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SIMULATION-BASED DECISION SUPPORT TOOL FOR EARLY STAGES OF ZERO-ENERGY BUILDING DESIGN

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ABSTRACT
There is a need for decision support tools that integrate energy simulation into early design of zero energy buildings in the architectural practice. Despite the proliferation of simulation programs in the last decade, there are no ready-to-use applications that cater specifically for the hot climates and their comfort conditions. Furthermore, the majority of existing tools focus on evaluating the design alternatives after the decision making, and largely overlook the issue of informing the design before the decision making. This paper presents energy-oriented software tool that both accommodates the Egyptian context and provides informative support that aims to facilitate decision making of zero energy buildings. A residential benchmark was established coupling sensitivity analysis modelling and energy simulation software (EnergyPlus) as a means of developing a decision support tool to allow designers to rapidly and flexibly assess the thermal comfort and energy performance of early design alternatives. Validation of the results generated by the tool and ability to support the decision making are presented in the context of a case study and usability testing.

KEYWORDS: design decision support, zero energy building, sensitivity analysis, energy simulation, thermal comfort, hot climates

1. INTRODUCTION
The modelling of net zero-energy buildings (NZEBs) is a challenging problem of increasing importance. The NZEBs objective has raised the bar of building performance, and will change the way buildings are designed and constructed. During the coming years, the building design community at large will be galvanised by mandatory codes and standards that aim to reach neutral or zero-energy built environments [1-3]. At the same time, lessons from practice show that designing a robust NZEB is a complex, costly and tedious task. The uncertainty of decision making for NZEBs is high. Combining passive and active systems early on is a challenge, as is, more importantly, guiding designers towards the objective of energy and indoor comfort of NZEB. Table 1 shows the six main building design aspects that designers should address early on during the conceptual stage. The integration of such design aspects during the early design phases is extremely complex, time consuming and requires a high level of expertise, and software packages that are not available. At this stage, the architects are in a constant search for a design direction to make an informed decision. Decisions taken during this stage can determine the success or failure of the design. In order to design and construct 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 [4-6].

Table 1

BPS is ideal to lower such barriers. BPS techniques can be supportive when integrated early on in the architectural design process. Simulation in theory handles dynamic and iterative design investigations, which makes it effective for enabling new knowledge, analytical processes, materials and component data, standards, design details, etc., to be incorporated and made accessible to practicing professionals. In the last ten years, the BPS discipline has reached a high level of maturation, offering a range of tools for building performance evaluation [7]. Most importantly, they open the door to other mainstream specialism, including architects and smaller practices, during earlier design phases.

However, despite the proliferation of BPS tools, the barriers are still high. Despite the proliferation of simulation programs in the last decade, there are no ready-to-use applications that cater specifically for the hot climates and their comfort conditions. Current design and decision support tools are inadequate to support and inform the design of NZEBs, specifically during early design phases. Most simulation tools are not able to adequately provide feedback regarding the potential of passive and active design and technologies, nor the comfort used to accommodate these environmental conditions [8]. Several studies show that current tools are inadequate, user hostile and too incomplete to be used by architects during the early phases to design NZEBs [9-12]. Architects suffer from BPS tool barriers during this decisive phase that is more focused on addressing the building geometry and envelope. In fact, architects are not on board concerning the use of BPS tools for NZEB design. Out of the 392 BPS tool listed on the DOE website in 2011, less than 40 tools are targeting architects during the early design phases, as shown in Figures 1 and 2 [13].

Figure 1

Figure 2

On the other hand, 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 simulating their performance. A recent study by the author [14], aiming at ranking BPS tools' most important selection criteria, showed that architects ranked intelligence above usability, interoperability and accuracy, as shown in Figure 3. Architects identified intelligence as the BPS tools' ability to inform the decision making and allow decision making on building performance and cost. Also architects indicated a lack of intelligence within the tools compared. The study revealed that architects and non-specialist users who want to design NZEBs frequently therefore find it difficult to integrate BPS tools into the design process.

Figure 3

Therefore, in order to deliver NZEBs we must lower the barrier between building design and performance, ensuring the best guidance is available during the critical decision making stages of NZEB design. Architects' decisions to design NZEBs should be informed. Research investigations in literature describe the reasons for these barriers, but little effort has been done to develop the required methods and tools that can predict the building performance in use and support the design decision making of buildings [11]. In order to overcome the barriers and achieve the aims identified earlier this research, a contextual decision support tool is proposed for NZEB design. This study is part of a larger research project that aims to lower the barriers of integrating BPS during the early phases in design. This paper presents a method and decision support building simulation tool under development that can be used as a proactive guide in the early design stages of residential NZEB design in hot climates. The paper proposes a sensitivity approach method embedded in a tool to provide better guidance for design decisions to deliver NZEBs. This is achieved through enabling sensitivity analysis to inform the decision making and allowing a variety of alternatives to be created in short time.

Section 2 presents an overview on the existing design process and simulation tools for zero energy buildings. Then Section 3 presents a tool description and mechanics. Section 4 is a case study that includes the validation of the results and usability testing. Finally, Section 5 and 6 summarize the research findings and tools strength and weakness suggesting future improvements.

2. DESIGN PROCESS AND TOOLS OF NZEBS

A building delivery process has traditionally been a discrete and sequential set of activities [15]. Designers start with rules of thumb to create a design, 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 [16-18]. During early design phases, 20% of the design decisions taken subsequently influence 80% of all design decisions [19]. 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.

2.1 NZEB design approaches

A NZEB is a grid-connected and energy-efficient building that balances its total annual energy needs by on-site generation [20]. 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 [21, 22]. Similar to the evidence-based design (EBD) approach that emphasises the importance of using credible data in order to influence the design process in Healthcare Architecture, the PBD has become a fundamental approach to evaluate the energy performance of buildings in Environmental Architecture. 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 [16,17,23, 24]. 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. The implications of the NZEB performance based design approach on the design process are discussed in the next paragraph.

