Refurbishment Methodology to Attain Thermally Comfortable near-Zero Energy Buildings Using Customizable Solutions

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Abstract
Prefabricated building refurbishment for energy upgrading is a viable option for the existing building stock, but solutions need to adapt to each case and user. The "RECO2ST" project (Horizon 2020) offers a methodology to achieve nearly zero energy refurbishment, through innovative modular elements for the opaque and transparent areas of the building envelope, covering diverse energy reduction strategies while improving thermal comfort and indoor air quality. This integrated approach is not usual in the field. The paper studies facade and active window technologies that supply climate strategies such as insulation, heat recovery and ventilation.

The methodology is demonstrated for three sample cases using a typical refurbishment scenario. It is evaluated through energy simulation and analysis of improvements in thermal comfort and indoor air quality indicators.

Keywords Energy refurbishment methodology; active window; vacuum insulation; thermal comfort; indoor air quality.

1.0 Introduction
Most of the existing residential building stock is not energy efficient and does not comply with modern standards. In certain regions, residential buildings are responsible for up to 40% of the primary energy consumption and about 25% of CO2 emissions (1). With over 27 million dwellings in 2016 (2), the housing stock in the United Kingdom has a large technical potential for improvement and thus achieve reductions of its emissions of up to 80% (3), as it is estimated that about 60-70% of the existing housing stock dates from before the first comprehensive energy regulations (4). The potential for improvement also translates to long-term work for construction companies dedicated to repair, maintenance and improvement (3).

Despite these figures, energy refurbishments must be carried out using a forecast approach that will reveal specific directions to achieve energy efficiency and user comfort for each particular case. This is backed by results from the Building Performance Evaluation (BPE) programme (5), based on the early work of Post Occupancy Review of Building Engineering (PROBE) (6) in the mid-1990's and the Low Carbon Buildings Programme (LCBP)(7), which evaluated building retrofit interventions and resulted in the following observations: i) Energy consumption was much higher than estimated, ii) Buildings are often feature-packed but not functional, iii) Building systems have complex, unmanageable (and often not integrated) controls, iv) Buildings are not finished when handed over and v) Low and Zero-Carbon (LZC) technologies were risky, fragile and not fully understood.

That research work has contributed to the notion that obtaining sufficient energy performance in building refurbishments is not only a desirable project goal, but a legal standard and requirement that must be met. The BREEAM Refurbishment and Fit-Out Technical Standard (RFO) for domestic and non-domestic buildings (8), and regional directives such as the 2002 European Union (EU) Energy Performance in Buildings directive (EPBD) (9) with its updates in 2010 (10) and 2018 (11), are useful instruments for compliance that require new technologies to address very low energy requirements such as nZEB (nearly-zero energy buildings).

The H2020 project RECO2ST – "Residential Retrofit assessment platform and demonstrations for near zero energy and CO2 emissions with optimum coST, health, comfort and environmental quality" (https://reco2st.eu/), will be used as an example illustrating the forecast methodology required previous to intervention that will help select the most suitable refurbishment combinations. The project addresses the challenges of residential nZEB refurbishment in different climate zones of Europe through a systemic three-step approach: Initially a Refurbishment Assessment Tool (RAT), under development, will be deployed to create refurbishment scenarios, empowering the decision-making of the building owner, public or private. Second, action plans for the renovation will be formed through Integrated Project Delivery (IPD) and finally a refurbishment package of innovative and customizable technologies will be installed ("Retrofit-Kit") for personalized renovation. The RECO2ST project proposes to reshape the practice of retrofit by using methods that adapt the retrofit efforts to each particular refurbishment case, allowing reductions in energy expenditures and improving occupants' thermal comfort and indoor air quality (IAQ) levels. The latter are usually overlooked in favour of energy performance.

