HOW TO INTEGRATE OPTIMIZATION INTO BUILDING DESIGN PRACTICE: LESSONS LEARNT FROM A DESIGN OPTIMIZATION COMPETITION

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ABSTRACT

As part of the Advanced Design + Optimization (ADOPT) project, we organized a design optimization competition in late 2012, with an original goal of testing building design optimization tools and their applications in design process. Despite that our original goal was missed due to software delays, the competition itself was a great success, with more than 200 people taking part and 3 winners selected from 30 final submissions. These submissions provide excellent insight into the (manual) optimization approaches taken by participants with diverse background and experiences. This paper presents in detail how the competition was organized, and analyses the submissions received. In addition, the application of design competition in classrooms is discussed. We believe the lessons learned from the competition will guide future development of optimization tools and their integration into the building design practice.

INTRODUCTION

This paper presents a building design optimisation competition held between November and December 2012. The competition was part the Advanced Design + Optimisation (ADOPT[i]) project funded by the UK Technology Strategy Board. In the project, DesignBuilder Software Ltd., De Montfort University and Zero Energy Design Ltd. teamed up to develop innovative building performance simulation software for assisting decision making in various stages of life cycle of buildings. The main goal of the project is to develop building design tools with robust algorithmic optimisation capability suitable for selecting practical and cost-effective energy-saving measures. A range of tools have been developed during the project, such as DesignBuilder JobServer and Optimisation, jEPlus+EA[ii], surrogate modelling methods, and the jEPlus Simulation Server (JESS) platform. The original purpose of the competition was to raise awareness of building design optimisation methods, and to test the usability of the ADOPT tools. However, the outcome from the competition exceeded our previous expectations in many ways. In this paper we will discuss the experiences and lessons learned from the competition.

The application of numerical optimization in building design has gained wide interest from both academics and practitioners. Applications of optimisation methods have been reported in many academic publications, most of which were carried out by coupling optimisation tools (e.g. Matlab Global Optimisation Toolbox, GenOpt [iii] , or research packages developed in house,) with building simulation tools. Such approaches are not suitable for practitioners, who are often constrained by time, programming skills, and access to suitable computing facilities. Specialized optimisation tools also exist, such as BEopt[iv] for residential buildings and Ecotect for shading devices. Whole-building optimisation tools that fit in various stages of the design process are yet to be developed. Early examples of such developments can be seen in Autodesk Vasari, IES OPTIMISE, and DesignBuilder Optimisation. The question remains, however, whether optimization tools can bring about a step change in building-design practice, and give us better buildings as a result. The intention of the competition is to find some answers to this question.

Why did we choose the format of a design competition? Compared to alternative methods for collecting information on how optimisation methods fit into real-life design process, such as surveys, interviews and focus groups, a competition is more ‘fun’. Firstly, participants can be more motivated to do their best in the task. Secondly, apart from the design brief and the information about the availability of tools, participants are not exposed to communications that may interfere with their own decision-making process. In this way, we (the organizers) can maintain a passive role, and derive findings only from submitted reports and feedbacks.

We had two questions in mind when designing the competition:

- What are the processes used by designers when approaching a challenging multi-criteria design problem?

- How useful are optimisation tools in such processes?

Since the planned competition was coincided with teaching activities of some of co-authors, we were able to test the competition in classroom for teaching purpose, which will be discussed further in the paper.

The body of the paper contains four parts: details of the design of the competition, analysis of the submissions and results, case study on design and optimisation approach used by competition entrants, and discussions on our experience of using the competition for training purpose.

DESIGN OPTIMISATION COMPETITION

When designing the competition task, we drew lessons from three sources as references. Reinhart and colleagues (Reinhart et al., 2011) reported their experience of teaching building energy simulation as a game to architectural students. The students were given 90 minutes to complete a task of improving an office building design with a total of over 400,000 design variants. The available design options included building forms, orientations, envelope configurations (roof, wall, window constructions and glazing ratios), external shading, lighting, and control options. Cost for each design is calculated using rough estimates and must fit within a set budget. The students were not required to carry out simulations. Instead, they submitted proposed designs to a team of modellers who carried out annual simulations and provided monthly fuel breakdown and heat balance reports back to the students. The students then submitted alternative designs after reviewing the results from the previous rounds. Due to the 90 minute time constraints, the students could only test up to 10 different designs during the game.

