

## **BRINGING BUILDING SIMULATION TO A WIDER AUDIENCE - A WEB BASED SIMULATION AND OPTIMISATION SYSTEM**

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### **ABSTRACT**

The paper describes the development of a new web based expert system that uses jEPlus+EA and EnergyPlus as core engines for finding optimum solutions for retrofit of zero carbon design of buildings. The main goal is to scale up the use of building simulation and optimisation techniques beyond traditional users such as engineers, architects and researchers, and bring it to a wider audience of non-traditional users.

The expert system is based on a web interface running on a portable tablet device, and is designed to run simulation and optimisation jobs in the background on a server. This makes it the first comprehensive application that runs dynamic simulation and optimisation through a web browser. Hence, it is platform independent, usable on tablet devices, and thus enables easy and quick energy assessment of buildings. The system is designed to be easy to use, it enables the user to quickly specify the building on a tablet and send it to a server for simulation and optimisation.

Empowering non-experts with a dynamic simulation tool, thereby providing an advanced design decision-making capability to a wider audience, will facilitate the scaling up of the zero carbon retrofit of buildings, thus providing greater confidence in achieving future environmental, social and economic objectives.

### **INTRODUCTION**

The emergence of building simulation began around 1960 through the use of manual degree-day procedure to estimate the energy consumption of buildings. This was performed by testing different types of HVAC system to fulfil thermal comfort requirements. ESP-r was one of the first simulation tools developed in 1974 (ESRU, 2015). It provided in-depth evaluation of a wide range of building elements that influence building energy performance. Hence, it enabled researchers and engineers to continually test the impact of fabric, air flow, plant and controls on the building (Strachan, 2008). ESP-r has evolved since, and has been used in vast amount of scientific publications, and is used as a consulting tool for architects, engineers and as a core engine for different simulation interfaces (Crawley, 2008). However, ESP-r interface feels more like a research

tool. Unlike other commercial tools, it lacks the comprehensive predefined data sets for testing e.g. new generation of insulation materials and glazing types (Heath, 2010). EnergyPlus (Crawley, 2001) is another popular building simulation tool designed for engineers, architects and research communities to effectively model energy and water usage in buildings. It allows professionals to evaluate and enhance building performance in terms of heating, cooling, ventilation, lighting and water usage. EnergyPlus popularity within the professional community is growing due to the simulation capabilities it offers, such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multi-zone airflow simulation, thermal comfort analysis, and the possibility to incorporate wide range of renewable energy systems. Another superior feature of this tool in comparison to others is that the tool is designed to work as a stand-alone simulation program with no user friendly interface. All its input parameters and output results formulated as ASCII text files allow this tool to easily integrate with wide range of graphical interfaces written in different programming languages. For example, DesignBuilder, jEPlus+EA, SeFaira and Opt-E-Plus are user interfaces that uses EnergyPlus as core engine.

Numerous other simulation programs are available, all having strengths and weaknesses. However, the common weakness of all of these programs is that their usage is confined within professional community, such as engineers, architects and researchers.

### **Simulation challenges for wider audience**

Regardless of whether or not they claim to have a 'user friendly interface', non-experts have found simulation difficult to learn and use. ESRI (2007) put forward several reasons for this: 1- Non-engineers seems to struggle to understand the concept of simulation especially since it involves creating a building model that replicates the physical structure of the existing building. This requires comprehensive understanding of drawing, building geometry, scaling and three dimensional spatial visitations; 2- It is hard to quantify the effects of uncertainty in building simulation in the model parameters, input values and the interactions between the various components that

make up the building model. This uncertainty is inevitable, as is introduced by the random function that generates stochastic events, and bring dynamicity to the building mode to explore all possibilities and hidden solution, which in some cases do not make sense, in particular, when there is lack of information about the building performance and building materials; 3- All models are prone to errors. This requires the user to have some expertise in statistics and probability theory to perform error analysis via mean and standard deviations. Furthermore, the model needs to run numerous times to reduce noise caused by errors; 4- The high impact of number of parameters and their ranges. Varying the number of parameters, usually generates hundreds of thousands simulation jobs and alternative results. This makes it time consuming to extract meaningful conclusion, but also requires huge computation resources.

