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Methodology for Evaluating Innovative Technologies for Low-Energy Retrofitting of Public Buildings

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Abstract

There is urgency to transform Europe into a low-carbon economy to reduce the risk of climate change and achieve sustainable energy security. One of the most cost-effective measures to meet energy reduction targets, as clearly specified in the "European Economic Recovery Plan", is to address performance of existing building stock. Buildings account for about 40% of the EUenergy consumption and one third of the GHG emissions. In particular, the state of the European building stock contains a high improvement potential. REtrofitting Solutions and Services for the enhancement of Energy Efficiency in Public Edification (RESSEEPE) is an EU funded project that focuses on the refurbishment of existing public buildings in three European cities: Coventry (UK), Barcelona (SP) and Skelleftea (SW). The aim of the project is to bring together design and decision making tools and innovative building fabric manufacturers to collaborate and improve building performance through low impact retrofitting interventions to achieve energy reduction in the region of 50%. The aim of this paper is to evaluate the process of low-energy retrofit and the selection and evaluation of low-energy technologies for retrofit. Specifically the paper looks at the decision making procedure to select advanced building technologies for high energy performance retrofitting, using Coventry University estates as a case study. The paper reviews innovative technologies and using analytical methods investigates the benefits of these potential technologies as applied to existing case study buildings within Coventry University. The interconnectivity of these buildings within the urban environment within which they sit is also evaluated.

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Keywords:Low Energy Retrofitting; Building Performance Modelling; Advanced Technology; Building Envelope; Performance Monitoring;

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1. Introduction

Energy consumption for providing comfortable and usable built environment accounts for about 40% of total energy consumption and about 36% of total Greenhouse Gas (GHG) emissions in Europe (Directive 2010/31/EU) [1]. With a significant proportion of existing buildings constructed at a period when there were no effective energy efficiency components within the relevant building codes, most of this old building stock is reaching the end of its useful life. It will require significant cost and environmental impact to replace these buildings with new construction, which annually represents about 1.5% of the building stock [2]. Therefore the state of European building stock presents significant challenges as well as improvement potential. There are a number of benefits and impacts of undertaking sustainable energy renovation of buildings as summarized in [3]:

- Economic: Energy cost savings, economic stimulus, property values and impact on public finances;
- Societal benefits such as reduced fuel poverty, health and increased comfort and productivity;
- Environmental benefits: reduced air pollution, carbon savings;
- Energy Systems Benefits: Energy Security, Avoided new generation capacity, reduced peak loads;

The low energy retrofit of existing buildings requires an all-inclusive approach that should consider the building fabric and building systems and the engagement of various stakeholders to ensure user satisfaction of the retrofit solutions implemented. Gupta and Banfield [4] in the study of 63 home energy efficiency retrofit discovered a number of beneficial and detrimental consequences associated with building energy improvements, some of the negative consequences identified included '*increased likelihood of overheating following fabric improvements, potential under-performance of low-carbon systems due to lack of understanding and inadequate installation and commissioning, along with adaptive energy behaviours leading to increased energy use and a widening gap between predicted and actual savings*' [4]. Therefore low-energy retrofit requires a systematic process of pre and post intervention performance evaluation to ensure that appropriate technologies are selected to deliver the desired comfort and planned energy reduction whilst avoiding unintended negative consequences.

This paper presents the ethos of the Retrofitting Solutions and Services for the enhancement of Energy Efficiency in Public Buildings (RESEEPE) project. The project brings together design and decision making tools, innovative building fabric manufacturers and a strong demonstration programme to demonstrate improved building performance through retrofitting. The ethos of the RESSEEPE project is to technically advance, adapt, demonstrate and assess a number of innovative retrofit technologies with a 50% energy consumption reduction targeted. A systematic process of building and technology selection implemented in the project targets the best possible retrofitting mix, customized to the needs of the particular building. The process includes the extrapolation of results to buildings with similar characteristics to evaluate the benefit of district level potential for low-energy retrofit.

