COMPUTATIONAL OPTIMISATION FOR ZERO ENERGY BUILDINGS DESIGN: INTERVIEWS RESULTS WITH TWENTY EIGHT INTERNATIONAL EXPERTS

Shady Attia[1], Mohamed Hamdy[2], William O'Brien[3], Salvatore Carlucci[4]
[1] Interdisciplinary Laboratory of Performance-Integrated Design (LIPID), School of Architecture, Civil and Environmental Engineering (ENAC), École Polytechnique Féderale de Lausanne (EPFL), Switzerland;
[2]Aalto University School of Engineering, Dept. of Energy Technology, Espoo, Finland;
[3]Dept. Civil & Environ. Engineering, Carleton University, Ottawa, Canada;
[4]Dipartimento di Energia, Politecnico di Milano, Milan, Italy.

ABSTRACT

This paper summarizes a study that was undertaken to reveal potential challenges and opportunities for integrating optimisation tools in Net/Nearly Zero Energy Buildings (NZEB) Design. The paper reviews current trends in simulation-based Building Performance Optimisation (BPO) and outlines major criteria for optimisation tools selection and evaluation. This is based on analyzing users' needs for tools capabilities and requirement specifications. The review is carried out by means of interviews with 28 optimisation experts. The findings are based on an inter-group comparison between experts. The aim is to assess the gaps and needs for integrating BPO tools in NZEB Design. The findings indicate existing limitations including model uncertainty, computation time, difficulty of implementation and steep learning curve. Future directions anticipated or needed for improvement of current tools are presented.

INTRODUCTION

Current building performance objectives have raised the bar of building performance, and will change the way buildings are designed and operated. This means that evaluating different design options is becoming more arduous than ever before. The building geometry, envelope and many building elements interact, thus requiring optimising the combination of the building and systems rather than merely the systems on an individual level (Hamdy et al. 2011 2001). One promising solution is to use automated building performance optimisation (BPO) paired with building performance simulation (BPS) as a means to evaluate many different design options and obtain the optimal or near optimal solutions (e.g., lowest life-cycle cost, lowest capital cost, highest thermal comfort) while achieving fixed objectives (e.g., net zero energy) (Charron et al 2006; Christensen et al, 2006; Bucking, 2010).

Despite optimisation's potential in NZEB design, it remains largely a research tool and has yet to emerge in common industry practice. As this paper reports, major obstacles to BPO in industry include lack of appropriate tools, lack of resources (time, expertise), and the requirement that the problem be very well defined (e.g., constraints, objective function, finite list of design options). The objective of this paper is to document the current state-of-the-art in terms of NZEB optimisation tools and practice. With this information presented, it is anticipated that software developers will be better informed of the needs of building design processionals.

LITERATURE REVIEW

What is BPO and its importance?

Automated building performance optimisation is a process that aims at the selection of the optimal solutions from a set of available alternatives for a given design or control problem, according to a set of performance criteria (e.g., minimum cost, energy, etc). Such criteria are expressed as mathematical functions, called objective functions.

In the architectural, engineering and construction (AEC) industry there is a growing research trend for automated optimisation approaches to be used to map out and find pathways to buildings designs with desirable qualities, be it aesthetics, geometry, structure, comfort, energy conservation or economic features, rather than focusing on one particular outcome. Although optimisation studies are most commonly performed in the early-design stage, where the majority of design decisions have yet to be made, optimisation approaches can be equally useful in the late-design stages for selecting and fine-tuning control strategies and HVAC design and during building operations to best select building control based on model-predictive control strategies (May-Ostendorp et al., 2011; Corbin, et al 2011; Candanedo et al., 2011; Hensen and Lamberts, 2011).

