Energy and Buildings 55 (2012) 889–902

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Review

Existing building retrofits: Methodology and state-of-the-art

Zhenjun Ma*, Paul Cooper, Daniel Daly, Laia Ledo

Sustainable Buildings Research Centre (SBRC), Faculty of Engineering, University of Wollongong, New South Wales (NSW) 2522, Australia

ARTICLE INFO

Article history:
Received 15 June 2012
Received in revised form 8 August 2012
Accepted 15 August 2012

Keywords:
Existing buildings
Systematic approach
Retrofit activities
Energy efficiency
State-of-the-art

ABSTRACT

Retrofitting of existing buildings offers significant opportunities for reducing global energy consumption and greenhouse gas emissions. This is being considered as one of main approaches to achieving sustainability in the built environment at relatively low cost and high uptake rates. Although there are a wide range of retrofit technologies readily available, methods to identify the most cost-effective retrofit measures for particular projects is still a major technical challenge. This paper provides a systematic approach to proper selection and identification of the best retrofit options for existing buildings. The generic building retrofit problem and key issues that are involved in building retrofit investment decisions are presented. Major retrofit activities are also briefly discussed, such as energy auditing, building performance assessment, quantification of energy benefits, economic analysis, risk assessment, and measurement and verification (M&V) of energy savings, all of which are essential to the success of a building retrofit project. An overview of the research and development as well as application of the retrofit technologies in existing buildings is also provided. The aim of this work is to provide building researchers and practitioners with a better understanding of how to effectively conduct a building retrofit to promote energy conservation and sustainability.

Contents

* Corresponding author. Tel.: +61 02 4221 4143.
E-mail address: zhenjun@uow.edu.au (Z. Ma).

0378-7788/$ – see front matter
http://dx.doi.org/10.1016/j.enbuild.2012.08.018

1. Introduction

The construction of buildings and their operation contribute to a large proportion of total energy end-use worldwide [1–3]. In the building sector, most energy is consumed by existing buildings while the replacement rate of existing buildings by the new-build is only around 1.0–3.0% per annum [4–7]. Therefore, rapid enhancement of energy efficiency in existing buildings is essential for a timely reduction in global energy use and promotion of environmental sustainability.

During the last decade, many governments and international organisations have put significant effort towards energy efficiency improvement in existing buildings. The federal government of the United States, for example, has provided significant financial assistance to support existing building retrofits [8,9]. In Australia, the Commercial Building Disclosure (CBD) programme, which came into effect on the 1st November 2010, requires the owners of Australia's large commercial office buildings to provide energy efficiency information to potential buyers or lessees [10]. In their 2009–2010 state budget, the Queensland government invested $8.0 million to progressively retrofit existing government buildings to increase their energy efficiency [11]. In 2010, the UK government made a significant commitment to upgrade the energy efficiency of 7.0 million British homes by 2020 aiming at reducing carbon emissions by 29% [12]. The International Energy Agency (IEA) has launched a set of Annex projects to promote energy efficiency of existing buildings, such as: Annex 46 – Holistic assessment toolkit on energy efficient retrofit measures for government buildings; Annex 50 – Prefabricated systems for low energy renovation of residential buildings; Annex 55 – Reliability of energy efficient building retrofitting; and Annex 56 – Energy & greenhouse gas optimised building renovation [13]. These efforts provided policy guidance, financial assistance and technical support for the implementation of energy efficiency measures in existing buildings.

At the same time, a significant amount of research has been carried out to develop and investigate different energy efficiency opportunities in order to improve energy performance of existing buildings [1,14–23]. The results have showed that energy use in existing buildings can be reduced significantly through proper retrofitting or refurbishment [17–23], which is described as work required to upgrade an aged or deteriorated building [14]. Building retrofitting or refurbishment is being considered as one of main approaches to realistically achieving reduced building energy consumption and greenhouse gas emissions.

Retrofitting of existing buildings has many challenges and opportunities. The main challenge encountered is that there are many uncertainties, such as climate change, services change, human behaviour change, government policy change, etc., all of which directly affect the selection of retrofit technologies and hence the success of a retrofit project. The subsystems in buildings are highly interactive. Different retrofit measures may have different impacts on associated building sub-systems due to these interactions, which results that the selection of the retrofit technologies becomes very complex. Dealing with these uncertainties and system interactions is a considerable technical challenge in any sustainable building retrofit project. Other challenges may include financial limitations and barriers, perceived long payback periods, and interruptions to operations [24,25]. The willingness of building owners to pay for retrofits is another challenge if there is no financial support from the government, particularly since the issue of "split incentives" is often a key factor where the cost of the retrofit generally falls to a building owner whereas the benefit often flows primarily to the tenants. On the other hand, retrofitting of a building offers great opportunities for improved energy efficiency, increased staff productivity, reduced maintenance costs and better thermal comfort. It may also help to improve a nation's energy security and corporate social responsibility, reduce exposure to energy price volatility, create job opportunities and make buildings more liveable [26,27]. Ernst and Young [26] has estimated that in New South Wales (Australia) between $25 million and $99 million in total economic activity could be realised by the year 2020 within the building energy efficiency market.

Nowadays, there is a great number of building retrofit technologies that are readily available in the market. However, the decision as to which retrofit technology (or measure) should be used for a particular project is a multi-objective optimisation problem subject to many constraints and limitations, such as specific building characteristics, total budget available, project target, building services types and efficiency, building fabric, etc. Financial benefit is not the single criteria for the selection of the retrofit technologies. The optimal solution is a trade-off among a range of energy related and non-energy related factors, such as energy, economic, technical, environmental, regulations, social, etc.

This paper aims at providing an overview of recent research and development in this field as well as the application of retrofit technologies to existing buildings. The generic building retrofit problem and a systematic approach to proper selection of cost effective retrofit measures are presented. Key retrofit activities, such as energy auditing, building performance assessment, economic analysis, risk assessment, measurement and verification of energy savings, etc., involved in a building retrofit, are also discussed.

2. Generic building retrofit problem

The building retrofit optimisation problem is to determine, implement and apply the most cost effective retrofit technologies to achieve enhanced energy performance while maintaining satisfactory service levels and acceptable indoor thermal comfort, under a given set of operating constraints. The following issues addressing the nature of a building retrofit problem should be carefully considered in a building retrofit project.

2.1. Key phases in a sustainable building retrofit programme

The overall process of a building retrofit can be divided into five major phases (Fig. 1). The first phase is the project setup and pre-retrofit survey. In this phase the building owners, or their agents, need to first define the scope of the work and set project targets. The available resources to frame the budget and programme of work can then be determined. A pre-retrofit survey may also be required in order to better understand building operational problems and the main concerns of occupants. It is common practice for building owners to select an experienced Energy Services Company (ESCO) to take responsibility for planning and implementing the building retrofit.

The second phase comprises an energy audit and performance assessment (and diagnostics). Energy auditing is used to analyse building energy data, understand building energy use, identify areas with energy wastes, and propose no cost and low cost energy conservation measures (ECMs). Performance assessment is employed to benchmark building energy use by using selected performance indicators or using green building rating systems. Diagnostics can be used to identify inefficient equipment, improper control schemes and any malfunctions happened in the building operation. Details of building energy auditing and performance assessment (and diagnostics) are briefly presented in Sections 3.2 and 3.3, respectively.

The third phase is the identification of retrofit options. By using appropriate energy models, economic analysis tools and risk assessment methods, the performance of a range of retrofit

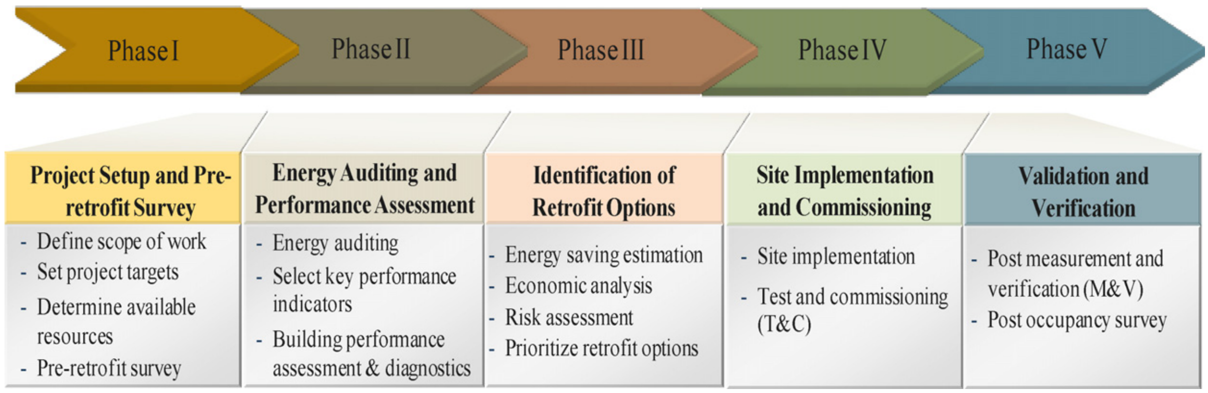

Fig. 1. Key phases in a sustainable building retrofit programme.

alternatives can be assessed quantitatively. The retrofit alternatives can then be prioritised based on the relevant energy-related and non-energy-related factors. It is worthwhile to note that a range of no cost and low cost ECMs that might have been identified during the energy auditing. Details of energy simulation, economic analysis and risk assessment are presented in Sections 3.4, 3.5 and 3.6, respectively.

The fourth phase is site implementation and commissioning. The selected retrofit measures will be implemented on-site. Test and commissioning (T&C) is then employed to tune the retrofit measures to ensure the building and its services systems operate in an optimal manner. It is worth noting that the implementation of some retrofit measures may necessitate significant interruption to the building and occupants operations.

The final phase is validation and verification of energy savings. Once the retrofit measures are implemented and well tuned, standard M&V methods [28,29] can be used to verify energy savings. A post occupancy survey is also needed to understand whether the building occupants and building owners are satisfied with the overall retrofit result. Details of the M&V methods are presented in Section 3.7.

2.2. Key elements affecting building retrofits

The success of a building retrofit programme depends on many issues. Fig. 2 shows the key elements that have significant impacts on building retrofits, including policies and regulations, client resources and expectations, retrofit technologies, building specific information, human factors and other uncertainty factors.

