In Jankovic, L., Ed. (2016) *Zero Carbon Buildings Today and in the Future 2016*. Proceedings of a conference held at Birmingham City University, 8-9 September 2016. Birmingham City University, Birmingham, UK.

TAKING A PASSIVHAUS CERTIFIED RETROFIT SYSTEM ONTO SCALED-UP ZERO CARBON TRAJECTORY

Ljubomir Jankovic and Shadi Basurra
Zero Carbon Lab, Birmingham City University, Birmingham, UK

ABSTRACT

The paper describes collaboration a between industry and academia in enhancing a Passivhaus certified system for retrofit and putting it onto a zero carbon trajectory. The system was initially developed for on-site stick construction, using fixed insulation thickness and under the current UK climate. The collaboration with the university has contributed to a product development that is adaptable to different buildings and future climates, achieved by multi-objective optimisation. This process considers carbon emissions and comfort as functions to be optimised, and applies a number of design variables, taking discrete values within specified ranges of these variables, and producing numerous combinations for a single design. Dynamic simulations are conducted over these combinations, producing a solution space that is subsequently searched by a genetic algorithm for optimum solutions. A resultant chart gives a range of trade-off solutions that enable the design team to enhance retrofit system and make it zero carbon ready. In addition to the design optimisation, the scaling up of this system is facilitated by onsite 3D laser scanning, which enables a transition to an offsite solution developed in flying factories. The paper reports on a practical application of this work to designing a retrofit for two semi-detached houses.

INTRODUCTION

Despite the changing national policies related to carbon emissions that are not always going in the right direction, the bottom line established by The COP21 meeting in Paris in 2015 was the importance for achieving net zero emissions during the second half of the century.

As 80% of the 2050 UK houses have already been built and the majority are very inefficient, developing a structured and scalable approach to retrofit is of paramount importance.

In response to achieving a scalable solution, a RetrofitPlus project was established in 2014 under grant funding from Innovate UK. The project aims to drive innovation in energy retrofit of homes that achieve 100% carbon emissions reduction, drawing upon academic, technology start-up and private sector expertise. It comprises a holistic package of approaches designed to increase trust, quality and performance, and reduce the price of retrofit.

These approaches can be summarised as follows:

1) Application of advanced site survey methods to establish a pre-retrofit base model
2) Application of state of the art simulation and optimisation methods to design retrofit solution
3) Development an off-site solution for upgrading the building envelope to a Passivhaus standard
4) Application of advanced predictive control methods for reduction of energy consumption
5) Establishing a feedback loop using post-occupancy monitoring to enable process improvement
6) Development of a serious gaming platform for user interaction with the monitoring and control system, and for energy competitions with like-minded neighbours
7) Development of an alternative financial solution for retrofit using complementary currency approach based on unit of renewable energy
8) Development of an awareness campaign to widely disseminate the benefits of retrofit and stimulate scaling up through public engagement.

ESTABLISHING PRE-RETROFIT BASE CASE

The buildings to be retrofitted were provided to the project by Birmingham City Council (Figure 1). The Council paid special attention to selecting properties with tenants who would not mind experimentation with the houses in which they live.

Figure 1 Two semi-detached houses to be retrofitted

This enabled the research team to conduct surveys in order to establish the base level pre-retrofit models to be used for design and production of an off-site construction.

A 3D laser scan was carried out by the University, in order to create a model that can be used for off-site measurements by the project lead industrial partner, in order to manufacture the retrofit system in their factory. Eight different laser scans were taken, one high resolution and one low resolution from each of the corners of the buildings. Special attention was paid to choosing scan positions in order to exclude or minimise obstructions from local vegetation and other site features, such as fences, short walls etc. The point clouds obtained from the scans were subsequently processed and stitched up into a unified point cloud to be used for offsite analysis and measurements (Figure 2). Subsequently, a training programme was developed and delivered to enable the application of the 3D laser scan in the off-site manufacturing process.

Figure 2 Unified point cloud for off-site analysis and measurements

This building type is known as Wimpey No-Fines dwelling, characterised with concrete construction without the sand fraction. The concrete was cast in situ, and approximately 300,000 dwellings were built using this method since the Second World War (Reeves and Martin, 1989). The original buildings had no thermal insulation, and loft insulation was subsequently added in certain cases. There are tens of thousands of dwellings of this type in Birmingham, and targeting this type seems appropriate for scaling up purposes.