The arrangement of the simulation game is clearly appropriate for the architectural students who have not received sufficient training in modelling. As a result, they have to rely on limited feedback from dedicated modellers. Also, due to the expensive nature of building simulation, the students can only explore a small number of design options, which makes it infeasible to adopt a "scientific" approach, such as carrying out sensitivity analysis on design parameters. This situation is rather similar to what architects face in real-life projects, i.e. their ability to explore design options is severely constrained by the limitations of communication, time and resources. For our purpose, however, the participants are expected to be sufficiently fluent with modelling, and the time/resources constraints are not as strict as those in the classrooms.

The second reference point was from the experience of one of the coauthors on organizing a competition between human design approach and algorithmic optimisation. The competition was carried out over the course of a 5 day MSc module at the Centre for Alternative Technology (CAT) in Wales. Students were given a building-design problem of a dwelling, which they optimised through trial-and-error and analysis of thermal, cost and embodied CO_2 models. At the same time the same design problem was approached using a surrogate-modelling optimisation approach. The design options included shape, glazing ratio, window and construction type, insulation, air-tightness, shading, lighting, heating and renewable systems. The total number of designs was over 900,000. All known designs had previously been calculated, so a comparison of the different optimisation approaches against the known Pareto front (carbon emission vs. cost) was possible.

For us, part of the purpose of this exercise is to see how optimisation algorithms perform compared to empirical design approaches. Ten students with 5 computers worked 10 hours per day for 2.5 days on the problem, and produced solutions that are comparable to what algorithms would find within 5 hours on one computer. The task was relatively simple and did not reflect the level of complexity that designers regularly face in non-domestic buildings. The above two examples both have prescribed design options and finite number of possible designs. We wanted a more open-ended problem of which neither the organizers nor the participants can know what the best solution is.

The example of open-ended problems came from the student modelling competitions of the IBPSA Building Simulation conferences. The competitions in BS'09 [v] and BS'11 [vi] were modelling of control strategies for the hybrid ventilation system of a public building. The building was predefined; however, participants had freedom to implement any control strategies using any modelling tools, as long as the comfort criteria were met. Entries were judged by the reported modelling approach and the resultant energy performance. In BS'13[vii], the competition task is to design an energy positive dwelling with a focus on matching renewable sources to predefined household consumption patterns. Since participants can use any simulation tools, as long as it is "validated code", the competition is open to abuse simply because of the error-prone nature of modelling.

We debated long and hard on whether to make submitting in DesignBuilder format a requirement of this competition. Unfortunately we could not find a viable alternative option that allowed us to check the quality of the models and to judge entries based on objective measures. (Just imagine how we were going to read through 30 EnergyPlus models to check errors if we had allowed IDF as a submission format!) In the end, we decided to allow only DesignBuilder submissions while allowing sufficient freedom for innovative designs. The competition should provide a good challenge for a range of different levels of skill with building design and building energy simulation. However, the

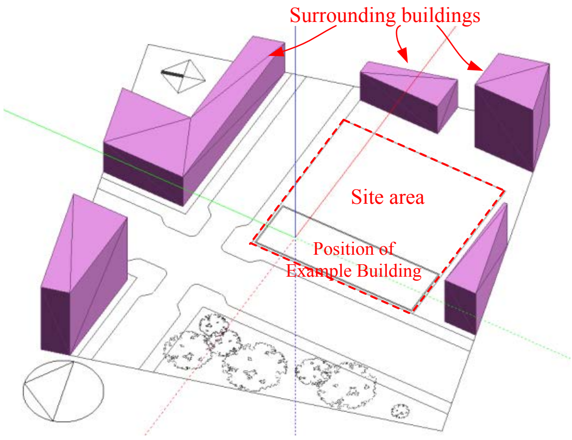

Figure 1 Building site layout

participants needed some experience with DesignBuilder and EnergyPlus simulation to enter the competition.