The RECO2ST project will deliver a Retrofit-Kit that is customizable for each project renovation. It features technologies that were chosen based on their cost effectiveness with regards to energy use, applicability for diverse climate zones and robustness in a wide range of building types and climate ones. They include: lightweight vacuum insulation panels (VIPs), smart flow windows, cool roofs and pavements, cooling evaporative facades, mechanical ventilation systems and nature-based technologies (NBT) for air quality treatment. Area and orientation permitting, energy self-generating technologies such as integrated photovoltaic panels can also be applied to help the building attain zero energy consumption or even plus energy levels. A wireless sensor network (WSN) and an Intelligent Energy Management System (IEMS) will be used to handle active systems within the building.

The integration of these technologies into personalized refurbishment packages for four demonstration sites will be conducted and validated. The renovation assessment tool will be tested on early adopter sites during the project. The modularity and adaptability of the RECO2ST Retrofit-Kit is key to achieving the expected performance, and the Least-Cost method to be developed in the project will facilitate achieving this performance for an optimal price level according to a personalized Renovation Action Plan developed quickly and accurately for each site under renovation. The demonstration sites will be refurbished into nZEBs, with expected maximum total energy savings between 71% and 99%, achieving excellent internal environmental quality and payback in less than 15 years.

2.0 Refurbishment Scenarios

The RECO2ST project deals primarily with energy refurbishment technologies for residential buildings in Europe. The primary target segment in this sector includes apartment blocks built previous to the establishment of energy saving measures, usually before the 1980s. The secondary target includes existing building projects made after that date wishing to upgrade to nZEB. It must be noted that the energy retrofit technologies are intended for application in the entire building volume, both internally and externally. Some of them would not be effective if they are individualized to specific apartments.

The renovation assessment tool and associated technologies will be demonstrated in four apartment block buildings (Spain, Switzerland, UK and Denmark) representing climatic and construction variability across Europe, totalling 67 apartments and 7000m^2 of built space. The methodology developed in the project will cover a wide spectrum of climatic zones associated with the different demonstration sites. This fact will serve to design a methodology valid in many of the territories in Europe and thus, it will foster the adaptability of the solution. Demonstration buildings were chosen to represent varied climatic conditions in Europe from heating-dominated to cooling-dominated locations. Therefore, location countries have differences in the implementation of BREEAM, EPBD, while additionally Switzerland has its own regulations which include avoidance of refrigeration cooling if possible. For the purposes of this paper the demonstrator of focus is in the United Kingdom. The UK demonstrator is located in West London and will be presented in more detail as an illustration of the methodology. It consists of a four story apartment block with 23 apartments. The demonstrator building has a built area of 4700 m^2 and was built in 1979 and is used for student accommodation. Similar to other residential blocks from the 1970's, the building consist of masonry blocks with a concrete flat roof construction and cavity insulation in the building envelope, resulting in a very high heating consumption. Windows were replaced in 2005 to double glazed units with openable parts. Cold bridges still exist at ground and roof levels and exposed walls. The apartment block has a radiator system through gas fired boilers for heating and hot water production with no or limited insulation of the water distribution system. Natural exhaust is done manually through the window openings only.

Since technologies need to be adapted for each particular location and project specifications, a selection process allows to determine those that are more suitable for each case. Specific steps for the methodology are shown in the next section.

3.0 Methodology

The RECO2ST methodology is conceptualized in this section and comprises the following steps. They include initial site and climate analysis for comfort strategies, technology delimitation to accomplish comfort strategies, calculations for energy and comfort performance, selecting the most suitable technology combinations from these calculations, and finally receiving a Retrofit Kit with the technology option selected by the design team, saving time in the planning process.

These steps will be automated using a Refurbishment Assessment Tool, which will cover a wide range of aspects relevant to refurbishment. Currently under development, the tool will present the best technology options accordingly, allowing designers and owners to decide based on their particular project needs.

The methodology will be illustrated through an example based on the demonstration phase of the project. As mentioned, in Section 2.0, four buildings located in different European cities were selected for intervention, with their construction age varying from the 1930's to the 1970's. In this paper we focus on the case for a University dormitory located in the outskirts of London, United Kingdom.