A team of surveyors was brought in to establish details about construction types, such as materials, layers, thicknesses, condition of the constructions etc. in the two dwellings. This information was subsequently used for creating building simulation models.

A number of thermal images of the building were taken, and these corroborate the absence of thermal insulation in walls (Figure 3). As it can be seen from this figure, higher heat losses, represented with brighter colours, are more intensive in positions that coincide with radiators inside the dwelling. Effectively, a significant proportion of heat from radiators ends up in the concrete and goes out into the atmosphere.

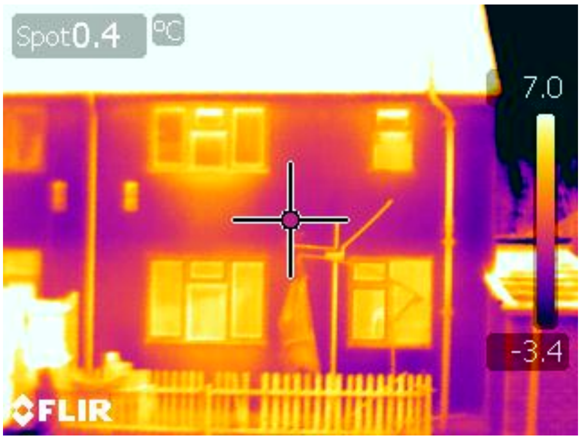

Figure 3 Thermal scan showing heat loss spots through solid wall that coincide with positions of radiators in the building

A University PhD student also carried out a detailed internal survey in order to create CAD drawings of the building. This information, together with the information from the structural survey, was used to create simulation models used in the design analysis. Electricity and gas bills were obtained from the occupants to facilitate calibration of the simulation models. The method is explained in the next section.

METHOD

The ultimate aim of the method is to look at a holistic set of design and user behaviour options and determine the approach for putting these buildings on a trajectory to zero carbon. This type of analysis requires multi-objective optimisation in order to investigate simultaneous influences of design and operational parameters and the conflicting constraints that these parameters introduce in the design process.

Before using the simulation model for multi-objective optimisation analysis, the model will first need to be calibrated on the basis of information from the energy bills. Instead of carrying out the calibration manually, in which a small set of parameters can be altered in order to obtain an accurate model, multi-objective optimisation can also be sued for this purpose. With this kind of calibration, a much larger parameter set can be investigated, and the calibrated model will correspond more closely to the actual building.

As renewable energy systems, which are necessary for zero carbon design performance, were not fundable under the current grant arrangement, knowing how best to prepare this building on the road to zero carbon is essential.

In Jankovic, L., Ed. (2016) *Zero Carbon Buildings Today and in the Future 2016*. Proceedings of a conference held at Birmingham City University, 8-9 September 2016. Birmingham City University, Birmingham, UK.

The method will then be determined by the ultimate set of tools needed to achieve this goal, and by the tools needed to convert the initial survey information into a suitable format for the final multi-objective optimisation analysis.

The ultimate tool therefore needs to be simultaneously capable of creation of bespoke objective functions for calibration using multi-objective optimisation, as well as carrying out standard multi-objective optimisation that will determine the trajectory of retrofit design to zero carbon. A simulation tool that fits this description is JEPlus+EA (Zhang, 2016), which uses EnergyPlus as its simulation engine.

The involvement of University PhD students determined the first tool to be used in this method. IES VE (IES, 2015) was chosen because the students had necessary skills and the licence to use it. This led to the creation of the initial simulation model of the building (Figure 4).

The question is then how to get from IES VE to JEPlus+EA. The path between the two tools was established vie DesignBuilder (DB, 2016) and EnergyPlus (NREL, 2016).

Although at the time of writing this text IES VE did not have a multi-objective optimisation capability, it is capable of 'talking' to other simulation tools. Thus IES VE model was exported as gbXML (Green Building XML) and imported into DesignBuilder (Figure 5).