1.1. RESEEPEE project description and pilot case studies

RESSEEPE is an EU funded project that focuses on the refurbishment of existing public buildings in three European cities: Coventry (UK), Barcelona (SP) and Skelleftea (SW) as shown in Figure 1. RESSEEPE aims to develop and demonstrate an easily replicable methodology for designing, constructing, and managing public buildings and district renovation projects to achieve a target of 50% energy reduction. For this purpose, a demonstration and dissemination framework with innovative strategies and solutions is developed for energy renovation at building and district level, based on the following pillars: three demonstration district retrofitting projects in three different countries representative of the breadth of EU climate conditions; cost-effective solutions for holistic energy performance improvement at building and district levels; systemic selection process to achieve optimal mix of intervention measures; development of a strategy for large scale market deployment throughout Europe); market and replication deployment plan, to ensure impact at business level; and wide impact exploitation strategy.

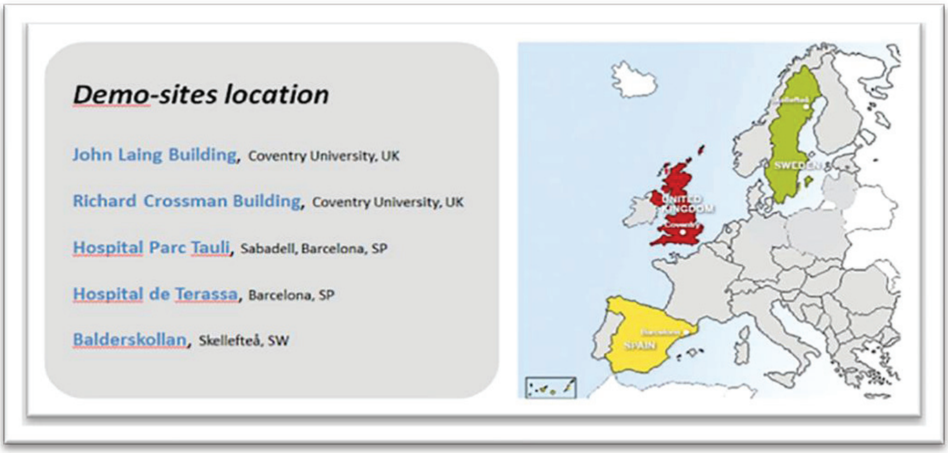

Fig.1. Demonstration Building across Europe

The RESSEEPE project aims to develop new methodologies for the diagnosis of the potential public district refurbishment taking into account the structural, energy analysis and end users in terms of social acceptance and financial constraints. This paper shows a Higher Education building case study used to demonstrate technologies developed specifically within the project. All the technologies are innovative or have innovative features with varying properties ranging from absolute state of the art to more thoroughly tested. These advanced technologies are not aimed at refurbishing the building as a whole; rather they're being applied in specific areas in order to evaluate the isolated performance. The idea behind the Living Lab pilot case is to monitor the performance of those installations in order to obtain results in a field lab, which allow us to make conclusions about the replicability.

1.2. Demonstration Buildings

Coventry University owns a large and diverse portfolio of built assets mostly constructed between 1930's to 1970's, with many reaching the end of their useful life due to poor energy and environmental performance and modern functionality. Coventry University therefore has to evaluate the options of renewing these assets either through new construction or extensive low energy retrofit to extend their life. Six university buildings were selected for deeper performance evaluation, which include Alan Berry, Ellen Terry, George Eliot, John Laing (JL), Richard Crossman (RC) and Student Centre Buildings. These are university buildings with a mixture of functions. Table 1 summarizes the features of the selected buildings.

