Achieving Informed Decision-Making using Building Performance Simulation

Shady Attia
Interdisciplinary Laboratory of Performance-Integrated Design (LIPID), School of Architecture, Civil and Environmental Engineering (ENAC), École Polytechnique Féderale de Lausanne (EPFL), Switzerland
http://lipid.epfl.ch/
shady.attia@epfl.ch

Abstract. *Building performance simulation (BPS) is the basis for informed decision-making of Net Zero Energy Buildings (NZEBs) design. This paper aims to investigate the use of building performance simulation tools as a method of informing the design decision of NZEBs. The aim of this study is to evaluate the effect of a simulation-based decision aid, ZEBO, on informed decision-making using sensitivity analysis. The objective is to assess the effect of ZEBO and other building performance simulation (BPS) tools on three specific outcomes: (i) knowledge and satisfaction when using simulation for NZEB design; (ii) users' decision-making attitudes and patterns, and (iii) performance robustness based on an energy analysis. The paper utilizes three design case studies comprising a framework to test the use of BPS tools. The paper provides results that shed light on the effectiveness of sensitivity analysis as an approach for informing the design decisions of NZEBs.*
Keywords. *Decision support; early stage; design; simulation; architects*

INTRODUCTION

The design of Net Zero Energy Buildings (NZEBs) is a challenging problem of increasing importance. The NZEB 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 galvanized by mandatory codes and standards that aim to reach neutral or zero-energy built environments (ASHRAE, 2008; EU, 2009; IEA 2009). At the same time, lessons from practice show that designing a robust NZEB is a complex, costly, and tedious task (Renard et al., 2008; Achten et al., 2009, Kurnitski et al., 2011; Marzal et al., 2011a; Zeiler, 2011; Attia, 2012a; Georges et al 2012; Pless 2012). The uncer-

tainty of decision-making for NZEBs is high (Athienitis, 2010; Kolokotsa, 2010; Marszal, 2011b).Designers have are faced with a pool of various choices to arrive to the NZEB performance objective. Combining passive and active systems early on is a challenge, as is, more importantly, guiding designers towards the NZEB objective that requires high energy and indoor comfort performance criteria. An international effort to define the main building design aspects for NZEBs is ongoing in the International Energy Agency (IEA) joint Solar Heating and Cooling (SHC) Task40 and Energy Conservation in Buildings and Community systems (ECBCS) Annex52 titled "Towards Net Zero Energy Solar Buildings" (Sartori, 2012). At this

stage, the architects are in a constant search for a design direction to make an informed decision. Also, decisions taken during this stage can determine the success or failure of the design. Twenty percent of the design decisions taken during early design phases subsequently influence 80% of all design decisions (Bogenstätter, 2000). In order to design and construct such buildings it is important to ensure informed decision-making during the early design phases of NZEBs.

Therefore, building performance simulation (BPS) tools have the potential to provide an effective means to support informed design decision-making of NZEBs. However, certain barriers block architects' use of BPS decision-support for NZEB design during early design stages. The most important barrier is informing design decisions prior to the decision-making and early on in the design process (Shaviv, 1999; Hayter, 2001; Charron, 2006). The barriers to informing the decision-making and providing guidance to architects during the early stages of NZEB design have been quoted by a number of previous studies around the world (Riether and Butler 2008; Weytjens , 2010; Attia 2011a,b). Currently, simulation tools are mostly used in the later stages of NZEB design by specialists as evaluation tools, rather than by architects as guidance tools. In this context, this paper aims to evaluate the effect of a simulation-based decision aid on achieving informed design decision-making by architects during early stages of the design of NZEBs.

