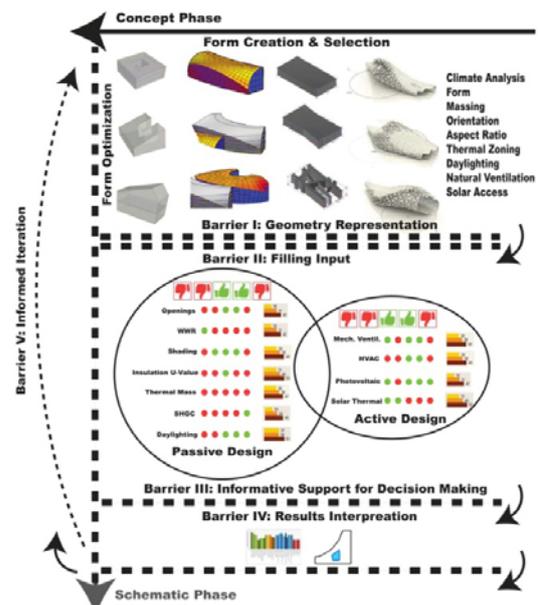

Figure 2: Barriers of decision making during early design stages

In order to support decision making during the early design phases it is important to include an informative tool for the early design phases that can model the complexity of the design. An energy simulation tool, ZEBO, was developed to help architects discover parameters that would achieve a zero energy building and inform them about the sensitivity of each parameter. The interface for ZEBO was built on the above mentioned guidelines. How the proposed tool intends to achieve these goals is explained in the following sections.

TOOL DESCRIPTION

In response to the barriers, requirements, and expectations identified earlier, a prototype of the proposed decision support tool was developed. The tool is a conceptual model for software under development called "ZEBO" that aims to address these shortcomings and test the validity of the method proposed (Attia 2012a&b). The tool allows for sensitivity analysis of possible variations of NZEB design parameters and elements during the early design phases in hot climates. Its added value resides in its ability to inform the decision prior to the decision making for NZEBs design. The tool is

contextual and is based on an embedded benchmark model and database for Egyptian residential buildings, which includes local materials and construction and allows the generation of code complying design alternatives (see Figure 3).

The initial target audience of ZEBO is architects and architectural students with little experience in building energy efficiency. The tool can be used by architects to lower the barrier to design NZEBs during the early conceptual phases. Typically, architects produce several design alternatives in the conceptual design phases. Thus this is the moment where the tool should be applied to assess the energy performance and energy generation potential for each design solution by studying the effect of the variation of different design parameters ranges. ZEBO also allows for comparative energy evaluations.

Simulation benchmark and database

One of the challenges to developing the tool was to implement a representative benchmark or reference building for dwellings. The benchmark should represent Egyptian flat apartments in narrow front housing blocks. For this study we selected a benchmark based on a recent research, conducted by the author (Attia 2010a & 2012c), to develop a benchmark models for the Egyptian residential buildings sector. The benchmark represents different settings of apartments that can be constructed in a detached, semidetached, or attached form. It was assumed to represent apartments in high urban densities of Egyptian cities, incorporating surrounding buildings and streets. The benchmark developed by Attia et al. (2012c) describes the energy use profiles for air-conditioners, lighting, domestic hot water and appliances in respect to buildings layout and construction. The benchmark simulation models were verified against the utility bills and field survey data for 1500 apartments in Alexandria, Cairo and Asyut.

For ZEBO a simple multi-dimensional rectangular zone was created to represent mechanically cooled apartment units. Despite the limitation of this reduction or abstraction of the underlying model, the tool coupled the model to the Egyptian climatic and urban context. The selected model is shown in Figure 5 and allows maximum design flexibility for a range of architectural early design parameters, including the sites' urban density and climatic conditions. Moreover, ZEBO is based on a knowledge base system that embeds the recommendations of the Egyptian Residential Energy Standard ECP306-2005 (HBRC 2005 and Huang et al. 2003). The prescriptive recommendations of the standards are translated into input default values depending on the selected site location and code. Also a self-developed materials library is embedded that allows the combination of the most common material constructions in Egypt, including glazing, insulation, and wall and roof construction (Attia 2012d).