Table 1: building description

Building Name	**Storey Height**	**Year of Construction**	**Description**
Alan Berry	2	1963	This building has a Curtain system with panels and 40% glazed proportion. Window frame in this building is metal with 6mm single glazed. The structure is a concrete frame system
Ellen Terry	4	1931	This building has a brick façade and 30% glazed proportion. Window frame in this building is metal Georgian style frame with 6mm single glazed. The structure is a steel frame system
George Eliot	6	1963 Refurbished 1993	This building has a Curtain system refurbished in 1993 and 30% glazed proportion. Window frame in majority of façade is UPVC with 12 mm double glazed. Windows of stairway and toilet is metal with 6mm single glazed. The structure is a concrete frame
John Laing	2	1970	This building has a brick façade and 30% glazed proportion. Window frame in this building is metal frame with 6mm single glazed. The structure is a concrete frame system
Richard Crossman	5	1971	This building has a brick façade and 30% glazed proportion. Window frame in this building is metal frame with 6mm single glazed. The structure is a concrete frame system
Student Centre	2	2005	This is a two storey building constructed in accordance with building control requirements. This building has a brick façade and 30% glazed proportion. Windows are Aluminium frame with Polyester powder coated with 12 mm double glazed.

1.3. Technology Development

A number of low energy technologies have been selected, developed and tested within the RESEEPEE project with a view to real life demonstration in the 3 selected pilot sites in Coventry, Barcelona and Skellefteå. Figure 2 shows the different level of maturity for all the selected technologies developed within the project, starting with observing and reporting basic principles of a technology through to actual demonstration and end-use monitoring. Table 2 summarizes the technology development, describing each technology and its development process.

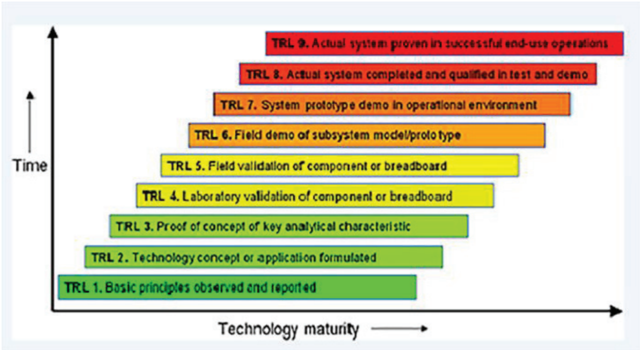

Fig.2. Technology Maturity Diagram

Table 2: Summary of Technology Development

Technology	Description of Technology and Development Process	Development Process
Aerogel –based mortar	**Aerogel mortar:** It consists of a very porous ultra-light material that combines aerogel with cement to provide super-insulating properties. Due to its low density and small pores this material shows a remarkably low thermal conductivity (λ), typically on the order of 0.015 W m-1K-1. This property makes this product highly interesting for insulating applications in construction. This is an innovative application of aerogel as rendering because although there are examples of insulating renderings using aerogel aggregates, they are not based in cement materials and their application is for inside building walls [5].	1. Aerogel- based materials have been **synthesised at lab scale** but also at **industrial level**. 2. The thermal conductivity of these aerogel granules is in accordance with literature reported values (**λ<0,020W/mK**).
Ventilated façade with photovoltaic panels	Among the emergent advanced façades, double-skin façades (DSFs) are an efficient solution to control the interactions of indoor and outdoor environments. As a basic definition, "Double-skin façade is a special type of envelope, where a second "skin", usually a transparent glazing, is placed in front of a regular building façade" [6]. Double skin façades can efficiently reduce the overall HVAC consumption in buildings by absorbing part of the solar radiation during winter and preventing overheating during warm periods [7]	1. Design and development of ventilated photovoltaic (PV) façades **finished**. 2. Optimization of the air gap and performance of PV modules
Vacuum Insulated panels (VIP)	**VIP** can be described as 'evacuated open porous materials inside a multi-layered envelope'. They are considered to be one of the most effective insulation materials available. VIPs consist of three components: the core, the envelope and getters (a reactive material to help maintain the vacuum, e.g. desiccants and opacifiers). The core of the plate is evacuated and determines the thickness of the plate. A foil envelope keeps the vacuum inside and avoids gas and moisture permeation into the core as long as possible [8].	1. Rigid, stable and slim VIP CombiPlate Element has been designed and fabricated. 2. Integration of VIP into a façade system - VIP CombiPlate Element. 3. **Software** - for easy VIP CombiPlate Element distribution on the intended area.
Electrochromic/ PV Window		1. Design and development ofEC/PV Windows at laboratory scale **finished.** 2. A PV powered EC window **prototype** has been **designed.**
Energy storage/ energy balance		1. An energy storage/energy balance **prototype** at lab scale has been **designed** coupling of batteries and supercapacitors with PV and mains grid supply. 2. The system's **functionalities** have been **validated**
Solar Thermal Collectors-UPC		1. A **new thermal solar panel** has been developed for Domestic Hot Water and Heating and Cooling applications. 2 Actual lab scale prototype is more efficient than the actual ones with a low increase of price. **NEW PRODUCT.**
PCM energy storage tubes (PCM)	**PCM:** The thermal storage capacity of a material is a measure of a material ability to absorb and store thermal energy and subsequently release it back to the environment after a period of time. There are two broad types of thermal storage materials, namely sensible and latent heat storage materials. Sensible heat storage materials include brick, concrete, rocks etc. The sensible thermal storage of these materials is as a result of the change in temperature of the materials. PCMs are material compounds that melt or solidify at certain temperatures to store or release large amounts of energy [9].	1. The use of PCM material as energy storage solution is going to be studied for the demosites as possible RESSEEPE solution (mainly passive cooling solution and heat recovery systems). 2. The improvement expected is based on combined solution in comparison with individual solutions, adding PCM products. **UPDATED SOLUTION**
Seasonal Thermal Energy Storage - STES		1. Implement seasonal heat storage solution. 2. Under this situation the control algorithm analysis improvement expected will increase the actual efficiency or energy saving in comparison with the actual ones. **BETTER PROCESS**