2.2 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 high performance buildings 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.

2.3 Barriers to integrating BPS during early design 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 [17]. Figure 4 illustrates the barriers of decision making during the early design stages of NZEBs design.

Geometry representation in simulation tools

Architects work in different ways through sketches, physical models, 2D and 3D computer generated imagery, and analytically – and thus have different requirements for representing and communicating their design form.

Filling input

The representation of input parameters in the language of architects is a challenge in many tools. There is a clear separation between architects design language and the building physics language of most tools. This difference is often addressed by using reduced input parameters or using default values. However, filling in the design parameters is an overlooked issue among BPS tools developers.

Informative support during the decision making

Design cannot easily predict the impact of decisions on building performance and cost. The building delivery process of NZEB requires instantaneous feedback and support to inform the decision making for passive and active design strategies. The disadvantage of most existing tools is that they operate as post design evaluation tools. Therefore, the informative support should be comprehensive enough to include geometry and envelope and systems.

Evaluative performance comparisons

During the early design stages the benchmarking and the possibility to compare alternatives is more important than evaluating absolute values. The ideas generation phase is iterative and comparative. Most existing tools do not emulate this process and focus on post-design evaluation.

Interpretation of results

The representation of simulation output and its interpretation is frequently reported as a barrier among architects [11, 14]. Analytical results presented in tables of numbers or graphs are often too complex and detailed, providing an excessive amount of information. The output representation often lacks variety and visual qualities. Analysis and simulation results should be displayed within the context of the 3D geometric model [25, 26].

Informed iteration

The most important barrier facing architects is cycling informed iterations for concept development and optimisation. In the past, architects iterated back on the design for functional and aesthetical optimisation purposes. For NZEBs they have to iterate for performance optimisation purposes. This requires an understanding of building physics and performance. Architects need fundamental understanding of basic building physics that allows them to interpret the simulation feedback and drive them to iterate back to the concept.

Figure 4

2.4 Simulation tools review

Almost no current tool addresses the design of NZEBs for architects during early design phases [27]. NZEBs design strategy addresses a design duo: First maximum energy efficiency and then the delivery of energy required from renewable systems. Almost no tool listed in Table 2 helps to answer this. A critical look at the existing tools in relation to the NZEBs design process shows that several barriers exist in integrating the current BPS at this stage. Therefore, future tools should allow both strategies in order to develop NZEBs and supplement the intuitiveness of the design process with analytical techniques and simulation methods.

Over the last few decades, a large number of BPS tools have been developed to help engineers during late design phases. Such tools were developed to produce data concerning buildings' numerical modelling, simulating the performance of real buildings. Those energy BPS tools require a complicated representation of the building alternatives that require specific and numerical attributes of the building and its context. Those tools can be classified under a main group named "evaluation tools" as shown in Table 2. The examples in Table 2 are meant to be indicative, not exhaustive.

Table 2

Evaluation tools include energy analysis computer tools. Although by being evaluative they produce results that do not actually provide any direct guidance as to how the NZEB design should be improved or the performance objective achieved. The use of evaluation tools in NZEB design is based on a post-decision trial and error approach, where the simulation results are compared to a desired value. If the results are not satisfactory the design is modified and the process is repeated. This approach is cumbersome, tedious, and costly and forces architects to rely on simulation experts during the early design stages. Recently, some plug-ins were developed to facilitate the geometry input and link architectural forms of visualisation and 3D representation with the evaluation tools. However, evaluative tools embed most integration barriers discussed in 2.3.

However, during the last decade, a range of design tools has been available to help architects in the design of more energy efficient buildings. Those tools are labelled "guidance tools", which were developed to facilitate decision making prior to design. They range from quite simple pre-decision evaluation and analysis tools to parametric and optimisation decision tools that aim to inform the design and integrate BPS during the early design process. However, Table 2 shows that most developed guidance tools are pre-decision evaluative tools. Despite their remarkable capabilities, most those tools have not been transferred effectively to the architectural community, and in particular architects during the early design stages. The uptake of most those tools among architects is very low, and does not allow continuity with the design process [12, 28- 30]. While they are quite useful to lower the "input filling" barrier, they could not lower the "informative support during the decision making" barrier. Currently, few non-public tools exist that support design pre-decisions, including jEPlus and iDbuild that allow parametric analysis or BEopt that allows optimisation analysis [31-33]. The potential of parametric tools is very high to bridge the "informative support" barrier because they can provide constructive feedback with very little iterations, and at the same time allow a wide range of solution space. In contrast to optimisation tools that reduces the solution space to a minimum.

In order to address these shortcomings, we identified the requirements of a tool that can be used for the design of NZEBs during early design processes. The author conducted a survey, comparison study and workshops on the use of BPS by architects for NZEB design in Egypt [34]. The guidelines of the new tool can be summarised as follows:

- Provide better guidance for design decisions to deliver NZEB in hot climates
- Enable sensitivity analysis to inform decision making and allow a variety of alternatives to be created in short time
- The comfort range criteria and design strategies can be adjusted to respond to local definitions of indoor comfort, local construction systems and local code requirements
- Improve accessibility to decision tools for small practices
- Integrate the new tool with sufficiently established, accurate tools
- Match the cyclic design iterations and extend the scope of tools to the conceptual phases of the design process
- Allow connectivity with established tools used by different disciplines and in later design stages.
- Very easy to use and to learn, and adaptable for the less experienced with minimum input

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.

3. TOOL DESCRIPTION

In response to the barriers, requirements, and expectations identified in section 2, 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 in section 2 [35]. 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 6).