Thermal comfort in hot climates

Designing NZEBs depend on the expected thermal comfort level. In Egypt comfort is adaptive and mechanical equipment such as ceiling fans are used mainly for occupancy satisfaction. It is known that air movement affects both convective and evaporative heat losses from the human body, and thus influence the thermal comfort and consequently influence the 'net zero' objective. For ZEBO we chose Givoni's comfort method (Givoni 1992) that allows adaptive comfort boundaries in relation to the increase of air movement by turning on fan or opening windows. As shown in Figure 5, a psychrometric chart allows the visualisation of outdoor or indoor dry bulb temperature and relative humidity area temperature. The chart can be used prior to, or after, design to estimate the necessity of installing an acclimatisation system.

Renewable systems

An extra integral module of ZEBO allows the estimation of the energy generation and required photovoltaic and solar water heater panel area. The solar active tool module is based on earlier research by the author (Attia 2010b) and informs the decision making on the physical integration within the building envelope, addressing the panels' area, mounting position, row spacing and inclination. The idea of this module is to inform the designer as early as possible on the spatial and physical implication of the NZEB objective. The renewable system module is an implementation of simulation results that estimate the average performance of a PV system in different locations and positions in Egypt. The simulation-generated data was matched with real measurements obtained from literature.
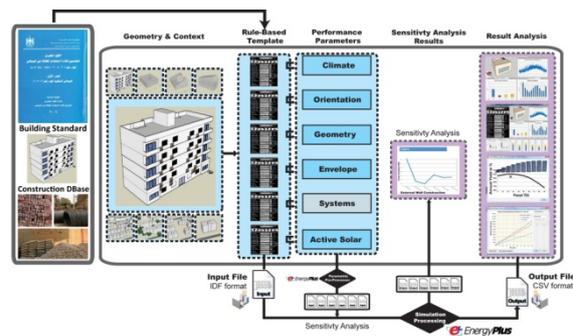

Figure 3 The flowchart of ZEBO.

Decision Support logic and sensitivity analysis

The use of sensitivity analysis prior to the decision making represents an informative approach for the robustness of the design decision in relation to energy and comfort. Based on the feedback obtained from sensitivity analysis results, the design decision is supported in relation to the possibilities of the parameter range. Therefore, the sensitivity analysis is a method that enables designers to take energy and comfort conscious decisions to reach the final performance goal. For the tool, a global sensitivity

analysis was undertaken to investigate the most early design parameters and their ranges (Hansen 2007, Hopfe 2009). Figure 4 illustrates the method used for the development of the tool. The designers investigates the sensitivity of a single parameter and its consequences on energy saving, energy generation or comfort. The sensitivity analysis result shows the whole parameter range and provides a pre-decision overview of the parameter range and intervals. The designer makes decisions based on this overview, and specifies a perturbation. Based on the compliance with the rules set, the designer can then repeat the process with other parameters before combining all perturbations and running a complete evaluation.

ZEBO allows sensitivity analysis to illustrate how variations in building design parameters can affect the comfort and energy performance. In fact, sensitivity design environments provide an opportunity to inform the decisionmaking. Therefore, the tool depends on the parametric pre-processor, a recent addition to EnergyPlus utilities that allows the accomplishment of sensitivity analysis. The parametric objects of EnergyPlus can be used in a single file as an alternative to maintaining a group of files with small differences. The user makes a series of simulations cloning the same IDF file but including all discrete intervals of a predefined parameter range, just by clicking the sensitivity analysis button. The Run Batch will run different simulations using the IDF input file. The user is then provided with a graph that shows the variation in annual energy performance in relation to the parameter intervals' range, in a way it can become an immediate yet comprehensive support to make informed design decisions.

Implementation, Interface, input, output and design flow and design continuation

ZEBO can accept input data required by the later phase tool EnergyPlus V7 and run a simulation with its engine (DOE 2013). EnergyPlus was selected because it is a free open source tool that allows third-party graphical user interfaces (GUIs and can be used in a cyclical process that allows continuity with the design process using the same input files. The tool is based on a one page interface that communicates with EnergyPlus via the input and output format that are in ASCII format. ZEBO creates an IDF input file and the simulation runs the EnergyPlus engine through a "RUN" batch-file. The simulation results are then generated in different formats, mainly HTML and CSV files. The programming language was written in Visual Basic 2008.