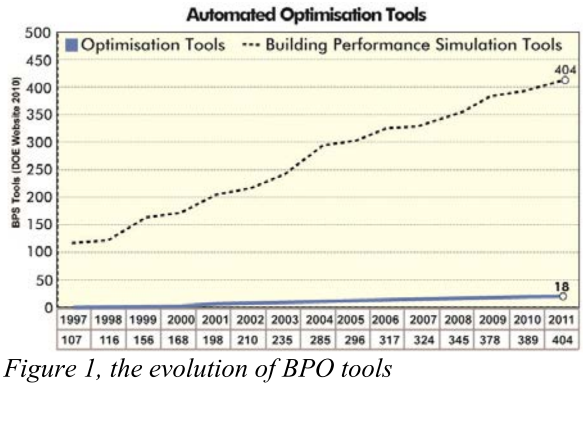

Figure 1, the evolution of BPO tools

Combination of BPO and Simulation

Inevitably, optimisation is coupled to BPS tools. BPS tools are essential in the process of building design aiming to assess their energy performance, environmental impacts, costs etc (Augenbroe, 1992). A number of energy simulation engines exist and are often used in different stage of the design process of a building (Crawley 2008, Attia 2011). Out of the 406 BPS tool listed on the DOE website in 2012, fewer than 19 tools allow BPO as shown in and Figure 1 (DOE 2012, Wall 1996).

When designers decide to improve the building performance, they usually make estimation for various values of the design variables to be modified in the building envelope, the heating ventilation and air-conditioning (HVAC) system and the types of energy generation and run the simulation many times. Then, designers will try to find the effect of the design changes on the simulation results and to conclude a relation between those variables and the objectives of the simulation. This is an inefficient procedure with respect to time and labour. Besides, the relation between the simulation variables and the objectives may not be simply understood, especially when there are many parameters to be studied, and possibly due to the nonlinearity of the problem. Therefore, a better design is not always guaranteed. To overcome such difficulties, automated simulation based BPO search techniques are applied. Progressions in building simulation tool development and in coupling complimentary BPS tools at run-time expand domains where BPS optimisation studies can occur. A number of researchers have coupled energy simulation tools with optimisation techniques through customized tools, commonly based on MATLAB™, or other dedicated software (Hamdy et al. 2011).

BPO Objectives (single/multi-objective functions)

Optimisation can be either single-objective or multi-objective according to the number of objective functions that define the optimisation problem. In the case of optimizing a single-objective function, an optimal solution of the problem is either its global maximum or minimum, depending on the purpose. In the case of multi-objective optimisation problems, a single solution may not be able to simultaneously minimize (or maximize) each objective function. Rather, when searching for solutions, one comes to limit variants such that, a further improvement towards the minimum value of one of the objective function causes a worsening of the closeness to minimum of the others. Therefore, the aim of a multi-objective optimisation problem consists in finding such variants and possibly in quantifying the trade-off in satisfying the individual objective functions. The role of the optimisation algorithm is to identify the solutions, which lie on the trade-off curve, known as the Pareto Frontier, which is a set of optimal solutions plotted in the form of a curve (named after the Italian-French economist, Vilfredo Pareto, see Figure 10.5).

Algorithms used in BPO

Optimisation of a building as a whole is a complex problem due to the number of design variables as well as the discrete, non-linear, and highly-constrained characteristics. The popular optimisation methods for solving multi-objective optimisation problems are generally classified into three categories: (1) enumerative algorithms, (2) deterministic algorithms, and (3) stochastic algorithms.

METHODOLOGY

A qualitative study design was employed, using semi-structured interviews. Optimisation experts working in academia or practice were recruited. Experts were identified as researcher or professional who has at least three or more publications in the field of BPO. The participants were identified from the IBPSA International and Regional Conference Proceedings between 1995 and 2010, industry experts and practice experts. A sampling framework was developed to include experts in the study from Asia, Europe and North America. These groups represented the range of possible optimisation users, from researchers and designers considering optimisation in the design of net zero buildings. A list of potential optimisation experts was created (40 potential experts) and circulated between the IEA Task 40 Subtask members. Every interviewed expert was asked to revise the list and add any potential candidate to be interviewed. Recruitment continued until experts from different countries had been represented and thematic saturation had been attained for the sample as a whole. An additional group of experts were during IBPSA 2011 Conference in Sydney. In total 28 experts were interviewed between January and November 2011.