DESIGNING AND CONDUCTING THE STUDY

Two types of data were collected, mainly preference and performance data. The preference data were used to collect information from participants using self-reported metrics. The performance data were used to collect information on the energy performance of the final design. Figure 1 shows the workshop framework with the different interventions and measured outcomes. During the design of the NZEB case study, the followings were documented during their evaluation: (i) the knowledge and sat-
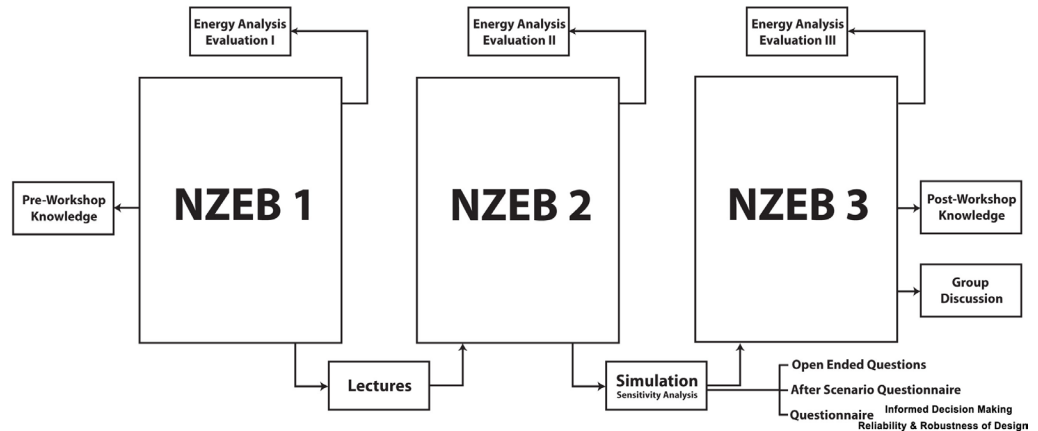
isfaction concerning the use of simulation for NZEB design, (ii) the decision-making attitude and behavior, and (iii) the energy analysis-based performance robustness of three groups. The energy evaluations were compared with the results of a quantitative assessment of the overall design performance. Finally the results were compared and presented.

Workshop design

Two types of data were collected, mainly preference and performance data. The preference data were used to collect information from participants using self-reported metrics. The performance data were used to collect information on the energy performance of the final design. Three workshops took place in Cairo to examine the effect of using the BPS tools and sensitivity analysis technique in the design of NZEBs. The workshops were announced and three groups of participants were recruited.

Prior to starting the workshops, participants were asked to achieve proficiency in the use of geometrical modelling in DesignBuilder (DB) using the video tutorials provided online. Additionally, ZEBO, a Graphical User Interface developed for Egyptian, was installed and used by all participants (Attia, 2012b). At the beginning of the workshop, participants were given an introductory crash course in use of DB and ZEBO, requiring a time investment of eight hours. Throughout the crash course, participants were required to follow a guidebook checklist on how to carry out successful simulations. The checklist was developed after reviewing the work of Bambardekar and Poerschke (2009) and Rocky Mountain Institute (RMI 2011) and was used to remind participants to use the minimum number of steps and to make the steps explicit. During the introductory tutorial participants were taught to: 1). create a simple building geometry model in ZEBO, 2). perform a simulation and sensitivity analysis exercise using ZEBO, 3). create a simple building geometry model in DesignBuilder, and 4). perform a simulation exercise in DesignBuilder, where the main building components as well as typical occupancy and equipment schedules were provided to

the participants.

During the software instruction portion of the workshop, participants followed procedures as demonstrated by the checklist and instructor to create a model. The RMI Building_Model_Checklist was used to remind participants about the minimum steps of the simulation and to make them explicit (RMI 2011). The checklist offered the possibility of verification and instils a kind of discipline of higher input performance. The use of the checklist was established for a higher standard of baseline performance.

CASE STUDIES FRAMEWORK

This section describes three different design case studies for NZEBs in which simulation was used to test and measure the ability to achieve informed decision-making for design. Three design workshops were organized early in 2011 in Cairo, Egypt, to design and develop three case studies. As mentioned before, we provided all participants with rudimentary software training and asked for volunteers for more in-depth study of the BPS tools package. The aim was to provide opportunities for all participants to attain basic proficiency in using the software package with the help of a checklist developed to enable them to better understand the complexities of performing simulations. This introduction to BPS is meant to build a common-ground for future

investigation of design decision support by BPS during the design development of the case studies in the workshops. Among the variety of definitions, in practice many practitioners have opted to meet the site NZEB goal, as with this approach there is no need to adjust for grid generation and transmission losses, utility emission rates, or utility cost structures. As these values can vary greatly by location, the site NZEB goal simplifies energy calculations and provides a more level playing field. Therefore for this study the NZEB definition is: "An NZEB is grid connected energy efficient building that balances its total annual energy needs by on-site electricity generation".