All of the above-mentioned competitions focus on energy, with either cost or comfort as a constraint. Real-life problems tend to be more complicated. In this competition, we define the following design objectives alongside functional specifications:

- Minimises operational carbon emissions.
- Minimises construction cost.
- Satisfies the comfort criteria based on ASHRAE 55 standard.
- Satisfies the minimum daylighting requirement.

The site is located south of London, not far from Gatwick Airport and the layout is shown in Figure 1. The building can be positioned anywhere within the red dashed site boundary.

A summary of the required building size is as below:

- Total floor area - 3,000m^2
- Total "Office" floor area (Office activity template) - At least 2,400m^2, of which at least 320m^2 are cellular offices
- Total "Utility" floor area (Utility activity template) - At least 420m^2
- Remainder of the space are "Circulation" floor area (Circulation activity template)
- Minimum storey height is 3.2m

Apart from the constraints mentioned above, participants have complete freedom to create any building form and internal layout. All design options that are available to participants are summarized in Table 1. All components are costed in DesignBuilder.

The competition entries must include a DesignBuilder model and a brief report form. The entries were judged through a 2 stage process. Stage 1 identified a short list of entries based on reported carbon and cost figures. The short list of successful entries were decided using a systematic technique. Each submission will have its operational carbon emissions and construction cost data plotted on scatter diagram (see Figure 3). The short list of designs will be identified as those that meet the competition requirements and lie closest to the "Pareto Front".

Stage 2 identified winners by further quality check of the models and subjective judgement on the following criteria:

- Daylighting and comfort performance of the building (as well as the cost and carbon performance already considered in Stage 1). The winning entries will provide a sensible balance between cost and carbon/energy performance.
- Practicalities – is the design actually buildable and would it work in practice?
- Innovation – credit will be given for creative use of new or unusual design techniques or building characteristics.
- Aesthetics – does the building design fit well within the site and look pleasing from the outside as well as fulfilling the needs of the occupants inside?
- Quality of the argument supporting the submitted design.
- Consideration and details that have gone into the submission.

The competition was launched on 24 October 2012 with a closing date for submission on 18 December, which was later extended to 28 December 2012. Due

Table 1 Available design options

Site and orientation	Anywhere in marked area
Building geometry and layout	Freedom on layout provided the floor area requirements are met
Materials	Fixed set of 46 options
Constructions	Free to define custom constructions using the 46 competition materials
Window size and position	Unlimited
Glazing type	Fixed set of 18 options, including double or triple glazing with different gases and coatings
Blinds	Fixed set of 5 options
Local shading	Fixed set of 9 options
Lighting	Fixed set of 5 options, including CFL, T5 and LED lighting. Some with daylight control
HVAC	Fixed set of 7 options, including Fan-coil, VAV, VRF, air-source heat pump, ground-source heat pump, low-temperature radiator and chilled beam systems. Some of them use only natural ventilation for cooling.
Control (schedules and setpoints)	Unlimited

to delays on our side, the DesignBuilder optimisation tool and the jEPlus online simulation facilities were not available to the participants until 23 November and 14 December, respectively. These delays have severely limited the usefulness of such tools to the participants. Winners of the competition were announced on 16 January, 2013.

RESULTS AND ANALYSIS

201 participants from 37 countries/regions registered for the competition, and downloaded the competition file package. By 28 December, 2012, 30 submission from 12 countries were received (see Figure 2). Spain stands out in the chart because the competition was used as an assignment for an MSc module, and the students (in groups) were required to make a submission. These account for 6 of the 10 entries from Spain. Among all entries, 14 were from academia, including students, and 16 were from practitioners.