The interview questions were formulated by the authors and classified under five categories; namely, background, methodology, output, integration in design and shortcomings and needs. The questionnaire aimed to probe the users' experience with computational optimisation tools and techniques for the design of NZEBs. Prior to interviewing the experts, the authors set up a pilot study to tests and improve the questionnaire reliability and internal validity. Comments and suggestions were requested from peer reviewers. Reviewers were asked to revise the questionnaire and provide critical feedback in order to optimise the clarity and relevance of the questionnaire.

INTERVIEW RESULTS & ANALYSIS

This section presents some of the interview results that interviewed optimisation experts in 2011. Each interview included 25 questions available in the final study report (Attia 2012) and publication (Attia et al. 2013). For this paper, representative questions that reflect the most important findings are selected. The complete results are presented and can be found in the final study report (REFERENCE). Prior to analysing the interview results, it is important to question the statistical significance of the interview sample. Thus the interview sample is highly representative of researchers.

Interviewee's Background

What is your major field of discipline?

28 experts were interviewed among them 24 had their background in engineering, two had their background in physics, one in architecture and one in computer science. Among the 28 experts, 26 identified themselves as researchers and two identified themselves as practitioners (Figure 2).

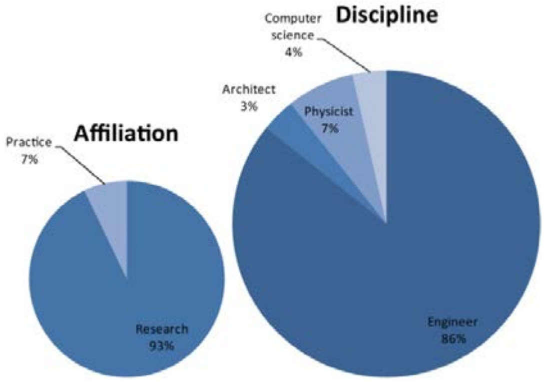

Figure 2, Field of discipline and affiliation of interviewed experts

The affiliation of the interviewed experts shows that they are mostly located in universities or research labs in the Northern Hemisphere. The majority of interviewees work in the United States (29%), UK (18%), Canada (14%), Finland (10%), Netherlands (7%), Germany (3%), Switzerland (3%) and Japan (3%).

How many projects or case studies have you performed and how long does each project or case study take?

On average 40% of all interviewees (11) conducted between 5 to 10 optimisation cases or projects, 32% (9) conducted less than 5 cases or projects and 11% (3) conducted between 10 to 15 optimisations while only 14% (4) conducted more than 15 optimisations. Most interviewees mentioned that they start with the model development and calibration followed by linking the simulation tool to the optimisation tool, and then run the optimisation. Figure 3 shows the time for each case or projects. Interviewees mentioned that the development and calibration of the simulation models are one of the time consuming steps, requiring in average two to three weeks of work. However, the running time of the optimisation simulations is the most time consuming process and depending on the model resolution, the time required for every case varies significantly.

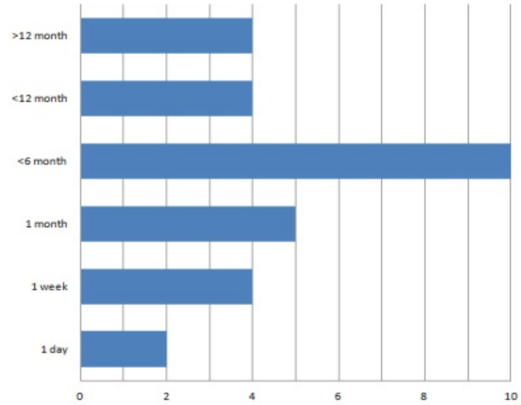

Figure 3, average total time per BPO case

What kind of tools do you use for optimisation (MATLAB, GENOPT, others)? To which simulation tool do you couple it?

Figure 4 reveals that MATLAB toolbox and GenOpt are the most used optimisations tools. The left figure indicates that the most used simulation tools among interviewees is (9) EnergyPlus and (7) IDA ICE followed by (5) TRNSYS and (3) ESP-r.