Policies and regulations are energy efficiency standards, which set minimum energy efficiency requirements for retrofitting of existing buildings. Governments may provide financial support and subsidies to assist building owners and developers in achieving the required energy performance targets through implementing energy retrofit measures. Often the range of government programmes available is complex, even within a single jurisdiction. A review of how the renovation policies are changing and the political strategies that have guided the promotion of housing renovation has been provided by Baek and Park [30]. A summary of public policies, such as European Energy Performance of Buildings Directive (EPBD), US Standard 189.1, on green buildings can be found in Ref. [24].

Client resources and expectations determine the project targets and goals, and thus determine which kind of retrofit technologies should be used. Since investment decisions for energy efficiency are quite complex, it is always difficult for clients to decide whether investment in retrofits is worthwhile. Based on a survey of one hundred firms, Harris et al. [31] identified the factors that influence a firm's decision on investment in energy efficiency. It was found that there are a large number of factors involved and the most widely used decision-making rule is the payback period. A study by Alajmi [32] showed that non-retrofitting ECMs with no or low capital investment only saved 6.5% of building annual energy consumption, while the retrofitting ECMs measures with significant capital investment can save up to 49.3% of annual energy consumption.

Retrofit technologies are energy conservation measures (ECMs) used to promote building energy efficiency and sustainability. Retrofit technologies range from the use of energy efficient equipment, advanced controls and renewable energy systems to the changes of energy consumption patterns, and the application of advanced heating and cooling technologies. Retrofit measures should be considered in their order of economic payback, complexity and ease of implementation [33].

The effectiveness of a building retrofit is also dependent on building-specific information, such as geographic location, building type, size, age, occupancy schedule, operation and maintenance, energy sources, utility rate structure, building fabric, services systems, etc. For a particular project, the optimal retrofit solutions should be determined by taking into account building specific information.

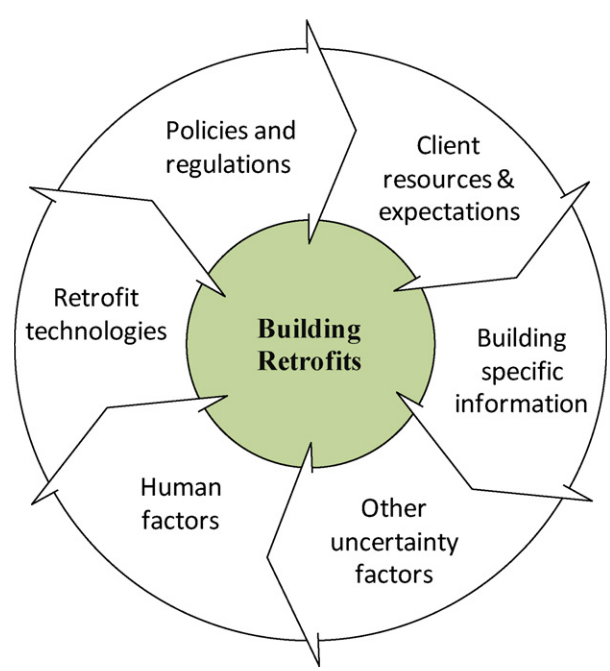

Fig. 2. Key elements influencing building retrofits.

Human factors are other important elements that affect the success of building retrofits. Human factors may include comfort requirements, occupancy regimes, management and maintenance, activity, and access to controls [33]. A survey by Owens and Wilhite [34] showed that 10–20% of domestic energy use in the Nordic counties can be saved from occupant behaviour changes alone. Yohanis [35] investigated householders' awareness, attitudes and behaviour in relation to domestic energy use. Santin et al. [36] studied the importance of household characteristics and occupant behaviour on energy use for space and water heating in the Netherlands. The results showed that occupant characteristics and behaviour significantly affect building energy use. The impact on energy use for heating is around 4.2%, for example. These studies showed that the changes of occupant behaviour, occupant controls and comfort range can lead to significant energy savings. The energy savings are often achieved with no or low capital investment.

As presented earlier, building retrofits are also affected by many uncertainty factors. A good estimation of uncertainty factors is essential to help select the best retrofit options to maximise building energy efficiency during its whole life span.

2.3. Other important issues related to building retrofits

The following issues also address the nature of the building retrofit problem.

- Each building is unique with different characteristics. The retrofit measures used in one building may not be suitable for use in another building.
- The benefit of using multiple ECMs is not the sum of the benefits by using each individual ECM due to the interactive nature among different building subsystems and different ECMs. Whether an ECM is recommended depends on its thermodynamic performance and the physical interactions among different ECMs [37].
- The selection of the ECMs is a multi-objective optimisation problem. Multi-objective optimisation is a scientific area that offers a wide variety of methods with great potential for the solution of complicated decision problems [38]. The criteria selection and weighting factor assignments are essential in the formulation of the optimisation problem for building retrofits.
- The optimisation problem can be developed by using model-based approach or model-free approach. In model-based approach, energy simulation models (or tools) are commonly used to estimate energy savings of different ECMs. The analysis of energy savings should recognise the modelling mismatch. Model-free approach does not require a "model" of the targeted system. Expert system is a typical model-free approach. The application of an expert system is affected by the richness of the knowledge database since the rules used are static and outside of the domain of expertise, threatening significant errors [39].
- In the model-based approach, the optimisation technique is used to search for the optimal solutions. For the multi-objective optimisation problem, global optimisation techniques, such as genetic algorithm (GA), branch and bound (B&B), simulated annealing (SA), etc., can be used to search for globally optimal retrofit solutions.

3. Sustainable building retrofits – methodology and strategies

3.1. A systematic approach for sustainable building retrofits

Fig. 3 illustrates a systematic approach to identifying, determining and implementing the best retrofit measures for existing buildings. It could be used for retrofitting any type of buildings requiring minor modifications. The overall retrofit strategy consists of two parts: (a) strategic planning and models/tools selection and (b) major retrofit activities in the whole building retrofit process. The strategic planning and models/tools selection are to provide necessary information and resource support for retrofit activities. This strategy was developed based on the retrofit phases and key activities presented in Section 2.1.

One thing needs to be addressed is that regular monitoring of building system operation and frequent review of the operational data in the persistence period (i.e. post-retrofit period) are needed to ensure that the system continues to operate in an efficient manner. This is essentially important for performance contracting projects that need to continuously determine energy savings.

3.2. Building energy auditing

Energy audits (and surveys) are investigations of energy use in a defined area or site. They enable an identification of energy use and costs, from which energy cost and consumption control measures can be implemented and reviewed [40]. Energy audits play an essential role in an energy retrofit programme to identify areas with energy saving potential and provide the information needed in building performance assessment.

Energy audits vary in range and depth. As per ASHRAE Handbook and Australian/New Zealand Standard, energy audits can be classified into three levels, including Level 1: walk through assessment, Level 2: energy survey and analysis, and Level 3: detailed energy analysis [40,41]. For a particular project, the appropriate energy audit level can be selected by taking into account the amount of details and level of accuracy required, budget available, project targets and goals defined, and scope of work covered.

There are a number of studies that have highlighted the importance of energy audits in sustainable building retrofits [32,42–47]. Xu et al. [42] pointed out that retrofit technologies reflect new equipment, new energy resources, new energy audit technologies, etc. Since energy audits can help better understand the energy performance of a building and its services systems, the potential retrofit opportunities can be identified based on the information collected during the energy audit [32,43–45]. In order to reliably predict energy savings from a set of proposed retrofit measures, the parameters of the simulation models can be calibrated through the use of energy audit data [46,47].

Commercial buildings nowadays are mostly equipped with comprehensive building automation systems (BASs) and building energy management and control systems (EMCSs) that allow the possibility of using BAS data and EMCS data in energy audits to assist in identifying energy conservation opportunities.

3.3. Building performance assessment and diagnostics

Existing buildings tend to undergo performance degradations, change in use, and unexpected faults or malfunctions over time [47,48]. These events often result in significant deterioration of the overall system performance, inefficient operation and unacceptable thermal comfort conditions. A study supported by the U.S. Department of Energy identified more than 100 types of faults that may happen in commercial building services systems and these faults can account for 2–11% of the total energy consumption of commercial buildings [49]. In a sustainable building retrofit, as presented earlier, building performance assessment and diagnostics are used to benchmark building energy use, identify system operational problems, and find energy conservation opportunities.

In the last two decades, the development of building performance assessment tools has been very active. This is reflected in the fact that a set of building rating tools are in the public domain, such as LEED, BREEAM, CASBEE, HKBEAM, GBTool, E-top, Green