Reported construction cost and operational carbon emissions of all entries are plotted on chart in Figure 3. In addition, a reference case is also included. The reference case is based on the example building included in the competition support pack, with minor changes so that it meets all competition requirements. Initial screening by design requirements and proximity to the Pareto front resulted in 8 submissions (see Figure 4) being shortlisted for the final round. Two of those (214 and 131) were later found to contain features that were disallowed according to the competition rules and were therefore disqualified. The red diamonds on Figure 3 are entries that were disqualified for some reason, typically:

- Discomfort or daylighting requirements not respected
- Constructions using non-competition materials
- Total building area outside the allowed limits
- Incorrect model options used.
- Site orientation changed

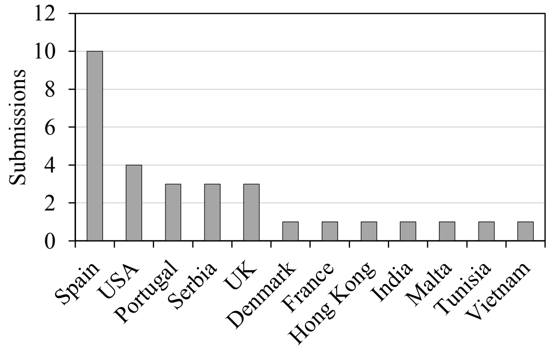

Figure 2 Submissions locations

Three winners were selected from the shortlist by a panel of judges from the ADOPT team which includes representatives from academia, industry consultants and software developers. All submitted material was considered in the final judging process. 1st Prize was awarded to Tran Tuan from the School of Architecture at University of Hawaii at Manoa, USA (109). Not only was Tran Tuan's design on the "sweet spot" on the Pareto front of best designs, but also demonstrated high architectural quality and attention to detail in the design and the report. Joint 2nd prizes went Amir Rezaei-Bazkiaei from Ebert & Baumann Consulting Engineers, USA (140), and Milos Seatovic from Quiddita, Serbia, (018). Rezaei-Bazkiaei's design is a very well thought out design using natural ventilation and based on a circular form, which is especially effective from the daylight and cost perspectives. The report explains in-depth the concepts and processes used in the design.