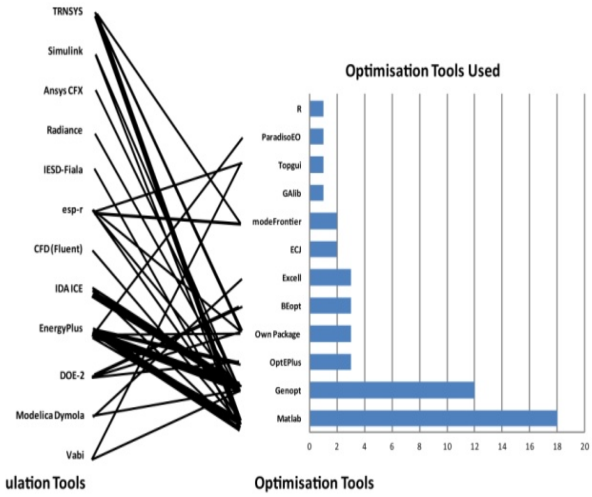

Figure 4, optimisation tools order by use (right) and simulation tools ordered by use (left).

Optimisation Methodology

Which building typologies have you used optimisation for and in which climates? (Residential, Offices, Retail, Institutional)

Figure 5 shows the building typologies, construction types and climate were the projects were optimised.

How many zones do you address in your model when running optimisations? And what kind of design variables do you set for optimisation?

64% of the interviewees used multi-zone model while 36% used single zones models. Interviewees indicated that the preference of choice between the single and multi-zone modelling depends on the model resolution (level of detail) and the expected interactions between the each thermal zone and the systems. Also, multi-zone models were used to differentiate between heated and non-heated zones and between frequently and less frequently used spaces of the building.

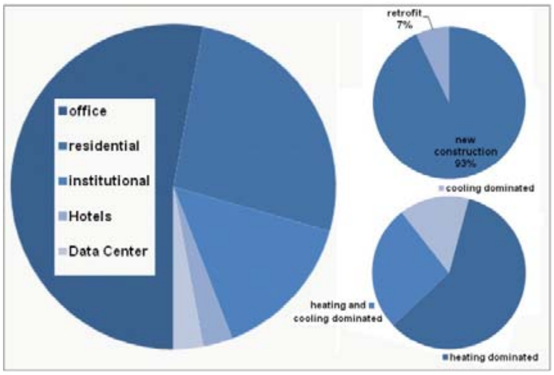

Figure 5, building typologies, construction type and climate

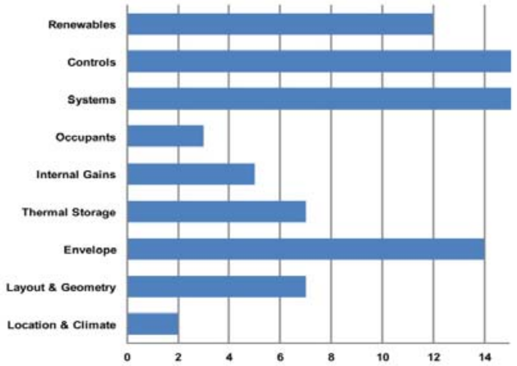

Figure 6, participants' choices of optimisation design variables

As shown in Figure 6, the most optimised design variables by the interviewed experts for NZEBs were systems and controls (53%) followed by the envelope (50%). The optimisation of control systems and, in particular, model predictive control was considered to be one of the most complex and dynamic design variables; therefore, design optimisation was beneficial. Renewable energy systems were optimised by 12 interviewees. Thermal storage, layout and geometry was optimised by 7 of the interviewees followed by internal gains 22. 2 of the experts optimised occupancy and 2 optimised location and climate. The analysis of Figure 6 shows that the most optimised design variables where late design parameters. According to the interviewees the choice of the design variable was based on the innovation of the design project and the complexity of a particular design variable.

What kind of objectives do you set for optimisation?