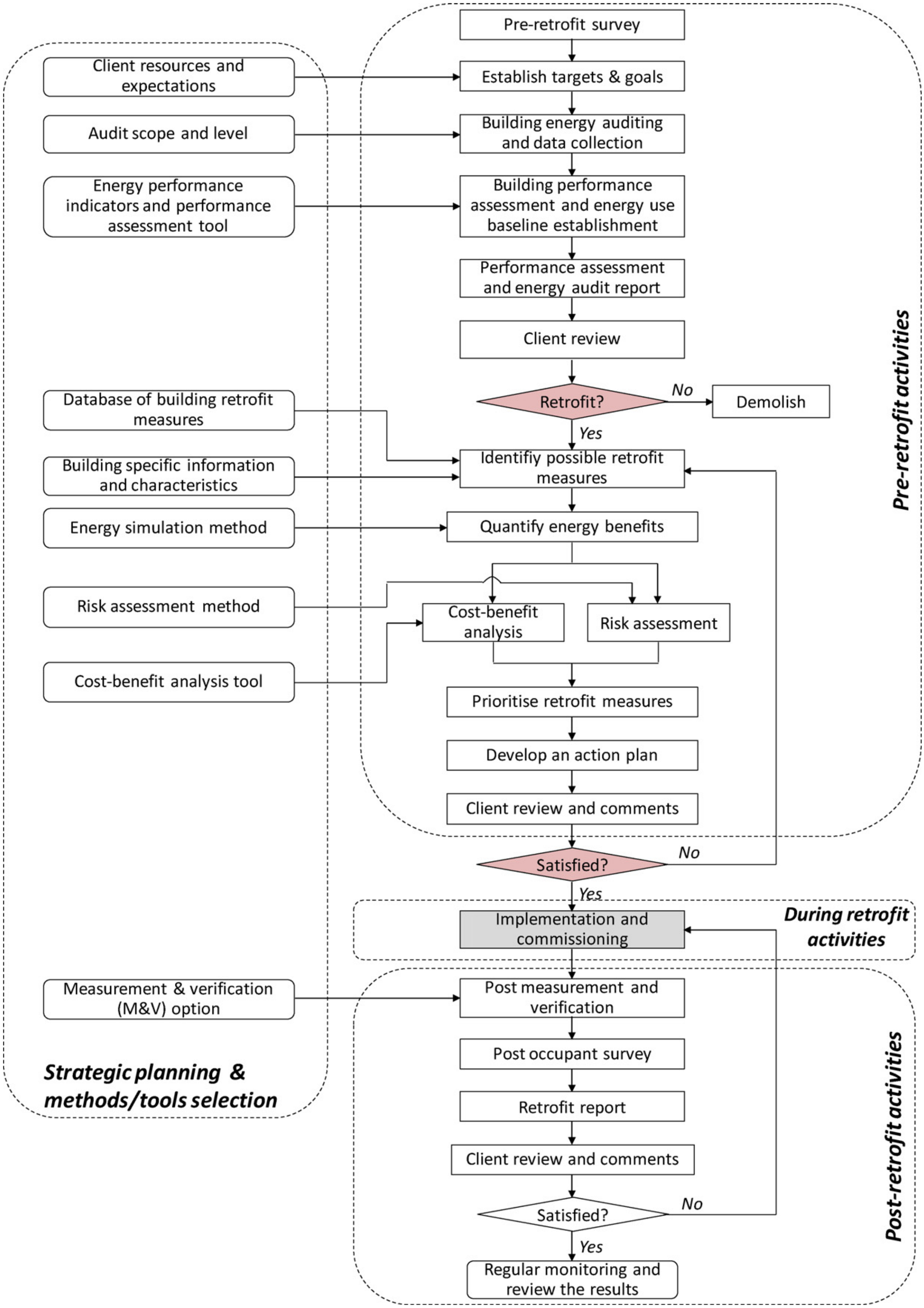

Fig. 3. A systematic approach for sustainable building retrofits.

Star, NABERS, etc. These rating tools provide a framework on how to evaluate and improve building energy and environmental performance. Although these rating tools vary in scope, criteria, structure and format, the rating process is usually conducted via benchmarking the assessed building against a set of prescribed quantitative and qualitative performance indicators (PIs) of diverse objectives [50]. Through examination of the difference between the PIs of the building assessed and the targeted PIs, the performance of the building can be quantified. A detailed comparison of a variety of building rating tools can be found in Refs. [51,52].

There is a wide range of research specifically focused on the development and application of appropriate models and strategies for building performance assessment and diagnostics. For instance, Richalet et al. [53] summarised three approaches to evaluating building energy performance, including computational-based approach relying on input data from energy audits, performance-based approach through analysis of building utility bills, and measurement-based approach with in situ measurement procedures. Poel et al. [54] provided an overview of the methods and software that can be used for energy performance assessment of existing dwellings. Mejri et al. [55] presented the application of model identification techniques for energy performance assessment of occupied buildings. Dascalaki et al. [56] stated that building typology can be adopted as a tool for estimating the energy performance of residential buildings. It can be employed for initial energy advice activities to give building owners a quick overview of building energy performance. Song et al. [57] developed an easy-to-use tool for fault detection and diagnosis of building air-conditioning systems. In the decision-making tool presented by Caccavelli and Gugerli [58], a diagnosis package was used to evaluate the general state of office buildings with respect to deterioration, functional obsolescence, energy consumption and indoor environmental quality. Details of the methods used for building diagnostics can be found in Ref. [59].

For a particular project, the appropriate performance assessment method and diagnostics tool can be selected by taking into account the client requirements, experience of energy services companies, major retrofit focus, etc.

3.4. Quantification of buildings' energy conservation benefits

Reliable estimation and quantification of energy benefits are essential in a sustainable building retrofit decision-support system for prioritisation of retrofit measures. The performance of different retrofit measures is commonly evaluated through energy simulation and modelling.

There are a number of whole-of-building energy simulation packages, such as EnergyPlus, eQUEST, DOE-2, ESP-r, BLAST, HVACSIM+, TRNSYS, etc., that can be used to simulate the thermodynamic characteristics and energy performance of different retrofit measures. For instance, TRNSYS was used by Santamouris et al. [60] to investigate the energy saving potential of green roofs in a nursery school in Greece. EnergyPlus was used by Chidiac et al. [18] and Ascione et al. [46] to simulate the effectiveness of retrofit measures for office buildings and historical buildings, respectively. Zmeureanu [61] employed DOE-2 to estimate the energy savings due to building retrofits. A detailed comparison of the capabilities of 20 building energy simulation packages can be found in Ref. [62].

Besides building energy simulation packages, a variety of energy simulation models have been developed and used to estimate energy performance of different retrofit measures. The models range from detailed physical models to grey box models and black box models. Asadi et al. [1] developed a multi-objective mathematical model to provide the decision support in the evaluation of technology choices for building retrofit strategies. This model explicitly allows for the simultaneous consideration of all available combinations of alternative retrofit actions. Rysanek and Choudhary [37] presented the development of a new transient building physics and energy supply systems modelling process for simulating the effect of large sets of building retrofit options. The strength of this model is in its applicability to real retrofit investment contexts with respect to decision-making. In the context of a particular case study, Murray et al. [63] stated that a static simulation modelling technique is sufficient as an underlying technique for retrofit analysis. An artificial neural network (ANN) was used by Yalcintas [64] to predict the energy savings for building equipment retrofits. Raftery et al. [65] presented an evidence-based methodology for calibration of whole building energy models. This methodology can improve model accuracy through using building verifiable information in the model calibration process. The calibrated models can be used to analyse and estimate the energy savings of different retrofit measures.

Building information modelling (BIM) can also be used to predict the energy performance of retrofit measures by creating models of existing buildings, proposing alternatives, analysing and comparing building performance for these alternatives and modelling improvements [24].

The studies above showed that energy simulation plays an essential role in analysing the performance of retrofit measures. Since different models (and tools) offer different prediction reliabilities with different uncertainties, the model (and tool) selection and its parameter identification are essential to ensure reliable estimates. It is worthwhile to note that simulation packages and energy models are generally developed based on certain assumptions. It is important for users to recognise the simulation uncertainties generated by such assumptions.

3.5. Economic analysis

The selection of retrofit measures is a trade-off between capital investment and benefits that can be achieved due to implementation of the retrofit measures. Economic analysis, which facilitates the comparison among alternative retrofit measures, can provide an indication of whether the retrofit alternatives are energy efficient and cost-effective.

A variety of economic analysis methods can be used to evaluate the economic viability of building retrofit measures. Some of them, such as net present value (NPV), internal rate of return (IRR), overall rate of return (ORR), benefit-cost ratio (BCR), discounted payback period (DPP), and simple payback period (SPP), can be used to assess the economic feasibility of a single retrofit measure. Alternatively, the life cycle cost method, the levelized cost of energy and other advanced analysis methods can be used to evaluate the cost effectiveness of multiple retrofit alternatives [66,67].

There are many studies related to economic analysis of building energy efficient measures. Remer and Nieto [68] identified that NPV is the most typical technique for optimal building energy assessment among 25 techniques. Verbeeck and Hens [69] discussed the economic viability of different retrofit measures through the use of the NPV method. The life cycle cost assessment was used by Kaynakli [70] to determine the optimum thickness of thermal insulation material in a building envelope and its effect on energy consumption. Peterson and Svendsen [71] used an economic optimisation method derived from the NPV method to determine the most cost effective energy efficiency measures. Nikolaidis et al. [72] employed four economic analysis methods, i.e. NPV, IRR, BCR, and DPP, to analyse energy saving measures in common types of Greek buildings. Huber et al. [73] studied the weights of social, cultural and economical factors in the decision-making process for implementing retrofits measures in domestic buildings.

The results from these studies have demonstrated that economic assessment techniques allow for selection of the most cost effective retrofit measures. This in turns aids the decision support process in making an optimal design of building retrofits.

3.6. Risk assessment

Risk assessment is the determination of the quantitative or qualitative value of risk related to a concrete situation and a recognised threat [74]. Risk assessment provides decision makers with information about the 'risk exposure' inherent in a given decision, i.e. the probability that the outcome will be different from the 'best-guess' estimate [66]. As presented earlier, a building retrofit is subject to many uncertainty factors, such as uncertainty in savings estimation, energy use measurements, weather forecast, the changes of energy consumption patterns, system performance degradations, etc. These uncertainty factors result that investment in building retrofits is highly uncertain. Risk assessment is therefore essential to provide decision makers with a sufficient level of confidence to select and determine the best retrofit solutions.

While there are many risk assessment and risk management methods available, probability-based risk assessment methods are probably the most commonly used methods. Probability-based risk assessment methods include expected value analysis, mean–variance criterion and coefficient of variation, risk-adjusted discount rate technique, certainty equivalent technique, Monte Carlo simulation, decision analysis, real options and sensitivity analysis [66].

There are a number of studies that have specifically focused on risk assessment and uncertainty analysis of building retrofits. For instance, Menassa [75] presented a quantitative approach to determining the value of investment in sustainable building retrofits by taking into account different uncertainties associated with life cycle cost and perceived benefits of this investment. A scalable and probabilistic methodology that can support large scale investment in building retrofits under uncertainty was recently developed by Heo et al. [47]. A sensitivity analysis of building energy retrofits was studied by Gustafsson [76], which showed that life cycle cost of the building is subject to only small changes so long as optimal strategies are chosen.

The results from the studies above show that risk assessment also plays an important role in a building retrofit.

3.7. Measurement and verification of energy savings

Measurement and verification (M&V) is the process of using measurement to reliably determine the actual savings created within an individual facility by an energy management programme [29]. The main purpose of M&V is to determine actual energy savings due to the implementation of retrofit measures. Energy savings can be determined by Eq. (1) through calculating the difference between the energy measured (or estimated) in the pre-retrofit period and post-retrofit period after accounting for the energy differences resulting from non-energy retrofit measure factors [28]:

$$E_{\text{saving}} = E_{\text{pre-retrfo}} - E_{\text{post-retro}} \pm E_{\text{adjust}} \tag{1}$$

where E_{saving} is the energy saving; $E_{\text{pre-retro}}$ is the energy use measured (or estimated) for a defined period in the pre-retrofit period; $E_{\text{post-retro}}$ is the energy use measured (or estimated) for a defined period in the post-retrofit period; E_{adjust} is the difference between the energy use in the pre-retrofit period and post-retrofit period, caused by any differences in non-energy retrofit measure factors, such as weather conditions, occupancy schedules, etc.