### **Building simulation as an assessment tool**

In the UK, 43% of all carbon emissions come from heating and cooling of existing buildings. The UK government identified almost 6 million houses with inefficient solid walls that require improvements, for which, it established its Green Deal<sup>1</sup> scheme. Green Deal enabled energy efficiency retrofit in homes to be financed through energy bill savings. However, Green Deal was discontinued in summer 2015, for several reasons, but in our opinion mainly because of low quality of the assessment process and consequent lack of trust. The Green Deal process started with an assessment phase to determine whether or not the building will materialise its potential savings, and if the cost going towards the improvements will be paid back within a predefined time span (Energy Saving Trust, 2015). Given the scale of such scheme, it was inevitable to use non-professionals to perform energy efficiency assessment. Green Deal assessors used steady state monthly average heat transfer calculations, effectively 12 sets of numbers, and did not consider any dynamic heat transfer over time. It is feared that the implementation of poor advice given on the basis of these basic and inaccurate calculations will influence the building energy performance and carbon emissions for many years to come. As energy efficient retrofit will remain to be a challenge for many years to come, the work presented in this paper will benefit any subsequent scheme that may supersede Green Deal in the future.

Despite the challenges for non-experts associated with the use of simulations and optimisation, such as conceptual complexity and high computational power requirement, these methods provide more accurate results as well as more realistic recommendations for designing/retrofitting of zero carbon buildings.

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<sup>1</sup> As of July 2015 Green Deal has been discontinued in the UK.

To support our claim further, we shadowed an assessor while conducting Green Deal assessments on site. Besides SAP's ease of use and speedy performance in delivering the results, which typically took between 15 and 20 minutes, we noticed the output reports are vague and deliver similar results. For example, many reports for two and three bedroom flats have similar energy saving suggestions in terms of required improvements and costs as three and four bedroom detached houses. Effectively, within the Green Deal, non-experts used non-expert software to deliver expert advice. If implemented, that advice would influence the building energy performance and carbon emissions for years to come, and could have a detrimental impact on technical, social and financial aspects of building performance on a large scale.

Our Retrofit Plus Web Application (Basurra, 2014) aims to scale up the use of building simulation, and make this powerful tool usable by non-skilled individuals, such as energy assessors, and equally applicable for new build as well as for retrofit of buildings.

### **METHODOLOGY**

In order to bring simulation tools to a wider audience for retrofit of zero carbon buildings, RetrofitPlus web App (Basurra, 2014) has been developed to support dynamic simulation in the design processes. Scaling up the use of simulation tools by non-expert is challenging because: 1- The system needs to offer a friendly user interface that can hide all the complexities associated with the concept of simulation, but also initiative to allow assessor to complete the survey with minimal number of steps; 2- Surveys are usually performed on the building site, hence, the expert system needs to work on portable devices such as tablets and smart phones; 3- The system needs to return the results quickly, since current Green Deal assessments are carried out in 20 minutes; 4- Simulation needs to be controlled from a portable device and generate few optimal results which comprise recommendations for retrofit packages, giving clear details about the material properties, cost and potential savings.

The RetrofitPlus expert system consists of three main features to address the above mentioned challenges connected to the simulation process and concept. These are explained in the following sections.

#### **Optimisation Engine**

Optimisation is used to select optimum results to minimise the number of solutions, which could exceed hundreds of thousands. It also saves some of the computation power and time. After creating the building model for energy simulation, the user will need to define the number of parameters to explore new solutions for retrofitting, which are not possible through traditional simulation approaches. As pointed out above, although using more parameters

will increase the likelihood of finding good solutions, it will result in a large number of solutions that can easily exceed hundreds of thousands. While this is computationally expensive, it also makes it impossible for an assessor to find optimum solutions manually. Hence, a multi-objective optimisation approach has been adopted for rapid exploration of the solution space. Optimisation refers to the selection process that looks for the best solution in relation to certain criteria, from a solution space that contains a set of available alternatives (George, 2014). It can be performed using single or multiple objectives. Single objective optimisation is the easiest as the algorithm looks for the best possible solution from the set of candidate solutions, and this is known as the global optimum. Multi-objective optimisation is computationally more complex as the objectives normally have negative correlations, such as minimising the cost of retrofitting will be conflicting with maximising energy efficiency (Coello, 2006).