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.

3.1 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 [36, 37], 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. 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 8 and allows maximum design flexibility for a range of architectural early design parameters, including the sites’ urban density and climatic conditions. The input parameters and output options are discussed in section 3.5. Moreover, ZEBO is based on a knowledge base system that embeds the recommendations of the Egyptian Residential Energy Standard ECP306-2005 I [38, 39]. 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.

3.2 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 [40] that allows adaptive comfort boundaries in relation to the increase of air movement by turning on fan or opening windows. As shown in Figure 8, 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. The chart can also estimate the impact of mechanically assisted ventilation using, e.g., ceiling fans in relation to forced wind speeds ranging from 0.5 to 2 m/s as a desirable strategy for unconditioned buildings in hot climates. This leads the designer to start thinking about the effectiveness of his or her passive design strategies in relation to active cooling system. The chart can visualise impact of any parameter change on thermal comfort opposite to many simulation tools that are unable to adequately simulate human thermal comfort as well as the acclimatization mechanical equipments such as ceiling fans in hot climates [41].

3.3 Renewable systems

Lessons learned from practice show the importance of informing architects with active system requirements to integrate them in the envelope and become a basic part of the NZEB design concept. Therefore, 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 [42] 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.

To identify the input parameters 5 mandatory questions are asked on two successive screens shown in Figure 6. On the first screen users are asked to select a city, module type and mounting position. The second screen asks for input regarding panel orientation (azimuth angle) and inclination. There are two additional elective questions on screen two that allow users to input values regarding the panel efficiency and/or nominal peak power. For every question, the user has to choose between different answers, corresponding to the various simulated cases. Instead of communicating those results in the form of textual/numerical data a graphical interactive interface is developed to convey the design guidelines in an visual way. The results are then compiled into performance graphs as shown in Figure 6.

Figure 6

3.4 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 consumption and comfort. Based on the feedback obtained from the 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 [43, 44]. Figure 5 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.

Figure 5

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 decision making. 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 effectuates 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.

3.5 Implementation, Interface, input, output and design flow and design continuation
ZEBO can accept input data required by the later phase tool EnergyPlus v6 and run a simulation with its engine [45]. EnergyPlus is a whole-building energy performance simulation tool developed by the US Department of Energy. EnergyPlus is the next generation of BPS tool that is under constant development and offers advanced simulation capabilities. The software is a free open source tool that allows third-party graphical user interfaces (GUIs). Therefore, EnergyPlus was selected because it 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 tool uses EnergyPlus's IDF format that allows connectivity with established tools used by different disciplines and in later design stages. ZEBO extracts the required output and presents them graphically on the same page. 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 6. Upon clicking the execution file, ZEBO opens the main page of the interface as shown in Figure 8. Input options are categorised on the upper left of the GUI, and are listed in Figure 7. 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 [45]. 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 [37]. The user is then allowed to change the parameter input without exceeding the minimum standard requirement.

Figure 7

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^{o} 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 (see section 3.6). 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 8. Graphs are generated by reading the CSV output file using Excel macros. Figure 8, 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 side of the screen.

Figure 8

4. 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.

4.1 Case 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 Typical Meteorological Year (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 3.

Table 3

The second step, after viewing the simulation results for the basecase (Figure 8), 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 10. 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 10, 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/m^2 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 [45].

Figure 9

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 11. 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.

Figure 10
Figure 11

4.2 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 10 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/m^2 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 [36] 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.

4.3 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 (see Appendix A). 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 complete a task successfully or they didn't. 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) [46]. 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 highest the score the more usable the website 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 [48] 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 (see Table 4). 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 Figures 12 and 13). 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 12

Figure 13

The quantitative metrics were used to establish a benchmark for each task providing a meaningful reference for improvement of the prototypes. As shown in Figure 14, the first prototype scored a good usability for nine questions, however for the last question, participants indicated that they needed to understand how the ZEBO worked in order to get going. Figure 15 illustrates the users' feedback after compiling the 62 responses. In general, the prototype usability wax improved when compared to prototype 1. Participants seemed more confident to use the tool, 85 percent compared to 72 percent, after adding the sensitivity analysis feature. This resulted in participants scoring higher for the use of ZEBO more regularly (75 percent compared to 62 percent). Also the tool complexity was reduced by almost 10 percent which resulted in easier of use (78 percent compared to 68 percent). Also the need to understand how the tool worked was improved exceeding the 60 percent threshold of good use.

Figure 14

Figure 15

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.

5. DISCUSSION & CONCLUSION

5.1 Summary of main findings

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.

5.2 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.

5.3 Comparison with existing tools

This discussion builds on earlier software review (section 2.4) that has provided a snapshot on the currently available BPS tools. According to literature, there are few tools that inform design prior to the decision making for early design stages, [30, 33] and in the same time addresses the zero energy objective, combining passive and active design strategies. The suggested tool is a parametric tool that can provide support decision making with very little iterations while addressing the zero-energy objective.

A recent publication by the Author, proves that most existing informative tools are exclusively local serving certain countries' context [49]. In fact, most BPS tools are developed in heating dominated countries. They cater for developed countries with high energy consumption patterns and different expectations for comfort. The main barriers in using those tools are related to the availability and compatibility of input data including weather, comfort models, building benchmarks, renewable systems, and operational characteristics. None of these tools, however, addressed the zero-energy target in a context of hot climate developing country as in our tool.

