In Proceedings of the 1st International Conference on Zero Carbon Buildings Today and in the Future, Birmingham City University, 11-12 September 2014.

DEVELOPMENT OF A WEB-BASED EXPERT SYSTEM FOR ZERO CARBON DESIGN AND RETROFIT OF BUILDINGS

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ABSTRACT

The paper reports on the development of an expert system that embodies a method for zero carbon design or retrofit of buildings. The system is an interactive computer based decision making tool, which allows the user to enter the type and range of design parameters to be investigated, perform background simulations, carry out multi-objective optimisation, and inform the user of the range of possible solutions and trade-offs, whilst fulfilling environmental, social and economic criteria for zero carbon design.

For simplicity, the system operation is demonstrated on a basic box model of a building, in order to simulate various design alternatives, explore scenarios and identify any conflicts or dependences, while satisfying the three aforementioned criteria. In order to minimise the system complexity, JEPlus was used to carry out parametric runs, whilst jEPlus+EA was used to carry out multi-objective optimisation, using EnergyPlus as a core simulation engine and NSGA as an optimisation engine. The purpose of the expert system is to provide advanced design decision-making capability to a wider audience and thus facilitate the scaling up of zero carbon retrofit of buildings. The paper reports on the early stages of the development of this system and the results obtained.

INTRODUCTION

Green Deal and its deficiencies

Green Deal was launched in the UK in January 2013 and is an innovative financing mechanism that allows companies to help people pay some of the cost of the energy efficiency improvements through saving on their energy bills. It replaces current UK policies, such as the Carbon Emissions Reduction Target (CERT) and the Community Energy Saving Programme (CESP). The Green Deal process consists of the following four stages: Assessment, Finance, Installation and Repayment (Energy Saving Trust, 2014). The most critical and vital stage is the assessment phase, where a decision is made about whether or not the assessed property can materialise its potential energy savings in the time planned, and if the finances going towards the cost of improvements can be repaid within a predefined time span. This critical phase is normally conducted by an adviser who is typically trained for between two and four days. Although the training courses can be intensive and financially expensive, they generally do not have clear entry requirements regarding prior knowledge of finance, building design and structure, insulation materials as well as HVAC devices and equipment. Consequently, in many cases assessors lack the necessary expertise in building behaviour and construction to be able to make correct decisions with regards to improving energy performance. To some extent, the technical knowledge that Green Deal assessors need in order to make such critical decisions is aided by the use of the Standard Assessment Procedure (SAP) software. SAP is the UK Government's methodology for comparing and assessing the energy and environmental performance of dwellings (Stroma, 2014). The assessors input various parameters regarding the basic description of the building, occupancy, electricity and heating energy usage, which it performs calculations on to arrive at an estimate of building energy performance.

The program uses steady state monthly average heat transfer calculations, effectively 12 sets of numbers, which hence do not consider any variable changes over time. Consequently, it simply provides answers to show results of specific inputs for particular function/s and fails to show how an output will behave for a particular input over time and how a building would respond to a change in one input level to another on a dynamic basis. Steady state modelling is usually easier to converge and configure, being also typically less time consuming, which is probably one of the main reasons for it being used in SAP calculation. However, given its aforementioned limitations when used for Green Deal investment decision making, this raises many questions regarding the validity of the results derived in terms of the cost and efficiency of building performance.

Moreover, SAP is not flexible when it comes to calculating a range of values/materials for multiple building parameters, such as walls and window types. For example, it is incapable of testing various wall constructions for each building façade in one operation, which means that it will constantly fail to explore possible alternatives that may allow the building in question to achieve better energy efficiency performance with a shorter payback period.