The main challenge faced in realising good M&V practice is the need to identify and quantify the energy changes resulting from changes in non-energy retrofit measure factors. In International Performance Measurement & Verification Protocol [29], there are four M&V options that can be used to estimate and verify energy savings, including Option A: retrofit isolation – key parameter measurement, Option B: retrofit isolation – all parameter measurement, Option C: whole facility, and Option D: calibrated simulation. Details of energy savings calculation methods and typical applications of each M&V option can be found in Refs. [28,29].

M&V has been widely used to verify and measure building energy savings. For instance, Lee [44] presented three case studies to verify annual energy savings associated with lighting retrofits using short- and long-term monitoring. Mozzo [77] discussed the importance of M&V in performance contracting projects. Roosa [78] used M&V Option A to estimate energy savings of three energy efficiency projects. Kromer and Schiller [79] discussed the use of uncertainty analysis in M&V and how to select an appropriate level of M&V for specific projects. Erpelding [80] performed a M&V study to validate the initial energy savings calculation due to the retrofit of a chiller plant. The results from these studies indicated that M&V is an effective approach to measuring, computing and reporting energy savings achieved by implementing retrofit measures.

4. Research and application of retrofit technologies for building performance enhancement

Building researchers and professionals have made significant efforts towards the development and application of various retrofit technologies and decision support tools to enhance building performance. The-state-of-the-art of such efforts in last two decades is presented below, which is intended as a summary of most of such studies completed to date.

4.1. Building retrofit technologies

Fig. 4 illustrates major possible retrofit technology types that can be used in building applications. The retrofit technologies can be categorised into three groups, they are, supply side management, demand side management, and change of energy consumption patterns, i.e. human factors.

The retrofit technologies for supply side management include building electrical system retrofits and the use of renewable energy, such as solar hot water, solar photovoltaics (PV), wind energy, geothermal energy, etc., as alternative energy supply systems to provide electricity and/or thermal energy for buildings. In the last 5 years, there has been an increasing interest in the use of renewable energy technologies as building retrofit solutions due to the increased awareness of environmental issues. The use of renewable energy technologies may bring more benefits for commercial office buildings where a utility rate structure includes time-of-use differentiated electricity prices and demand charge is applied.

The retrofit technologies for demand side management consist of the strategies to reduce building heating and cooling demand, and the use of energy efficient equipment and low energy technologies. The heating and cooling demand of a building can be reduced through retrofitting building fabric and the use of other advanced technologies such as air tightness, windows shading, etc. Low energy technologies may include advance control schemes, natural ventilation, heat recovery, thermal storage systems, etc. Details of particular retrofit technologies that can be used in building retrofit projects can be found in Refs. [5,23,67,81,82].

For different retrofit measures, the cost to implement and potential benefits that can be achieved are different. A diagram for representing the cost to implement retrofit measures versus the environmental (CO_2 emissions reduction) benefits of the energy hierarchy is illustrated in Fig. 5 [82]. It can be found that retrofitting building fabric, building services systems and metering systems requires less cost investment while providing much more environmental benefits, as compared to retrofit measures using renewable

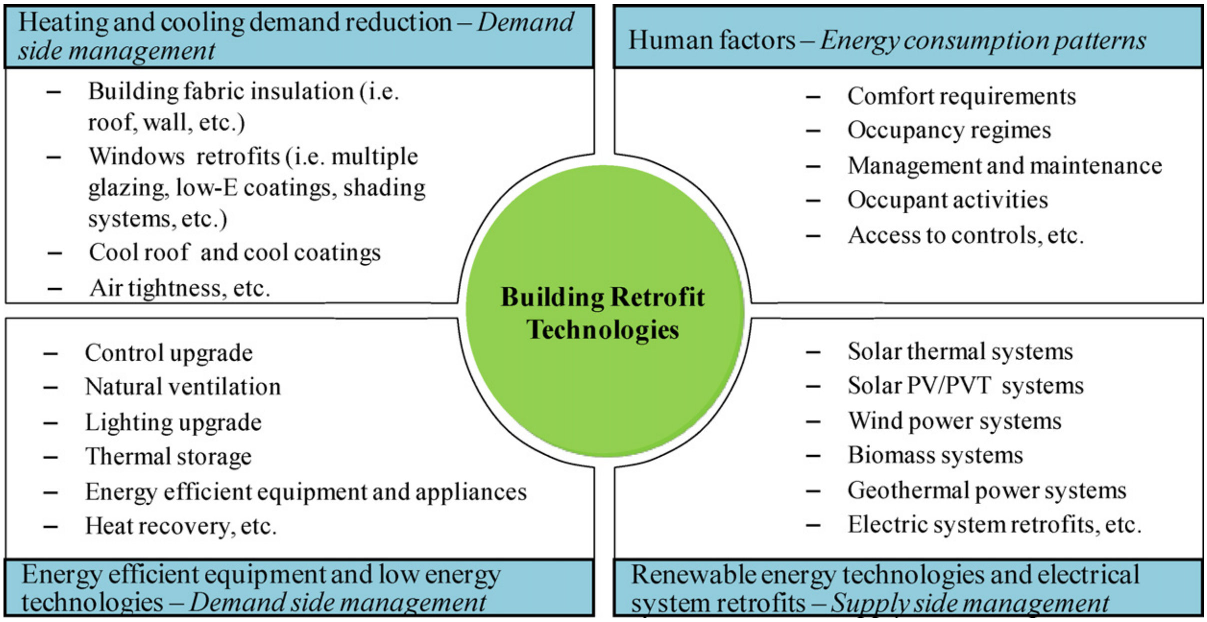

Fig. 4. Main categories of building retrofit technologies.

energy technologies. Therefore, the project targets and client's concern for the environment have a significant impact on the selection of retrofit technologies.

4.2. Retrofit studies on commercial office buildings

In this section, the major retrofit studies on commercial office buildings are reviewed and major outputs are summarised.

Guo et al. [83] developed a software tool integrating knowledge-based and database approaches to solving commercial building lighting retrofit problems. Simple tests showed that this tool can meet two main validation criteria, i.e. consistency of performance, and the ability to be modified to reflect other practices.

Dascalaki and Santamouris [84] reported on the energy conservation potential of selected retrofit options for five office building types in four different European climatic zones using computer simulations. The retrofit options used include interventions on the building envelope, HVAC, artificial lighting systems, and the integration of passive components for heating and cooling. Rey [85] developed a multiple criteria methodology for evaluating office building retrofit strategies. This methodology takes into account environmental, socio-cultural and economic criteria simultaneously.

The use of deep retrofits (i.e. whole building retrofits) for existing commercial building stock was discussed by Olgyay and Seruto [86] and Fluhrer et al. [87]. Olgyay and Seruto [86] discussed creative elements of whole building retrofit and pointed out that whole building retrofit is a gateway to climate stabilisation. Fluhrer et al. [87] employed a commercial building as a case study to compare the difference between whole building retrofit approach and the typical retrofit approach commonly used by ESCOs. The results showed that more energy (i.e. 38%) can be saved by using whole building retrofit, as compared to using the typical retrofit approach.

Barlow and Fiala [5] discussed how adaptive comfort theories might influence future low energy office refurbishment strategies based on building surveys. The results showed that active adaptive opportunities play an important part in future refurbishment strategies for existing office buildings. Passive interventions need to be included in future refurbishment strategies.

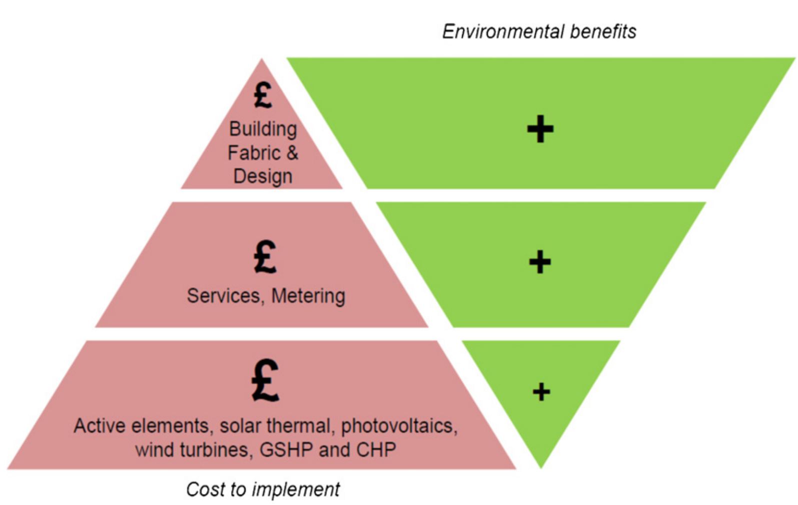

Fig. 5. Cost versus environmental benefits of the energy hierarchy [82].

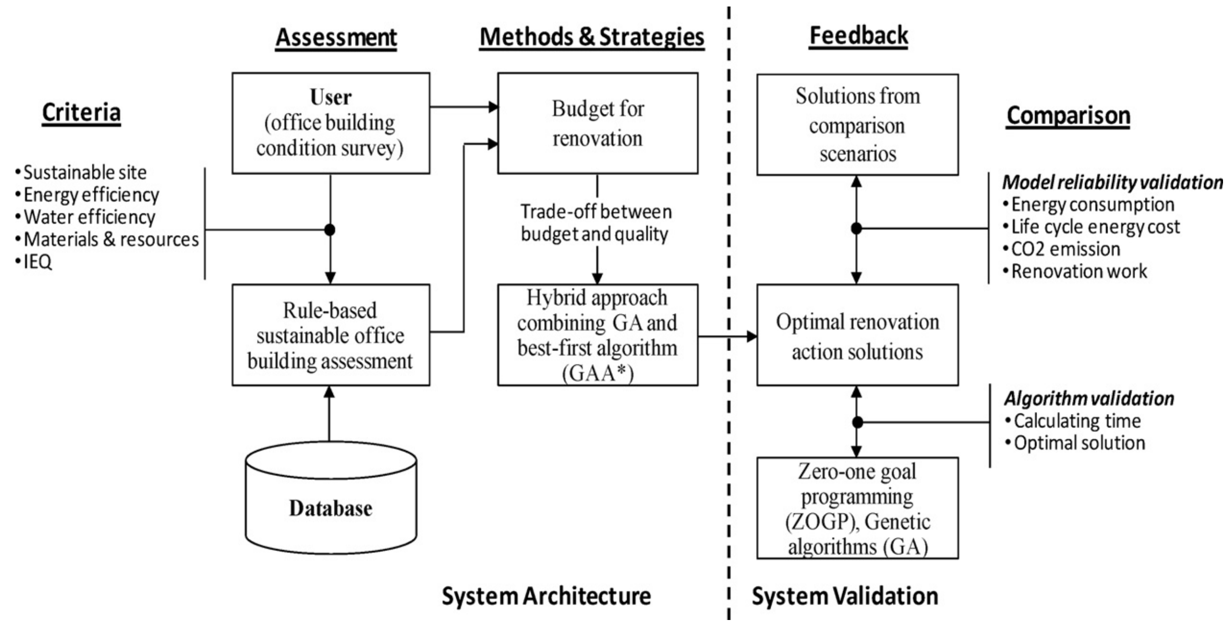

Fig. 6. Architecture of the decision support system developed by Juan et al. [92].

