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Use of Adaptable Solutions to achieve near-Zero Energy Buildings through a combined thermal and comfort performance approach

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Abstract
The existing residential building stock in many industrialized countries is large but extremely energy inefficient, despite the existence of energy directives that apply mostly to new construction. Prefabricated building refurbishment for energy upgrading is a viable option for the existing building stock, but solutions need to adapt to each case and usage in order to respond to specific requirements. The "RECO2ST" project (Horizon 2020) is used as example of a forecast methodology that can help achieve nearly zero energy refurbishments, through selection of 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 Technical Note studies a series of 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.

Practical Application
The methodology helps to reduce guesswork for actions to be taken in order to refurbish and upgrade the existing housing stock to comply with current energy directives. It takes into account at the same time energy performance and user comfort, as expressed through indoor air quality.

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

Introduction
An extremely large percentage of the existing residential building stock worldwide is not energy efficient and does not comply with modern thermal and indoor air quality comfort standards, deterring the achievement of climate action plans and objectives. The large majority of the directives that mandate high performance buildings are mostly applicable to new buildings, and not all countries provide regulations towards energy upgrading of the existing housing stock in order to meet current expectations and standards. To exemplify this, in Europe residential buildings are responsible for up to 40% of the primary energy consumption and about 25% of CO_2 emissions[1] [2]. For the particular case of the United Kingdom, which had over 27 million dwellings in 2016 [3], its housing stock offers a large technical potential for improvement and thus achieve emission reductions of up to 80% [4], as it is estimated that about 60-70% of the existing

housing stock dates from before the first comprehensive energy regulations [5]. The potential for energy improvement also translates to long-term work for construction companies dedicated to repair, maintenance and upgrade [4]. This is shown in Figure 1, where the age and amount of building stock previous to 1980 is detailed. Building stock up to 1990 would also be eligible for deep energy upgrading due to not being able to meet current expectations and national targets for near-zero energy buildings[6].

Despite these figures, the deep energy renovation rate must increase dramatically if significant changes are to be made in order to meet UK obligations on greenhouse gas and energy demand reductions by 2050, estimated at 1.5 homes per minute[7]. A new approach for energy analysis and solution providing must be sought to reach such requirements. Since deep retrofits are usually a “one-off” activity in the lifetime of a residential building, there is no room for on-site “guesswork” or taking decisions that imitate similar constructions. However, bringing in a consultancy firm to do a detailed study might add to the final costs beyond those where the dwelling owner might decide to carry out a retrofit. Therefore, 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 which results in decreased time for analysis.