2. Methodology

A range of building performance evaluation protocols are used for pre and post retrofit evaluation of buildings and technology performance. The aim of the building performance evaluation is to assess three key factors, namely building and system characteristics, environmental factors and occupant perception [10]. These performance evaluation protocols are applied at different stages of the project: building selection stage, pre-retrofit or feasibility studies stage, installation and post installation stages. The purpose of the building performance evaluation strategy is:

- Monitor the objective measures of comfort within buildings (temperature, humidity, CO2)
- Investigate building fabric performance, U-value and infrared thermography surveys;
- Evaluate user satisfaction of key stakeholders;
- Evaluate the installation process;
- Model the current performance of the building;

Therefore the methodology followed will include: experimental monitoring, modelling, benchmarking of energy and environmental performance and surveys to key stakeholders and people involved in the installation process.

2.1. Stakeholder Engagement Process

For the evaluation of user perception, user satisfaction surveys have been carried out before and after the retrofitting activities among the users of the building. This provided a range of data set to compare the user satisfaction pre and post interventions. Stakeholder engagement events will be organized to gather feedback. Interviews will also be done with the stakeholders in the installation process: technology providers, contractors, etc. Their views, in conjunction with researcher assessment of the installation process will provide data from which lessons can be learned and evaluations can be made. Figure 3 summarizes the strategy for stakeholder engagement.

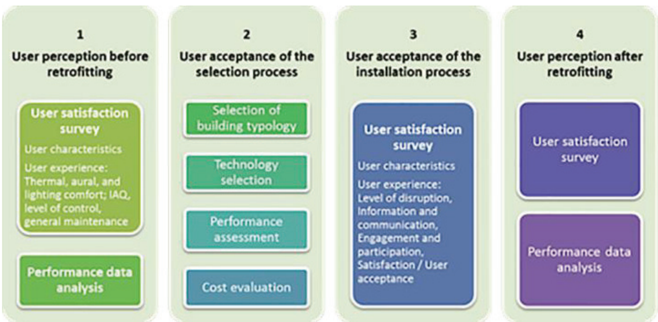

Fig.3. Evaluation of social acceptance

For the evaluation of the performance of the building fabric the key performance criteria should include the analysis of the existing constructive documents of the building in order to get the maximum information about the composition of the external walls, and the measurements of the actual building performance by using non-destructive testing. In order to obtain this performance the following strategies will be followed: definition of the existing building fabric composition, Thermal imaging camera, Infra-red and Heat flux sensors, light level sensors and Indoor Environmental Quality measurements (CO2, Temperature and Humidity). Monitoring will be continued after installation to evaluate the benefit of the intervention. It's significant to note that part of the objectives of the RESSEEPE project will be to explore and test these products further, attaining clear results on performance, reliability and future possibilities. The building performance Evaluation Strategy will include a district scale performance evaluation, modelling the district level impact and extrapolating the results obtained for the replicability of the model.