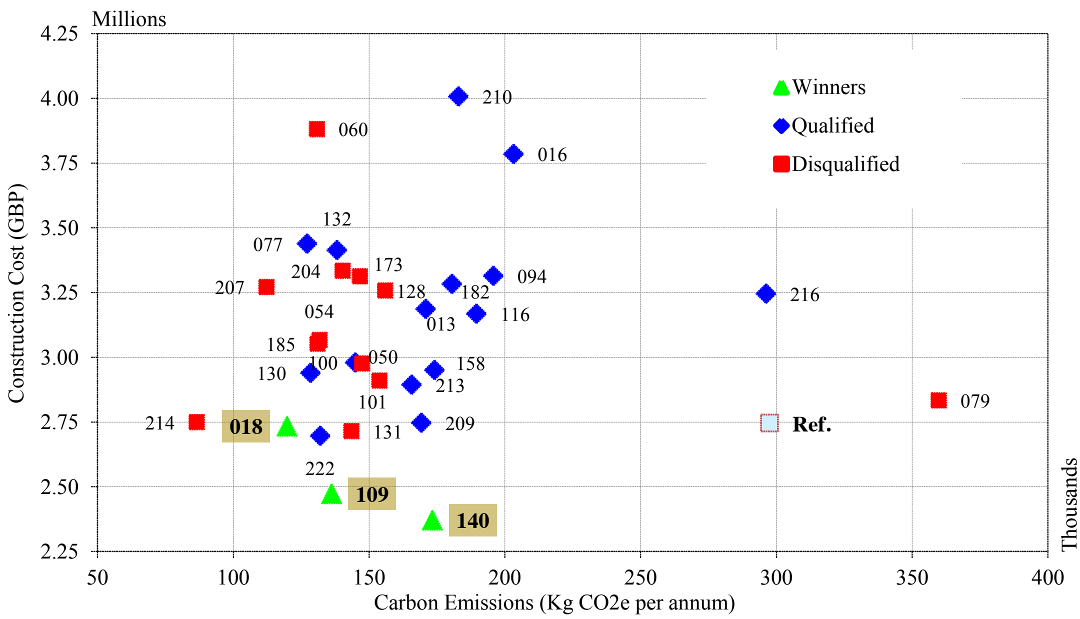

Figure 3 Operational carbon emissions vs. construction costs

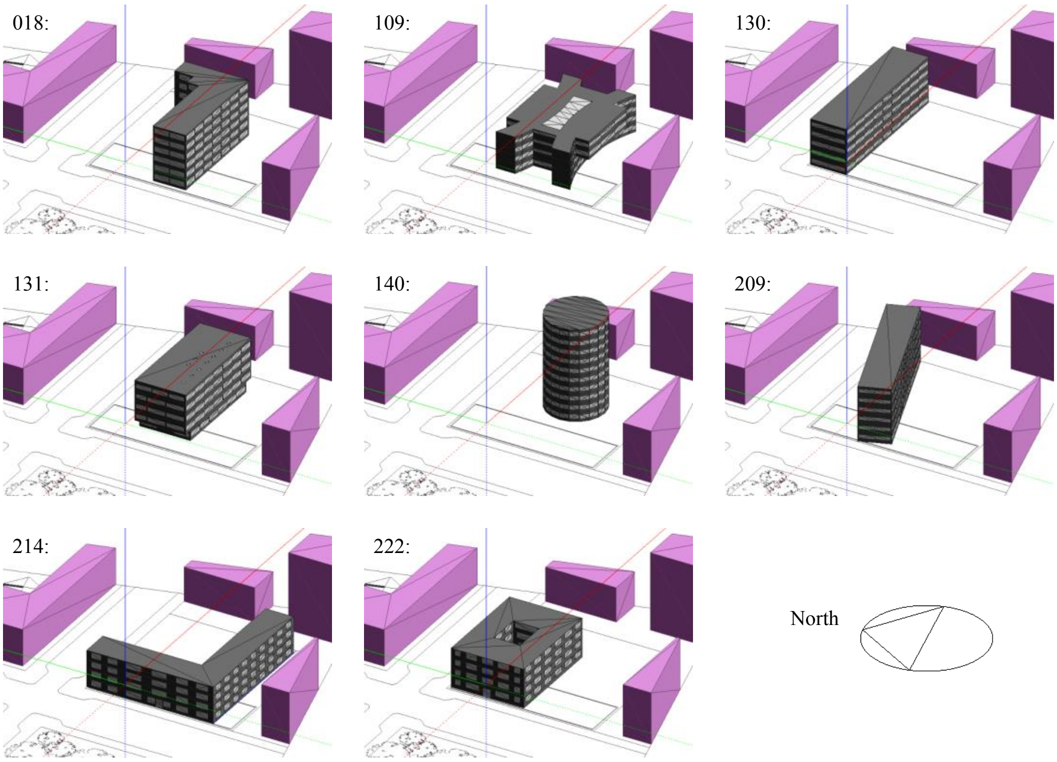

Figure 4 Shortlisted submissions

Seatovic's submission is a well-researched design having the lowest carbon emission in the competition, with natural ventilation with good HVAC control. The design also uses PCMs in external walls and ceilings.

Looking at reported carbon emission figures from all qualified entries (18 in total), the average value is 168.2 ton CO_2, representing a 43.5% reduction from the reference building provided to entrants. Average construction cost is GBP 3.09 million, 12.6% higher than the reference case. However, there are five entries with construction cost on par or lower than the reference case, with entry 140 showing 13.6% savings on cost. These results have shown great potential for improving building energy performance and reducing cost by careful analysis with simulation tools. Further investigations by some of the judges showed that there is still room for improvement on even the best entries. We will make the submissions available online and invite further discussions from the community.

We did a quick survey on the design solutions entrants have selected for their designs. They are summarized in the table below. Please note these include all entries.

From the submitted models and summary reports, it is clear to see that entrants have put in a substantial amount of effort in researching and improving their designs. 13 entrants reported time spent on the competition. The average is 132 person-hours. This include a large proportion of time spent on waiting for simulation results, as the competition models often take more than an hour to simulate. One entrant reported 40 hours spent on design/analysis, and 300 hours on simulation. From the authors' own experience, the ratio can be even worse. This situation highlights the need for faster models, faster computers, automated optimisation processes, or all of these. In fact, 10 out of the 18 entrants who have left feedbacks in the report forms explicitly commented on the need for speed. The remote simulation option (via jEPlus link) was enabled in DesignBuilder at the very late stage of the competition, so few participants were able to take advantage of this facility. Nevertheless, over half (16) of the entrants reported using the DesignBuilder optimisation tool. In the next section, we will further analyse the design approach and optimisation tools used by participants.