To address the NZEB objective, the interface first addresses the passive design strategies and then the active design strategies. The overall conceptual flowchart is illustrated in Figure 4. Upon clicking the execution file, ZEBO opens the main page of the interface as shown in Figure 5.
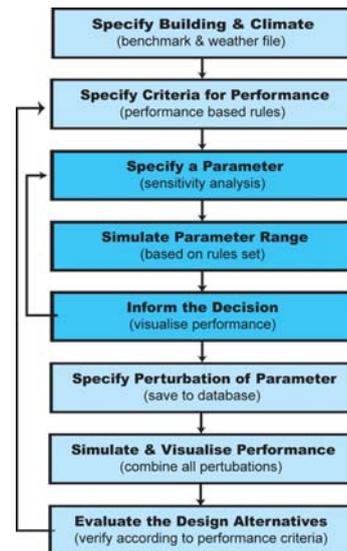

Figure 4 Tool workflow scheme.

Input options are categorised on the upper left of the GUI. Input categories are divided into eight groups: Weather File, Orientation, Zone Dimensions, North and South Window Width and Type, Shading Devices and Dimensions, Wall Type, Wall Insulation Type and Thickness, and Roof Insulation Type and Thickness. The weather file is selected by a pull down menu. The file is an EPW file type for eleven Egyptian cities downloaded from the DOE EnergyPlus weather file library (DOE 2013). Once the weather file is selected, the standard requirements of the chosen location are automatically set as default values, allowing the creation of the baseline case (Attia 2012c). The user is then allowed to change the parameter input without exceeding the minimum standard requirement.

The main purpose of the passive design intervention is to reduce the cooling demand. For example, the building can be rotated into eight directions every 45° degrees. Three horizontal scroll bars allow the modification of the height, length and depth of the housing or office unit. Designers can define windows. They can check the window option and modify the window width and type. Eleven different window types can be chosen representing arrangements of typical Egyptian window types in addition to more energy efficient types. It is possible to define the horizontal shading options and determining the shading device locations and dimensions above the windows. Also the wall section can be selected, including the wall type, insulation material and insulation thickness. At the end of this process, and prior to pressing the EnergyPlus button, the tool will update the EnergyPlus input file with the input parameters.

The active design intervention can be done as a last step as it depends on the total energy consumed. The solar active module allows the selection of different parameters including the PV panel type, panel tilt,

panel orientation, panel efficiency and mounting to optimise the electrical yield. Once the simulation has been run, the output graphics are displayed upon clicking on any of the 11 output buttons illustrated in Figure 5. Graphs are generated by reading the CSV output file using Excel macros. Figure 5, illustrates an example of the output graphics. For each case, the ZEBO output screen displays the results in three different graphs: the outdoor temperatures graph located in the upper right corner of the screen, the monthly end use graph in the bottom right side, and the energy consumption breakdown graph on the bottom left of the screen.

CASE STUDY

In order to test the validity and usability of the tool we took two measures. First use a case study as an example how a hypothetical design concept would be developed and to discuss how the results generated by the tool are sufficiently accurate for the NZEB design. Second use a usability testing study.

To test the validity of the proposed tool of ZEBO, we present a hypothetical design example for an apartment in narrow front housing block in Cairo. The first step is to create a basecase in ZEBO. The user selects a building type, and the weather file for Cairo, a TMY2 weather file. Then the user has to select the targeted standard for minimum performance. The choice of standard determines many of the defaults and assumptions that go into the simulation model. The tool is currently limited to the Residential Energy Standard ECP306-2005-I. For this case the Egyptian standard was chosen. The tool then automatically loads a complete EnergyPlus input file for a single zone with complete geometry description that complies with the Egyptian building energy and thermal indoor environment standard. The user can change the building geometry, including the height, floor plan dimensions and number of floors in the building, in addition to the other input parameters mentioned earlier. However, for this case study we chose not to make any changes and run the default file to create a basecase according to Table 1.