5.4 Future research

ZEBO is a starting point to provide better guidance for design decisions to deliver NZEBs in hot climates. The tool in its current state has significant limitations and designers will still require more information in order to make informed decision. For better usability, the tool can include a fully visual input interface and allowing users to add new building templates for new building types or case studies. It can have T-shape, H-Shape, U-shape and courtyard shaped templates, or even better integrate an OpenGL modeller. Also the interface can be expanded to include more building systems and components, especially different envelope types and cooling systems at different cities in Egypt using suitable COPs (coefficient of performance). Also the scope of the tool can be extended further to achieve the net zero objective for existing buildings or on a larger scale (cluster or neighbourhood). Concerning the usability testing the study will address the tool efficiency and effectiveness as a complementary testing to the satisfaction testing. On the level of decision support further developments of the tool can incorporate economic indices to achieve net zero energy cost effectively. The tool can be linked to optimisation algorithms too. This can create more viable alternatives and allows the exploration of a wider search space for complex designs. This development can include economy and cost, which may be of interest for designers, researchers, energy legislators and policy makers.

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Table 1, the six main building design aspects of NZEBs design

1. Metric:	There are several definitions for NZEBs that are based on energy, environmental or economic balance. Therefore, a NZEB simulation tool must allow the variation of the balance metric.
2. Comfort Level and Climate:	The net zero energy definition is very sensitive toward climate. Consequentially, designing NZEBs depends on the thermal comfort level. Different comfort models, e.g. static model and the adaptive model, can influence the 'net zero' objective.
3.Passive Strategies:	Passive strategies are very fundamental in the design of NZEB including daylighting, natural ventilation, thermal mass and shading.
4.Energy Efficiency:	By definition, a NZEB must be a very efficient building. This implies complying with energy efficiency codes and standards and considering the building envelope performance, low infiltration rates, and reduce artificial lighting and plug loads.
5.Renewable Energy Systems (RES):	RES are an integral part of NZEB that needs to be addressed early on in relation to building from addressing the panels' area, mounting position, row spacing and inclination.
6. Innovative Solutions and Technologies:	The aggressive nature of 'net zero' objective requires always implementing innovative and new solutions and technologies.

Table 2, Classification of BPS tools allowing design evaluation and design guidance

	Evaluative			**Informative**	
Support (Technique)	Post-decision Evaluative	Geometry Plug-in	Pre-decision Evaluative (Para & Opt.)	Pre-decision Informative (Parametric)	Pre-decision Informative
Iterations	High	High	Medium	Low	Low
***Renewable Systems**			SolarShoeBox[15]* Energy 10[18]*		
Energy Efficiency	EnergyPlus[15] * TRNSYS[15]* Esp-r[15]*	OpenStudio [14], IES VE-Ware [15]	Vasari MIT Advisor[15] BDA[15] Desgin Inent	DesignBuilder[15] jEPlus[15]	BeOPT[15]* OptiPlus[15]

Daylighting & Facades	IES VE[15]*		HEED[19 [1]Solar House[21] Sunrel[22]	iDbuild[15]	OptiMaison[15]
		SunTools [16]	COMFEN[15] NewFacades[15] Lightsolve[15] Diva		

Table 3: Reference model and output plots

Building Description	Basecase 1	Parametric Range
Orientation	0^o	0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o
Shape	Rectangular (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 WWR	45%	50, 45, 40, 35, 30, 25, 20, 15
Exterior Wall U-Value	1.8 W/m^2 K	2, 1.8, 1.6, 1.4, 1.2, 1, 0.8, 0.6, 0.4
Roof U-value	1.4 W/m^2 K	1,4, 1.2, 1, 0,8, 0.6
Floor U-value	1.6 W/m^2 K	1.4, 1.2, 1
Single Clear Glazing	Tv = 0.9	1, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3
SHGC	0.75	1, 0.75, 0.5, 0.25
People Density	0.033 people/m^2	NA
Lighting Power Density	6 W/m^2	NA
Plug Loads	7 W/m^2	NA
Outside Air	20 (m^3/h per person)	NA
Infiltration	0.7 ach	NA
HVAC Type	On-Split+separate	NA
Cooling COP	ventilation	NA
Thermal Comfort Model	2.00	NA
Cooling set point (^{o}C)	Givoni	NA
Relative Humidity (%)	24	NA
Fan Efficiency (%)	60	NA
Water Heater (%)	70	NA
PV Type	Amorph,mchrist,pchrist	NA
PV Surface	0-100	NA
Cell efficiency	6%-14%	NA
Inverter efficiency	None	NA