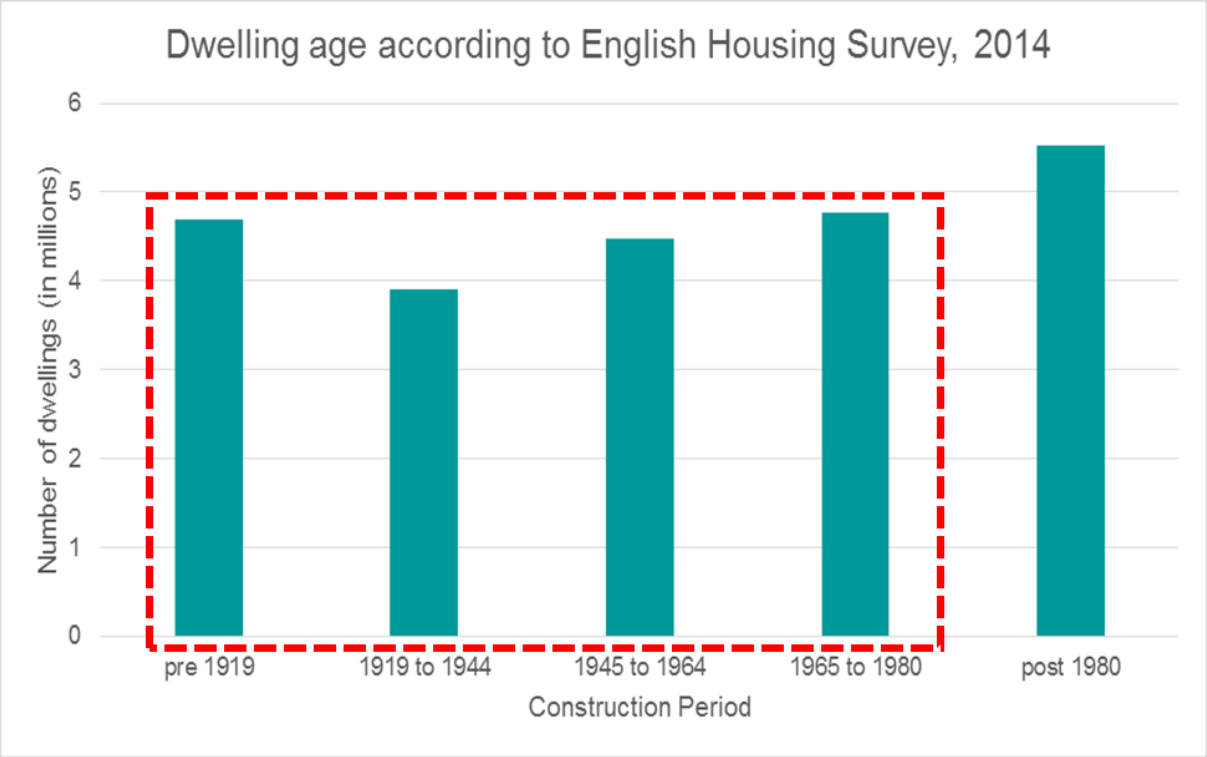


Figure 1. Age and amount of domestic buildings eligible for energy refurbishment according to data from English Housing Survey 2014.

Previous research work shows that selecting the most appropriate energy-saving technologies for each case ensures that retrofit performance meets occupant satisfaction. This is backed by results from the Building Performance Evaluation (BPE) programme[1], based on the early work of Post Occupancy Review of Building Engineering (PROBE)[8] in the mid-1990’s and the Low Carbon Buildings Programme (LCBP)[9], 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 [10], and regional directives such as the 2002 European Union (EU) Energy Performance in Buildings directive (EPBD) [11] with its updates in 2010 [12] and 2018 [13], are useful instruments for compliance that require new technologies to address very low energy requirements such as nZEB (nearly-zero energy buildings) in cases where it is mandatory to perform energy upgrading of an existing building.

Building refurbishments in dwellings for energy improvement have also become a point of interest for UK Government policy, as expressed in the Building Missions targets of halving the cost of existing retrofit but achieving the same performance standards of new buildings, by acting on the supply chains[14].

The Horizon 2020 project RECO2ST – "Residential Retrofit assessment platform and demonstrations for near zero energy and CO2 emissions with optimum coST, health, comfort and environmental quality"[15] , will be used as an example illustrating the forecast methodology required previous to intervention that will help select the most suitable refurbishment combinations of adaptable solutions that meet both energy and comfort expectations. 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 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 most analysis procedures in favour of exclusively achieving energy performance.

The integration of these technologies into customized 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 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.

Application Objective and Study Methodology

The objective of this note is to present a forecast approach for the necessary steps that must be followed in order to apply sound energy retrofits, based on well-known evaluation tools that can help to speed-up analysis, eliminating the number of incorrect decisions made for energy refurbishments on the field. Although basic knowledge of

widespread simulation tools is needed under the current version to verify the assessment, the goal is that the RAT tool will provide faster evaluations for use by non-experts.

In order to present the approach, first the characteristics of different building technologies used for energy upgrading are shown in a similar manner to the choices that planners would face. Afterwards, the tools available for analysis are laid out with an explanation on how to use them and make best use of the results to obtain a set of comprehensive choices. These steps can be later automated through future software development or similar.