OPTIMISATION IN DESIGN PROCESS

Participants were required to summarize in the report forms the design approach taken. Although the level of detail varies widely among submissions, they do provide useful insight into the entrants' thought processes. However, a systematic review of all 30 submissions was not possible within the time constraints of this paper. Here, we report only a few selected cases to demonstrate the different approaches a (human) designer may take to tackle a challenging problem.

The first example is entry 214, submitted by an experienced energy consultant and DesignBuilder user. Below is the reported approach (with edits by the authors):

Table 2 Summary of submitted design solutions

Form	Typically 4-5 storeys high (73%); majority have a rectangular shape (including square, 'L', 'H' and courtyard forms); only 33% have circular, pentagonal, or irregular polygonal shapes; about half of the designs have a wide aspect facing south; a few designs have jagged levels to provide self-shading.
Layout	There is not a clear pattern arising from the submitted designs. Some put Utility and Circulation areas as internal zones or on the North side of the building. The effect of this on energy consumption requires further investigation.
Window size	26.7% of entries have high glazing level (window to wall ratio > 0.6); 33.3% have a window to wall ratio lower than or equal to 0.4; the remainder (40%) have medium glazing level.
Roof light	40% of designs have skylights, sun spaces or atria
Construction	20% of cases have external walls insulated to the UK best practice level or higher. Most constructions have internal exposed medium to high thermal mass. Only 4 designs have chosen external walls and roof with no dedicated thermal mass layer. Three entrants used PCMs. One of them used PCMs as the only internal thermal store.
Lighting	3 entries went for LED lighting. Others chose T5, most with linear control. Only 4 entries did not have lighting control.
Heating	Low temperature hot water heating (43.3%), VRF (26.7%), ground source heat pump (13.3%), air source heat pump (10.0%), fan coil unit (6.7%), and 1 under-floor heating (disallowed)
Cooling	17 entries (56.7%) have natural ventilation only. 12 entries have mechanical cooling, with VRF accounting for 8 of them. 1 used another system that is not allowed in the competition.
Control	All entrants adjusted temperature control set points in attempt to meet the comfort criteria.

1. To find plan forms that could achieve a 2% daylight factor over 50% of the area with a window to wall ratio between 30 and 40% (figures guided by experience from UK practice). A shallow plan building is decided to meet the requirement of daylighting and effective cross ventilation.
2. To find optimum position and orientation with regard to daylight for these plan forms on the site including shading from adjacent buildings. This was done by numerous simulation on single zones on different floors to establish a minimum glazing area consistent with the daylight requirements. Glazing types and depth of building were also investigated to meet the daylight requirements.
3. The decision to adopt a naturally ventilated, heated only design approach came from experience and knowledge of UK climate.
4. The decisions on Internal layout, type of structure, lighting system and heating system was guided by experience. Low cost has been one of the main drivers in selecting these components.
5. Control strategy for heating and natural ventilation ensuring windows cannot be opened when heating is on. Both switchover dates between heating and natural ventilation, and the starting time of daily heating schedule are checked taking into account of the comfort requirements.
6. Finally, the glazing ratio, the heating set point and the natural ventilation set point were fine tuned to achieve lowest carbon emission while meeting the comfort and daylighting requirements. A short run of DesignBuilder optimisation was carried out. The optimisation result, though far from optimum, was used to guide the final decisions.
7. Further checks on the final model to see if it meets current UK building standards were performed. This step was not reported by anyone else in the competition.

It is clear that the entrant was able to make most of the design decisions based on his own experience in the field and a good understanding of the problem at hand. Simulation trials and optimisation were only needed for fine tuning of some of the parameters, such as position of the building, glazing ratio, depth of building, and temperature set points etc. This is evidently an efficient way to achieve good designs (note: 214 was disqualified for setting incorrect internal gain schedules. With that error corrected, the design shows very similar performance and cost to submission 018, one of the 2nd prize winners). However, a human designer is confined by his/her own experience and presumptions. In this example, instead of the 4 storey L-shaped building, a 8 storey rectangular block of the same depth could be put along the north edge of the site to receive more daylight and solar gain.