Effectiveness of single and multiple retrofit measures on the energy consumption of office buildings was investigated by Chidiac et al. [18]. A screening methodology was further developed by the authors [19] in order to determine the feasibility and cost effectiveness of different retrofit measures for office buildings. This methodology uses the concept of building archetype modelling to develop a database, which is then employed to formulate a set of mathematical equations to estimate energy consumption of office buildings based on a set of key variables.

Hestnes and Kofoed [20] evaluated a set of retrofit strategies designed for ten existing office buildings. The retrofit strategies considered include combinations of building envelope improvements, the use of passive cooling techniques, lighting, and HVAC improvements. The results showed that it is possible to significantly reduce building energy use through implementing retrofit strategies. However, the selection of retrofit strategies should be based on the very specific building energy characteristics.

Cooperman et al. [88] presented that retrofitting building envelope is a key step to improve energy performance of commercial buildings. Current windows retrofit technologies include multiple glazing, low-E coatings, noble gas fills or vacuums between glazings, and electro-chromic windows.

A multi-criteria rating methodology, named as Office Rating MEthodology (ORME), was developed by Roulet et al. [89] to rank office building retrofit scenarios according to a list of parameters including energy use for heating, cooling and other appliances, impact on external environment, indoor environmental quality, and cost. ORME was developed based on principal component analysis (PCA) and ELECTRE family algorithms.

A refurbishment guide for existing office buildings was developed by Arup [90]. In this guide, the upgrading of existing office buildings can be achieved through the implementation of a six-step plan, including determining the baseline, establishing goals & targets, reviewing building maintenance, housekeeping and energy purchase strategy, crunching time: establish or demolish, and selecting optimal upgrade initiatives and getting started.

Decision support tools are useful for quickly identifying and determining optimal retrofit measures. Flourentzou et al. [91] presented an interactive decision aid tool (TOBUS) for office building retrofits. This tool has seven modules, including building description and dimensions, building diagnostics, indoor environmental quality, energy use, retrofit scenarios, cost analysis, and reporting results. It can support the user in establishing a complete file of building state and help to identify the actions required to upgrade building performance. Juan et al. [92] developed an integrated decision support system to recommend a set of sustainable renovation actions for existing office buildings. Fig. 6 shows the architecture of this decision support system, which was developed based on the consideration of trade-offs among renovation cost, improved building performance, and environmental impacts. The optimal solution was determined using an optimisation technique that combines A* graph search algorithm with genetic algorithms (GA). A decision support model for evaluating energy saving measures in typical existing office buildings was developed by Doukas et al. [93]. Fig. 7 illustrates the model architecture. The model was developed based on the experience database through systematic incorporation of energy data collected from the building energy management system to calculate building performance indicators (PIs). The calculated PIs are then compared with the corresponding standard PIs to evaluate building energy performance. A priority list of energy saving measures for retrofits will be provided based on the comparison results and a financial evaluation.

The studies above have demonstrated that energy and environmental performance of existing commercial office buildings can be improved greatly if the retrofit measures are selected and implemented properly. However, most of these studies were carried out based on numerical simulations. The actual energy savings due to the implementation of the selected retrofit measures were not reported. More research and application work with practical case studies on commercial office building retrofits is essentially needed. This can help to increase the level of confidence of building owners to retrofit their buildings for better performance.

4.3. Retrofit studies on residential buildings

In literature, there are also a number of studies focused on residential building retrofits. Goldman et al. [94] introduced the retrofit experience in US multifamily buildings based on the analysis of measured data from a database of dwelling units. It was shown that the retrofit costs ($370/unit) for fuel-heat buildings were much lower than that for electric-heat buildings

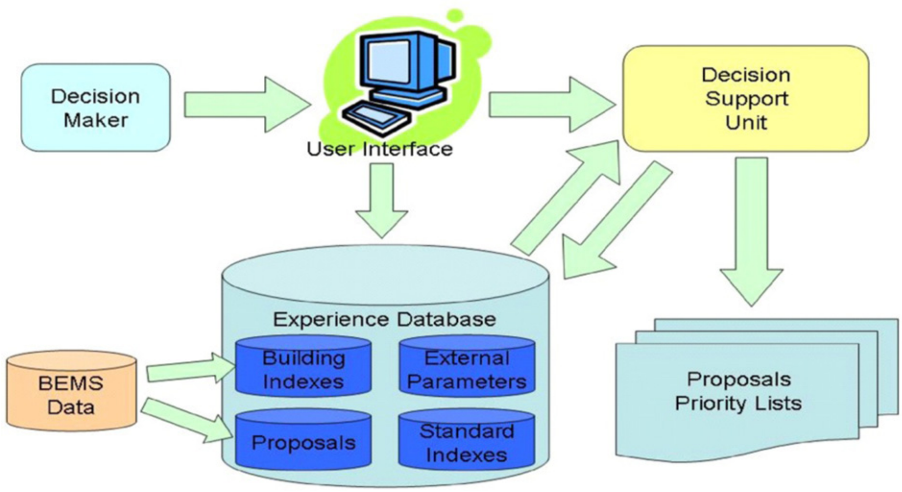

Fig. 7. Illustration of the decision support model developed by Doukas et al. [93].

($1600/unit). The payback periods for fuel-heat buildings and electric-heat buildings were 6 years and 20–25 years, respectively.

The energy savings and cost effectiveness of individual retrofit options in single family buildings were studied by Cohen et al. [95], based on analysing metered energy consumption and actual installation costs. The results showed that the ceiling insulation and wall insulation are cost effective while the windows replacement is not a good retrofit option since it has a very small normalised annual energy saving (2–5%).

The retrofit of the heating systems in residential buildings was examined by Gustafsson and Bojic [96] using the OPERA model. The mixed integer linear programming (MILP) method was used as the optimisation technique. Optimal fenestration retrofit of an apartment building by using MILP was studied in Ref. [97]. Both studies showed that the MILP is effective in identifying the optimal solutions. The retrofit of residential buildings in hot and arid climates was studied by Al-Ragom [98]. The analysis showed that substantial savings could be achieved at the national level even if the implementation cost was fully supported by government.

Hens [99] reported on the results due to the retrofit of a two-storey house built in 1957. It was shown that the benefits of using solar boiler and PV panels are minimal compared to using better insulation, energy efficient windows, better air-tightness, upgraded ventilation, and central heating.

Bin and Parker [100] compared the initial and retrofit ecological footprint of a century home. The environmental performance of the house during the three phases (i.e. pre-use phase, use phase and post-use phase) of its full service life was examined. The results showed that enhancing energy performance by renovation is an environmentally sound action for houses with decades remaining in their service life.

Alanne [101] proposed a multi-criteria 'knapsack' model to help select the most feasible renovation actions in the conceptual phase of a renovation project. A case analysis of a real Finnish apartment was performed to test the applicability and functionality of the model proposed. Gorgolewski [102] developed a method for optimising the renovation strategies for housing refurbishment. A life cycle cost method was used to assess and compare the performance of different retrofit measures and to give an indication of financial benefits over the life of the retrofit measures. Goodacre et al. [103] presented a cost-benefit analysis framework to assess the potential scale of the benefits from comprehensive upgrading of the heating and hot water systems in the English housing stock. The authors pointed out that uncertainty surrounds the precise nature of energy savings.

The cost–benefit analysis and emission reduction of lighting retrofits in Malaysia residential sector were presented by Mahlia et al. [104]. Annualised costs and cash flow were used to calculate economical impact of lighting retrofits. The cost–benefit was determined as a function of energy savings due to the retrofit of efficient lighting systems. Dodoo et al. [105] analysed the life cycle primary energy implication of retrofitting a four-storey wood-frame apartment building to a passive house standard. The results showed that retrofitting of the building to the passive house standard reduced final energy use, but the primary energy significance mainly depends on the type of energy supply system used.

A hierarchical pathway towards zero carbon building refurbishment was proposed by Xing et al. [23] to decouple built environment from fossil fuels and integrate with local renewable energy. Zero carbon refurbishment can be achieved through retrofitting building fabric, the use of more efficient building services equipment, and micro generation.

Zavadskas et al. [106] presented a new approach to determining the effectiveness of house retrofits based on expected energy savings and the increase in market value of the renovated buildings. The analysis indicated that the choice of retrofit scenarios depends on strategic urban development programmes, and the condition of panel houses and their environment, renovation cost, heating energy saving and expected increment of market value.

Zhao et al. [107] developed a three-grade check and evaluation system for energy efficient retrofit of existing residential buildings in heating areas of northern China. This system was developed based on a multi-index comprehensive evaluation method combined with life cycle assessment theory, analytical hierarchy process method, post-evaluation thought, and successful degree evaluation method.

Stovall et al. [108] performed a series of experiments to examine wall retrofit options. The results from the experimental tests were applied to an energy model to estimate whole house energy impacts. It was found that external insulative sheathing is especially effective in reducing the heat transfer through walls with greater framing heat transfer paths.