Most participants participated in a previous introductory workshop on BPS tools in 2010 (Attia et al., 2011). Before or parallel to that, all participants were instructed in various analysis techniques, including reading a sun path diagram, analyzing thermal comfort, using the Database of Egyptian Building Envelop (DEBE) (Attia and Wanas, 2012), and using the Weather Tool and Climate Consultant for climate visualization (Milne, 2011). Weather Tool is a visualization and analysis program for hourly climate data. It recognizes a wide range of international weather file formats as well as allowing users to specify customised data import formats for ASCII files. It also provides a wide range of display options,

Item	Pre-test mean	Post-test mean	Mean difference	T	P	N
How would you assess your ability to design NZEB? (EECA)	5.40	7.30	-1.900	-5.01	0.0007	10
How would you assess your ability to design NZEB? (FOFA)	4.00	6.13	-2.130	-8.66	0.0318	23
How would you assess your ability to design NZEB? (OPEN)	3.57	6.68	-3.110	-8.88	0.0001	19

Table 1
Pre- and post-test analysis.

including both 2D and 3D graphs as well as wind roses and sun-path diagrams. The tool allows generating full psychrometric and bioclimatic analysis, which is a unique mechanism for assessing the relative potential of different passive design systems. Solar radiation analysis can be accurately determined and optimum orientations for specific building design criteria. The tool allows comprehensive pre-design climate/site analysis. Climate Consultant is a graphic-based computer program that displays climate data in several of ways useful to architects, including temperatures, humidity, wind velocity, sky cover, solar radiation graphics and psychrometric charts for every hour of the year. Climate Consultant 5.0 also plots sun dials and sun shading charts overlaid with the hours when solar heating is needed or when shading is required. The psychrometric chart analysis shows the most appropriate passive design strategies in each climate, while the new wind wheel integrates wind velocity and direction data with concurrent temperatures and humidities and can be animated hourly, daily, or monthly. Figure 2 illustrates the workshop's design outcomes.

RESULTS

The effects of the use of BPS and sensitivity analysis, was evaluated by means of three design case studies using a control trial and extended usability testing for preference and performance indicator. The following paragraphs identify the influence of BPS knowledge on the decision-making attitudes and patterns. Then the results of the scenario questionnaire are reported. Then the improved design through the energy performance comparison of the three case studies using BPS tools is verified. Final-

ly, the outcome of the open-ended questions and workshop discussions together with associated material and observations are presented. An extended paper has been published including detailed analysis results (Attia et al., 2013).

Satisfaction: Using self-reported metrics, the background knowledge and understanding of NZEBs design and the satisfaction with the use of BPS decision-support were determined.

Knowledge: Evaluating the effectiveness of BPS tools in informing design required an understanding of the participants' pre- and post-simulation knowledge. Respondents completed pre- and post-simulation surveys to assess the value of the BPS tools to further the participants' understanding of NZEBs' design influences and their relation to the use of simulation. In order to assess participants' knowledge about NZEB design issues, participants were asked "How would you assess your ability to design NZEB?" Table 1 shows the paired t-test analysis of pre- and post-responses, showing a statistically significant increase. A significant increase in knowledge uptake was recorded for the three groups. Moreover, the repetition of this increase in all three group samples is strong evidence that the use of BPS increased the knowledge uptake. This indicates participant perception of growth in informative knowledge of the basic tenets of decision-making.