Common optimisation criteria in building design are various costs such as initial capital cost, annual operating cost, and life cycle cost, energy consumption and recently, environmental impact. 70% of all interviewees use multi-objective optimisation versus 30% who use single objective optimisation. Regarding the objectives, all interviewees (28) chose to use energy as the most used optimisation objective, while 64% (18) chose to cost. Thermal comfort followed (10) as the third most important objective while some interviewees indicated that they consider comfort as a constraint so I would not call it an objective. As shown in Figure 7, Carbon emissions (5), lighting energy (2) and indoor air quality (1) were ranked at the end.

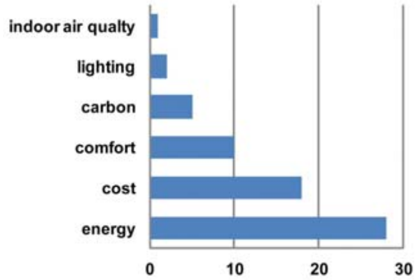

Figure 7, participants' choices of optimisation objective functions

What kind of constraints do you set for optimisation?

There was agreement among most interviewees (22) to set thermal comfort as the main constraint followed by cost (4). Interviewees refer to comfort conditions defined by standards. There was an agreement to consider constrains as primarily to define the feasible domain. Penalty terms are used in the optimisation work to both guide the optimizer away from infeasible regions and to consider the impact of thermal comfort boundaries on the optimisation. Constraints in this case were boundary or equation based.

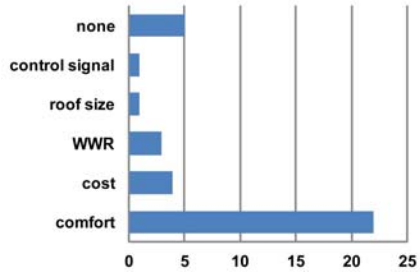

Figure 8, participants' choices of optimisation constraints

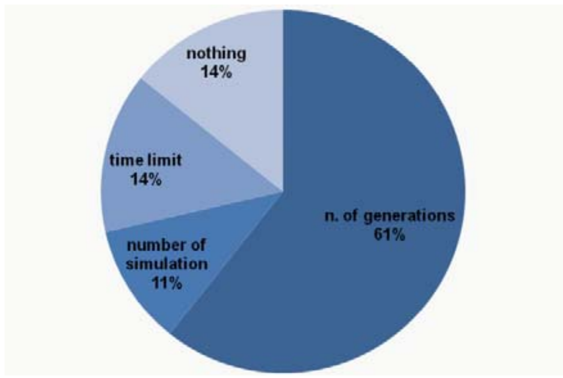

Figure 9, participants' choices of optimisation stopping criteria

Under which setting you run your optimisation, what is your methodology? What kind of stopping criteria do you set for optimisation?

The answer to this question depended on the algorithm used. Interviewees indicated that some algorithms have stopping criteria built in; others run for a prescribed number of generations or simulations. However, as shown in Figure 9 most interviewees (17) set a number of generations as stopping criteria for their optimisation work. Some interviewees set a time limit (4), or no stopping criteria at all (4) while few (3) set a number of simulations.

5.3 Output

Do you have GUI for your own optimisation tool? And which kind of output analysis visualisation did you do using optimisation tools (1-14)?

75% of interviewees indicated that they do not have an environment or package with a GUI for output post processing and analysis visualisation. Most interviewees are forced to process and convert the output data using different processing tools, such as DView, Excel, gnuplot or writing scripts in MATLAB, in order to create interpretable output results. Figure 10 illustrates the 14 most used output analysis graphs. 22 of the interviewees use the graph 10.5 allowing plotting the solution space using the Pareto Front. Interviewees indicated that the Pareto Front include many solution that they can pick from a variety of solutions. This was followed by Figure 10.8 (15 interviewees) that allows the visualisation of energy, cost or carbon emissions of different solution cases representing the base case versus the optimized case. Also Figure 10 and 10 were selected by 12 interviewees to visualize the impact of any parameter variation. In general, every respondent had his or her own custom visualization techniques, for example line plots (Figure 12.2) or time series (12.7) are used for controls and in the case of comfort scatter plots (Figure 10.2) are used.