2.2. Building Performance Modelling

There are a number of building and system modeling software tools used within industry and academia for the predictive analysis of building systems and their impact on energy and environmental performance. Each program has unique features in terms of modelling resolution, solution algorithms, intended target audience, modelling options and ease of use vs. flexibility [11]. IES Virtual Environment is an integrated suite of applications linked by a Common User Interface (CUI) and a single Integrated Data Model (IDM). This means that all the applications have a consistent "look and feel" and that data input for one application can be used by the others. The modular structure of the software allows for integrated building performance analysis in multiple domains (i.e. thermal, airflow and daylight) [11]. Crawley et al [12] critically evaluated twenty major softwares such as EnergyPlus, ESP-r, ICE, and TRNSYS. IESVE was categorized as one of the softwares that has undergone the most rigorous validation studies with the most powerful modelling capabilities.

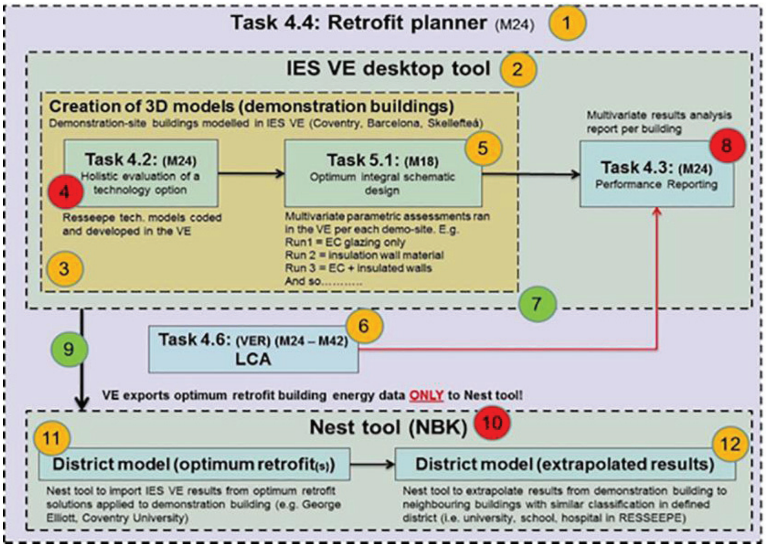

Fig.4. Building performance modelling process

Building Performance Modelling is an integral part of the pre and post retrofit evaluation of building performance. The pre-retrofit modelling focuses on the evaluation of potential impact of the various technologies on specific pilot buildings. The post retrofit evaluation includes validation of the initial results with real monitored data and the extrapolating of the results to other buildings within the urban district. Detailed performance modelling and simulation will be carried out to predict potential energy and carbon savings from the retrofit process and intervention strategies for each demo site building, Figure 4 shows the process of building performance modelling using IES virtual environment developed for the project which includes the following key steps:

- Estimate the energy needs/consumptions before retrofitting
- Evaluate the impact of the solutions on the energy demand/consumption
- Justify the expected performance of the systems based on energy, economy, environment, comfort.
- Retrofit some areas of a building, and extrapolate the results to the whole building to evaluate the overall potential savings in the building after its refurbishment.

3. Decision Making and Technology Selection Process

A number of technologies have been developed within the RESEEPEE project, however not all of these technologies will be suitable for all the buildings and climatic conditions that characterize the pilot sites within the project. Figure 5a shows the decision making criteria used to evaluate suitability of technologies for specific location, building energy and environmental performance as well as building use condition. The decision making criteria also includes the whole life cycle cost and environmental life cycle of the components system. In the refurbishment projects there are certain limitations such as architectural and structural constraints, local regulations and organizational procedures that need to be considered during the selection and evaluation process.