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 some weaknesses with the current system: 1- building orientation isn't considered in the calculation; 2- the system operates on imprecise data, i.e. it generates the results based on the assumption that all walls have the same depth and insulation materials; 3- although the system requires estimates of window size and types, it ignores the windows quantity and locations; and 4- although lights are categorised into two types efficient/non-efficient, the power rating information for each light point is disregarded in the calculation. As a consequence, we are of the view that most Green Deal output reports are vague and deliver high variations in cost. Regarding which, 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. Moreover, the assumption that all walls are the same causes a significant variation, whereby, for example, if a Victorian house has 65% solid walls and the remaining 35% pertaining to a new extension has cavity walls, then all would be treated as either solid or cavity.

Effectively, within the Green Deal, non-experts use non-expert software to deliver expert advice. If implemented, that advice will 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.

Empowering non-experts with expert software

Given the above discussion, our objective is to empower non-experts with expert software that will carry out the decision making for them. The three ingredients of this approach are: 1) dynamic simulation, which implements transient heat transfer every hour of the simulation year, thus performing calculations on 8,760 sets of numbers, equal to the number of hours in the year, rather than steady state SAP calculations using 12 sets; 2) parametric simulation, which implements a variation of design parameters, such as insulation thickness, glazing type, air tightness, thermal mass and others; and 3) optimisation of the solution space in order to find a trade-off between design parameters, according to performance, comfort, and cost criteria.

Dynamic simulation will show how an output will behave for a particular input over time, and how the result of the former operation can influence the input variables of the subsequent one. It can be seen as an iterative steady state calculation based on a fixed time step, introducing time delays to outputs arising from the effect of thermal mass in the building, with constantly changing parameters, whilst bearing in mind the considerably higher resolution of the hourly simulation in comparison with monthly average calculation.

One downside of this approach, which presumably is why it has been avoided in SAP in the first place, is that dynamic simulations are slower and mathematically more complex than a steady state simulation, and are normally used by genuine experts. Moreover, parametric runs of dynamic simulations generate considerable numbers of results, in fact, that may exceed hundreds of thousands, which will make it hard for anyone to draw firm conclusions or be able search through the outcomes to select the best result. For instance, our research revealed that for a handful of design variables, such as wall construction, glazing types, thermal mass, air tightness, external shading, heating set points, heating systems and renewable technology, and with several values for each variable, the total number of possible building designs and corresponding simulations exceeds 400,000. Hence, the problem of finding the optimum solution is similar to that of finding a needle in a haystack.

There are various methods that can be deployed to search the solution space. However, most of the conventional methods, such a point-to-point search, are too slow and unreliable, as they can easily lock into a local, rather than global, minimum, and therefore end up with a sub-optimum solution.

For this work, we are going to use genetic algorithms that search the solution space in parallel, and are much less prone to locking into sub-optimum solutions. Genetic algorithms, such NSGA-II, will be running in the background of this system to select only a set of the best available results using the three main objectives of cost, thermal comfort, and zero carbon emissions. The output of this process, will be a 'shopping list' of design parameters which allow informed trade-offs to be made between these three main objectives. In this way, the non-expert energy assessor will be empowered with expert software that runs a far more sophisticated and higher resolution process than SAP, whilst not requiring any additional expertise. This approach will enable a much higher quality of advice on building retrofit, thus ensuring a much more positive and long lasting effect on the environment. The front end of this software will run on a hand-held tablet, which will be used to send a job to a simulation server, a number crunching machine that will search the solution space, and return the results within the same time as the SAP assessment, but with an immeasurable improvement in 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, always up to date, universally accessible and platform independent: it can run on all tablets/mobile phone devices.

BACKGROUND

Because of the increasing awareness of climate change, and the realisation that heating and cooling of buildings contribute almost 43% of all the UK's carbon emissions, designing energy efficient buildings has become a fundamental main objective for UK planning policies pertaining to new buildings (GOVUK, 2014). Energy and the environmental performance of buildings complex dynamic issue, hence numerous studies in the past have used dynamic simulation to capture such this behaviour with the aim being to incorporate the results in the design process so as to enhance the building energy performance.