Satisfaction (After-Scenario Questionnaire): The After-Scenario Questionnaire (ASQ) developed by Lewis (1995) was used to measure three fundamental areas of usability: effectiveness (question 1), efficiency (question 2), and satisfaction (all three questions). The results, shown in Figure 3, indicate a low level of satisfaction regarding the ease of com-

	Design Cases	Knowledge Improvement		Design Improvements	Performance Improvements	
		Pre-test	Post-test		kWh/m^2	kWh/m^2
C1-EECA		5.4	7.3	-Optimised Orientation & Geometry -Optimised Envelope Insulation -Optimised WWR -Optimised PV & ST Sizing	24.7	14.7
C2-Blue		4.00	6.13	-Optimised Orientation & Geometry -Optimised Glazing -Optimised WWR	24.5	8.8
C2-Green				-Optimised Orientation & Geometry -Optimised Envelope Insulation -Optimised Glazing -Optimised PV & ST Sizing	23	10.3
C2-Orange				-Optimised Glazing -Optimised Solar Protection -Optimised PV & ST Sizing	22	12
C2-Purple				-Optimised Heat Protection -Optimised Solar Protection -Optimised PV & ST Sizing	23.8	12.2
C2-Red				-Optimised Orientation & Geometry -Optimised Envelope Insulation -Optimised WWR & Glazing -Optimised PV & ST Sizing	21.5	9
C3-Blue		3.57	6.68	-Optimised Orientation & Geometry -Optimised WWR -Optimised PV & ST Sizing	14.3	7.45
C3-Green				-Optimised Orientation & Geometry -Optimised Envelope Insulation -Optimised Glazing	17.5	7.13
C3-Orange				-Optimised Orientation & Geometry -Optimised Envelope Insulation -Optimised WWR & Glazing -Optimised Solar Protection	16.5	7.3
C3-Red				-Optimised Envelope Insulation -Optimised WWR -Optimised Solar Protection	22	10

I am satisfied with the ease of completing the design using the ZEBO and other BPS tools
I am satisfied with the amount of time it took to complete the design using ZEBO and other BPS tools
I am satisfied with the support information provided by ZEBO and other BPS tools

62 | 38
42 | 58
88 | 12

I am satisfied with the ease of completing the design using the ZEBO and other BPS tools
I am satisfied with the amount of time it took to complete the design using ZEBO and other BPS tools
I am satisfied with the support information provided by ZEBO and other BPS tools

57 | 43
47 | 53
84 | 16

I am satisfied with the ease of completing the design using the ZEBO and other BPS tools
I am satisfied with the amount of time it took to complete the design using ZEBO and other BPS tools
I am satisfied with the support information provided by ZEBO and other BPS tools
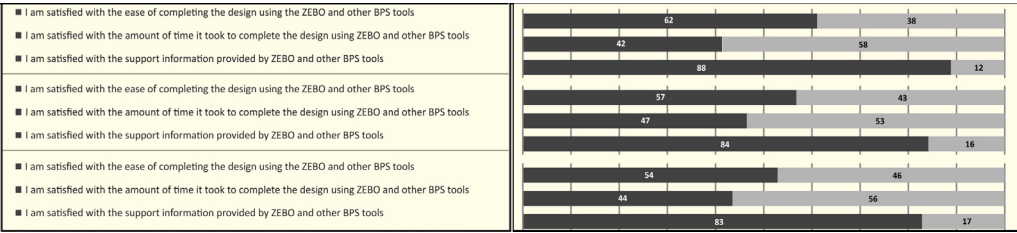
54 | 46
44 | 56
83 | 17

Figure 3
After Scenario Questionnaire Results of the EECA, FOFA and OPEN groups respectively.

pleting the design using ZEBO and other BPS tools for all groups. Similarly results indicate a low level of satisfaction with the amount of time taken to complete the design using ZEBO and other BPS tools. On the other hand, participants' satisfaction with the information support was reported to be high. Surprisingly, the patterns of answers of the three groups almost match. These findings have unlimited generalizability because the sample size for the factor analysis was relatively large (52 participants). Also the resulting factor structure was very clear.

Decision-making attitudes and patterns: Another self-reported usability metric was a post-workshop questionnaire that was administered to participants regarding how far using ZEBO and other BPS tools informed their decision-making and led to higher reliability and robustness of the NZEB design. Participants were asked to fill in an online questionnaire with six questions.