A number of processes have been carried out to evaluate the suitability of specific technologies for a particular demo-site. Figure 5b shows the six evaluation procedures that were carried out for all demo-sites to ensure that the technologies selected will meet the objectives of the project both in terms of achieving 50% energy reduction within a specified budget. The process includes the data collection for each pilot building which is essential for understanding the performance of existing buildings and the development of BIM models of the demo buildings to enable sharing of data across various systems and partners. In conjunction with the building owners both economic and financial investment evaluations have been carried out to ensure reasonable payback can be achieved and initial capital investment is within the project or clients' expenditure budgets.

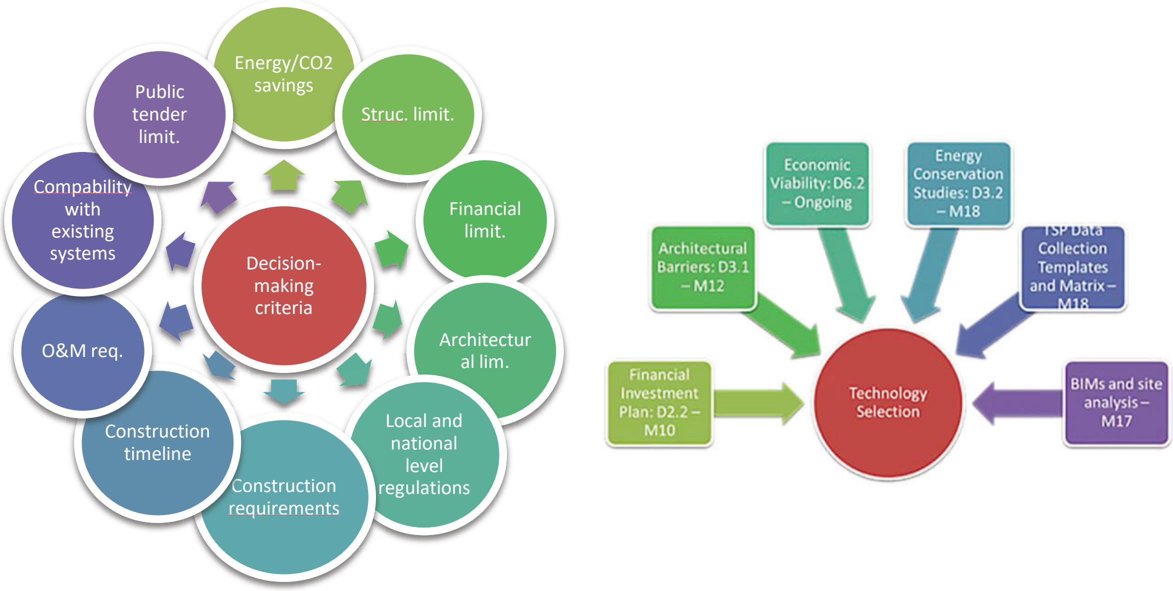

Fig. 5. (a) Decision Making criteria for technology selection; (b) Technology selection process.

After going through this selection procedure a mix of technologies were selected for each demo-site. This selection also included the input of building owners relative to other objectives for refurbishment such as space utilization and the energy/carbon reduction strategy. The selection procedure considers the level of development of each technology and the objective of the demonstration. Coventry University demo-site developed a dual strategy, with John Laing Building used as a living lab to field test technologies, extrapolating data to the entire building, and Richard Crossman Building as a whole building retrofit with high investment from Coventry University.The selection of technologies in RC relied on innovative technologies that are already available in the market to reduce the risk for the university. Table 3 shows the mix of technologies selected for each demo-site, the total area of interventions are 3660 m^2 and 9395m^2 for JL and RC Buildings respectively. The total retrofit area and the mix of technologies will enable the project to monitor performance of the technologies as individual systems and the benefit of having these technologies working together to achieve the objectives of the project. Having a mix of technologies in the different buildings will generate critical mass of performance data that is essential for extrapolation to the urban district. This process will lead to the development of a retrofit analyzer that will help building owners in selecting the best mix of technologies for retrofitting specific building types.