Table 1: Reference model and output plots

Building Description	Basecase 1	Parametric Range
Orientation	0°	0°, 45°,90°,135°,180°,225°,270°, 315°
Shape	Rect.(12mx10m)	12x10, 12x11, 12x12, 10x10
Floor Height	3 m height	3,4
Number of Floors	1	1,2,3,4,5,6,7,8
Volume	360 m^3	NA
External Wall area	72 m^2	NA
Overhang	None	0.0, 0.5, 1, 1.5, 2
Fin	None	0.0,0.3,0.5,0.8,1.0,1.5
Roof area	120 m^2	NA
Floor area	120 m^2	NA
Windows area	28 m^2	NA
Window Wall Ratio	45%	50, 45, 40, 35, 30, 25, 20, 15
WWR	1.8 W/m^2 K	2, 1.8, 1.6, 1.4, 1.2, 1, 0.8, 0.6, 0.4
Exterior Wall U-Value	1.4 W/m^2 K	1.4, 1.2, 1, 0.8, 0.6
Roof U-value	1.6 W/m^2 K	1.4, 1.2, 1
Floor U-value	Tv = 0.9	1, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3
Single Clear Glazing	0.75	1, 0.75, 0.5, 0.25
SHGC	0.033 people/m^2	NA
People Density	6 W/m^2	NA
Lighting Power Density	7 W/m^2	NA
	20 (m^3/h per p.)	NA

Plug Loads	0.7 ach	NA
Outside Air	On-Split+sep.	NA
Infiltration	ventilation	NA
HVAC Type	2.00	NA
Cooling COP	Givoni	NA
Thermal Comfort	24	NA
Model	60	NA
Cooling set point (°C)	70	NA
Relative Humidity (%)	Aph,MC, PC	NA
Fan Efficiency (%)	0-100	NA
Water Heater (%)	6%-14%	NA
PV Type	None	NA
PV Surface		
Cell efficiency		
Inverter efficiency		

The second step, after viewing the simulation results for the basecase (Figure 5), is performing sensitivity analysis. The designer is encouraged to run sensitivity analysis for any selected parameter. This step introduces designers to the impact of varying the parameter values prior to the decision making. The sensitivity analysis results form the basis for informed decision making. Opposite to the classical design approach, where simulation is used as a post-decision evaluative tool, the designer is informed on the impact of his decision prior to the decision making.

In this case study we chose to examine the wall construction type. Upon selecting the PA checkbox next to the Wall Construction Type a new window pops up to asking the user to confirm his choice, which will require the running of 8 files for at least 2 minutes. Upon confirmation, the results are generated by EnergyPlus and the output is presented as shown in Figure 5. Based on the sensitivity analysis results, the designer is encouraged to select the most energy saving wall construction type. Based on the two sensitivity analysis graphs in Figure 5, the user can see the impact of the different construction types, and hence will probably select the wall construction type (7) with the lowest energy consumption (U value = 0.4 W/m2 K for basecase wall). Once the output is displayed, the user can move on to the photovoltaic tool module. This step is done as a last step where five inputs (location, PV type, panel tilt, panel orientation, panel efficiency) are requested to optimise the electrical yield (DOE 2013).

Thus ZEBO allows the designers to explore further parameter variations while indicating the optimal value in relation to energy consumption. The designer then makes an informed design decision and enters the decision as an input and reruns the whole simulation. On the same screen the total energy consumption can be compared to the reference case results Figure 5. ZEBO also allows the architect to easily make multiple informed decisions at once and run the simulation button. EnergyPlus actuates the latest changes and the result is presented.

Results validity

By examining the results of the basecase simulation the consumption was 19.85/kWh/m2/year (U value = 1.78 W/m2 K for wall construction 1). Based on the sensitivity results shown in Figure 5 the wall construction with the lowest energy consumption was selected. Accordingly the energy consumption was

reduced around 16% to reach 16.61/kWh/m2/year (U value = 0.421 W/m2 K for wall construction 7). Compared to the 8 wall constructions the wall construction 7, comprising a 125 mm double wall with 50mm glass wool insulation, had the best energy performance. This result is consistent with the findings of (Attia 2010a) for low energy design. The case results shows that the tool decision support bring significant savings without any time for design iterations. This helps to extend the application of sensitivity analysis to guide the decision making before the building is designed using appropriate energy principles.
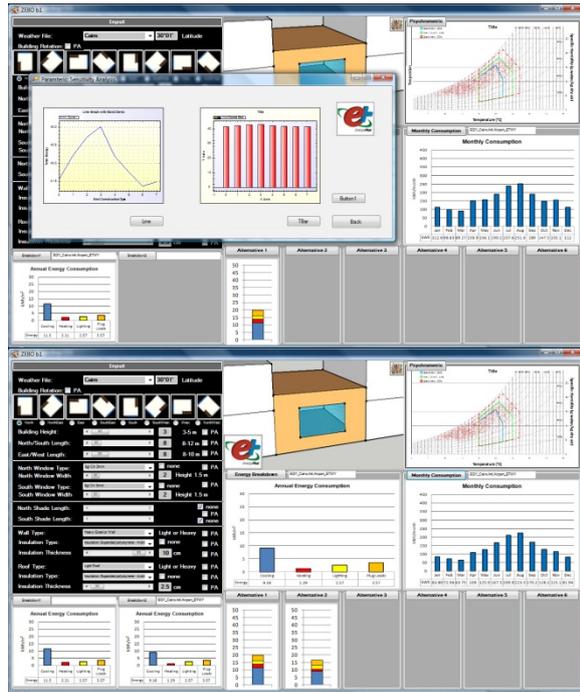