Multi-objective optimisation methods can be further categorised into two types: heuristic; which may not necessarily find true optimum solutions, but offer high probability of efficiently exploring such solutions or at least getting close to one (Evins, 2013); and iterative, e.g. gradient-based, which can take many iterations to compute a local minimum by taking steps proportional to the negative of the gradient (Evins, 2013). For more details about different optimisation approaches currently available, the reader is invited to consult technical literature, such as Coello (1999). In practice, there are tens of optimisation methods, but only a few have been widely recognised and used. One of these is the Nondominated Sorting Genetic Algorithm II (NSGA II) (Deb, 2002), which has become very popular in the recent years due to its computational efficiency and good performance. Like most optimisation techniques, it searches through the solution space to

find a set of optimal trade-offs, while treating all objectives as being equally important (i.e. non-dominated solutions) and the output set contains the optimal solutions, called Pareto sets or Pareto fronts. A typical Pareto front is shown in Figure 1.

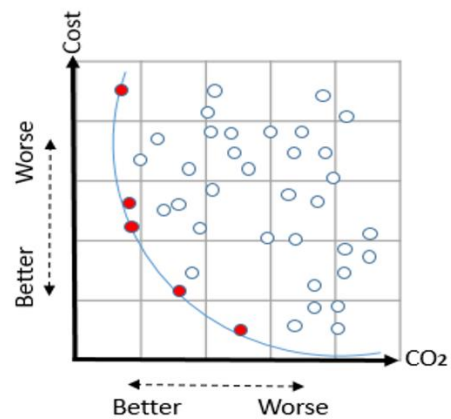


Figure 1 Illustration the of Pareto front shown in red.

RetrofitPlus utilises the EnergyPlus simulation engine which provides detailed calculation for the whole building.

The program presents a range of design options, each of which minimises energy use at a particular economic cost, also known as the Pareto optimum or Pareto front, which are effectively the results closest to their origin axis on a graph, with each axis representing an optimisation objective (Caramia, 2008). The following objectives have been set as the main goals: cost, thermal comfort and carbon emissions (as a constraint).

The outputs are presented in a simple form so as to allow non-expert users to understand the trade-offs between the objectives, and that retrofit recommendations cannot be improved in one direction (e.g. cost) without being degraded in another (e.g. building energy efficiency).

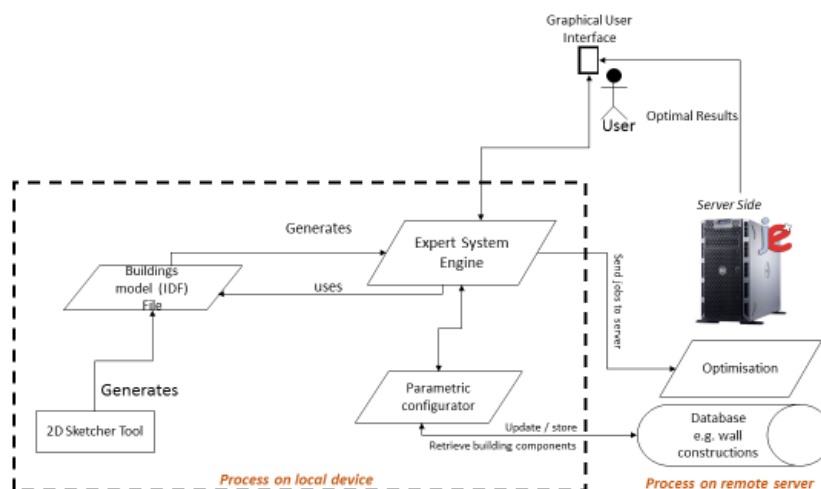


Figure 2 An overview of the system structure and components dependencies

### Remote Simulation on portable device

The front end of this software runs on a hand-held tablet (see Figure 5), which is used to send a job to a simulation server, a number crunching machine that searches the solution space, and returns the results within a few minutes, but with an immeasurable improvement in information quality. Google Web Tool (GWT) (GWT, 2014) has been used to enable the expert system to run as a web application. This makes the expert system the first comprehensive web based user interface that runs dynamic simulations and optimisation using jEPlus+EA (via EnergyPlus) through a web browser, hence it requires no installation, is always up to date, universally accessible and platform independent, as it can run on all tablets/mobile phone devices. Battery power is vital for portable devices, hence, using the local device to perform simulation will be slow and will cause fast battery drainage. To resolve this, the system sends a simulation jobs to EnergyPlus via jEPlus+EA simulation and the optimization tool (Zhang, 2015) that resides in our group's X3200 simulation server. The simulation and optimisation are performed in parallel and the system report manager displays the results and recommendations in a user-friendly format back on the portable device. See Figure 2 for the an overview of the Expert system's structure and component dependencies.

### Friendly user interface

The interface was designed to be clean and easy to learn and use. RetrofitPlus Web Application consists of five main software modules: 1- RetrofitPlus manger; 2-Sketcher tool; 3-Parametric configurator; 4-Simulation and optimization engine; and 5-Report manager.