Table 3: Technologies Implemented in UK Pilot Buildings

Demo-site **Technology**	**John Laing Building, Coventry (m^2)**	**Richard Crossman Building, Coventry (m^2)**
EPS-G Panels	57	X
Aerogel Based Insulating Mortar	57	X
Vacuum Insulated Panels	56	X
Solar PV	X	9,395
Seasonal Thermal Energy Storage (Water and PCM)	301	X
EC Windows	56	X
Ventilated Façade	28	X
LED Lighting	X	2,600
High Efficiency Windows	28	9,395
BIPV	57	X
Solar Thermal Collectors - UPC	X	X
Solar Thermal Collectors	X	X
Building Fabric Improvements	X	934
Total Area of Site Affected	**3,660**	**9,395**

4. Results and Discussion

The initial analysis and technology selection has been completed which led to the installations. One important component of the selection process includes the building performance modelling using IES virtual Environment. Current and post retrofit conditions of JL and RC Buildings have been developed which gives us indicative potential savings that can be achieved. Figure 6 shows RC building Model with an indication of retrofit action.

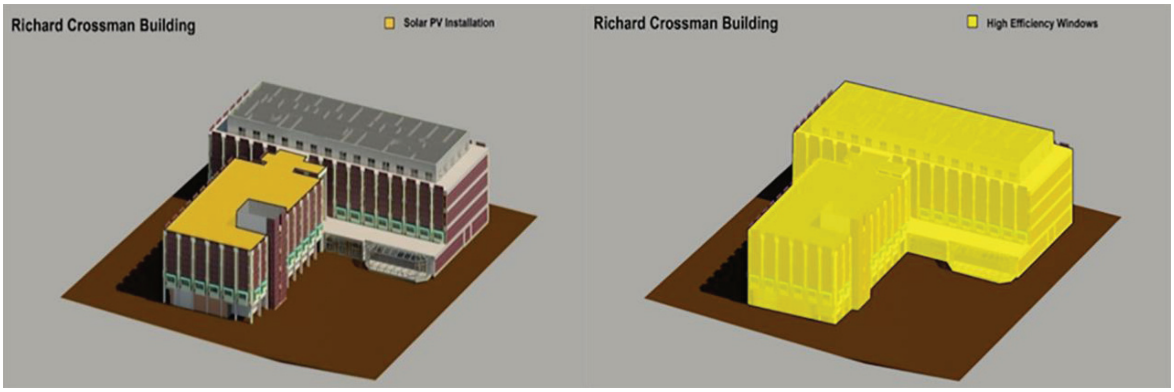

Fig. 6. IES-VE 3D Model of Richard Crossman Building

The results of the modelling of Richard Crossman (Table 4) show significant reduction in total energy consumption for the entire building in the region of 49%, which meets the initial project objective of 50% post retrofit energy reduction. The modelling shows an increase in electricity consumption in the retrofit scheme due to an increase in air-conditioning in areas that were otherwise naturally ventilated. Even though there is as light increase in electricity consumption this will be offset by the 75kWp Solar PV system that has been integrated in the building. The monitoring of these systems and the energy consumption of the building over the coming months will be used to validate the simulation result and calibrate the simulations for extrapolation of results to other buildings within the urban district.

Table 4: IES-VE Simulation Results – Richard Crossman Building

	Richard Crossman Building		
	Pre	**Post Full**	**Change**
Boilers energy (MWh)	2593.3398	749.8302	71.09%
Total system energy (MWh)	3180.573	1097.0815	65.51%
Total nat. gas (MWh)	2593.3398	749.8304	71.09%
Total electricity (MWh)	1103.2562	1168.4075	-5.91%
Total Carbon Emissions (Kgco2)	1132751	632847	44.13%
Total energy (MWh)	3696.5952	1885.3925	**49.00%**
Total energy (MWh/m2)	0.393464098	0.200680415	**49.00%**
Total energy (KWh/m2)	393.4640979	200.6804151	**49.00%**
Total grid disp. Elec (Mwh)	0	-32.8447	