Figure 5a, Reference model and output plots including sensitivity analysis results.5b, model and output plots for design alternatives comparison.

Usability testing

The main objective from the usability testing and evaluation was to assess the usability of the interface and the ability of decision making by performing usability tests on the different prototype versions. The usability testing comprised effectiveness, efficiency, and satisfaction metrics for a group of core tasks supported by the tool in order to allow comparison with future design prototypes of ZEBO. To achieve the goals of the usability study, two main iterations of usability testing have been carried out during the development of prototype 1 and 2 of ZEBO. This was done to achieve feedback from designers and potential users. The ISO definition of usability (ISO 9241-11, 1998), comprising the three attributes-effectiveness, efficiency, and satisfaction was used as the basis for the metrics collected. For effectiveness, a rubric was established to judge whether task performances were scored as a pass or fail. Each participant was asked to perform a

simulation run for a pre-defined building aiming to find the answer to a specific question. To measure the tool success participants were asked to perform a simulation and find the total cooling load (kWh/year) for the hypothetical building in Cairo. Participants provided their answers in structured way, using a paper form. The task had a set of two-choice responses. Either participants completed a task successfully or they did not. The success of task depends on users completing a performance simulation. By matching the simulation results for cooling loads users were given a ''success'' or ''failure'' score. Typically, these scores were in the form of 1's (for success) and 0's (for failure). By having a numeric score, the average binary success rate was calculated. Moreover, a stopwatch was used to measure the attribute of efficiency, the time spent per task in minutes and seconds. The third attribute, satisfaction, was collected using the System Usability Scale (SUS) (ISO 1998). To guarantee the internal validity of the test a set of 10 ordinary (pre-defined) SUS questions were used. A paper based survey was conducted using Likert scale. Users have expressed their agreement with the questionnaire questions on a scale ranging from 1 to 5. (1='strongly disagree' - 5=strongly agree'). Scores were added and the total was multiplied by 2.5. A mean score was computed out of the chosen responses with a range between 0 and 100. The higher the score the more useable the tool is. Any value around 60 and above is considered as good usability.

The usability iteration for ZEBO prototype 1 took place in August 2010 with 27 users comprising architects, architectural engineers and architectural students. The second usability testing round was achieved during the organization of four design workshops of Zero Energy Buildings in Cairo conducted in January 2011. Four users' focus groups tested the tool. Three testing groups comprising architects, architectural engineers and architectural students (62 users) were handed a list of tasks showing the required actions. After installing ZEBO, every user was shown a short tutorial video (Attia 2011b) illustrating the elements of the interface and their meaning. Additionally, every participant was interviewed after conducting the usability testing to follow up and get a valuable understanding of the tools' limitations. The feedback was incorporated in the ZEBO prototype 2 and followed by a second usability testing.

We evaluated effectiveness by calculating the mean values of task completion for each task, as well as the mean and standard deviation for all tasks combined (Prototype1 M=0.685, SD=0.353, Prototype2 M=0.74, SD=0.565). Efficiency (mean time per task) was presented for individual tasks as well as for the full set of tasks (Prototype1 M=456s, SD=103.0s, Prototype2 M=821s, SD=525s). Satisfaction was evaluated by reversing the scale values and computing the mean SUS scores for each group and