Refurbishment Scenarios and Description of Sample Available Technologies

The RECO2ST project deals primarily with energy refurbishment technologies for residential buildings in Europe. The primary target segment in this sector includes residential blocks built previous to the establishment of energy saving measures, usually before the 1980s. The secondary target group includes existing building projects made after that date wishing to upgrade to nZEB as they are still eligible to increase their energy performance and indoor comfort. 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 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. For brevity, three technologies are described here:

1-Lightweight vacuum insulation panels (VIPs)

These panels are commercially available[16], and are quite thin compared to their conventional counterparts, having thicknesses up to 20 mm. This makes them ideal for energy refurbishments, where the thicknesses involved in traditional insulation materials would reduce daylight availability, become a critical weight issue or change the character of the building. They consist of a sandwich construction of two thin polyurethane or silica core panels enclosing a vacuum cavity, preventing heat transmission. The entire panel is surrounded by a reflective foil to reduce gains from radiation and to reduce tampering with the vacuum valve. This makes them ideal for upgrading insulation levels of a building without adding significant thickness to an existing wall. With those characteristics, the panels can have U-values of 0.35 W/m^2-K, considering heat losses due to aging and manipulation of edge joints during installation time. A schematic cross section is shown in Fig. 2

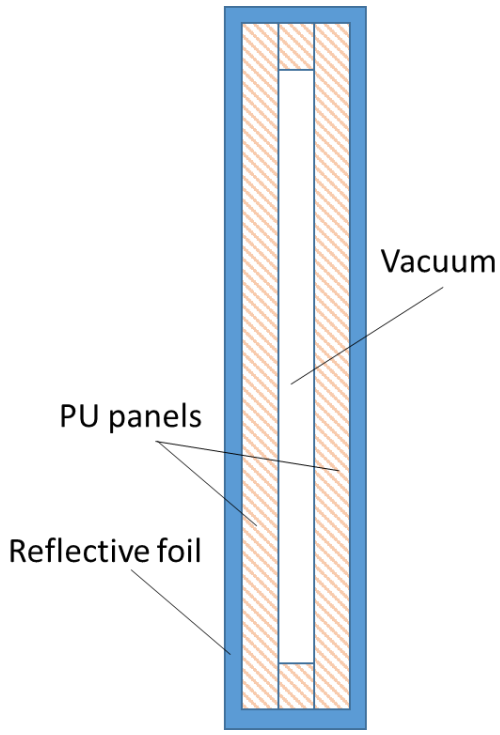


Figure 2. Schematic cross-section of the vacuum insulation panels (VIP).

2-Smart flow windows

This type of window was tested extensively as part of a research project, although now it is commercially available[17]. It consists of three window panes. Two are fixed and the third is part of an openable chamber. For winter operation, 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. As the glazed surface has a lower temperature differential than surrounding areas, occupants have a more positive appraisal of thermal qualities in the space. This makes this type of window to be known also as a “comfort window”. This is shown in Fig 3.

For summer operation and to enable ventilation, the chamber can be opened, leaving only the fixed double pane. Overheating is avoided since air can continue to flow through the air grills. 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. Entire operation of the window can be done manually or through automation.