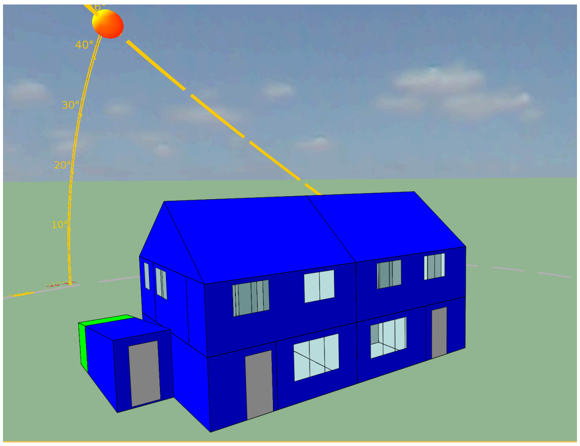

Figure 4 IES VE model created from the initial survey

Although DesignBuilder has the multi-objective optimisation capability, it has less flexibility when it comes to the creation of bespoke objective functions that can be suitable for calibration. However, as DesignBuilder uses EnergyPlus as its simulation engine, just like JEPlus+EA, this route to the ultimate tool for this analysis appeared to be promising.

DesignBuilder model was subsequently used to export EnergyPlus input definition file (IDF). That file was then imported into EnergyPlus (Figure 6) and edited to prepare it for JEPlus+EA.

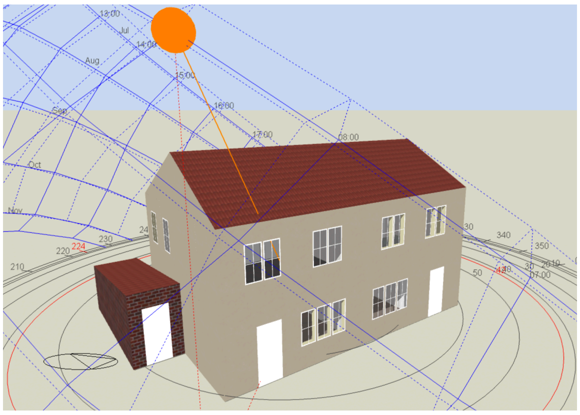

Figure 5 Model imported into DesignBuilder

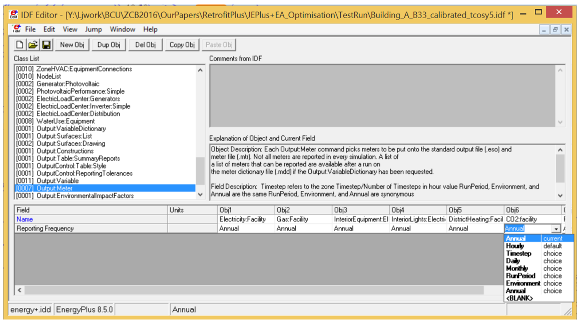

Figure 6 Model imported into EnergyPlus IDF editor

The preparation for JEPlus+EA involved changing EnergyPlus output frequency from hourly to annual, and disabling the plant sizing within the model.

SIMULATIONS AND RESULTS

Calibration

The calibration process in JEPlus+EA was set using parameters that influence electricity and gas consumption (Figure 7). For calibrating electricity consumption the lighting power density and miscellaneous gains power density were set as parameters to be varied. For gas energy consumption the heating set temperatures and infiltration rates were set as parameters to be varied. The objective functions were set as absolute values of relative errors between measured and simulated energy consumption as follows:

$$\varepsilon = \frac{abs(Measured - Simulated)}{Measured} \cdot 100\ [\%] \qquad (1)$$

Equation (1) was used for both gas and electricity objective functions.

After the completion of the optimisation process, the JEPlus+EA scatterplot gives interactive access to the results (Figure 8). In case of calibration, we are not interested in the minimum values as we would be in the case of optimisation, but we are interested in the points that are the closest to the origin of the co-ordinate system. Thus placing the cursor on that point brings up a popup window with the calibration parameter set, the 'chromosome' that determines the