3.1 Site Analysis

The dormitory building was built in 1979, it has an overall North-South orientation and consists of different activity areas, but the focus of the energy refurbishment will take place in the sleeping quarters, increasing occupant comfort. An energy performance operational rating was made in 2016, listing the entire building as C. Occupants also complain about lack of thermal comfort during the year and low ventilation rates.

The external wall is made of bricks and has cavity insulation, while the rest of walls are brick partition walls. Apart from the cavity external wall, it has a double-glazed window with a 45% window-to-wall ratio (WWR) facing to the North or South. Usage was assumed as continuous occupancy due to the diverse user profiles, and to better understand the effect of each technology on energy, comfort and IAQ throughout the day and the year.

The existing heating system consists of a hot water boiler feeding a radiator network. For simplification the calculations assumed that it met capacity at all times. Currently, the radiator network operates as an on/off system without any smart operating systems. Additionally, there is no ventilation or cooling system in the rooms, with users depending on passive ventilation from the small opening sections of the windows. However, in order to assess the improvements due to the addition of ventilation technologies, an idealized single-coil cooling system was added as a way to calculate equivalent energy used for cooling. A scheme of the typical room is shown in Figure 1.

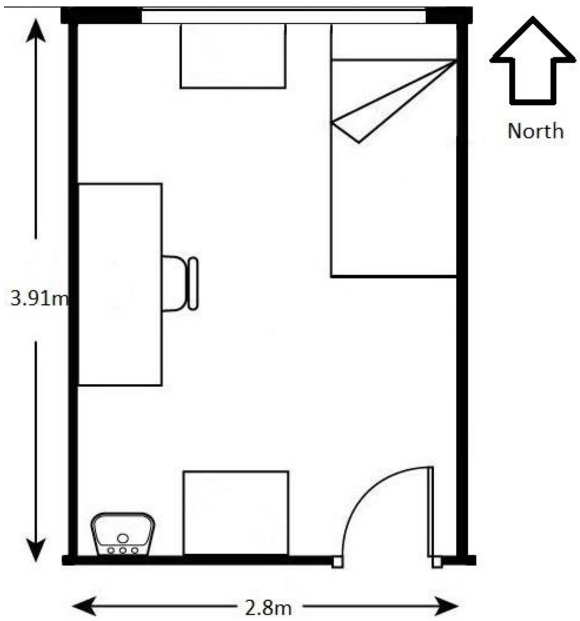


Figure 1 Dimensions of the typical North dormitory unit

3.2 Climate Analysis

In order to know which technologies will be used, a study needs to be made first to define the best possible climatic strategies that will bring comfort for the location. Climate analysis for user comfort can be made for all the year using the pyschrometric chart (12). Different tools exist to accomplish this task, for this paper the software Climate Consultant v6.0 was used (13) and applied to Gatwick as an available weather file.