Nabinger and Persily [109] performed a retrofit study in an unoccupied manufactured house to investigate the impacts of air-tightening on ventilation rates and energy consumption. The results showed that the reduction in the house infiltration rates depends on weather conditions and the manner in which the heating and cooling system is controlled, but in general these rates were reduced by one third due to the retrofits.

Table 1
Summary of key findings from previous studies.

No.	Reference	Building type	Major retrofit technologies used	Savings determination method	Major results
1	Chidiac et al. [18]	Canadian office building in Edmonton, Ottawa and Vancouver	Heat recovery; Day-lighting; Boiler efficiency economizer; Preheat upgrade; Lighting load reduction.	Simulation program, EnergyPlus	The use of five retrofit options could achieve 20% reduction in electricity consumption for Edmonton, Ottawa and Vancouver, and 30%, 32% and 19% reduction in natural gas for each of the respective cities.
2	Ascione et al. [46]	A historical building hosting presidential offices and some classrooms	Modification of indoor temperature set-point; Infiltration reduction; Increase of the vertical wall thermal insulation; Replacement of the old boiler with a condensation gas heater.	Numerical model calibrated by experimental data	Could achieve 22% primary energy savings. The total cost of the refurbishment would be 53,280 € with a discounted payback period of 11 years and a net present value of 30,748 €.
3	Santamouris et al. [60]	A nursery school building	Green roof.	Experimental test and simulation	In summer period, the cooling load reductions for non-insulated building and insulated building with the green roof were 15–49% and 6–33%, compared to that without using the green roof, respectively.
4	Verbeeck and Hens [69]	Five Belgian residential buildings	Insulation measures; Glazing measures; Solar collectors and PV cells.	Building simulation model and net present value	Roof insulation, better performing glazing and efficient heating system appeared to be the most effective measures. Floor insulation appeared to be profitable in most cases (if easily accessible).
5	Dascalaki and Santamouri [84]	Five types of office buildings in four climatic regions in Europe	Building envelope improvement; Using passive systems and techniques; Installation of energy saving lighting systems and use of daylight; Improvement of heating, cooling and ventilation systems.	Simulation model developed	For enclosed/light/skin dependent/cellular office buildings, the combination of all retrofit options resulted in a reduction of total energy use ranging from 48% in the North Coastal to 56% in the North European climatic regions.
6	Fluhrer et al. [87]	Empire State building	Windows upgrading; Insulated reflective barriers; Tenant day-lighting, lighting and plugs; Chiller plant retrofit; Using a new air handling layout unit; Demand control ventilation; Balance of direct digital controls; Tenant energy management.	Energy and financial modelling	Can achieve a 38% reduction in energy use, save 105,000 metric tonnes of CO_2 over the next 15 years, and has an incremental net present value of approximately $22 million.
7	Goldman et al. [94]	Multifamily buildings	Heating controls and heating system equipment retrofits (for fuel-heat buildings); Window retrofits and insulation of water heat tank and installation of low-flow showerheads (for electric-heat buildings).	Analysis of measurement data from the database	Energy consumption after the retrofits decreased by 12–15 MBtu/unit in fuel-heat buildings and by 1450 kWh/unit in electric-heat buildings. Energy savings were between 10% and 30% of pre-retrofit energy use in 60% of the buildings studied.
8	Cohen et al. [95]	Single family buildings	A range of retrofit options, such as ceiling insulation, wall insulation, foundation insulation, windows replacement, heating system retrofits, etc.	Analysis of metering data and actual installation costs	Both ceiling and wall insulation are cost effective with normalised annual consumption savings ranging between 12 and 21% and average cost of conserved energy values between $1.60 and $6.50/GJ.
9	Al-Ragom [98]	A two-story house	Wall and roof insulation; Change of glazing system and decrease of window area.	DOE-2.1E and simple payback method	The use of wall and roof insulation and reflective double glass with reduced window area can achieve annual energy consumption of 293 kWh/m^2 in hot and arid climates.
10	Bin and Parker [100]	A two-storey single detached brick house built in 1910	A high level insulation of the roof, walls, foundation and basement floor; Air sealing and replacement of windows and doors; The adoption of renewable energy and energy efficient appliances.	Life cycle energy analysis	The environmental upfront cost of the retrofits will be offset within 2 years although the renovations resulted in additional embodied environmental impacts.
11	Mahlia et al. [104]	Residential sector	Retrofitting incandescent lamps with more efficient compact fluorescent lamps (CFL).	Simple energy calculation	The potential monetary savings were $37 million, $74 million and $111 million for 25%, 50% and 75% replacement of the lamps (for 5000 operation hours of efficient lighting), respectively.
12	Stovall et al. [108]	Typical houses in multiple locations	Wall retrofits including replacing the cladding, adding insulation under the cladding, and air sealing methods for replacement windows.	Energy modelling and experimental tests	Annual utility cost savings could be 10% for most locations. Additional savings are possible through the adoption of either low-e storm windows or replacement vinyl-framed double-paned windows.
13	Nabinger and Persily [109]	An unoccupied manufactured house built in 2002	Installing house wrap over the exterior walls, sealing leakage sites in the living space floor and leakages in the air distribution system, and tightening the insulated belly layer.	Site measurement	The retrofits reduced building envelope leakage by 18% and duct leakage by 80%, resulted in 10% energy savings.
14	Stefano [111]	The campus of Melbourne University, Australia	Replace 1.2 m fluorescent lighting fixtures with the electronic ballasts, T8 magnetic ballasts, T8 electronic ballasts, and T5 electronic ballasts.	Simple energy calculation	The installation of four lighting technology alternatives would result in energy savings of 13.9%, 20.5%, 24.4% and 64.9%, respectively.

Boait et al. [110] studied the performance of domestic ground source heat pumps (GSHPs) in retrofit installations in UK. It was found that the seasonal performance of GSHPs was not good as that reported in studies from continental Europe. The thermal time constant of the building is a critical factor to be considered in retrofit projects incorporating heat pumps.

Jaggs and Palmer [43] introduced an evaluation tool, named as Energy Performance Indoor Environmental Quality Retrofit, to identify the most appropriate refurbishment or retrofitting actions for apartment buildings. In this tool, there are four technical aspects, including indoor environmental quality, energy use, costs, and retrofit measures, to deal with the assessment of the building condition and recommendations for refurbishment.

The studies above showed that appropriate selection of retrofit technologies is very important in building retrofits to achieve maximum energy and environmental performance. It is worthwhile to note that some methods developed for residential buildings can also be used in other types of buildings.

4.4. Research studies on other types of buildings

The studies addressing building retrofits that do not fall into commercial office buildings and residential buildings are grouped as other types of buildings herein.

Xu et al. [42] developed a set of critical success factors of energy performance contracting (EPC) for sustainable building energy efficiency retrofit of hotel buildings. The critical success factors were categorised into six clusters, including (a) project organisation process; (b) project financing; (c) knowledge and innovation of EPC, sustainable development and M&V; (d) implementation of sustainable development strategy; (e) contractual arrangement; and (f) external economic environment.

Santamouris et al. [60] investigated energy and environmental performance of an experimental green roof system installed in a nursery school building. The results showed that a remarkable energy saving was achieved due to the reduction of cooling load during the summer period after the installation of the green roof system.

Stefano [111] reported on the potential to save electricity and reduce electricity related carbon dioxide emissions at Melbourne University by modelling the installation of four energy efficient lighting technology alternatives to replace 1.2 m fluorescent lighting fixtures. The four energy efficient lighting technology alternatives considered were the electronic ballasts, T8 magnetic ballasts, T8 electronic ballasts, and T5 electronic ballasts. The key results are summarised in Table 1.

Energy efficient retrofit of historical buildings was studied by Ascione et al. [46] and Bastianini et al. [112]. Ascione et al. [46] proposed a multi-criteria approach for the energy refurbishment of historical buildings and employed a numerical energy model to simulate the energy performance effectiveness and economical feasibility of several retrofit actions. The results showed that significant energy and economic benefits can be achieved by using optimal retrofit actions. Bastianini et al. [112] presented the results of a real scale experimental work regarding the retrofit and monitoring of a historical building using 'Smart' carbon fibre reinforced polymers (CFRP) with embedded fibre optic Brillouin sensors.

The energy and environmental benefits due to the implementation of retrofit actions in six public buildings were investigated by Ardente et al. [17]. The results showed that most significant benefits were from the improvement of envelope thermal insulation. The renovation of HVAC plants and lighting systems provided significant energy benefits as well.

Fonseca et al. [113] discussed the development and implementation of an easy-to-use expert system for lighting retrofits in public schools. The prototype computer-based system can evaluate eleven different areas of a school facility, and can identify suitable lighting solutions from 17 distinct bulb types and 38 ballast types. Gatton [114] examined particular characteristics of the predetermination of energy inefficient public buildings, and cost effective energy retrofit alternatives and how they can be solved by an expert system.

Kaklauskas et al. [115] developed a multivariate design and multiple criteria analysis method for building refurbishment. A total of 12 stages were designed to determine the significance, utility degree and priority of the retrofit alternatives. This method allows for the evaluation of economic, technical, qualitative architectural, aesthetic and comfort aspects. The main public building from Vilnius Gediminas Technical University, Lithuania, was used as an example to demonstrate how to use this method to determine the best retrofit options.

These studies also showed that retrofitting is an effective solution to promote energy efficiency and sustainability of existing buildings.

5. Conclusions

This paper presented a systematic methodology for appropriate retrofits of existing buildings for energy efficiency and sustainability. An overview of previous studies related to the investigation and evaluation of energy performance and economic feasibility of different retrofit technologies for building applications is provided. The major findings from previous studies are summarised in Table 1. The concluding remarks and recommendations for future work in this area are as follows.

(1) There is a large body of research on building retrofits available in the public domain. However, existing buildings continue to be upgraded at a very low rate. For instance, existing commercial building stock is currently being retrofitted at a rate of approximately 2.2% per year only [86].
(2) Previous studies have demonstrated that energy and environmental performance of existing buildings can be improved significantly through appropriate retrofits.
(3) Most previous studies were carried out using numerical simulations. Actual energy savings due to the implementation of retrofit measures in real buildings may be different from those estimated. More research with practical case studies is needed to help increase the level of confidence in potential retrofit benefits.
(4) Whole-of-building retrofit with comprehensive energy simulation, economic analysis and risk assessment is an effective approach to identifying the best retrofit solutions. Further research work and investigation in this regard are needed to facilitate cost effective building retrofits.
(5) To achieve building resilience due to the effects of climate change, more research on low energy adaptive strategies for building applications is needed.
(6) Appropriate selection criteria and weighting factor assignments are essential in the formulation of multi-objective optimisation problems to select the most cost effective retrofit strategies. Major concerns of building owners in regard to retrofits should be carefully considered during the development of the optimisation problem.
(7) Human factors directly affect building energy use. More comprehensive research associated with investigating human factors on building retrofits is needed.
(8) Since investment in building retrofits has a high degree of uncertainty, more research on risk assessment of building retrofits is also needed.