5.4 Integration of Optimisation with Design Process

This part of the interview was structured around a series of open questions in order to get more insights on the integration of optimisation techniques in the design process. A selection of the comments and their frequency are classified as follows:

What opportunities you see in integrating optimisation techniques in NZEB design process?

According to the interviewees BPO has been applied successfully in some NZEB projects. However, the building simulation community still rarely uses optimisation and little investment has been made to advance BPO. However, interviewees indicated that many opportunities in integrating simulation based BPO in NZEB design and operation. The most mentioned opportunities include:

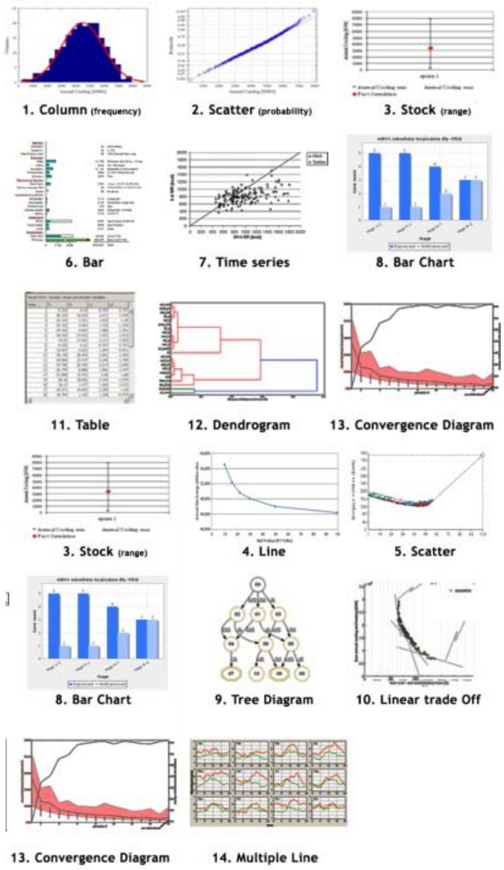

Figure 10, 14 different output analysis visualisations (10.1 Solution fitness, 10.2 Solutions Probabilities, 10.3 Solution range, 10.4 Solution line, 10.5 Solution Space (Pareto Front), 10.6 Parametric Weights, 10.7 Time series, 10.8 Solution Comparison, 10.9 Solution Tree (Dendrom-Hale), 10.10 Linear Trade Off - Hopfe), 10.11 Table, 10.12 Dendrogram (clustering of variables-Bucking 2010), 10.13 Fitness and average Fitness, 10.14 Thermal contour plot)

- Support the decision making for NZEB design. The rise of simulation has been driven by many things, including government policy that pushes the design of low energy buildings and use of performance-based building energy codes. At present, any increase in the use of optimisation will be driven by the extent to which aids design decision making. In this respect, one of the most powerful forms is multi-object optimisation, since it provides a set of solutions that lie on the trade-off between two or more conflicting design objectives. The trade-off can be used to explore the impact of less capital investment on the increase in carbon emissions. This kind of information being useful in decision making of NZEB requiring little effort and generates different ideas and alternatives.
- Designing innovative integrated NZEBs and thermal (and visual) comfort control systems is difficult because they involve complex systems that interact dynamically. Optimisation algorithm can help in finding the optimal and/or near optimal

solutions regarding the design and sizing of passive and active energy systems and finding the balance between demand and production.

- Achieving cost-effective NZEBs by analyzing and synthesizing multi-physics systems that may include passive and active facades, lighting controls, natural ventilation, HVAC, and storage of heat in the building structure combining advanced technologies such as micro-CHP, PV, PVT, solar collectors and micro-wind turbine). The complexity of such systems pose a serious challenge to designers and BPO provides an opportunity for optimal and cost-effective design decision during building design and operation including the existing building stock.
- Allow optimal systems scheduling through Model Predictive Control (MPC) taking into account the dynamics of NZEB systems and anticipated future energy load. When solving the optimal control problem using MPC algorithm, it determines near-optimal control settings during design and operation and improve the NZEB load matching problem.