Informed decision-making: Figure 4a and 4b show that participants' questionnaire responses vividly indicate agreement with the statements "guides your decision-making" and "informs your decision-making". With regard to the "guiding" question, Most of Group 1 respondents strongly agreed or agreed while few were undecided. The results of Group 2 and Group 3 were similar. In total, 71.2% of participants recognized the importance of BPS tools in guiding the decision-making of NZEBs design even though 6.0% of all three groups disagreed with the statement. With regard to the "informing" question and as shown in Figure 3b most of participants recognized the importance of BPS tools in informing the decision-making of NZEBs design and none of the questionnaire respondents disagreed with the statement. In Group 1, 2 and 3, almost all respondents strongly agreed or agreed with the statement while few were undecided. However, as shown in Figure 4c, participants disagreed with the statement "makes you confident about your decision-making". In total one third of participants disagreed that the use of ZEBO and other BPS tools made them confident about their decision-making in NZEBs design while almost half of respondents were undecided. In the open-ended questions and discussion respondents indicated that the simulation process and the results have to be well presented and understood, so that they can gain confidence from the
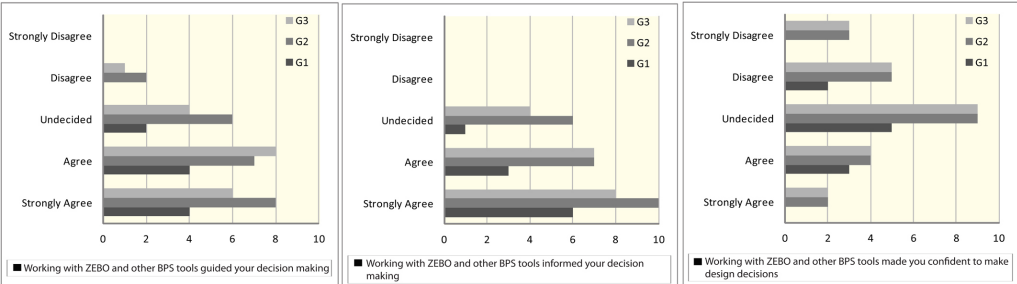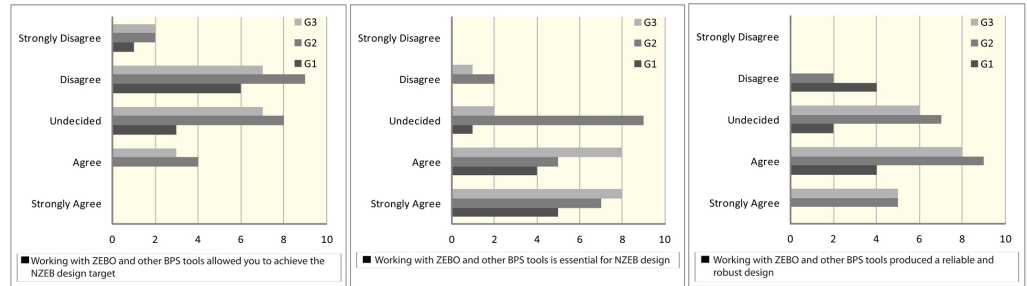

Figure 4
Participants' responses to a question related to guidance of decision making, informed decision making and confidence in decision making.

information.

Reliability and robustness of design: Figure 5a shows that participants' questionnaire responses indicate disagreement with the statement "allowed you to achieve the NZEB design target". In total more than half the participants disagreed that the use ZEBO and other BPS tools allowed them to achieve the NZEB design target while one third were undecided According to Figure 5b, more than two third of participants agreed that the use ZEBO and other BPS tools is essential for NZEB design. More than half participants agreed that the use ZEBO produced reliable and robust NZEB design while one third of respondents were undecided (see Figure 5c). To avoid any ambiguity of the terminology the term reliable and robust was explained before the questionnaire. For most participants having to use ZEBO or Design-Builder which are graphical user interfaces for EnergyPlus was sufficient to produce reliable and robust NZEB design.