The starting point for RetrofitPlus simulation and optimisation is making a building skeleton that encapsulates the basic requirements for the project, such as building location, number of levels, and floor area. After manually validating input values, the system provides a sketching area where users are able to generate the building skeleton using the system's Sketcher module. The first step in the system is to create the building skeleton in an easy and quick fashion, while still being able to represent the geometric data of the actual building accurately. RetrofitPlus uses a 2D grid (see Figure 3) to generate the building from inside out, with the user being able to create the building room-by-room using polygons. These are used to provide a visual aid, which shows the room locations inside the building and attached windows, but the user is still required to provide accurate depths and widths of these polygons.

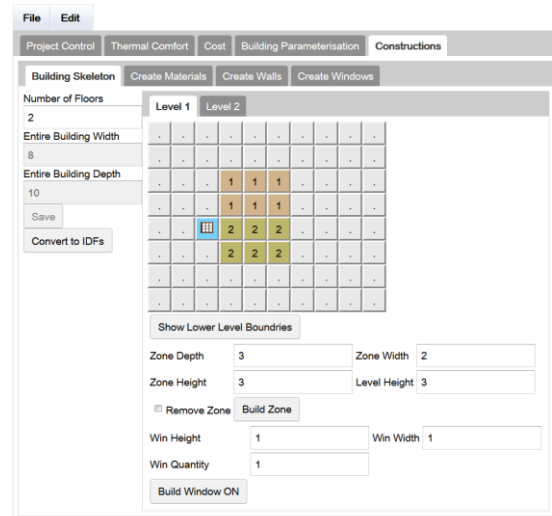


Figure 3: Basic & functional graphical interface of the expert system. It shows the 2D representation of the building skeleton. This is subsequently converted into a 3D physical representation that consists of a complete set of building components as shown in Figure 4.

When the building skeleton is completed, the system manger calls the parametric configurator to convert a basic 2D representation of the building skeleton created by the user into 3D. Figure 4 shows the 3D representation of the 2D grid, after being converted into DFX file format.

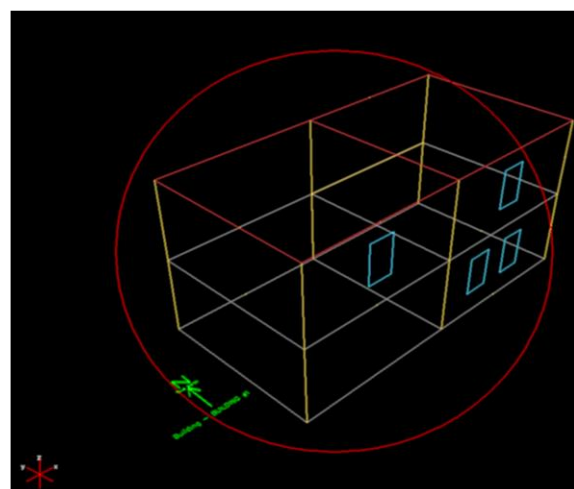


Figure 4: de.caff DXF Java Viewer package used to display a building geometry in 3D, which was specified via the expert system 2D grid. This basic building consists of four zones three of which have fenestration surfaces.



Figure 5: The Expert System Web Application while running on portable devices such as iPad Air and iPhone 5s

The resultant 3D model consists of all building components, including wall height, depth, orientation and types (interior or exterior). In addition to holding accurate information on building geometry, they are associated with newly generated interface controls that allow for their manipulation and hence users are able to specify with a few touches a range of parameters for some/all of these components. For example, various types of glazing parameters can be tested within the building window. Figure 7 shows how parameter ranges are selected. Each parameter value, such as wall construction type, will appear in the list, and the user needs to press to activate/inactivate these parameters, hence to decide whether or not these will be considered in the optimisation process. Assessors are also able to insert and create new building constructions using existing and new wall and glazing materials based on manufacturers standards information and material properties.

These will later be inserted into a database, after undergoing a verification process, hence can be utilised by different assessors for various optimisation jobs. Figure 6 shows how a building construction is created in the Expert System.

After the user enters relevant parameters, the system manager converts all values and ranges stored in the parametric configurator into logical format (known as an IDF file) used by EnergyPlus simulation. The simulation and optimisation are performed in parallel by the X3200 simulation server and the system report manager displays the results and recommendations in a user-friendly format.