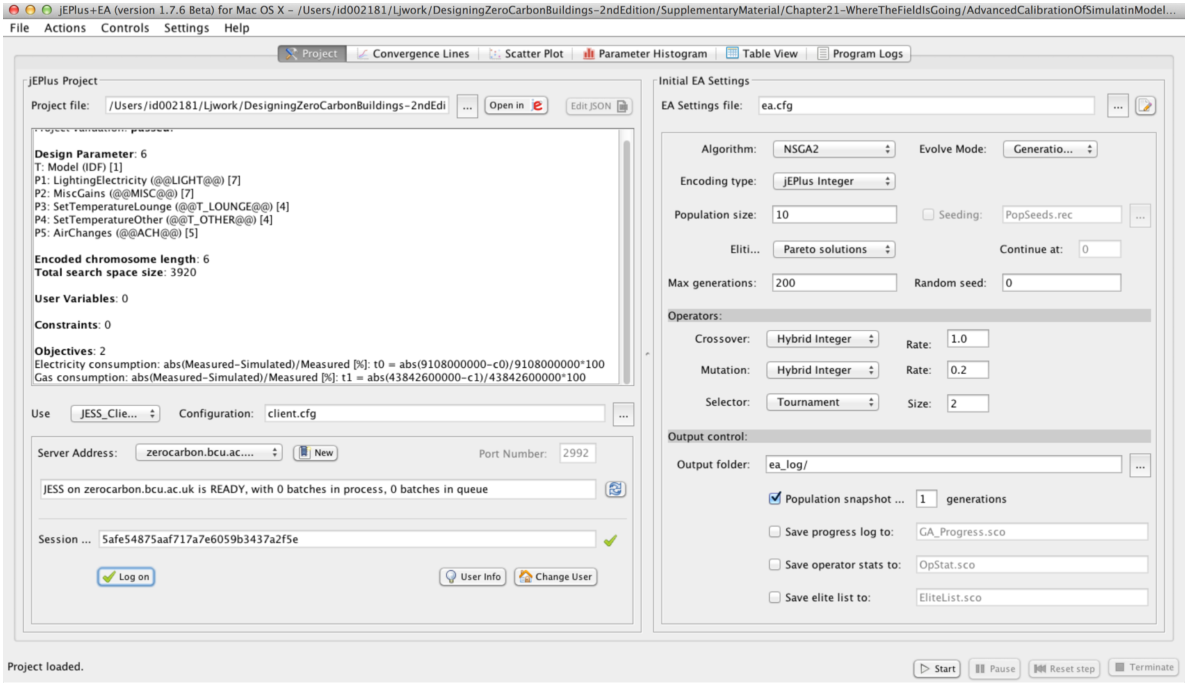

Figure 7 JEPlus+EA project set for calibration purpose

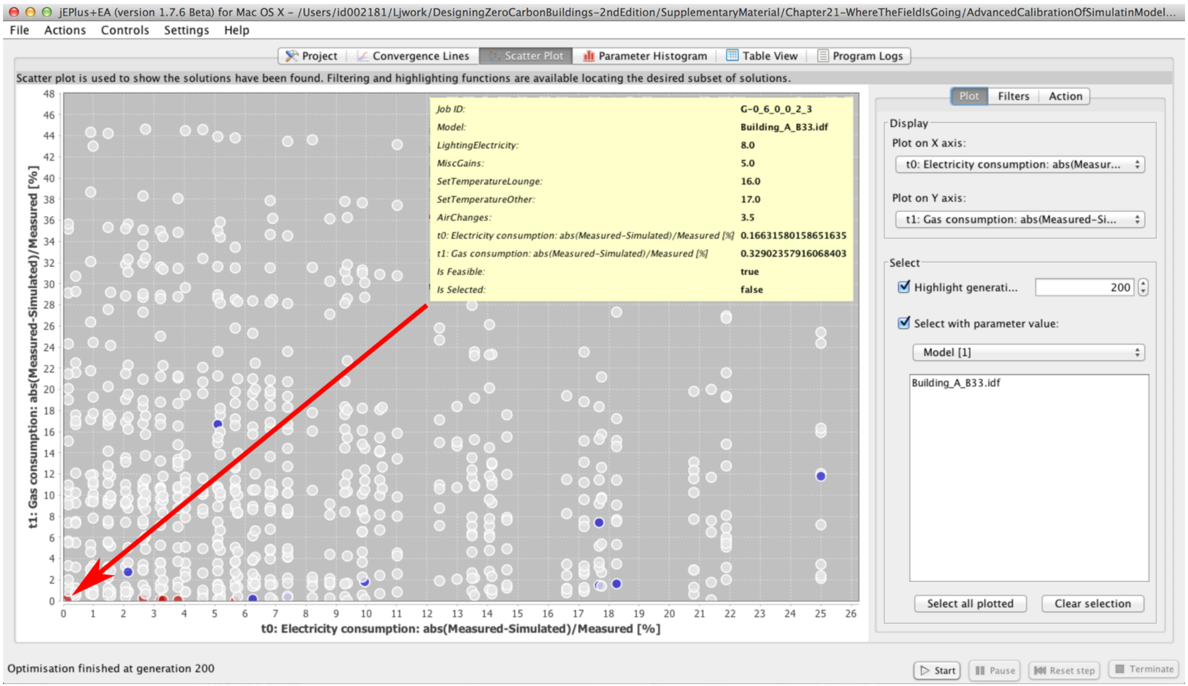

Figure 8 Calibration results in JEPlus+EA: the value nearest to the origin of the coordinate system contains the calibration parameter set

values of parameters that resulted in the most accurate simulation. As it can be seen from that figure, the errors of the calibrated model are 0.17% in respect of electricity consumption and 0.33% in respect of gas consumption, meaning that the model is 99.83% accurate in respect of electricity consumption and 99.67% accurate in respect of gas consumption.

These values were subsequently inserted into EnergyPlus model for a test run, and the result were identical to those obtained by JEPlus+EA. Thus these calibration values were subsequently carried forward into multi-objective optimisation analysis.

Multi-objective optimisation

Multi-objective optimisation was subsequently carried out in order to minimise discomfort hours and carbon emissions, using a range of technical and behavioural parameters (Figure 9). The technical parameters were: three different thicknesses of TCosy wall insulation: 150mm, 200mm and 225mm, combined in pairs with the identical TCosy roof