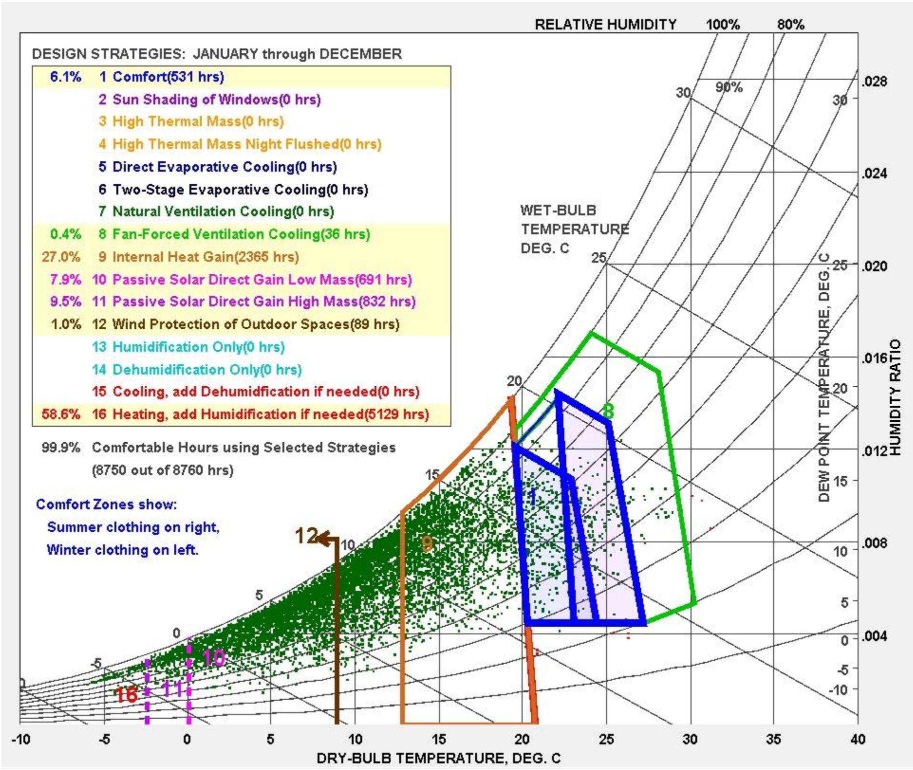


Figure 2 Climate analysis for comfort strategies for London Gatwick (weather file) using Climate Consultant (2)

As it can be seen in Figure 2, the project location is a heating-dominated climate, although care must be taken to also include comfort strategies for summer, such as ventilation cooling. Although the climate analysis software suggests *all* the strategies that could be followed, particular project factors must be taken into account as well. A non-exhaustive list includes budget, available space and area for the retrofit, municipal regulations regulating the placement of certain technologies, etc.

3.3 Technology Delimitation

Decisions for action in this case would be as follows: Given the comfort strategies derived from the climate analysis, it can be found that RECO2ST technologies closely following the recommendations include vacuum insulated panels (VIPs) to maintain internal heat gains (14), and smart flow windows that supply forced ventilation through vents while supplying thermal comfort through controlled surface temperature (15). In this case, nature-based technologies could also be applied for increased IAQ, but the particularities of temporal accommodation and budget limitations might make them impractical for long-term maintenance in a student dormitory setting.

Energy self-generation technologies such as PVs are assessed independently from the comfort climate analysis, and instead must be considered from the point of view of available solar rights and budget. Therefore, they are not considered in this study in order to maintain generalization of the methodology.

Specific characteristics of the selected technologies are given in the following section.

3.4 Energy, Thermal comfort and Indoor Air Quality Calculations

After delimiting the technologies to be used, testing must be made for the best possible combinations. Due to their modularity, a series of combinations are possible. Although a first approach would be to perform calculations for each case, that type of procedure is time-consuming and could potentially lead to missing on some possible combinations or lead to incompatible ones. The RECO2ST project proposes an analysis kit where this has been done beforehand, saving time for the designer by delimiting possible combinations. However, we present here three different options for clarity of the methodology, and to show how each option has influence on energy usage, thermal comfort and IAQ.

Energy analysis in this paper has been done with EnergyPlus (16), as a leading whole-building simulation software package that has been independently validated in different conditions. It has become a *de facto* standard for predicting building performance in terms of energy consumption, indoor thermal comfort and most recently, indoor air quality. The cases that were considered for energy modelling include:

a) Basecase

Representing the existing situation, a module with measurements of Figure 1 is used, with either a North- or South-oriented window.

b) Lightweight vacuum insulation panels (VIPs)

These panels are commercially available, and are quite thin compared to their conventional counterparts (20 mm), with a sandwich construction enclosing a vacuum cavity preventing heat transmission. With those characteristics they can reach U-values of 0.35 W/m^2-K, considering aging and edge losses

c) Smart flow window

This window is the product of another research project although now it is commercially available, and consists of three window panes. Two are fixed and the third is part of an openable chamber. During winter, the chamber is closed, and outside air can flow through air grills into the chamber where it is heated up passively. As the hot air ascends due to buoyancy effect, a patented valve lets the accumulated heated air into the indoor space.