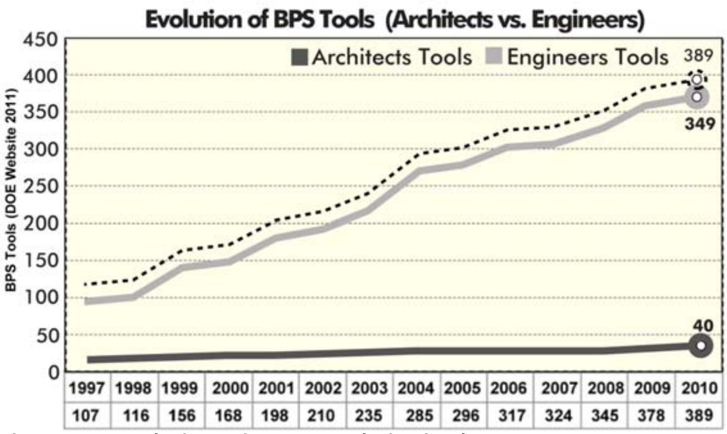


Figure 1: Evolution of BPS Tools in the last 10 years

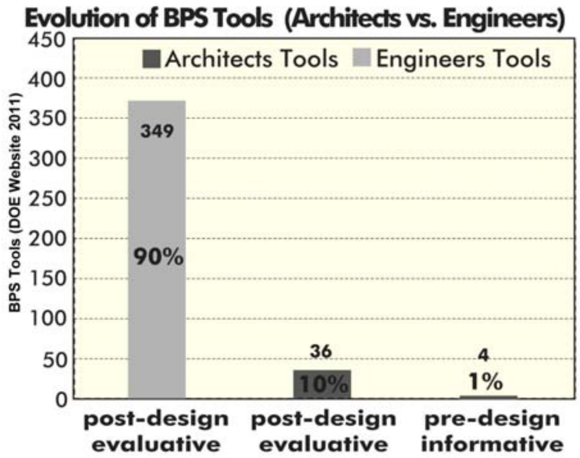


Figure 2: Classification of BPS Tools dor pre- and post-design decisions

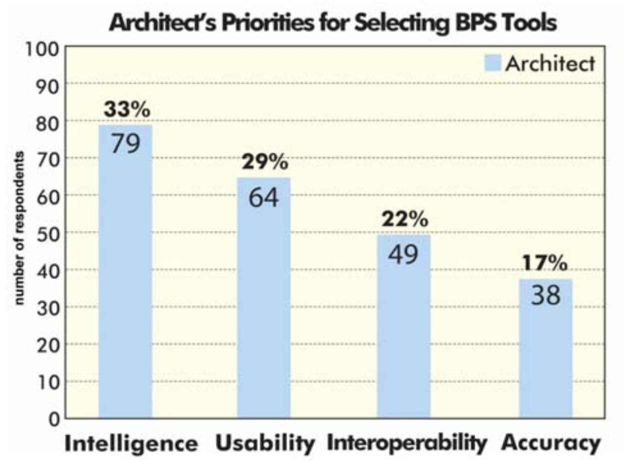
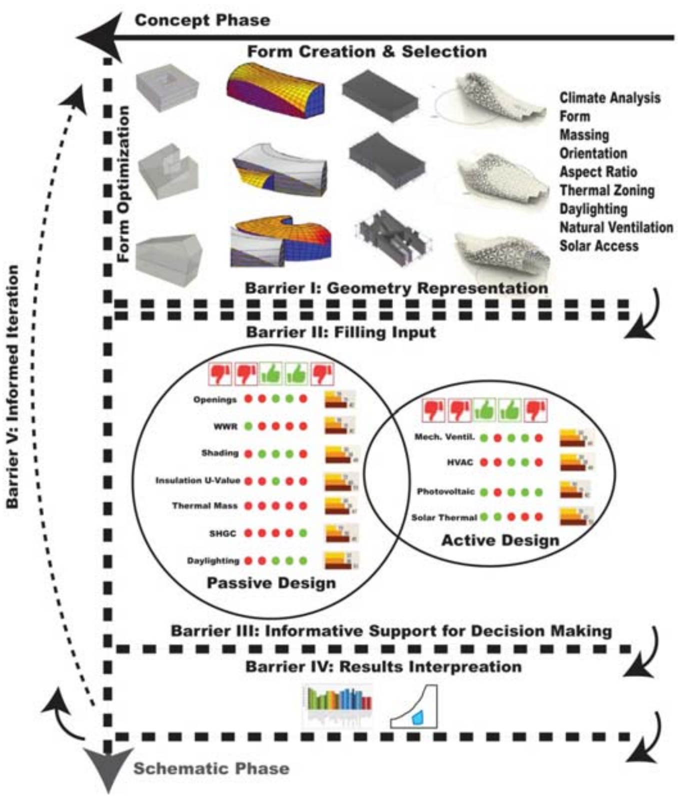


Figure 3: Architects ranking the most important features of a simulation tool [14]