for all participants (Prototype1 M=0.737, SD=11.2, Prototype2 M=0.812, SD=8.52). The theoretical questions for the study were analyzed further using Excel Statistical Analysis Toolpak to discover moderate to high correlations existing between effectiveness, efficiency, and satisfaction. The different satisfaction collection methods revealed no significant difference between methods (Zazelenchuk, 2002). The quantitative data representing effectiveness and efficiency were shared with the design team on per-task basis (see Figure 6). Given that there was no significant difference discovered between the three conditions applied in the study, users' satisfaction measures were presented as an average post-task score for all participants.
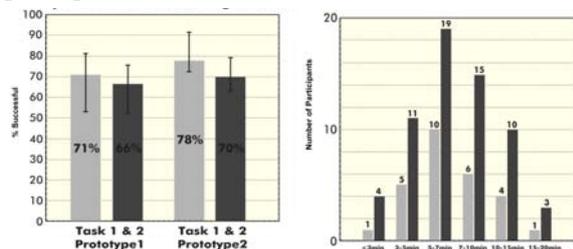

Figure 6, Mean time per task., Binary success data for performing simulation.

From the analysis some main strengths and limitations were revealed. Overall, the reactions were particular positive on the tools effectiveness. From the analysis it emerged that there is a great potential for the interface. From the open questions and post testing interviews users appreciated the embedded benchmark and the ability to size and simulate the renewable system. Respondents were also particularly enthusiastic about the sensitivity analysis feature that supports the decision making intuitively and reduce the number of design iterations for each parameter and total design. Having comfort evaluation expressed through the psychrometric chart for forced wind speeds (ranging from 0.5 to 2 m/s) seemed extremely helpful to easily interpret the weather and they found great value in connecting comfort with weather and desirable passive deign strategy. However, the post usability testing interviews revealed other limitations. For example, many users indicated their unfamiliarity with the tool's assumptions and were uncertain about communicating the tool results with their clients. Some users found the benchmark very useful but preferred to use other more comprehensive tools beside ZEBO. Other suggested using the tool as an educational tool. Also users suggested a better guidance on the tool use. Many users suggested using the tool with an expert guidance or as an educational tool. Another main reservation many users had was the difficulty to interpret and explain the output results. This had a direct influence on respondents' confidence in the results and the reliability of the

tool's results to communicate them with the client. The results of this usability testing will be embedded in next prototype and expanded to a more formal case study design in the near future.

DISCUSSION & CONCLUSION

The simulation-based design support tool was found to promote informed decision making for zero energy building design during early design stages. It increased the knowledge about the zero energy building design lessened the uncertainty of decision making. Participants who used ZEBO reported a high level of knowledge and operated their design from an informative decision support approach rather than an evaluative trial and error approach. This congruence between decision making and design objective in the context of higher knowledge accords with our definition of informed decision making of ZEB design. However, based on the interface usability testing the current prototype has not reached a usability level that satisfied the needs of designers. As such, the tool is a starting point for the development of widely usable tool.

Strength and limitations

This is the first simulation based decision support tool for early stages of zero energy building design in Egypt. The tools' strength is its capacity to inform design prior to decision making, while managing large sensitivity simulations and presenting complex data in easily comprehensible, fast and comparative formats. Basing the tools on a representative benchmark for Egyptian residential building and local building components and system linked to a detailed simulation engine like EnergyPlus is reinforcing the tools result validity and certainty in decision making. The tool is easy to use, with an interface structure that is based on matching the passive and active design strategies for the net zero objectives. The tool can help achieve the energy performance goal while exploring different ranges of a thermal comfort in hot climates to achieve the performance objective. ZEBO's strength is in its capacity to reduce decision conflict and the need for tedious design iterations to achieve the performance objective, while creating a variety of alternatives in a short time, which match the early design cyclic explorations and iterations. Better informed decisions, especially at the earliest conceptual design phases, will improve the design of NZEBs. It is hoped that several design trials, currently in progress using the tool, will allow a greater impact on architects' decision making and actual design outcomes, and enable integration of BPS tools to proceed further than the decision support level reached in this study.

However, the tool in its current state can hardly attract large enough numbers of users. The usability testing results revealed that the tool seems more useful if used with the support of an expert to use ZEBO or in the hands of an educator for design

exploration. Also the decision making support of current prototype can only handle energy issues while many users expect other environmental and economical indices. One of the main limitations identified during the workshops was the geometry and non-geometric input. Users suggested links to Google SketchUp for geometry input and user interface improvements to insert input visually (not numerical or textual). Similarly the tool is limited to its own library of a generic rectangular single-zone template with few alternatives for building components and systems.

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