During summer, the chamber can be opened, leaving only the fixed double pane while avoiding overheating, since air can continue to flow. Programmed night ventilation can also be implemented by opening the entire window through sensors or timers. Vents where air is let into the space can also be regulated for complete closure if needed.

d) Smart flow window + lightweight vacuum insulated panels

This case would represent the addition of the two technologies, since they do not interfere with each other (opaque and glazed areas of the façade being covered).

These options would be normally accompanied by the use of sensors and a simplified IEMS to make windows active and control radiators.

4.0 Results

Results for the North and South orientations are given in the graphs of Figure 3. They show energy consumption, thermal comfort and indoor air quality for the two cases. Energy consumption is shown in terms of kWh per square metre per year, while thermal comfort as a measure of percentage of people *satisfied* with their space, as derived from the PMV scale (predicted mean vote) (17). PMV measure was used in order to assess both the conditioned and unconditioned times of the year. IAQ was measured in terms of CO2 concentrations in ppm. Although CO2 would require extremely large concentrations to become dangerous in an indoor space (18), it is used as an indicator of human activity and perception of space quality. The target range of 200-500 ppm was taken as a limit where it is considered to be close to outdoor air quality. Concentrations up to 1,000ppm are considered acceptable for indoor spaces.

4.1 Energy results

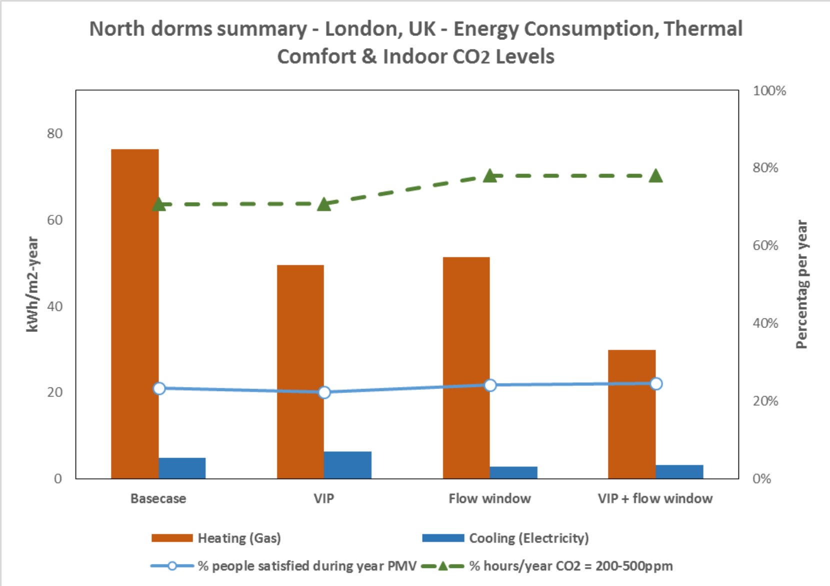
It can be seen that given their use as student dormitories, the basecases already have low energy consumption, given the small space volume and moderate energy saving features such as the double glazed window. However, calculations for thermal comfort coincide with reports from users, who do not find the spaces comfortable.

The addition of technologies separately achieved heating consumption reductions in the range of 35% for North and 43% for South. However, by adding both technologies, heating reductions achieved were 60% for heating in the North orientation and 75% for heating in the South orientation. Cooling was reduced by 45% in the South and only by 25% in the North by adding both technologies.

4.2 Thermal Comfort

In terms of thermal comfort, maximum improvement was modest, increasing 1% and 2% for the North and South respectively when compared to the basecase. However, some of the reasons for this reside in the starting setup for the room, where single-sided ventilation is available. It has been measured through experimental work that contribution to thermal comfort from single-sided ventilation is only 1% for the entire year (19).