Figure 4: Barriers of decision making during early design stages



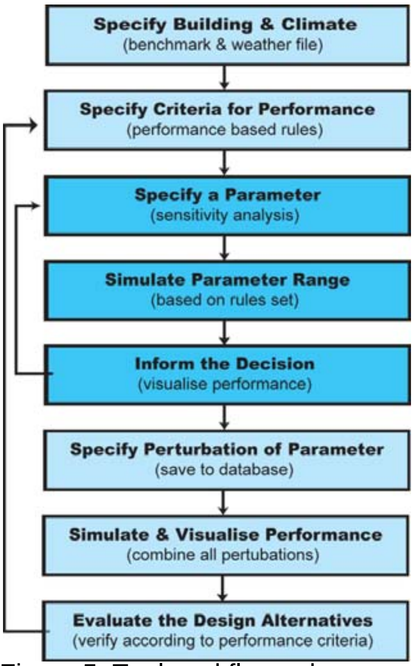


Figure 5: Tool workflow scheme

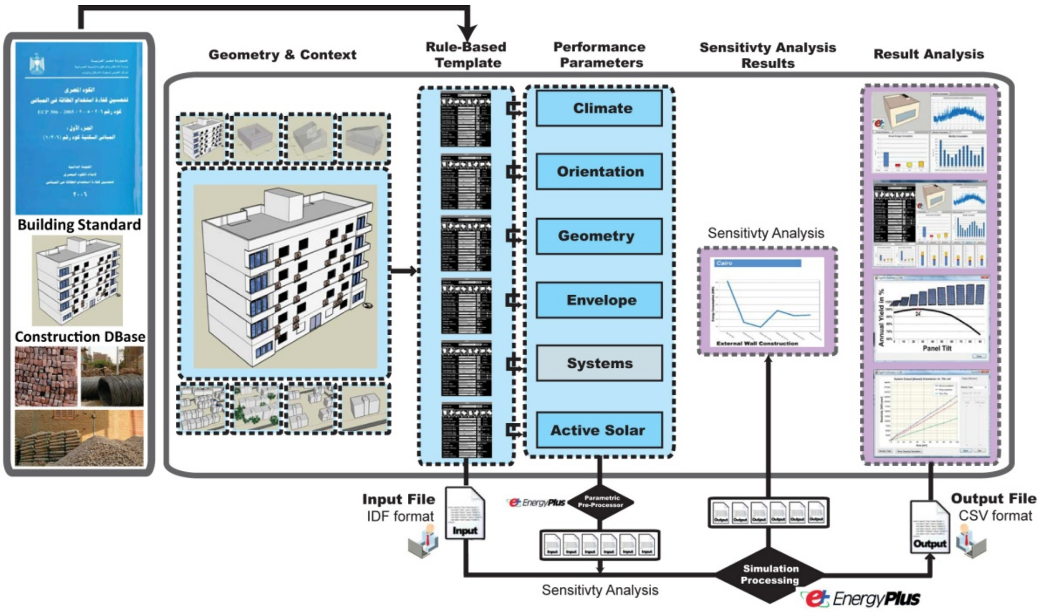


Figure 6, The flowchart of ZEBO

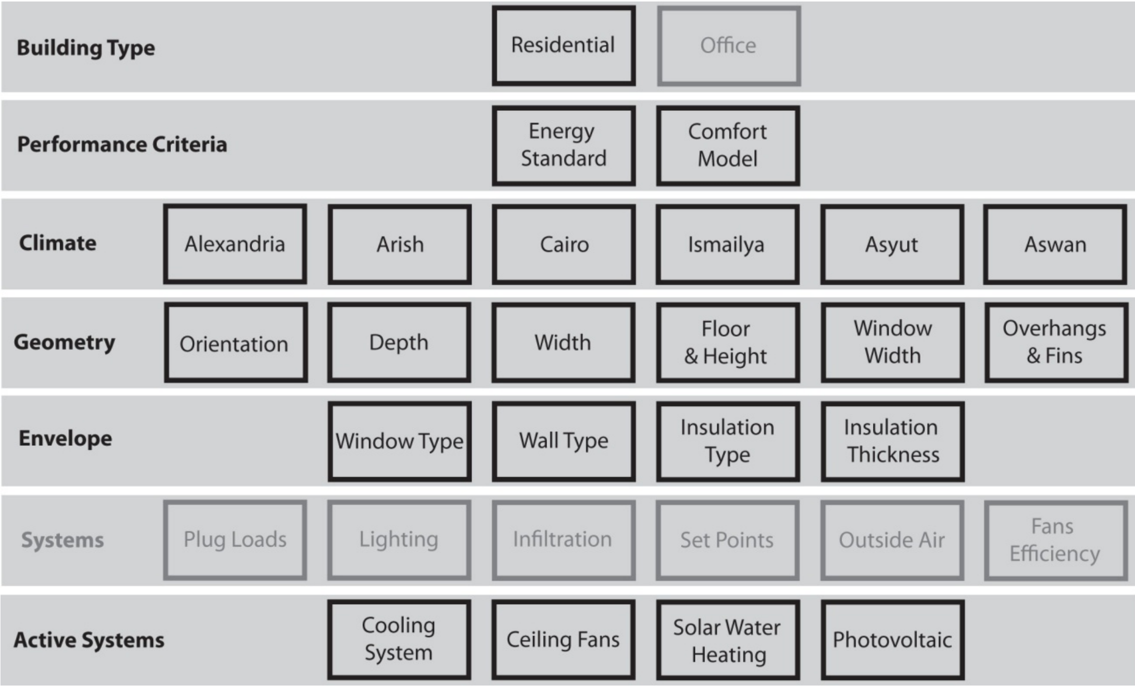


Figure 7: Reference model and output plots

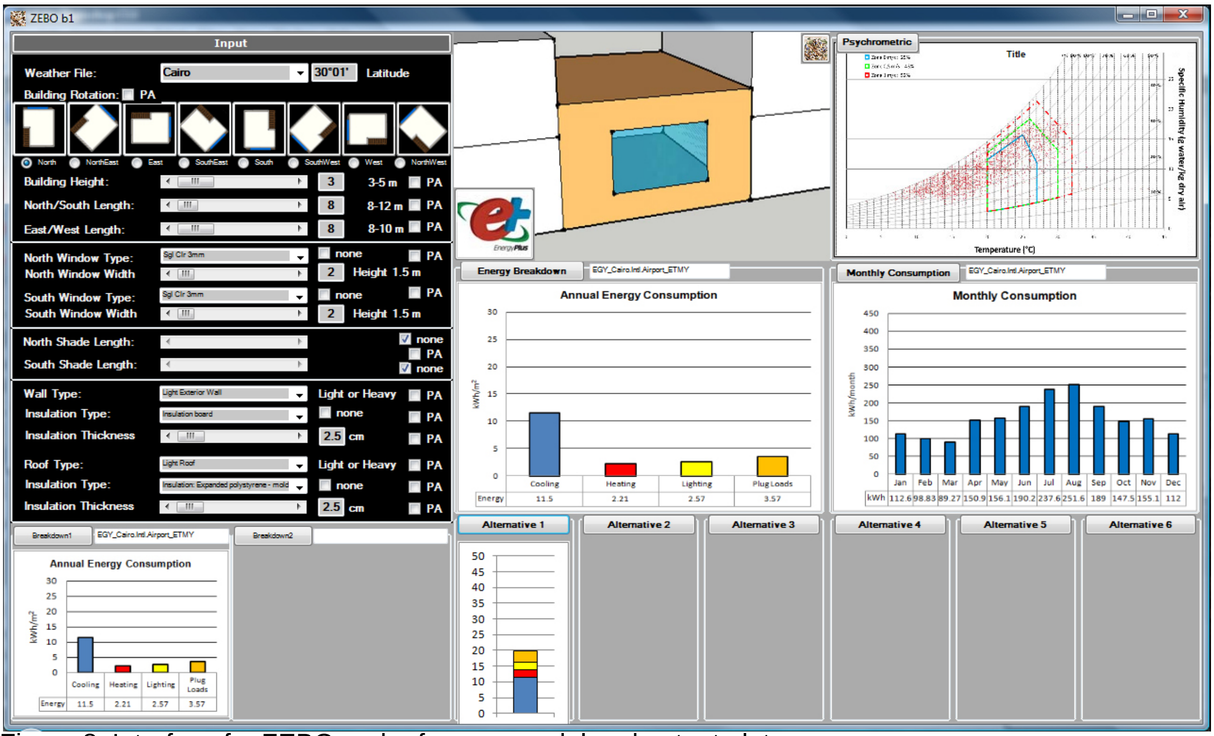