Verifying the effect of BPS: This section presents the combined effect of BPS on design, knowledge and energy performance improvements of the design projects. A significant increase in knowledge uptake was recorded for the three groups. Also the new design incorporated optimized changes which were compatible, acceptable to the designers. Their introduction was a result of sensitivity analysis and parametric variation of the different design parameters listed below:

- The geometry was redesigned to reset the mass correctly with orientation close together.
- The solar protection was redesigned so that it maximizes the shading of openings and envelope.
- The openings ratio and glazing type were significantly improved in the third design round.
- Extra envelope insulation was added so that all envelopes thermal performance improved by at least 50%.
- The PV & ST sizing and architectural integration was optimized in all designs

DISCUSSION AND CONCLUSIONS

The paper findings indicate that the use of BPS tools and the sensitivity analysis technique in the design of NZEBs demonstrated a strong correlation between increased usage and achieving informed decision-making. The main purpose of using BPS tools was to assess their ability on informing the decision making by using a simple parametric tool (ZEBO) and a detailed comprehensive tool (DesignBuilder). The aim of the study was not to compare those tools or expose participants to a broader composition of tools; rather it was assess the mechanics and process of using BPS tools to inform the decision making. In order to evaluate BPS and sensitivity analysis as a tool for informing decision-making, participants completed several questionnaires assessing their informative effectiveness. The questionnaires reveal participants' perceptions of the simulation's informative importance in their design decision-making. Specifically, the open-ended questions and group discussion addressed the value of and barriers to the use of simulation as a decision-support method. To validate the study findings a formal energy analysis

measure was employed in this respect. A group discussion was also used as an informal triangulation to facilitate the validation of the survey results reported below:

1. There is a relationship between BPS usage and better energy performance outcomes.
2. Parametric Analysis features were found to promote informed decision making.
3. The case studies revealed a significant difference in knowledge levels before & after
4. NZEB design ambitions should be tempered by the complexity of design and design process.
5. A more pre-decision approach is required to meet the uncertainty of decision making of designers.
6. Value of usability testing and other user experience measurements (self-reported metrics) is high as a research methodology.
7. Four factors that promote or inhibit the uptake of BPS as decision support in architectural practice:
   a) Interactional usability,
   b) Decision support (informative),
   c) Users' skills
   d) Contextual integration.

Limitations of the study

The validity of the study's findings is potentially open to criticism as only three design groups were used for this study. It would have been desirable to recruit architects from a greater number of design practices to ensure a broader socioeconomic and geographic population distribution. Also the limitations of ZEBO, including its limited library, abstraction of underlying model, ability to handle only energy issues and the shoebox approach that blocks free 3D geometrical representation, forced the participants to use DesignBuilder. Respondents reported that this step hindered the decision support process.

Another limitation was the fact that participants in Workshops 2 and 3 participated in a randomized controlled trial of an NZEB design after which they all completed a written questionnaire. However, we would argue that this study differed significantly in that it focused on the informative aspects of BPS tools, which were not featured in the trial. A quantitative methodology (survey and performance analysis) and a qualitative methodology (discussion) were employed in this study.

Implications for design practice and future research

Our proposed method of using BPS tools and, in particular, the use of sensitivity analysis for achieving informed decision-making raise a number of challenges for developers of BPS tools, not least of which is the difficulty of accommodating them within the pressures of deadlines and budgets. There is also the challenge of balancing the decision-making of architects as BPS users with those of experts/scientific reference groups, particularly in situations of performance uncertainty/equipoise.

Regarding geometry, the use of BPS tools and sensitivity analysis cannot be achieved if existing tools do not provide seamless model exchange and full geometrical representation. Coupling simulation and decision support techniques to architectural geometrical drawing tools is crucial.

Arguably, the use of BPS tools and sensitivity analysis is too simplistic in that it presupposes a linear progression from intuitive and uncertain decision-making to informed decision-making. In reality, the decision-making for NZEBs design is more complex and might follow a different developmental path wherein the factual design content, for instance, would require both intuitive and informed decision-making in order to develop other design features of the NZEBs. Moreover, the proposed case studies do not take into account other factors, such as the influence of aesthetics and economy, which could have an impact on decision-making about NZEBs in a real/natural design setting.

Nevertheless, the principle of informing the decision-making for NZEB design, whether applied in parts or as a whole, still holds true in our opinion; we suggest further research to test it and other future methods and techniques of BPS. In doing so, it is

hoped that designers of NZEBs and international research groups such as IEA: Task 40 will have at their disposal a clearer vision of the use of BPS tools for achieving informed design decisions.

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