MySQL database has been implemented, and all window and wall materials are stored in database tables on the server side. This helps to efficiently manage the expert system raw data, but also to speed up data retrieval and provide central data accessibility. The database therefore acts as data portal, hence it can be populated/accessed by users in a distributed fashion. This will help increase the accuracy and maintain the consistency of building parameters such as building materials, fabrics, HVAC systems etc.

We compared the recommended system specifications for RetrofitPlus web based expert system with well known simulation tools such as DesignBuilder (Designbuilder, 2015) and IES-VE (IES, 2015). Table 1, shows that designing the system as a web application, which runs optimisation over a remote server, allowed RetrofitPlus software to stand out in various aspects.

Table 1: Comparison of the recommended system requirements of DesignBuilder, IES and RetrofitPlus web application

Recommended System Requirement	DesignBuilder	IES	RetrofitPlus
Operating system	Windows 2000, XP SP2 or Vista running on	Windows Vista, 7, 8, Mac OS X	Platform independent – Any internet browser that runs javascripts i.n. FireFox, Internet Explorer and Google Chrome and Safari
Processor	2.4 GHz processor (or faster)	2Ghz+ Intel Pentium / AMD Athlon CPU	1GHz or less since the jobs are executed on the remote X3200 simulation server
RAM	2GB Ram	2Gb RAM	Was tested with 1GB using iPhone 5
Pointing device	Mouse and keyboard only	Mouse and keyboard only	Touch screen and/or mouse and/or keyboard
Free disk space	5GB free disk space	5GB or more	1GB as the results are kept at the server, and are discarded eventually when not in use.
Target user	Architects and Engineers. Separate package is offered for energy assessors but doesn't include optimisation.	Architects and Engineers	Non-experts such as Energy Assessors, Architects and Engineers.

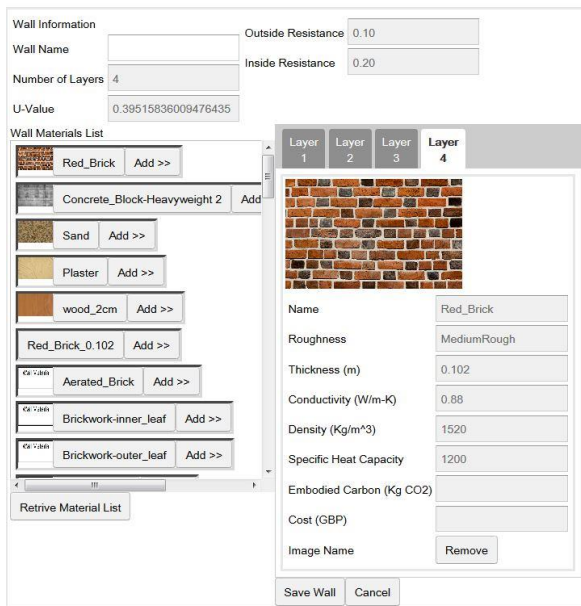


Figure 6: An example of the Expert System while creating a wall construction object consisting of four layers of wall building materials.



Figure 7: An example of the Expert System while performing parametric settings on different wall constructions.

## RESULTS

Using RetrofitPlus web application software, a building model was created, and a multi-objective simulation was carried out using the optimisation on the simulation server. The building model is a simple two story detached house, with four zones of a total area of 95m<sup>2</sup>. A flat roof and glazing were installed on the southern elevation. This basic building structure was used for simplifying the modelling process, reducing the number of variables and reducing the simulation time required.

London/Gatwick weather data (ASHRAE, 2001) was used in the optimisation process. The optimisation analysis looked at three groups of design variables: 1- building fabric; 2- cooling and heating strategies, including shading, natural ventilation, infiltration rate; 3- various lighting densities (see Table 2 for more details about the choices of parameters and their value settings). This simple example is only used for demonstration purposes to show how the Expert system performs multi-objective optimisation. More specifically it shows how it deals with finding the best solutions for retrofit. There are two conflicting objectives in this example: reducing the energy consumption used for heating and reducing the energy consumption from cooling the house. Energy for both has been calculated as a sum of the annual consumption.

Table 2: Optimisation / parametric analysis settings used for the building model.