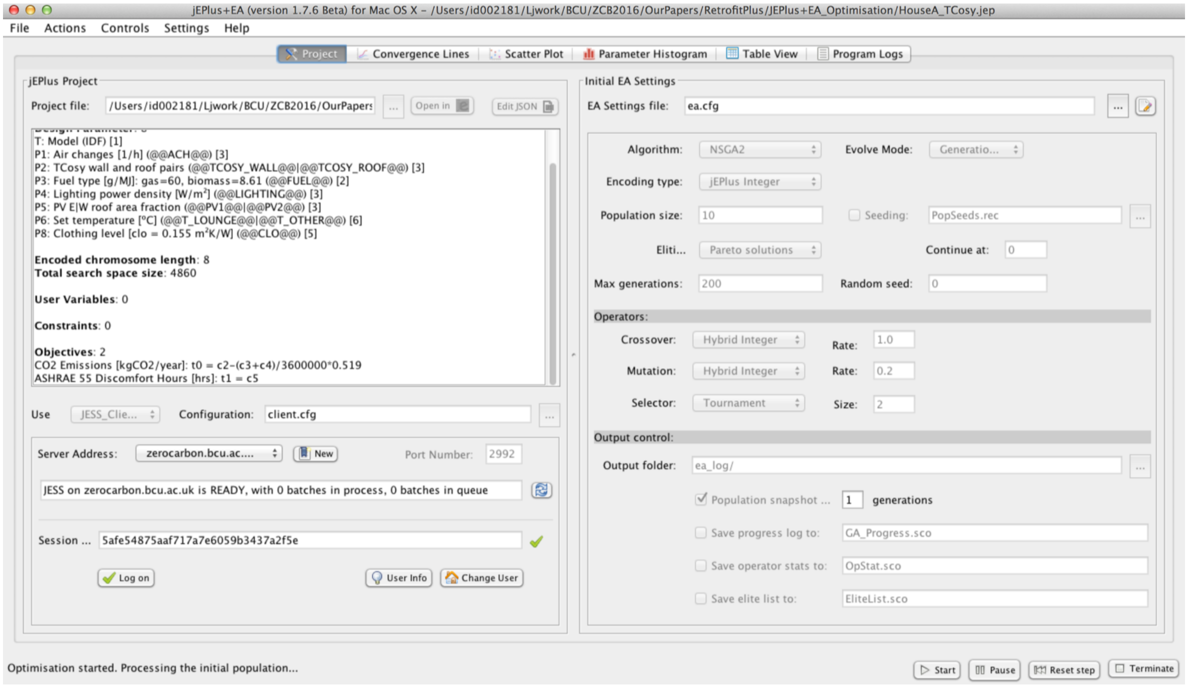

Figure 9 JEPlus+EA project set for optimisation purpose

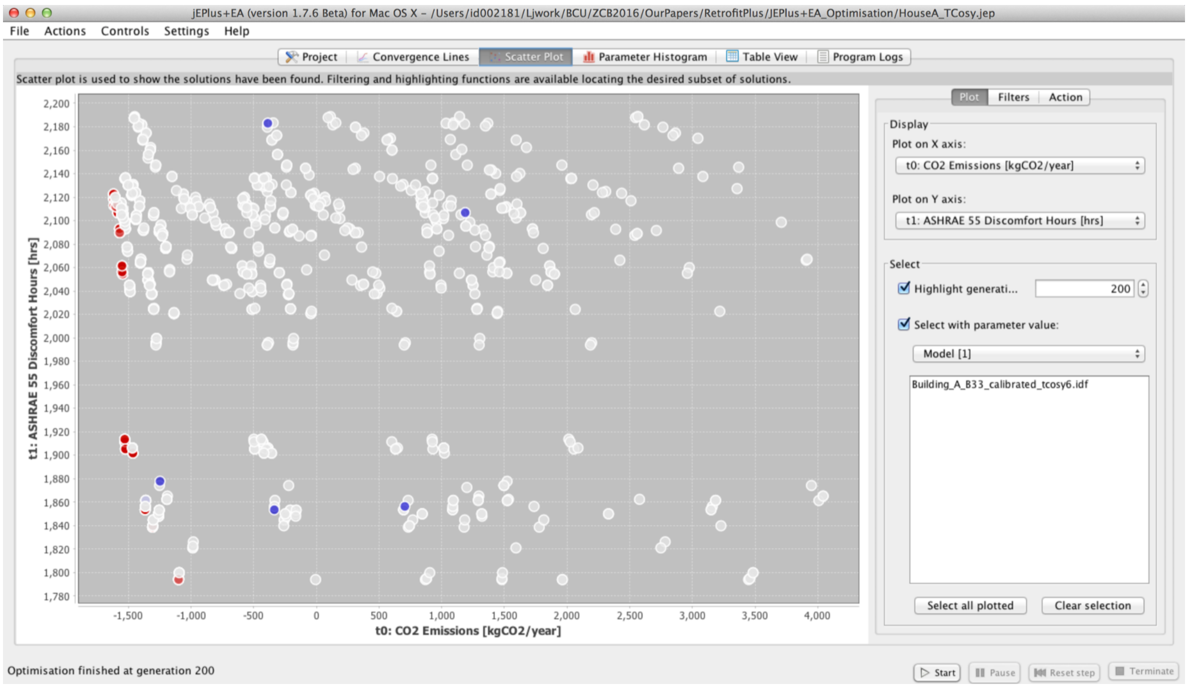

Figure 10 Optimisation results in JEPlus+EA

insulation thicknesses; infiltration air changes per hour; fuel type (gas or biomass); lighting power density; and two different PV arrays (East side of the roof only, and East and West side combined).

The parameters that are left to the occupants to adjust are deemed to be behavioural parameters as follows: room set temperature and clothing level.

The results of multi-objective optimisation are shown in Figure 10. Investigating the scatterplot in this figure by placing the cursor above individual points helps to determine and plot a journey from a minimum intervention to zero carbon (Figure 11).