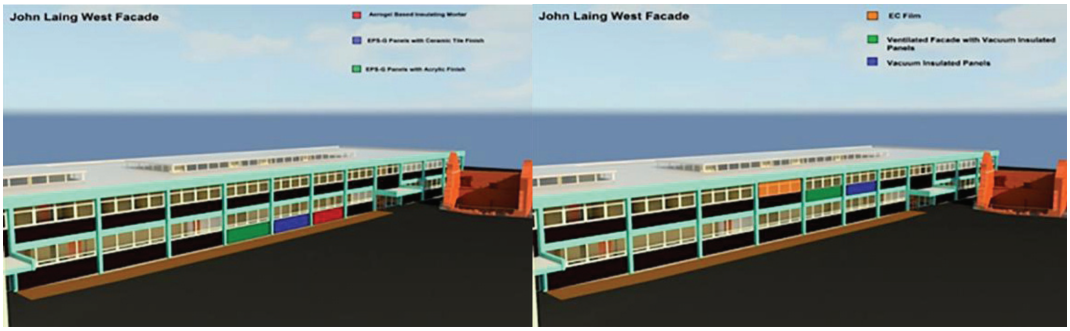

Fig. 7. IES-VE 3D Model of Sir john Laing Building

Figure 7 shows the 3D model of JL Building indicating the location of installed technologies on the building façade. Because the strategy on this building is to test the technologies on some sections of the building, the modelling equally focuses on the performance of individual spaces that have technology interventions. Table 5 shows that there is no significant change in electricity consumption, but there is an 11.8% reduction in boiler and natural gas consumption which leads to a total reduction of 10.58% and 9.67% for energy and carbon emission respectively.

Table 5: IES-VE Simulation Results – Sir John Laing Building

	John Laing Building		
	Pre	**Post Full**	**Change**
Boilers energy (MWh)	418.7628	371.2533	**11.35%**
Total system energy (MWh)	448.8424	401.3487	**10.58%**
Total nat. gas (MWh)	418.7628	371.2533	**11.35%**
Total electricity (MWh)	30.0797	30.0954	**-0.05%**
Total Carbon Emissions (Kgco2)	106064	95810	**9.67%**
Total energy (MWh)	448.8424	401.3487	**10.58%**
Total energy (MWh/m2)	0.122634536	0.109658115	**10.58%**
Total energy (KWh/m2)	122.6345355	109.6581148	**10.58%**

The performance monitoring, such as indoor environmental sensors, heat flux sensors, electricity and gas meters have been installed to monitor individual technologies. Data from the monitoring will be used to calibrate the simulation and use it to extrapolate the benefit of these technologies to the entire building. The calibrated models and simulations will also be used to extrapolate results to other buildings within the urban district.

4. Conclusion

The ethos of the RESEEPEE project is to achieve significant energy reduction in buildings through retrofit with innovative fabric and building systems components. A methodology for pre and post monitoring evaluation of retrofit action has been developed to achieve the objective of the project. Building performance models and whole life performance evaluation methodologies have been used to select appropriate technologies suitable for specific buildings and their function. The initial performance modelling and simulation shows that if these technologies are installed in a whole building retrofit, then it is possible to achieve energy reduction of up to 50% percent in public buildings. Achieving building energy reduction of this magnitude in existing building stock is essential for achieving the ambitious energy and carbon reduction targets in various EU countries. Even though the technical feasibility, energy and environmental analysis tends to be the focus of this type of analysis, this project finds that effective stakeholder engagement is essential for achieving the socio-economic and environmental benefit of low-energy retrofit. User evaluation has been used to take targeted action to reduce discomfort identified by building users. In the process of developing the building model for performance evaluation, there is a major problem of lack of data and difficulty to collect data with non-invasive methods. Sharing data amongst project partners has been found to be a challenge at the beginning of the project with several partners requiring similar data but in different formats. An attempt has been made in this project to develop building information modelling (BIM) processes to optimize information sharing. The next stage of the project is to collect performance data over summer and winter, calibrate models and extrapolate results to the urban district.

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