The evolution of building energy simulation tools started around 1960, when simplified manual methods, such as the degree-day procedure, were used to estimate the energy consumption of buildings, while using various types of HVAC systems in order to meet thermal comfort requirements. One of the early simulation tools that allowed for in-depth evaluation of the building elements, which influence the energy performance of buildings was ESP-r. It was developed in 1974, and was one the few tools that enabled designers to explore the complex relationships between buildings form, fabric, air flow, plant and control (Strachan, 2008). Many scientific publications used ESP-r for simulation of building fabric and network mass flow, and it is still being used as a consulting tool by architects, engineers, and multi-disciplinary practices as well as a core engine in other simulation environments (Crawley, 2008). However, the program's user interface appearance is complex, feeling more like a research tool than one for general usage, and 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). Another popular simulation tool is EnergyPlus, which is used by engineers, architects and researchers to model the performance of buildings in terms of heating, cooling, lighting, ventilation, energy flows and water use. Moreover, it facilitates various innovative simulation capabilities, such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone airflow simulation, thermal comfort analysis, and incorporation of renewable energy systems. Its inputs and outputs are formulated as ASCI text files to allow easy interactions with various front end user friendly graphical interfaces, such as DesignBuilder, jEPlus+EA, SeFaira and Opt-E-Plus, most of which have been designed to be used by professional engineers, architects and researchers.

As most of the building simulations mentioned above, regardless of whether or not they have a "user friendly interface", were designed to be used by these professionals, other practitioners have found them difficult to apply. Regarding which, ESRI (2007) put forward several reasons. 1- The simulation concept is difficult to grasp by non-engineers as it involves building a model of the physical building, which requires various drawing skills, three-dimensional spatial visualisation and buildings geometry. 2- There is some degree of uncertainty that affects a model's input data, its parameters and interaction within the model. These uncertainties are incorporated into a model by introducing randomness into the modelling process to capture dynamic, stochastic events, which results in some events not appearing to make sense, especially when there isn't a complete understanding of building behaviour. 3- Errors are inevitable and exist in all models, which will require some knowledge of statistics and probability theory to conduct error analysis using the mean and standard deviations. Also, users need to run the model numerous times in order to investigate alternatives, and to minimize the error ratio. 4- Dynamic simulation, and the variations in the number of parameters normally result in hundreds of thousands simulation runs to be performed, which is time consuming and requires huge computation resources. 5- Varying a few parameters in a simulation can produce thousands of alternative results. Although a higher number of results is good for an effective error analysis, it can become confusing and time consuming to make realistic and meaningful conclusions regarding the performance of the tested model.

In sum, dynamic simulations are powerful tools, in comparison to steady state calculations, however, their associated challenges mentioned above have restricted their usage to a limited number of professionals. Hence, steady state calculations, despite their naivety, are still being used to perform Green Deal assessments and to produce energy performance certificates, which are crucial to the national planning policy framework devised by the UK government to reduce carbon emissions from buildings. Our Retrofit Plus project (RetrofitPlus, 2014) aims to scale up the use of building simulation, and make this powerful tool usable by non-skilled individuals, such as Green Deal assessors, and equally applicable for new build as well as the retrofit of buildings.

THE EXPERT SYSTEM

To scale up the use of building simulations for the retrofit of zero carbon building, RetrofitPlus has been developed to support dynamic simulation and optimization in the design process. Scaling up the use of dynamic simulations and their optimisation by non-expert users is the main objective of the software, but also is the main challenge. This is because it requires the system to accomplish simulations quickly, be able to run on portable devices, offer easy to use and the friendliest possible graphical user interface and have only a few optimum results shown in detail with clear recommendations regarding suitable material properties, costs, and systems for retrofit in zero carbon buildings. RetrofitPlus utilizes the U.S. Department of Energy's whole-buildings simulation engine EnergyPlus (Crawley, 2001), 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 objective (Caramia, 2008). The following objectives have been set as the main goals: cost, thermal comfort and zero carbon emissions (as a constraint).

The reports will be simple 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).

Overview

RetrofitPlus consists of five main software modules 1- RetrofiPlus 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, orientation, 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. 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.