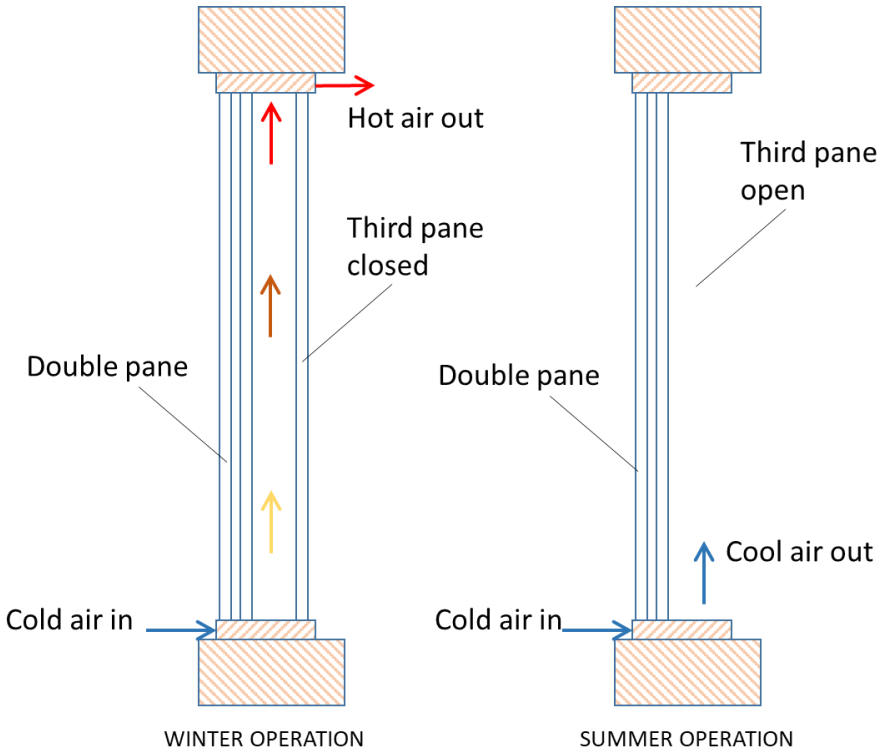


Figure 3. Operational principles for the smart flow windows during winter (left) and summer (right).

3-Nature-based solutions (NBS) for air quality treatment

The technology is based on the principles of photosynthesis and consequent carbon reduction[18]. Specially selected plants are placed on glazed enclosures with mechanical ventilation systems that draw air into them. This allows the plant to reduce the amount of carbon dioxide available in a space by absorbing it and releasing oxygen in return. The system, which doubles as a decorative element, contains all the elements to provide additional nourishment to the plants.

Other technologies available for refurbishment in this particular project include: cool paints for facades, roofs and pavements, and smart mechanical ventilation systems. 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 renovation assessment tool and associated technologies will be demonstrated in four apartment block buildings located in Spain, Switzerland, Denmark and the UK, representing climatic and construction variability across Europe, totalling 67 apartments and 7,000m^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.

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

Methodology of the Forecast Approach

The forecast approach 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, 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 technical note we focus on the case for a University dormitory located in the outskirts of London, United Kingdom as an example of residential use.

Site Analysis

For the purposes of this note, the demonstrator to be examined 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 units used for student housing. 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 bedrooms, increasing occupant comfort. An energy performance operational rating was made in 2016, listing the entire building as C. In terms of indoor quality, there are complaints about the lack of thermal comfort during the year and low ventilation rates, producing an environment perceived with stale air. The demonstrator building has an area of 4700 m^2. It 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. 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 according to each orientation. Windows were replaced in 2005 to double glazed units with upper opening parts. Exhaust ventilation is done manually through the window openings only.

Cold bridges still exist at ground and roof levels and in exposed walls. The apartment block has a water-based radiator system fed by gas boilers, with no or limited insulation of the water distribution system. Currently, the radiator network operates as an on/off system without any smart operating systems. For simplification the calculations assumed that it met capacity at all times. Usage of the dormitory area 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 different seasons of the year.

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 that would have been used for cooling, presenting an estimate of the cooling demands. A scheme of the typical room is shown in Figure .