To sum up, there is still a long way for building scientists and professionals to go in order to make existing building stock be more energy efficient and environmentally sustainable.

References

[1] E. Asadi, M.G. Silva, C.H. Antunes, L. Dias, Multi-objective optimization for building retrofit strategies: a model and an application, Energy and Buildings 41 (2012) 81–87.
[2] DOE, Buildings Energy Data Book, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC, USA, 2010.
[3] Australia OEH, New South Wales of the Environment, 2009, http://www.environment.nsw.gov.au/soe/soe2009/index.htm (accessed on 23.11.11).
[4] Annex 50, Prefabricated systems for low energy renovation of residential buildings, http://www.ecbcs.org/annexes/annex50.htm (accessed on 25.11.11).
[5] S. Barlow, D. Fiala, Occupant comfort in UK offices – how adaptive comfort theories might influence future low energy office refurbishment strategies, Energy and Buildings 39 (2007) 837–846.
[6] S. Roberts, Altering existing buildings in the UK, Energy Policy 36 (2008) 4482–4486.
[7] ACC, Building Refurbishment Guide, Adelaide City Council, Australia, 2007.
[8] DOE, DOE to fund up to $454 million for retrofit ramp-ups in energy efficiency, http://energy.gov/articles/doe-fund-454-million-retrofit-ramp-ups-energy-efficiency (accessed on 03.01.12).
[9] HUD/U.S., http://portal.hud.gov/hudportal/HUD (accessed on 03.01.12).
[10] DOCC&EE, Commercial buildings in Australia, Department of Climate Change and Energy Efficiency, Australian Government, http://www.climatechange.gov.au/what-you-need-to-know/buildings/commercial.aspx (accessed on 12.12.11).
[11] Queensland Government, ClimateQ: Toward a Greener Queensland: Improving Energy Efficiency in Existing Government Buildings, http://www.climatechange.qld.gov.au/pdf/factsheets/8govlship-b1.pdf (accessed on 10.01.12).
[12] DECC, Warmer homes, greener homes: a strategy for household energy management, UK Department of Energy and Climate Change, http://www.decc.gov.uk/ (accessed on 10.01.12).
[13] IEA, http://www.ecbcs.org/ (accessed on 10.12.11).
[14] F. Flourentzou, C.A. Roulet, Elaboration of retrofit scenarios, Energy and Buildings 34 (2002) 185–192.
[15] Z.J. Ma, S.W. Wang, Building energy research in Hong Kong: a review, Renewable and Sustainable Energy Reviews 13 (2009) 1870–1883.
[16] Z.J. Ma, S.W. Wang, Enhancing the performance of large primary-secondary chilled water systems by using bypass check valve, Energy 36 (2011) 268–276.
[17] F. Ardente, M. Beccali, M. Cellura, M. Mistretta, Energy and environmental benefits in public buildings as a result of retrofit actions, Renewable and Sustainable Energy Reviews 15 (2011) 460–470.
[18] S.E. Chidiac, E.J.C. Catania, E. Morofsky, S. Foo, Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings, Energy 36 (2011) 5037–5052.
[19] S.E. Chidiac, E.J.C. Catania, E. Morofsky, S. Foo, A screening methodology for implementing cost effective energy retrofit measures in Canadian office buildings, Energy and Buildings 43 (2011) 614–620.
[20] A.G. Hestnes, N.U. Kofoed, Effective retrofitting scenarios for energy efficiency and comfort: results of the design and evaluation activities within the OFFICE project, Building and Environment 37 (2002) 569–574.
[21] K. Golić, V. Kosorić, A.K. Furundžić, General model of solar water heating system integration in residential building refurbishment – potential energy savings and environmental impact, Renewable and Sustainable Energy Reviews 15 (2011) 1533–1544.
[22] T.M.I. Mahlia, H.A. Razak, M.A. Nursahida, Life cycle cost analysis and payback period of lighting retrofit at the University of Malaya, Renewable and Sustainable Energy Reviews 15 (2011) 1125–1132.
[23] Y.G. Xing, N. Hewitt, P. Griffiths, Zero carbon buildings refurbishment – a hierarchical pathway, Renewable and Sustainable Energy Reviews 15 (2011) 3229–3236.
[24] L. Tobias, G. Vavaroutsos, et al., Retrofitting Office Buildings to be Green and Energy-Efficient: Optimizing Building Performance, Tenant Satisfaction, and Financial Return, Urban Land Institute (ULI), Washington, DC, 2009.
[25] Climate Works Australia, Australian Carbon Trust Report: Commercial Buildings Emissions Reduction Opportunities, 2010.
[26] Ernst, Young, Business opportunities in a low carbon economy, Final report, Industry and Investment NSW, 17.09.10.
[27] P. Sweatman, K. Managan, Financing Energy Efficiency Building Retrofits: International Policy and Business Model Review and Regulatory Alternatives for Spain, Climate Strategy and Partners, Spain, 2010.
[28] AEPCA, A Best Practice Guide to Measurement and Verification of Energy Savings, Australian Energy Performance Contracting Association, South Melbourne, Australia, 2004.
[29] EVO, International Performance Measurement & Verification Protocol – Concepts and Options for Determining Energy and Water Savings, vol. I, Efficiency Valuation Organization, Washington, DC, USA, 2007, Available at: http://www:evo-world.org
[30] C.H. Baek, S.H. Park, Changes in renovation policies in the era of sustainability, Energy and Buildings 47 (2012) 485–496.
[31] J. Harris, J. Anderson, W. Shafron, Investment in energy efficiency: a survey of Australian firms, Energy Policy 28 (2000) 867–876.
[32] A. Alajmi, Energy audit of an educational building in a hot summer climate, Energy and Buildings 47 (2012) 122–130.
[33] CIBSE, Energy Efficiency in Buildings: CIBSE Guide F, Chartered Institution of Building Services Engineers, London, 2004.
[34] J. Owens, H. Wilhite, Household energy behaviour in Nordic countries – an unrealized energy saving potential, Energy 13 (1988) 853–859.
[35] Y.G. Yohanis, Domestic energy use and householders' energy behaviour, Energy Policy 41 (2012) 654–665.
[36] O.G. Santin, L. Itard, H. Visscher, The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, Energy and Buildings 41 (2009) 1223–1232.
[37] A.M. Rysanek, R. Choudhary, A decoupled whole-building simulation engine for rapid exhaustive search of low-carbon and low-energy building refurbishment options, Building and Environment 50 (2012) 21–33.
[38] C. Diakaki, E. Grigoroudis, D. Kolokotsa, Towards a multi-objective optimization approach for improving energy efficiency in buildings, Energy and Buildings 40 (2008) 1747–1754.
[39] S.W. Wang, Z.J. Ma, Supervisory and optimal control of building HVAC systems: a review, HVAC&R Research 14 (2008) 3–32.
[40] Standards Australia, Australian/New Zealand Standard: Energy Audits (AS/NZS 3598:2000), Standards Australia International Ltd and Standards, New Zealand, 2000, ISBN:0733735762.
[41] ASHRAE, 2011 ASHRAE Handbook – HVAC Applications, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 2011.
[42] P.P. Xu, E.H.W. Chan, Q.K. Qian, Success factors of energy performance contracting (EPC) for sustainable building energy efficiency retrofit (BEER) of hotel buildings in China, Energy Policy 39 (2011) 7389–7398.
[43] M. Jaggs, J. Palmer, Energy performance indoor environmental quality retrofit – a European diagnosis and decision making method for building refurbishment, Energy and Buildings 31 (2000) 97–101.
[44] A.H.W Lee, Verification of electrical energy savings for lighting retrofits using short- and long-term monitoring, Energy Conversion and Management 41 (2000) 1999–2008.
[45] M. Santamouris, E. Dascalaki, Passive retrofitting of office buildings to improve their energy performance and indoor environment: the OFFICE project, Building and Environment 37 (2002) 575–578.
[46] F. Ascione, F. Rossi, G.P. Vanoli, Energy retrofit of historical buildings: theoretical and experimental investigations for the modelling of reliable performance scenarios, Energy and Buildings 43 (2011) 1925–1936.
[47] Y. Heo, R. Choudhary, G.A. Augenbroe, Calibration of building energy models for retrofit analysis under uncertainty, Energy and Buildings 47 (2012) 550–560.
[48] Z.J. Ma, S.W. Wang, Online fault detection and robust control of condenser cooling water systems in building central chiller plants, Energy and Buildings 43 (2011) 153–165.
[49] K.W. Roth, D. Westphalen, M.Y. Feng, P. Llana, L. Quartararo, Energy impact of commercial building controls and performance diagnostics: market characterization, energy impact of building faults and energy savings potential, Final Report, TIAX LCC, Cambridge, MA, 2005.
[50] C.K. Chau, J. Burnett, W.L. Lee, Assessing the cost effectiveness of an environmental assessment scheme, Building and Environment 35 (2000) 307–320.
[51] A. Haapio, P. Viitaniemi, A critical review of building environmental assessment tools, Environmental Impact Assessment Review 28 (2008) 469–482.
[52] R. Reed, A. Bilos, S. Wilkinson, K.W. Schulte, International comparison of sustainable rating tools, Journal of Sustainable Real Estate 1 (2009) 1–22.
[53] V. Richalet, F.P. Neirac, F. Tellez, J. Marco, J.J. Bloem, HELP (house energy labeling procedure): methodology and present results, Energy and Buildings 33 (2001) 229–233.
[54] B. Poel, G.V. Cruchten, C.A. Balaras, Energy performance assessment of existing dwellings, Energy and Buildings 39 (2007) 393–403.
[55] O. Mejri, E.P.D. Barrio, N. Ghrab-Morcos, Energy performance assessment of occupied buildings using model identification techniques, Energy and Buildings 43 (2011) 285–299.
[56] E.G. Dascalaki, K.G. Droutsa, C.A. Balaras, S. Kontoyiannidis, Building typologies as a tool for assessing the energy performance of residential buildings – a case study for the Hellenic building stock, Energy and Buildings 43 (2011) 3400–3409.
[57] Y.H. Song, Y. Akashi, J.J. Yee, A development of easy-to-use tool for fault detection and diagnosis in building air-conditioning systems, Energy and Buildings 40 (2008) 71–82.
[58] D. Caccavelli, H. Gugerli, TOBUS – a European diagnosis and decision-making tool for office building upgrading, Energy and Buildings 34 (2002) 113–119.
[59] J.M. House, G.E. Kelly, An overview of building diagnostics, in: Proceedings of the Workshop Diagnostics for Commercial Buildings: From Research to Practice, Pacific Energy Centre, San Francisco, CA, June 16–17, 1999, 1999.
[60] M. Santamouris, C. Pavlou, P. Doukas, G. Mihalakakou, A. Synnefa, A. Hatzibiros, P. Patargias, Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece, Energy 32 (2007) 1781–1788.
[61] R. Zmeureanu, Assessment of the energy savings due to the building retrofit, Building and Environment 25 (1990) 95–103.