This 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 a range of parameters for some/all of these components. For example, various types of glazing parameters can be tested within the building window facing south. After the user enters these parameters, the system manager can convert all values and ranges stored in the parametric configurator into logical format (known as an IDF file) used by EnergyPlus simulation. The system manager sends a simulation job to EnergyPlus via jEPlus+EA simulation and the optimization tool 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.

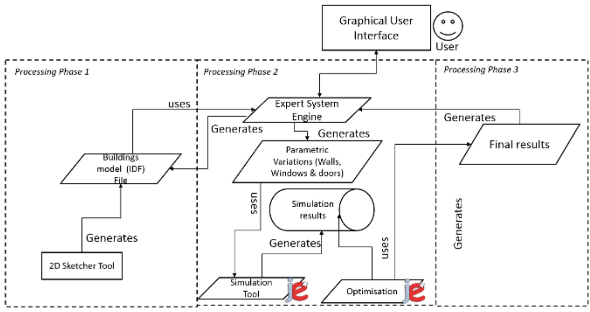

Figure 1: An overview of the system structure and components dependencies.

Graphical User Interface

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 to generate building plans from the inside out, with the user being able to create a building room-by-room using polygons. These are used so as to provide a helpful 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.

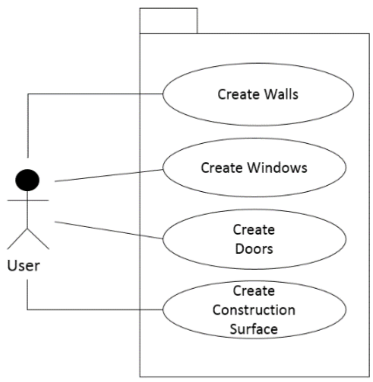

Figure 2: A basic UML Use Case diagram. It represents high-level simple user interaction with the system, and the four main actions needing to be performed to complete dynamic simulation assessment on a building.

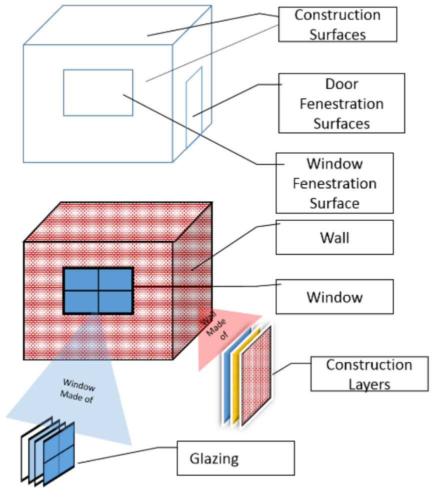

Figure 3: Logical representation of the building created from the 2D sketcher, which includes building geometry, orientations and surfaces. This enables the user to test various materials against these building construction components.

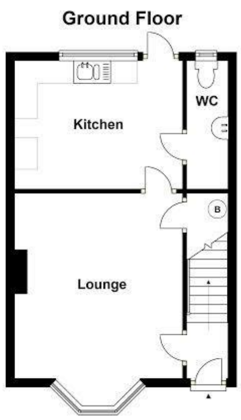

Figure 4: Example of a basic ground floor plan of a house

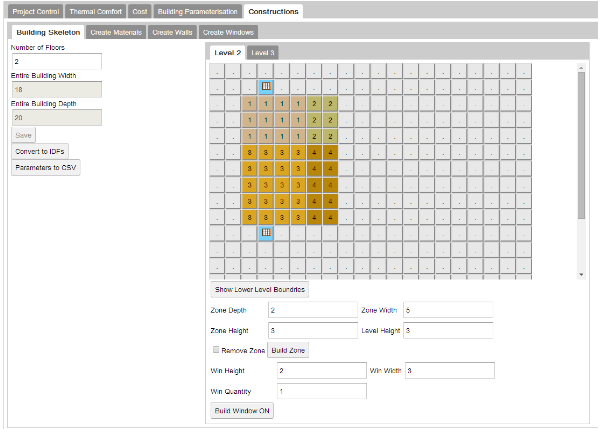

Figure 5: Basic & functional graphical interface of the expert system. It shows the basic 2D representation of the building skeleton, created to represent the floor plan in Figure 4. This is subsequently converted into a 3D physical representation that consists of a complete set of building components.