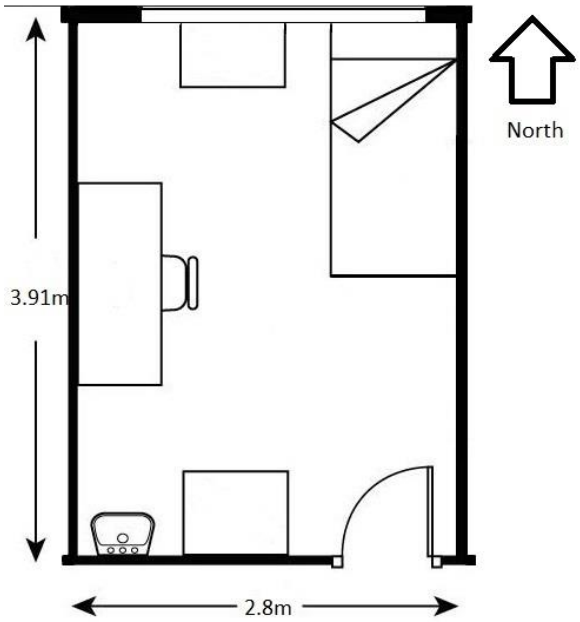


Figure 4 Dimensions of the typical North dormitory unit

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 different periods of the year using a well-known tool such as the pyschrometric chart [19], which plots the conditions for human tolerance to humidity and temperature combinations due to weather conditions presented by a particular location. Different tools exist to map different strategies that can be applied to achieve occupant comfort on the chart. For this note, the software Climate Consultant v6.0 was used [20] and applied to London Gatwick airport as an available weather file close to the study location. The software allows to visualize the impact that pre-defined strategies have to extend the number of hours of the year where comfort is possible. These strategies can then be translated into specific technological offerings for application according to the building's orientation.

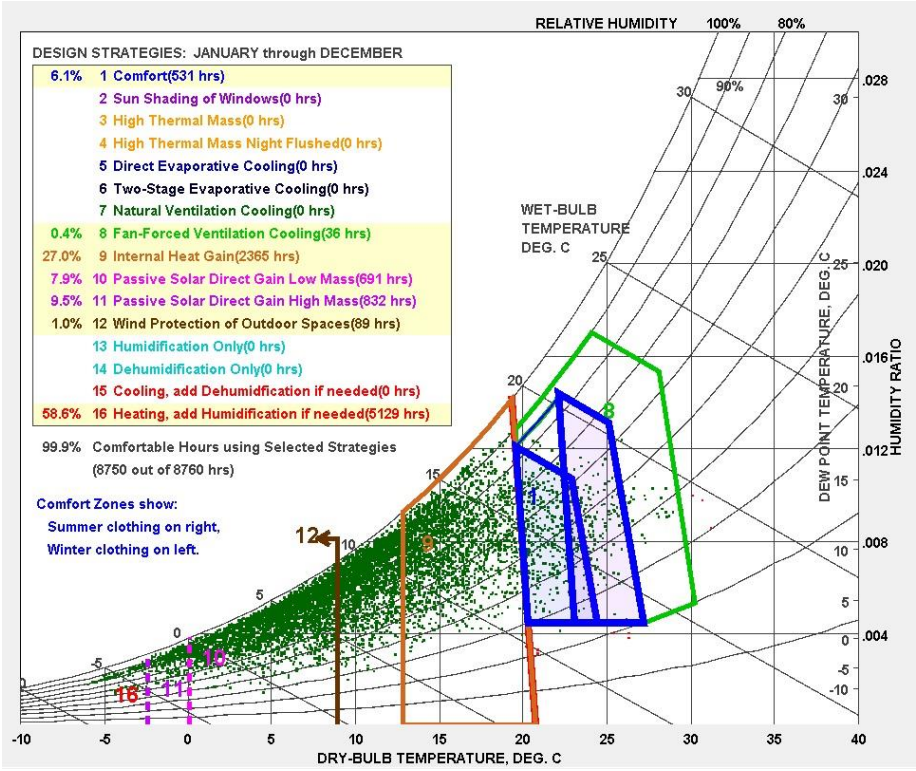


Figure 5 Climate analysis for comfort strategies for London Gatwick (weather file) using Climate Consultant software

As it can be seen in Figure , the project location is a heating-dominated climate for most of the year. However, care must be taken to also include strategies for summer, such as ventilation cooling in order to provide occupant comfort for that period. 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 concerning the placement of certain technologies, etc.

Technology Delimitation

An example is given on a set of decisions that would be taken for the demonstration building. Given the comfort strategies derived from the climate analysis of Figure 5, it can be found that available technologies closely following the recommendations include: vacuum insulated panels (VIPs) to maintain internal heat gains, and smart flow windows that supply forced ventilation through vents while supplying thermal comfort through controlled surface temperature. 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. Instead, they must be considered from the point of view of solar obstructions from vegetation and neighbouring buildings, structural support feasibility, as well as budget. Therefore, they are not considered in this study in order to maintain a generalization of the methodology for relationship between occupant comfort, indoor air quality and energy savings.