[62] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, Building and Environment 43 (2008) 661–673.
[63] S.N. Murray, B. Rocher, D.T.J. O'Sullivan, Static Simulation A sufficient modelling technique for retrofit analysis, Energy and Buildings 47 (2012) 113–121.
[64] M. Yalcintas, Energy-savings predictions for building-equipment retrofits, Energy and Buildings 40 (2008) 2111–2120.
[65] P. Raftery, M. Keane, J. O'Donnell, Calibrating whole building energy models: an evidence-based methodology, Energy and Buildings 43 (2011) 2356–2364.
[66] F. Kreith, D.Y. Goswami, Energy Management and Conservation Handbook, CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA, 2008.
[67] M. Krarti, Energy Audit of Building Systems: An Engineering Approach, 2nd ed., CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA, 2011.
[68] D.S. Remer, A.P. Nieto, A compendium and comparison of 25 project evaluation techniques. Part 1. Net present value and rate of return methods, International Journal of Production Economics 42 (1995) 79–96.
[69] G. Verbeeck, H. Hens, Energy savings in retrofitted dwellings: economically viable, Energy and Buildings 37 (2005) 747–754.
[70] O. Kaynakli, A review of the economical and optimum thermal insulation thickness for building applications, Renewable and Sustainable Energy Reviews 16 (2012) 415–425.
[71] S. Peterson, S. Svendsen, Method for component-based economical optimisation for use in design of new low–energy buildings, Renewable Energy 38 (2012) 173–180.
[72] Y. Nikolaidis, P.A. Pilavachi, A. Chletsis, Economic evaluation of energy saving measures in a common type of Greek building, Applied Energy 86 (2009) 2550–2559.
[73] A. Huber, I. Mayer, V. Beillan, et al., Refurbishing residential buildings: a socio-economic analysis of retrofitting projects in five European countries, in: World Sustainable Energy Days 2011, 2011, Available at http://www.fedarene.org/documents/projects/EEW2/WSED2011/Huber.pdf (accessed on 12.01.12).
[74] http://en.wikipedia.org/wiki/Risk_assessment (accessed on 15.01.12).
[75] C.C. Menassa, Evaluating sustainable retrofits in existing buildings under uncertainty, Energy and Buildings 43 (2011) 3576–3583.
[76] S. Gustafsson, Sensitivity analysis of building energy retrofits, Applied Energy 61 (1998) 13–23.
[77] M.A. Mozzo, Measurement and verification of savings in performance contracting, Energy Engineering 96 (1999) 33–45.
[78] S.A. Roosa, Measurement & verification applications: Option A case studies, Energy Engineering 99 (2002) 57–73.
[79] S. Kromer, S.R. Schiller, Measurement and verification protocols – M&V meets the competitive and environmental marketplaces, Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings 4 (2000) 4227–4238.
[80] B. Erpelding, Monitoring chiller plant performance, ASHRAE Journal 4 (2008) 48–52.
[81] N.V. Baker, The Handbook of Sustainable Refurbishment: Non-domestic Buildings, Earthscan, London, UK, 2009.
[82] Fusion, A Review of Retrofit Technologies, Salford Centre for Research & Innovation in the Built & Human Environment, University of Salford, UK, 2010.
[83] B. Guo, C. Belcher, W.M. Kim Roddis, RetroLite., An artificial intelligence tool for lighting energy-efficiency upgrade, Energy and Buildings 20 (1993) 115–120.
[84] E. Dascalaki, M. Santamouris, On the potential of retrofitting scenarios for offices, Building and Environment 37 (2002) 557–567.
[85] E. Rey, Office building retrofitting strategies: multicriteria approach of an architectural and technical issue, Energy and Buildings 36 (2004) 367–372.
[86] V. Olgyay, C. Seruto, Whole-building retrofits: a gateway to climate stabilization, ASHRAE Transactions 116 (Part 2) (2010) 244–251.
[87] C. Fluhrer, E. Maurer, A. Deshmukh, Achieving radically energy efficient retrofits: The Empire State Building example, ASHRAE Transactions 116 (Part 2) (2010) 236–243.
[88] A. Cooperman, J. Dieckmann, J. Brodrick, Commercial envelopes, ASHRAE Journal 53 (2011) 134–136.
[89] C.A. Roulet, F. Flourentzou, H.H. Labben, M. Santamouris, I. Koronaki, E. Dascalaki, V. Richalet, ORME. A multicriteria rating methodology for buildings, Building and Environment 37 (2002) 579–586.
[90] Arup, Existing Buildings Survival Strategies: A Toolbox for Re-energising Tired Assets, Arup and Property Council of Australia (PCA), Victorian Division, Australia, 2008.
[91] F. Flourentzou, J.L. Genre, C.A. Roulet, TOBUS software – an interactive decision aid tool for building retrofit studies, Energy and Buildings 34 (2002) 193–202.
[92] Y.K. Juan, P. Gao, J. Wang, A hybrid decision support system for sustainable office building renovation and energy performance improvement, Energy and Buildings 42 (2010) 290–297.
[93] H. Doukas, C. Nychtis, J. Psarras, Assessing energy-saving measures in buildings through an intelligent decision support model, Building and Environment 44 (2009) 290–298.
[94] C.A. Goldman, K.M. Greely, J.P. Harris, Retrofit experience in U.S. multifamily buildings: energy savings, costs, and economics, Energy 13 (1988) 797–811.
[95] S. Cohen, C. Goldman, J. Harris, Energy savings and economics of retrofitting single-family buildings, Energy and Buildings 17 (1991) 297–311.
[96] S.I. Gustafsson, M. Bojic, Optimal heating-system retrofits in residential buildings, Energy 22 (1997) 867–874.
[97] S. Gustafsson, Optimal fenestration retrofits by use of MILP programming technique, Energy and Buildings 33 (2001) 843–851.
[98] F. Al-Ragom, Retrofitting residential buildings in hot and arid climates, Energy Conversion and Management 44 (2003) 2309–2319.
[99] H. Hens, Energy efficient retrofit of an end of the row house: confronting predictions with long-term measurements, Energy and Buildings 42 (2010) 1939–1947.
[100] G. Bin, P. Parker, Measuring buildings for sustainability: comparing the initial and retrofit ecological footprint of a century home – the REEP house, Applied Energy 93 (2012) 24–32.
[101] K. Alanne, Selection of renovation actions using multi-criteria knapsack model, Automation in Construction 13 (2004) 377–391.
[102] M. Gorgolewski, Optimizing renovation strategies for energy conservation in housing, Building and Environment 30 (1995) 583–589.
[103] C. Goodacre, S. Sharples, P. Smith, Integrating energy efficiency with the social agenda in sustainability, Energy and Buildings 34 (2002) 53–61.
[104] T.M.I. Mahlia, M.F.M. Said, H.H. Masjuki, M.R. Tamjis, Cost-benefit analysis and emission reduction of lighting retrofits in residential sector, Energy and Buildings 37 (2005) 573–578.
[105] A. Dodoo, L. Gustavsson, R. Sathre, Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard, Resources, Conservation and Recycling 54 (2010) 1152–1160.
[106] E. Zavadskas, S. Raslanas, A. Kaklauskas, The selection of effective retrofit scenarios for panel houses in urban neighborhoods based on expected energy savings and increase in market value: the Vilnius case, Energy and Buildings 40 (2008) 573–587.
[107] J. Zhao, Y. Wu, N. Zhu, Check and evaluation system on heat metering and energy efficiency retrofit of existing residential buildings in northern heating areas of china based on multi-index comprehensive evaluation method, Energy Policy 37 (2009) 2124–2130.
[108] T. Stovall, T. Petrie, J. Kosny, P. Childs, J. Atchley, K. Sissom, An exploration of wall retrofit best practices, in: Thermal Performance of the Exterior Envelopes of Buildings X, Proceedings of ASHRAE THERM X, Clearwater, FL, December, 2007.
[109] S. Nabinger, A. Persily, Impacts of airtightening retrofits on ventilation rates and energy consumption in a manufactured home, Energy and Buildings 43 (2011) 3059–3067.
[110] P.J. Boait, D. Fan, A. Stafford, Performance and control of domestic ground-source heat pumps in retrofit installations, Energy and Buildings 43 (2011) 1968–1976.
[111] J.D. Stefano, Energy efficiency and the environment: the potential for energy efficient lighting to save energy and reduce carbon dioxide emissions at Melbourne University, Australia, Energy 25 (2000) 823–839.
[112] F. Bastianini, M. Corradi, A. Borri, A. Tommaso, Retrofit and monitoring of an historical building using Smart CFRP with embedded fibre optic Brillouin sensors, Construction and Building Materials 19 (2005) 525–535.
[113] D.J. Fonseca, K.B. Bisen, K.C. Midkiff, G.P. Moynihan, An expert system for lighting energy management in public school facilities, Expert Systems 23 (2006) 194–211.
[114] T.M. Gatton, Expert system to determine energy-saving retrofit potential of public buildings, Fuel and Energy Abstracts 37 (1996) 378.
[115] A. Kaklauskas, E.K. Zavadskas, S. Raslanas, Multivariant design and multiple criteria analysis of building refurbishments, Energy and Buildings 37 (2005) 361–372.