DISCUSSION

The holistic approach developed here not only deals with technical but also with behavioural parameters. The reason for this is that dwellings with poor thermal insulation are expensive to heat, and occupants sometimes cannot fully afford that expense. The approach taken here shows that the occupants can adjust their behaviour after the retrofit,

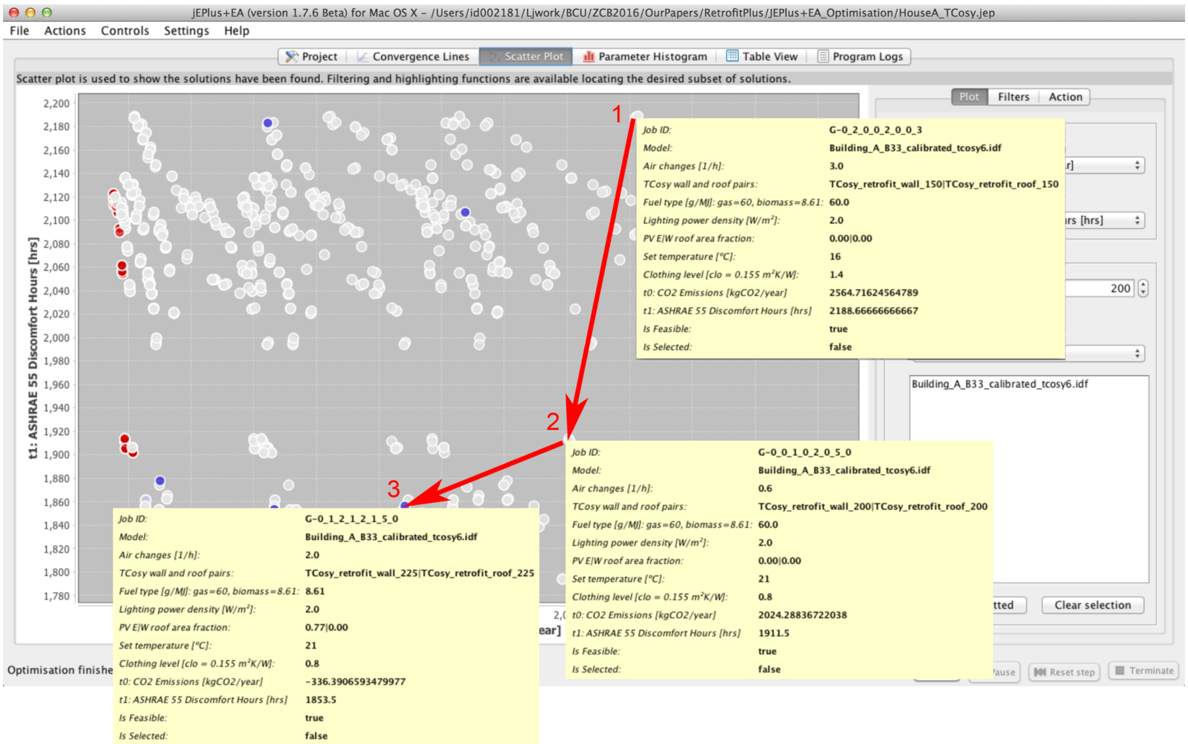

Figure 11 Plotting the trajectory to zero carbon

by increasing the set temperature in their home and reducing the amount of clothing, whilst spending less amount of energy. Ultimately, zero carbon performance can be achieved with the addition of renewable energy, as other prerequisites have been prepared by this analysis.

The trajectory in (Figure 11) starts with a minimum intervention in point 1: 150mm wall and roof insulation TCosy system is added, whilst using the existing gas boiler, keeping the infiltration rate high, and without adding any PV. The room set temperature is as low as the calibration value of 16 ^{o}C, and the clothing level is quite high at 1.4 clo. Carbon emissions are 2,565 kgCO2 per year and discomfort hours 2819 per year.

Point 2 has an increased TCosy insulation level of 200mm in the walls and roof, Passivhaus air tightness of 0.6 ACH, but still with the existing gas boiler and with no PV. Behavioural parameters show increased set temperature to 21 ^{o}C and reduced clothing level to 0.8 clo. Carbon emissions are down to 2,024 kgCO2 per year, and discomfort hours are reduced to 1912 per year.

Point 3 is characterised with 225mm TCosy insulation in walls and roof. The existing gas boiler is replaced with biomass heating, and the first stage of PV array has been added on the east side of the roof. The behavioural parameters are the same as in the previous case, with 21 ^{o}C set temperature and clothing level of 0.8 clo. Even with higher infiltration of 2 ACH in this particular case, the building is carbon negative, with -336 kgCO2 per year, while discomfort hours have been reduced further to 1854.