The next example is from entrant 209, who was studying building energy and design at postgraduate level at the time of the competition. In fact, quite a few submissions from students have shown strong academic rigor in their approaches. Unfortunately we can only present one example in this paper. According to the report, the final design was the result of investigating 83 different building models. In total, 210 hours were spent on the project. Features of the design approach are summarized below.

1. Low cost is a primary goal that was pursued throughout the design process. Some decisions were made purely on the basis of cost.
2. Simple rectangular shape was chosen, after comparing with different massing, e.g. compact, tall, or U-shaped forms.
3. Zero cost decisions (orientation, set points) were made first. Set points were adjusted individually, by analysing the sources (zones and time) of discomfort.
4. "Sensitivity analysis" was carried out on a range of design options, including shape, orientation, internal partition, external wall and roof construction and colour, window type, shading, HVAC system, lighting system, and set points, in order to establish the influence of each option on different objectives and the "relevance" metric.
5. In effect, the "sensitivity analysis" was used as a learning process, to make up the designer's lack of experience in building energy performance to some extent. All following decisions were based on the result of the sensitivity analysis.
6. The orientation of the building was later fine tuned by rotating it at 5 degree steps. And the glazing ratio was tuned up based on the discomfort measure only.
7. The entrant is clearly uncomfortable with dealing with multiple objectives simultaneously. Various metrics were introduced along the process to assist decision making. Without a systematic plan, this method is less effective and more error-prone.

This approach represents an attempt to explore alternative design solutions systematically. The most remarkable feature is the use of a non-dimensional metric that combines all design objectives (carbon, cost, comfort and daylight). The metric is named as "relevance" and is used in the sensitivity analysis for determining the relative importance of each design parameter. The "relevance" measure effectively converts the multi-objective problem into a single objective problem. Optimisation experts will be quick to point out the issues with such approach, i.e. the arbitrary formula of "relevance" is likely to dictate final conclusions. However, humans are innately inefficient when dealing with multiobjective problems. Converting them into single objective problems is a natural process and probably the only way to tackle complex problems without the aid of numerical optimisation tools.

The entrant tried to use DesignBuilder optimisation to fine tune the glazing ratio (40%-48%), heating and cooling setback temperatures. However, due to software errors, DesignBuilder did not finish the task. Many participants left positive feedbacks about the optimisation facility, but were frustrated by the lack of maturity and simulation speed at the same time. The deficiencies of the existing tool include:

- Optimisable design variables only apply to the building level. It is not yet possible to optimise individual glazing ratios on different facades, or temperature settings in different zones, for example.
- Inadequate integration of constraints handling in the multi-objective optimisation gives rise to inefficiency.
- Parallel simulation only became available in DesignBuilder towards the closing date of the competition period. Without parallel simulations, optimisations can take a very long time, especially when using the full building model.
- The remote simulation option (through the jEPlus link with DesignBuilder) is not working reliably enough.

EXPERIENCE IN THE CLASSROOM

When designing the competition, the co-authors had a vision that the material could be a useful pedagogic resource for building energy training. This idea was tested in the classroom as part of an MSc course. The Rovira i Virgili University, Tarragona, Spain (URV) offers a master's degree course on Air Conditioning Technologies and Energy Efficiency in Buildings. It includes a 10-session/30-hour module on building energy simulation, in which two of the co-authors teach. DesignBuilder and EnergyPlus are used in this module to help students develop analytical skills and understand the impact of different architectural design variables on the environmental and energetic performance of buildings. Concept of optimisation is also introduced to the students, albeit only briefly due to time constraints in class. Nevertheless, the students are exposed to the systematic approaches to optimal designs for buildings.