Specific analysis of the selected technological combinations is given in the following section.

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, with the number of possibilities increasing rapidly as more technologies are added. Although a first approach would be to perform calculations for each case, such procedure is resource-consuming and limitations on time allocated for energy analysis could potentially make the analyst to miss on some combinations or choose incompatible ones. Optimization algorithms might make analysis more complex. The forecast methodology 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 that illustrate energy analysis within the methodology, and to show how each option has influence on energy usage, thermal comfort and IAQ.

Energy analysis in this note has been done with EnergyPlus[21], as a leading whole-building simulation software package that has been independently validated in different conditions. It has become a *de facto* standard software package for predicting building performance in terms of energy consumption, indoor thermal comfort and most recently, indoor air quality. The cases with either a North- or South-oriented window that were considered for energy modelling include:

a) Basecase

Representing the existing situation, using a module with measurements as in Figure with adiabatic internal partitions.

b) Lightweight vacuum insulation panels (VIPs) on the external façade only

c) Smart flow window only

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, with 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 control valves in radiators, opening of windows according to CO_2 levels, as well as night ventilation.

Results

Results for the North and South orientations are given in the graphs of Figure . They show energy consumption, thermal comfort and indoor air quality for the two orientations and with the different technology combinations applied. Energy consumption is shown in terms of kWh per square metre per year, while thermal comfort is presented as a measure of percentage of people *satisfied* with their space, as derived from the PMV (predicted mean vote) scale [22]. PMV measure was used in order to assess both the conditioned and unconditioned times of the year. IAQ was measured in terms of CO_2 concentrations in ppm. Although CO_2 would require extremely large concentrations to become dangerous in an indoor space [23], 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.

Energy consumption

It can be seen that given their use as student dormitories with a limited number of appliances, the basecases already have low energy consumption, since there is a small space volume to condition and existing moderate energy saving features are present such as the double glazed window.

The addition of separate technologies 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.