Simulation

RetrofitPlus uses EnergyPlus (Crawley, 2001) as the simulation engine that can model complex interactions that are important for optimisation, as discussed later in the paper. It simulates various technologies that will be used for retrofit in zero carbon buildings, including radiant heating, under floor heating and thermal comfort, amongst others (Ellis, 2006). Moreover, RetrofitPlus uses jEPlus+EA Client to help run the simulation remotely, via a server and executes multiple EnergyPlus simulations jobs simultaneously (Zhang 2012), which reduces simulation time by up to 20 minutes for jobs that would last several hours if run on PCs. Hence, the Green Deal/energy efficiency assessor will only have to wait for approximately the same amount of time as that needed by SAP before receiving the results and being able to take the customer though the range of optimum solutions suggested by the RetrofitPlus software.

Optimisation Engine

After creating the building model for energy efficiency testing, the user will need to define the number of parameters to explore new solutions for retrofitting, which are not possible through traditional approaches, such as SAP. 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 nigh on 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 answer set, 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, while maximising the energy efficiency performance (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 the many optimisation approaches currently available, the reader is invited to consult technical literature, such as Coello (1999).

In reality, 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. These are typically shown in graphs as a convex or non-convex fronts. The former shape is easier to deal with since giving up a percentage on one objective (say 10%), results in a corresponding percentage improvement in another, i.e. around 10%, whereas regarding the latter, finding the optimum solution can be hard, for it could mean giving up a large percentage on one objective (say 20%), to get a small improvement in the second, i.e. around 5% to 10%.

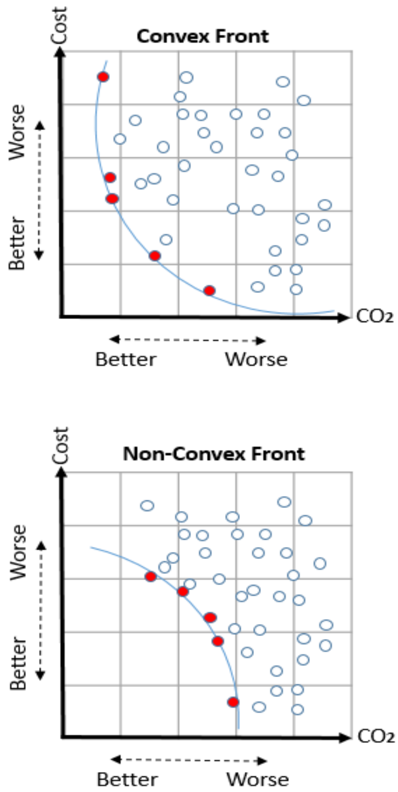

Figure 6: Illustrates the two typical types of Pareto fronts: convex and non-convex.

NSGA-II ranks Pareto optimum solutions based on their values, but also uses the density function to estimate density of dominant solutions around the optimum. This is performed by calculating the average distance to other points on either side of the solution. This density value is the so-called crowding distance, and is used to prioritise non-dominant solutions when they have similar ranks. In this case, NSGA-II chooses the solution that exists in the less dense area in the graph. Moreover, it does not require external memory and this makes it computationally efficient with large sets of solutions. Although this algorithm is quick and efficient, its average running time can easily exceed hours when varying a small number of parameters. In addition, since the expert system needs to be able to run from tablets, this can make it even slower. Hence, to speed up the simulation process, and minimise computation cost, the simulations and optimisations will be run on a server. To this end, Google Web Tool (GWT) has been used to enable the expert system to run as a web application. This makes the expert system universally accessible and platform independent: it can run on all tablets/mobile phone devices and will require no installation.