Since the module (November 2012) coincided with the Competition, it was decided that the final coursework for the students is participating in the Competition. Ten students were paired between themselves to form five teams. Interestingly one team broke up during the process, so finally six submissions were made. The students were motivated to do well in the Competition and achieved excellent results:

1. Two submissions were shortlisted for the final stage, including one achieving target carbon and cost measures very close to the prize winners. One project was not shortlisted, but not far off. On the other end, three submissions were among the worst designs: one with high CO_2, one with excessive cost, and one failed to meet the comfort requirement. It should be noted that all students were new to the software tools used in the Competition.

2. In this module, students focused on architectural design aspects of buildings. Most of them have engineering or HVAC background, and received training on building energy systems on the same course. Combining this and the typical practice in Spain may help explain that 4 out of the 6 submissions used active cooling (VRF or Fan Coil system) in their designs.
3. In teaching, systematic approaches for exploring design options were introduced. This was reflected in the submissions. All students adopted a strategy to optimize building characteristics first, and system operations next. Most reported the use of parametric analysis and simplified models during various stages of the design process.

We tried to collect further feedback from the students regarding their experience from participating in the Competition. A brief questionnaire (in Spanish) was given to all students. Questions include:

1. To what extent the contents taught in the module was useful in the Competition?
2. Was participating in the Competition relevant to your knowledge and skills on building design?
3. Did you enjoy doing the Competition as the final coursework?

Students were asked to choose from (in effect) “not at all”, “a little”, “just enough” and “very much” for an answer. In addition, they were encouraged to give comments on the main technical challenges they have met, and suggestions on future improvements of the course and the Competition.

Three votes of “a little”, six “just enough” and one “very much” were received for Q1. Five of the students expressed that the course was too short for mastering a software package like DesignBuilder. Also received were five comments on the inclusion of more practical examples, such as working with complex buildings, application of optimization processes, and interpretation of simulation outputs.

Q2 and Q3 received identical responses from the students: five answered “just enough” and the other five, “very much”. This means that all students considered their participation in the competition as a positive experience. In general, students considered that the competition was well organized. Some commented on accepting only DesignBuilder model submissions limits the tools can be used in the competition. Also, the competition may contain two categories, for entrants with different levels of skills and experiences.

From the experience, we consider the Design Optimisation Competition is a great pedagogic resource. It is an excellent way to motivate students to extend knowledge and improve skills. With the right tools in place, it would be possible to train the new generation of practitioners with optimisation-based design skills and systematic approaches. These are crucial for delivering better buildings for the future.

CONCLUSION

The application of numerical optimization in building design has gained ever-increasing interest from both academics and practitioners. Commercial software vendors have been working on tools for bringing optimization to the industry. However, can optimization tools really bring about a step change in building-design practice, and give us better buildings as a result? No clear answer has yet emerged.

We organized the Design Optimization Competition in late 2012 as part of the ADOPT project. The original purpose of the competition is to test optimization tools developed in the project, and to analyze how they fit into the design process. We failed to achieve this goal, due to software delays. Apart from that, the competition is an excellent success that provided us rich source of information, especially insights into the existing design strategies and approaches.

The competition set out a challenging task. The participants were provided with a specific site plan, and were asked to come up with a design that “optimizes” both operational carbon emissions and construction cost, while fulfilling requirements on thermal comfort and daylight use. The participants have a large (practically infinite) number of design options to explore. These options include building form, geometry, and internal layout, orientation, construction, openings, shading options, lighting and HVAC, and control parameters.

The submitted designs represent a wide range of principles and strategies. It was very interesting to see the contrast between the approach taken by an experience designer and that by a student who is studying building energy performance. The student relied more on systematic experimentation to identify patterns and links between design variables and performance. The designer, on the other hand, used his wealth of experience to guide key design decisions. However, in both approaches, we saw the limitation of manual “optimization”, i.e. human designers are not effective in dealing with multiple variables or multiple objectives. This is where optimization tools have much to offer.

The full details of the competition, including all support documents and models, and all submissions from the participants, will be made publicly available on the ADOPT website[i]. This can be a valuable resource for both research and education. Our experience of using the competition in postgraduate training has shown that students enjoyed the learning experience from the competition. It is a good method to impart the concept of design optimization to the future practitioners.

ACKNOWLEDGEMENT

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