How can it be integrated into the decision making? How should optimisation become more practically applied during early design phases?

There was an agreement among interviewees: that prior to any integration effort there must first be commercial tools available with integrated simulation and optimisation that allow seamless link between the simulation model and the optimisation process. Currently, the time and knowledge required implementing separate simulation models and optimisation algorithms is limiting the use of BPO in practice. However, on the long term the integration of BPO can be achieved through:

- Requiring optimisation as a standard activity during NZEBs design and operation. BPO can be integrated and become standard in practice. Consequently BPS tools will integrate optimisation techniques and the number of users will increase dramatically. In the coming year, I expect it to be a standard feature in NZEBs.
- Planning optimisation early in the design process. BPO should be introduced in early phases of design as part of the Integrated Design Process (IDP). The use of optimisation should start during schematic design stages. Models should be simple with some geometrical zoning simplification. Using a standard reference building and testing all kind of technologies can help in establishing initial design concepts and solutions which can have an impact on all stakeholders. Showing results from the starting point can have a strong impact on cost, energy and thermal comfort and will allow a range of ideas and solutions.
- Informing all building stakeholders on the importance of optimisation. Comparison studies on buildings with optimisation and buildings without optimisation will inform designers and clients. The optimisation community should show designers that the use of optimisation tools produce better results. By providing demonstration projects and real physical buildings beside the optimisation models for simulation users. This will raise the confidence in the optimisation and lead to more detailed, accurate and certain optimisation models with operation patters and hours. Education in academia and practice is key to guiding professionals how to perform optimisation.

5.5 Optimisation Shortcomings

What are the major practice obstacles of integrating optimisation techniques in NZEB design?

The major obstacles of integrating optimisation techniques in NZEB design can be classified under two main categories: (1) soft obstacles and (2) hard obstacles. The main four soft obstacles and their frequency from the survey are listed as follows:

- Low return and the lack of appreciation among the AEC industry (19 interviewees)
- Lack of standard systematic approach to perform optimisation in most cases researcher follow many different methods and ad-hoc approaches without a structure and categorisation in use (16 interviewees)
- Requirement of high expertise (11 interviewees)
- Low trust in the results (5 interviewees)

Interviewees' indicated that in practice, there is a lack of awareness and confidence on the use of optimisation. Also it is very important that users understand the optimisation process. There is a large educational need before BPO gets applied routinely in the design process.

Regarding the hard or technical obstacles, the interviewees' comments and their frequency are listed as follows:

- Uncertainty of simulation model input (27 interviewees)
- Long computation time (24 interviewees)
- Missing information on cost, occupancy schedules, etc. (19 interviewees)
- Difficulty of problem definition (objectives arrangement, constraint violation) (12 interviewees)
- Missing environments integrating and linking simulation and optimisation seamlessly (16 interviewees)
- Low interoperability and flexibility of models for exchange between different design, construction, simulation, cost estimation and tools (11 interviewees)
- Lack of environment with friendly GUI allowing post processing and visualization techniques (7 interviewees)

Interviewees' agreed that computation time is very long and this might well inhibit the initial take-up of optimisation in practice. The optimisation processes also magnifies the idea of "rubbish-in-rubbish-out" since rather than simulating a single design solution, the errors or inaccuracies in a optimisation are exposed across a wide range of the design space. This may lead to a need for better education and improved user interfaces for simulation, as well as more work on the uncertainty associated with simulation models.

Which tools would you recommend?

10 interviewees recommended GenOpt, (6 interviewees) MATLAB, (4 interviewees) BeOpt, (2 interviewees) modeFrontier and (1 interviewee) Topgui.

What features would you like to find in future tools?