The above trajectory is just one of the choices that design team will have to develop the retrofit. Exploration of the scatter plot in Figure 10 will give more options to for the trajectory than those shown in Figure 11.

The ventilation system before the retrofit was through openable windows. After the retrofit, this will be an MVHR system embedded within the prefabricated building envelope. It should be noted that the ventilation system was not explicitly modelled, but its contribution after the retrofit was taken into account through the design variable ‘air changes per hour’.

Although discomfort hours in Figure 10 and Figure 11 appear to be high, this is due to constant clothing levels kept throughout each annual simulation. Further significant improvements of thermal comfort can be achieved through the application of an adaptive clothing algorithm. This is based on a further development of a method initially reported by Huws and Jankovic (2013), which will be published elsewhere in due course.

CONCLUSIONS

The paper reported a holistic approach to retrofitting an existing building, as part of Innovate UK funded project. A detailed site survey using 3D laser scanning, thermal imaging and manual inspection and measurements have facilitated the development of a dynamic simulation model. A series of simulation tools were used to prepare the model for calibration and for design of retrofit using multi-objective optimisation. The calibration identified a parameter set that is more than 99.6% accurate with reference to the actual energy consumption figures obtained from past annual energy bills. The design of retrofit involved a variation of technical parameters and behavioural parameters. The technical parameters considered were wall and roof insulation thickness, air tightness, fuel type, lighting power density, and two different sizes of a PV system. The behavioural parameters were room set temperature and clothing level.

The optimisation was conducted with reference to two objective functions: thermal comfort and CO2 emissions. The resultant scatter plot provides the design team with a decision-making tool, which enables a series of informed choices to be considered.

As the project funding could not support the installation of a PV system, the results of this analysis ensure that a trajectory to zero carbon is established, and pre-requisites are fulfilled for the building to become zero carbon at a later stage.

The optimisation results demonstrate opportunities for occupants' change of behaviour, in terms of increased room set temperatures and a reduction of clothing levels. As the initial calibration identified low set temperature in the building as a starting point, potentially indicating a fuel poverty situation, the scope for behaviour change revealed by this analysis demonstrates a positive step towards better health conditions in the building.

The process described in this paper is part of a wider RetrofitPlus approach, which will be scaled up through future work.

NOMENCLATURE

ACH, air changes per hour;

clo, unit of clothing resistance: 1 clo = 0.155 m^2K/W;

gbXML, Green Building XML – a standard for sharing building properties between different building design and analysis tools;

ε, relative error;

$MVHR$, Mechanical Ventilation with Heat Recovery;

$TCosy$, an innovative approach to retrofitting pioneered by RetrofitPlus lead partner Beattie Passive.

ACKNOWLEDGEMENTS

The work presented in the paper is part funded by a grant reference number 101614 from Innovate UK, and matched by funding from Retrofit Plus Project Consortium: Beattie Passive Retrofit Ltd, iZdesign Ltd, and InteSys Ltd, and with Birmingham City University as academic partner. The support from Birmingham City Council by providing the buildings to retrofit is gratefully acknowledged.

REFERENCES

DB (2016) DesignBuilder Building Simulation Software. DesignBuilder Software Ltd. Available at: http://www.designbuilder.co.uk (Accessed: 24 May 2016).

Huws, H., and Jankovic, L. (2013) 'Implications of Climate Change and occupant behaviour on future energy demand in a zero carbon house'. In *Proceedings of IBPSA Building Simulation 2013 Conference*, 25th - 30th August 2013, Chambery, France.

IES (2015) VE for Engineers. Integrated Environmental Solutions Ltd. Available at: https://www.iesve.com/software/ve-for-engineers (Accessed: 24 May 2016).

NREL (2016) EnergyPlus. National Renewable Energy Laboratory. Available at: https://energyplus.net/ (Accessed: 24 May 2016).

Reeves, B. R. and Martin, G. R. (1989) The structural condition of Wimpey No-Fines low-rise dwellings. Building Research Establishment, Garston, Watford.

Zhang, Y. (2016) JEPlus+EA optimisation GUI for EnergyPlus and TRNSYS. Available at: http://www.jeplus.org/ (Accessed: 24 May 2016).