Figure 8: Interface for ZEBO and reference model and output plots

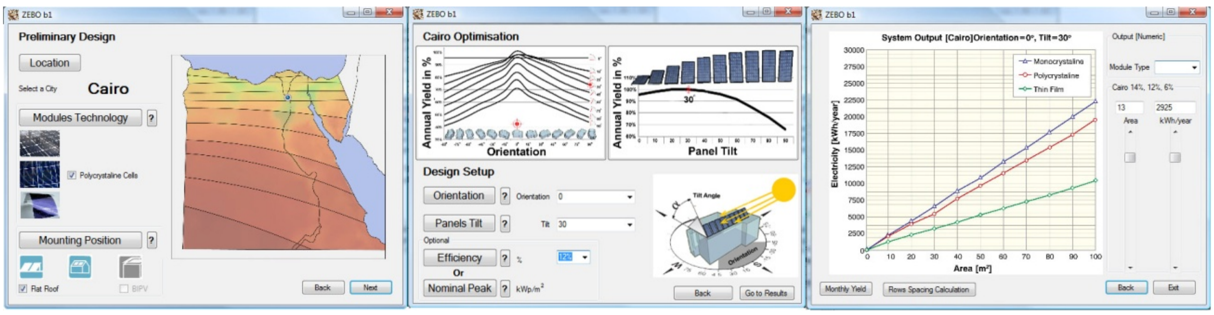


Figure 9: Annual electric yield of amorphous, polycrystalline and mono-crystalline panels

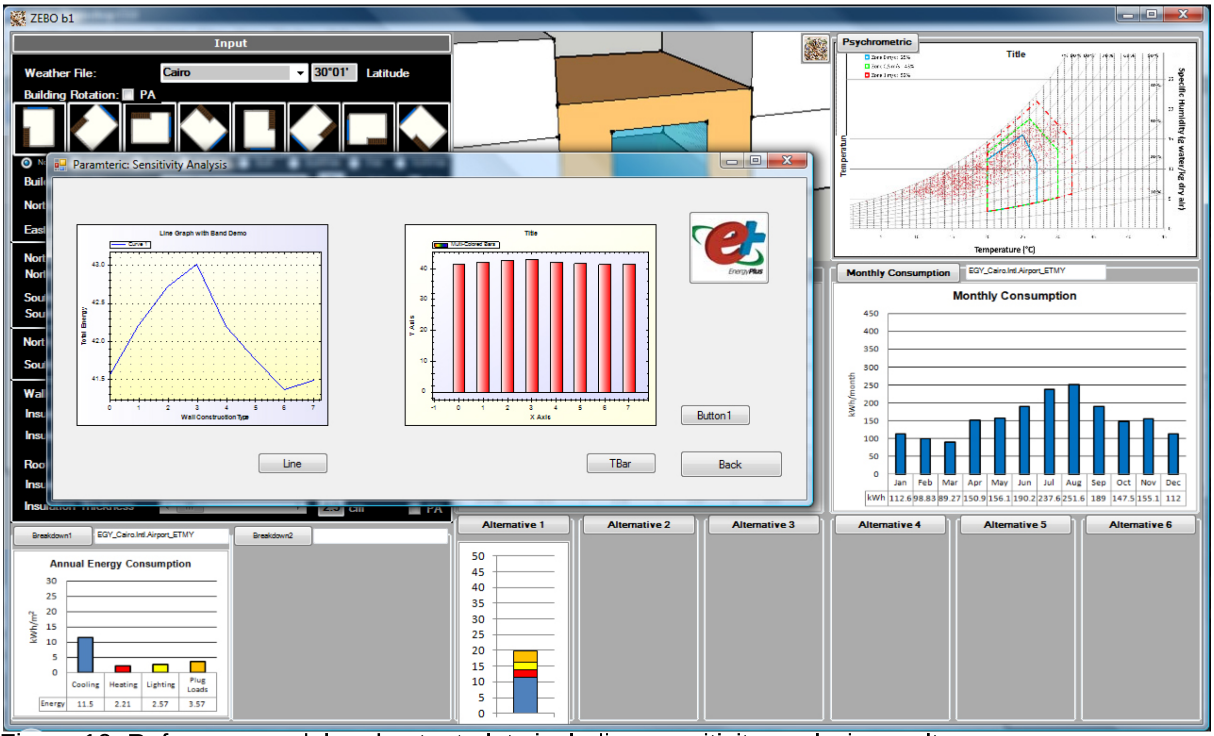


Figure 10: Reference model and output plots including sensitivity analysis results