Interviewees mentioned many ideas that contrast the hard obstacles mentioned previously. However, some significant ideas on future feature of optimisation tools include:

- Performing optimisation in real time within a BIM model and allowing adjustment on the fly
- Allowing parallel computing to reduce computation time
- Developing better GUI and model the building in 3D
- Coupling simulation and optimisation
- Connecting real physical building components performance to optimisation models for better information on cost and occupancy, etc.
- Allowing automation of building simulation with some default templates and strategies
- Profiting from the gaming industry by developing interactive optimisation environments for example talking to an oracle friend or wizard that guides the optimisation process for better input quality and error detection and diagnostics

DISCUSSION & CONCLUSION

From the interview results, three themes were identified: the optimisation context, the locus of optimisation, and the factors that inhibit the uptake of BPO as decision support in the design of NZEBs.

Summary of main findings

Decision support, time, knowledge, lack of tools, and uncertainty were the themes that ran through the experiences of the interviewed experts. The factors that inhibit the uptake of BPO are not only related to the optimisation techniques or the tools themselves, but also to the simulation models inputs, causing significant restraint in the AEC industry take-up.

Interviewees' opinions about BPO, and their subsequent experiences, were found to be mostly influenced by their research work and community. From the evidence available, the optimisation process did not, in general, seem to be systematic and design centred, apart from a small group of experts who used BPO in real design practice.

Strengths and limitations of the study

The methodology used in this study literature review and structured interviews was appropriate to generate hypotheses from a large population sample. Verbatim transcriptions were undertaken and selected quotations were not edited (Attia 2012). There was independent analysis of the data and concordance in the identification of themes. The choice of setting, IBPSA and IEA, allowed experts to be recruited from practices who represent a range of NZEB and simulation groups. Furthermore, the experts formed a representative sample in terms of the outcomes related to BPO. The experts were made aware at the beginning of the interviews that the interviewer was a researcher, architectural engineer and IEA SHC Task 40/ECBCS Annex 52 member. While this knowledge may have been helpful in allowing experts to feel comfortable in an AEC setting, thereby facilitating discussions about building performance related matters, this knowledge may have had an impact on the data. Specifically, the experts may have felt obliged to align their views with what they perceived to be the established IBPSA standpoint, for instance offering a more positive opinion on BPO than they would have done otherwise.

The number of the expert group means that statistical representation cannot be claimed. Furthermore, it was not possible to ensure that the expert represented a desired broad range of optimisation groups. The sampling strategy was therefore prospective rather than purposive, and it would have been preferable to interview more experts who declined the survey and experts who do not speak English, as all of the interviewed were English speakers. Finally, it would have been preferable to interview more experts who work in practice.

Implications for practice and future research

The finding that BPO is surrounded by issues of uncertainty imposes new obligations on researchers and software developers. This involves embracing more design-centred optimisation work in addition to setting systematic frameworks of performing optimisation for design decision support, uncertainty and communication, and optimisation-based building solutions. Moreover, reliable and accurate information on building performance is crucial for experts to create robust informed design choices. Optimisation performed for designers needs to explain the impacts on the design quality both before and after the use of optimisation, and the associated uncertainties need to be discussed.

Furthermore, recognition is needed that optimisation is necessary for complex NZEBs. Designers do not rely on optimisation sufficiently due to the lack of public domain design packages integrated with open domain, object oriented analysis tools. They are also influenced, often strongly, by the design complexity, limited time and investment pressure. Policymakers must therefore respond accordingly and recognise that BPO does not start and finish in the research labs. BPO could be required as a standard activity during NZEBs design and operation and made available in a range of public NZEB design practice. The greatest possibilities to use BPO, however, are afforded by the researchers, notwithstanding the real issue of computation time and the seamless integration of simulation and optimisation model with design models.

At present, the integration of BPO into the design process is a research issue. While this sample of experts confirms that BPO will add value to the design, we do not have the proof. If we have solid proof, designers will be very likely use optimisation techniques because it enhances the buildings they are designing, so they can get better buildings. More research is needed on the experience of designers with BPO. Research has to show designers that the use of BPO produce results better than their design. This would also allow the development of better BPO tools that are both accurate and support the decision-making.

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