Expected Results & Report

For demonstration purposes, the results shown in Figure 7 were generated by the expert system's core engine jEPlus+EA (via EnergyPlus) when simulating a basic box model similar to that used in the study (Huws, 2014), with floor area of 60m^2 , a flat roof and a single fenestration surface (for glazing) on the south elevation.

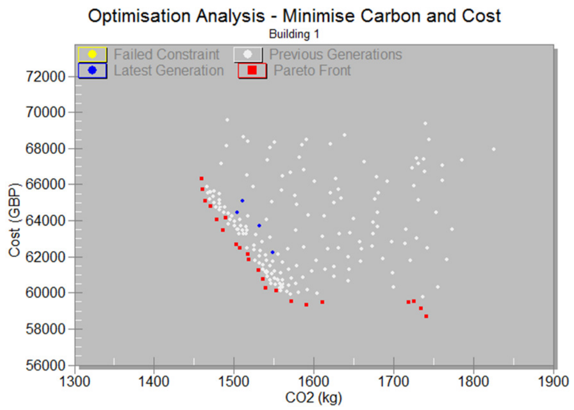

Figure 7: Results obtained from simulating a basic box model. The red points represent a convex Pareto front (Adapted from Huws and Jankovic, 2014).

The box model was tested against various parameters, such as changing the building fabric, altering the cooling/heating strategies and varying the ventilation techniques. NSGA-II in this case looked at two objectives: 1) minimising costs and 2) reducing carbon emissions. The figure clearly shows the convex Pareto front solutions, which are marked in red and a much larger number of sub-optimal solutions, marked in white. Although the 22 Pareto front solutions are proportionally smaller in number in comparison with the 200 non-optimum ones, these are still hard for the customer to understand when digesting the recommendations for retrofitting in a zero carbon house.

Looking at existing SAP and Green Deal Assessment software, for which considerable effort has been put into the user friendliness aspect of their look and feel, we realised that our expert system needs to show between three and five solutions only. Hence, all Pareto fronts will be re-ranked again based on material availability, cost and the user's thermal comfort.

Despite the fact that diagrams such as that shown in Figure 7 are a good visual aid for customers to understand the performance of their home when tested against various retrofit plans, this can still be challenging for a non-expert. Hence, the report the system generated will be easy to digest, and each solution will be ranked based on customer priority in the context of the three main objectives: cost, thermal comfort and building performance.

CONCLUSIONS

In this paper, we described the development of an expert system that uses jEPlus+EA and EnergyPlus as core engines for finding optimum solutions for zero carbon design or the retrofit of buildings. We have demonstrated at this early stage of the development of the tool that it could be used for simulation and optimisation techniques for people other traditional users, such as engineers, architects and researchers. In fact, the main objective of this expert system is to scale up the use of dynamic simulation and optimisation techniques by making them available to non-expert users, in particular Green Deal assessors others responsible for issuing energy efficient certificates.

Despite the challenges associated with the use of these techniques, such as conceptual complexity and high computational power requirement in comparison with SAP and Green Deal Assessment, they provide more accurate results as well as recommendations for designing/retrofitting of zero carbon buildings. Using the well known NSGA-II genetic algorithm, the system simultaneously optimises conflicting objectives as well as social and economic performance, whilst treating the zero carbon goal as a constraint. The expert system is designed to run simulation and optimisation jobs as a web application on a server, which makes it the first comprehensive web based user interface that runs dynamic simulation and optimisation through a web browser. Hence, it is platform independent, being usable on tablet devices and this will enable easy and quick assessment on building sites.

Running such computationally heavy simulation operations on a remote server not only minimises simulation time, but also prolongs tablet devices' battery power. Moreover, the system is designed to be easy to use, and very generic in order to minimise the time to complete a Green Deal assessment. Empowering non-experts, such as Green Deal assessors and SAP users, 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 environmental, social and financial objectives.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by the UK Technology Strategy Board through the Retrofit Plus project funding, Grant Reference 101614.

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