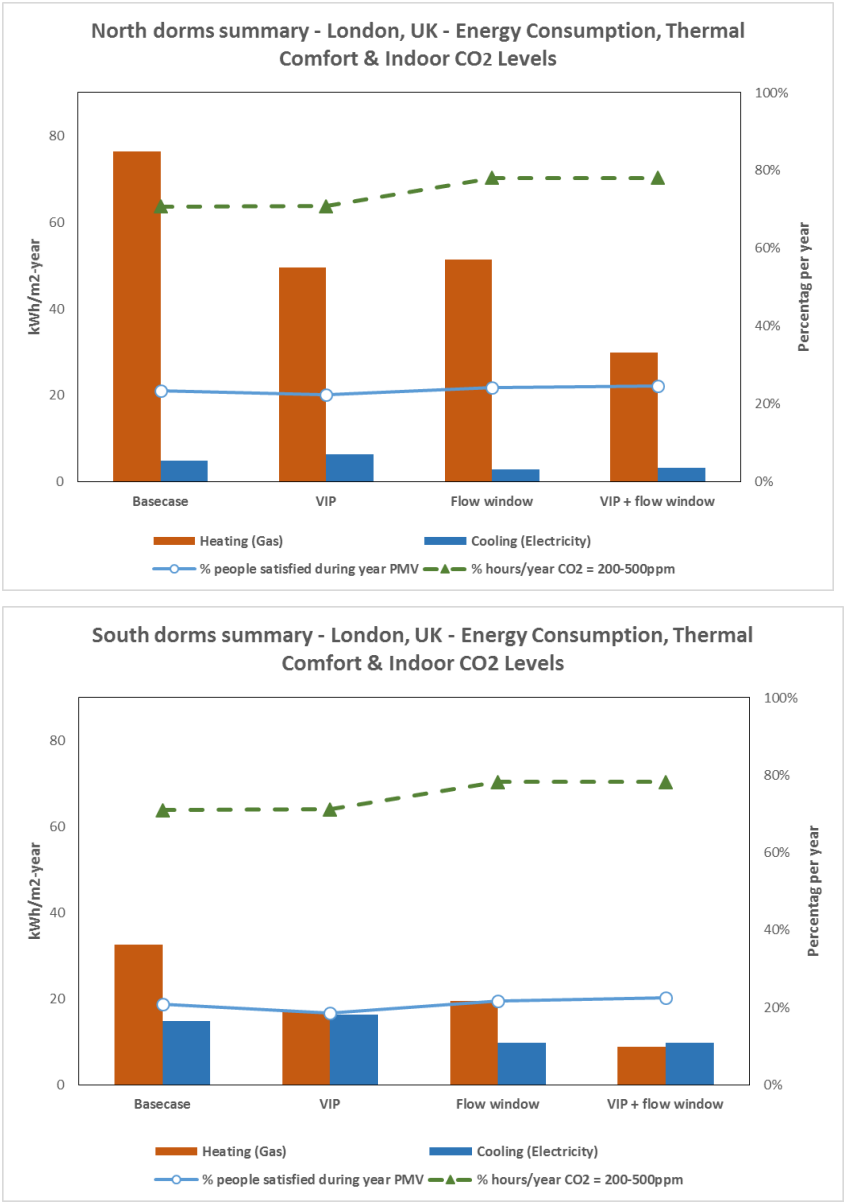


Figure 6 Energy consumption, thermal comfort and indoor CO_2 levels for North and South oriented dorms located in London, United Kingdom.

Thermal Comfort

Despite low energy consumption in the basecase, calculations for thermal comfort reflect a low acceptance percentage for the PMV. This coincides with reports from users of the demonstration building, who do not find the spaces comfortable under their current configuration. In terms of thermal comfort, maximum improvement using the technologies was modest, increasing 1% and 2% for the North and South respectively when compared to the basecase. However, some of the reasons are to be found in the starting setup for the room, where only single-sided ventilation is available as the main source of outdoor air. It has been measured through experimental work that contribution to thermal comfort from single-sided ventilation is only 1% for the entire year [24].

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. Due to the same proportion of window area, the combination of VIP and smart flow window, however, increased the perception of thermal comfort.

Indoor Air Quality

The studied spaces had starting acceptable IAQ levels for CO_2 for a large amount of the year (60% of the hours with levels within 200-500ppm in the basecase), although the situation could be improved. As it might have been expected, adding the smart flow window allowed for improved CO_2 levels that bring it closer to the sensation of outdoor air. The total amount of hours with levels within 200-500ppm increased to 80% with the smart flow window for both orientations. The multi modal window also allowed for night ventilation during summer, bringing an increased perception of thermal comfort during that season.

Discussion

It has been observed that although the 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 condition before the retrofit. Designers would get feedback on this situation and consider if they can introduce further measures to increase cross-ventilation, for example. In this way the process also contributes to fundamental design improvements within the retrofit, and is not dependent on addition of technologies to obtain high comfort performance.

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 further during the course of the project in four different locations in Europe, using a set of key performance indicators that will verify application in different climates. It will also include occupant feedback to monitor their acceptance under real-life conditions.

Conclusions

This Technical Note has demonstrated a forecast approach for an energy and comfort assessment methodology to speed up decisions to be taken when intervening the existing residential building stock by reducing analysis time for energy and comfort, but that will ensure a minimal level of performance in both areas. Even though the methodology is based on the study of a range of predefined energy-saving solutions, it can be used to take decisions on a wide amount of technological combinations for different situations, leaving the designer to decide which combination to apply based on project particularities while ensuring the minimal performance level. Indoor air quality is also taken into consideration as an integral part of this new methodology. This is not usually found in other energy refurbishment approaches, which only focus on energy as its main driver.

The methodology also provides smartness to the fabric of an existing building by allowing new operation modes for elements such as windows, 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 allows to consider different intervention measures, with the final decisions still under control of the designer who will study the 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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