Parameter name	Values
Glazing coating	Two window construction options: including single and double glazed windows with reflective & non-reflective coating
Combined infiltration and mechanical ventilation rate (ac/h)	0.1, 0.3, 0.5, 0.7, 0.9
Building fabrics	5 Options
Shading	None & overhang
Fresh air rate supplied by mechanical ventilation (m <sup>3</sup> /s-person)	0.01, 0.005, 0.015, 0.02
Lighting density (W/m <sup>2</sup> )	12, 4, 8, 16, 20, 24

Figure 8 clearly shows the Pareto front solutions, ranked 1 in blue and a much larger number of sub-optimal solutions, ranked as 2 and 3 in red and orange. Although the number of Pareto front solutions are proportionally smaller in number in comparison with the rest sub optimal solutions, these are still hard for the customer to understand when digesting the recommendations for retrofitting in a zero carbon house. Looking at the current tools for simplified energy assessment that are known to have user friendly interface, we came to conclusion that only three to five solutions can be presented to a customer at once. Hence, all Pareto fronts will be re-ranked again based on material availability, cost and the user's thermal comfort.

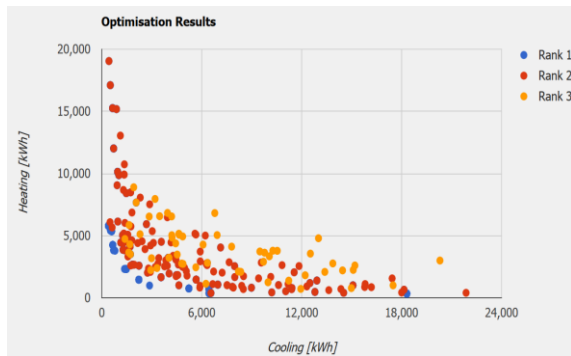


Figure 8: Optimisation results - the blue points represent the Pareto front.

## DISCUSSION

We have held a live software demonstration of the RetrofiPlus expert system during a teaching session on the MA course 'Zero Carbon Architecture and Retrofit Design' taught by Prof. Lubo Jankovic at Birmingham City University, UK. All of the attendees were experienced IES-VE users. Although the student sample cannot be considered as non-expert, and therefore is unlike the target audience, it is essential at this stage of development to get more of the practical and technical views on the software functionality to increase its efficiency and accuracy of the results.

The demonstration started by creating a basic model of a two floor house similar to the models shown in Figure 4, consisting of two zones at each level, and with windows located in different positions to the south. The students were shown how to build the model, locate the windows and later view the visual outcome in standalone dxf viewer software. We demonstrated how to create walls and add new materials to the system, and perform a basic parametric simulation, by changing the number of layers materials. All students were given feedback sheet, which contained three basic questions and freeform space to write their feedback. The questions were as follows: 1-what do you like about the software?; 2-what you dislike about the software?; 3-what needs to be improved?

Various comments were received at the demonstration, most of which were verbal, and written feedback was also handed in at the end of the session. Most positive comments were related to the ease of use and the minimum requirement to learn how to use the tool, as well as comments about the high quality of results and the fact that optimisation can run remotely, away from the building site, while the results were obtained swiftly from a powerful remote server.

However, some comments were about adding extra features. For example: 1- adding visual representation of the building while being

constructed; 2-showing the building orientation; 3-allowing various window shapes such as circular and oval; 4-changing the application name; 5-adding visual representation for solar shading; 6-providing the user with different types of ready made building geometries, to enable the user to select and edit a model to match the real building instead of building a model from scratch on the site.

## CONCLUSION

This paper describes the development of web based expert system that utilises jEPlus+EA and EnergyPlus core engines to perform multi-objective optimisation for the retrofit of zero carbon design of buildings. The application uses the well known NSGA-II genetic algorithm for optimisation, to help explore the trade-off between various design options, and their impact on the thermal, economic and comfort performance. We have demonstrated at this development stage that the tool can empower non-expert energy assessors with dynamic simulation functionality, thereby providing an advanced design decision-making capability to a wider audience, and thus increasing the confidence in achieving environmental, social and financial objectives.

The expert system is designed to run as a standalone software tool that is platform independent, and can run on tablet devices, hence it makes it possible to perform quick assessment at building sites. This makes it the first comprehensive web based user interface that runs dynamic simulation and optimisation through a web browser. We found that that a typical three bedroom house can take up to 20 minutes to optimise on the remote server, although this will vary with model complexity. The expert system is designed with the objective to be easy to use and learn, and to be generic to minimise the number of steps an energy assessor need to complete on building site. Hence, we believe that we have provided an advanced design decision-making tool to a wider audience, and thus facilitated greater confidence in achieving environmental, social and financial objectives via the use of building simulation by non-experts.

## ACKNOWLEDGEMENT

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