Combining VIP insulation with a conventional double glazed window increased thermal discomfort, since the latter has a large area. It can be inferred that the surface temperature difference between insulated wall and conventional double glazed window reached perceived thermal discomfort limits. The combination of VIP and smart flow window, however, increased the perception of thermal comfort.



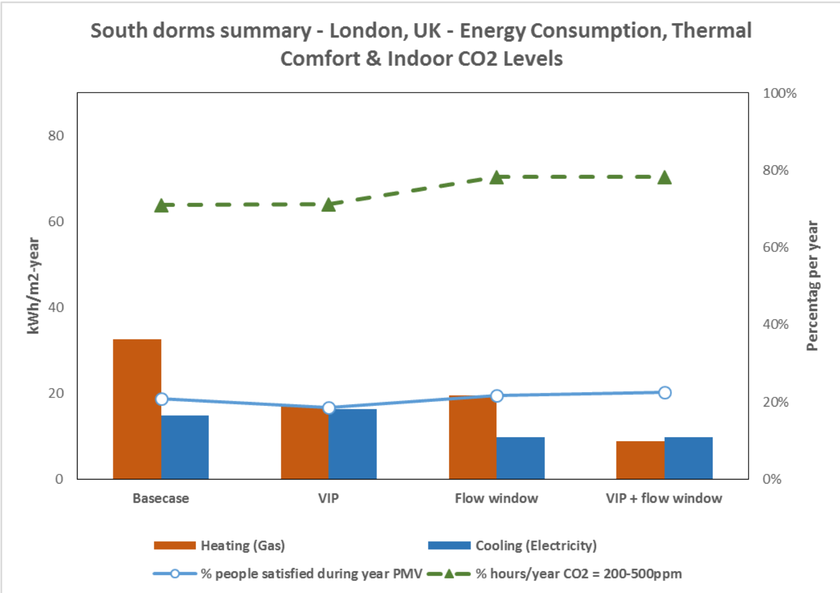


Figure 3 Energy consumption, thermal comfort and indoor CO2 levels for North and South oriented dorms located in London, United Kingdom.

4.3 Indoor Air Quality

Although the studied spaces had starting acceptable IAQ levels for CO2, as it might have been expected, adding the smart flow window allowed for improved CO2 levels that bring it closer to the sensation of outdoor air, from 60% of hours per year of CO2 levels within 200-500ppm in the basecase, up to 80% with the smart flow window for both orientations. The multi modal window allowed for night ventilation during summer, bringing also an increased perception of thermal comfort during that season.

5.0 Discussion

It has been observed that although RECO2ST technology options provide significant energy consumption reductions when they are applied separately, the highest energy savings are achieved when they are applied together. In this way they can also improve thermal comfort and IAQ, since they can cover the necessary comfort strategies needed throughout the year. Although the improvements in terms of thermal comfort were small, this is in part due to the existing situation before the retrofit. Designers would get feedback on this and consider if they can introduce further measures to increase cross-ventilation.

The use of sensors and smart controls becomes complementary with the technology options, therefore users and facility managers are not tied to their functioning. Basic strategies could still be covered manually in case of maintenance.

As mentioned, the methodology will be verified during the course of the project in four different locations in Europe, using a set of indicators that will verify performance of the methodology in different climates. It will also include occupant feedback.

6.0 Conclusions

This paper has demonstrated the energy refurbishment methodology proposed by RECO2ST, where a particular situation is analysed from the point of view of thermal comfort, and while using a range of predefined solutions, it can be used to determine solutions for particular situations. Indoor air quality is also taken into consideration as an integral part of this new methodology. This is not usually found in other refurbishment methods, which only focus on energy performance.

The methodology also provides smartness to an existing building but does not make it depend exclusively on electronic devices. Sensors and building management systems complement the strategies and help to achieve improved performance both for energy and thermal comfort. The methodology also allows to consider different intervention measures, with the final decisions still under control of the designer who will consider particularities of each project.

Further research will also help to fine tune and receive user feedback on the suitability of each measure from the point of view of thermal and indoor air quality comfort.

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