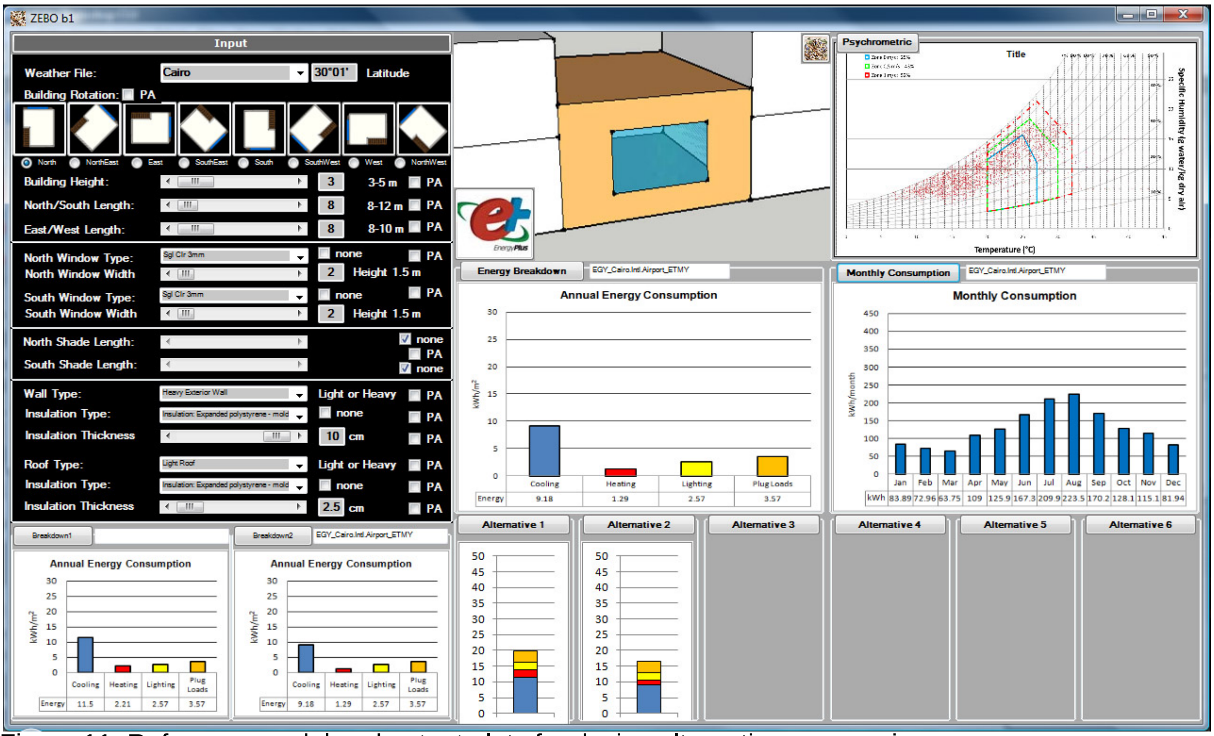


Figure 11: Reference model and output plots for design alternatives comparison

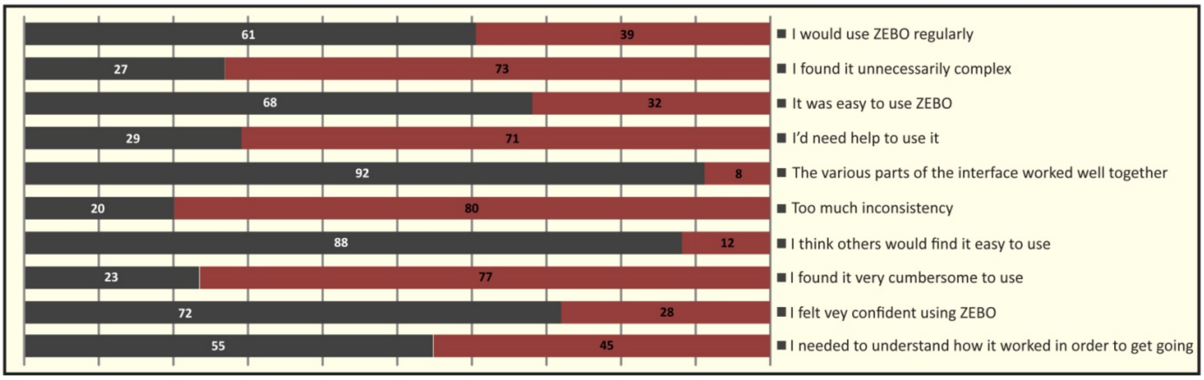


Figure 12: Usability testing of ZEBO prototype 1 using system usability scale

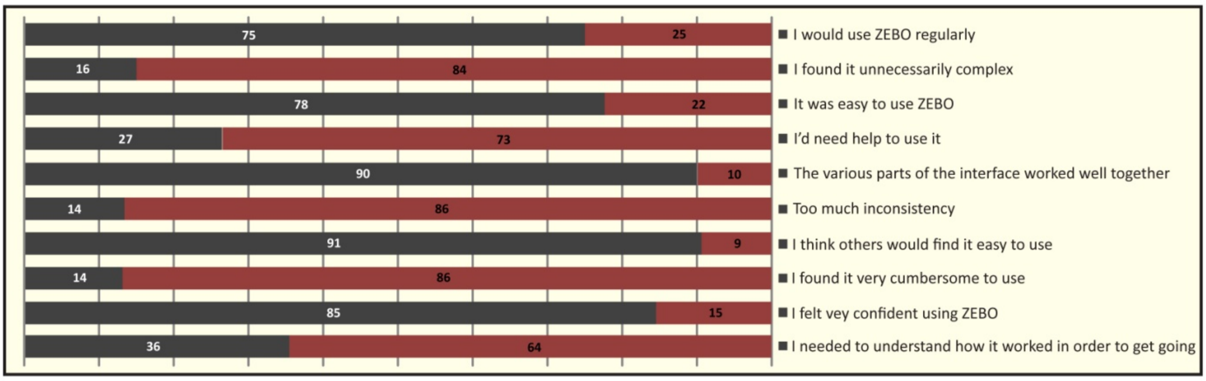


Figure 13: Usability testing of ZEBO prototype 2 using system usability scale