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The challenge of sustainable building renovation: Assessment of current criteria and future outlook

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Abstract

The building sector is one of the key consumers of energy worldwide. Thus, the retrofitting of existing buildings provides excellent opportunities for reducing energy consumption and greenhouse gas emissions. This paper presents a critical review of the research undertaken on housing retrofits and discusses the approaches driving the assessment of energy-efficiency measures. It is clear from the existing literature that many retrofitting strategies are quite similar in their approaches, the most common of these being passive strategies such as insulation of the envelope, replacement of windows, and air sealing. However, the assessment methodologies differ broadly and widely, which restricts a comparison of the results across various studies. This current state of the art review highlights the need to apply a life cycle approach in order to find the optimal retrofitting solutions, and to identify the real improvement potential of housing renovation. Life cycle assessment and life cycle cost methodologies have been analyzed by discussing the existing limitations, which can be mitigated by sensitivity analysis. Finally, whilst social impacts were addressed in a few studies, life cycle social assessment was not conducted in any of the papers reviewed.

Keywords: housing renovation, retrofitting, sustainability, life cycle assessment, life cycle cost.

1. Introduction

Buildings account for 16-50% of total worldwide energy consumption (Saidur et al., 2007), with 40% of Europe´s energy consumption being building-related (European Parliament and Council, 2012). The majority of the current European residential building stock was built during the 1940s-

1970s, and is of a low standard, especially with regard to energy performance (Häkkinen, 2012). However, the replacement rate of existing buildings in Europe is approximately only 1.0-3.0% per year (Barlow and Fiala, 2007, Roberts, 2008). Therefore, the current challenge is to take action in this stock, which is a consequence of the high demand for housing which existed in the middle of the last century in Europe, where there was low industrial production and no standards of comfort.

It is well known that the retrofitting of building stock is a priority for both Europe and developed countries. However, there is a key issue that must be properly addressed. In particular, it is important to know which are the criteria currently used for assessing energy-efficiency measures. In recent years, many authors have analyzed the potential for renovating existing housing stock in terms of energy saving and reducing CO_2 emissions. However, whilst assessment criteria differ, retrofitting strategies are broadly similar. Nemry et al. (2010) analyzed the potential of residential buildings in Europe to reduce environmental impacts and financial costs through the life cycle approach. The improvement of the envelope (additional roof insulation, additional facade insulation, and new sealing to reduce ventilation) yielded a significant potential for environmental improvement. For the majority of buildings, it represented at least 20% compared to the base case. Using a case study in Italy, Dall'O et al. (2012) developed a procedure to evaluate the potential energy savings of retrofitting residential buildings in a municipality, and found that the BAU (business as usual) scenario achieved only a reduction of 2.7%, while with the optimal scenario it was possible to reach 24.8% of energy savings. Ahern et al. (2013) estimated the benefit of thermal retrofit measures for Irish housing stock, including fabric improvement measures and inflation rate measures. Heating costs and CO_2 emissions were based on Ireland's national Dwelling Energy Assessment Procedure (DEAP). According to their study, thermal retrofit measures in the detached housing stock had the potential to reduce heating costs and CO_2 emissions by almost 65% for houses built before 1979, and around 26% for newer homes. Mata et al.(2013b) employed a bottom-up method (Mata et al., 2013a) to assess the application of a spectrum of energy saving measures (insulation of envelope, replacement of windows, reduction of the indoor temperatures to 20ºC, heat recovery systems, etc.). These measures had the potential to reduce the final energy demand of the Swedish residential sector by 53%. The measures that provided the greatest savings were those that involved heat recovery systems (22%) and a reduction of the indoor temperature (14%). However, this is due to the higher indoor temperature over the day during the heating period, which, according to the measurements is 21.2ºC in single-family dwellings and 22.3ºC in multi-family dwellings (Boverket, 2009). Upgrading the U-values of the building envelope and windows had a lower impact on annual energy savings (Mata et al., 2013b), which is attributable to the superior building envelopes used in northern European countries (Balaras et al., 2007).

The construction sector plays a key role in global sustainable development. Strategies to make buildings more sustainable rely mostly on life cycle approaches, covering the three main aspects of sustainability: environmental, economic, and social (Gervásio et al., 2014). The use of such an approach at the beginning of a design process has been identified as a decisive tool in the pursuit of sustainable construction. Most fundamental decisions influencing the life cycle performance of a building are taken in the very beginning of the design process. If, for example, LCA is used at the end of a project, the environmental optimization potential cannot be exploited (Wittstock et al., 2012). As shown in Fig.1 (Kohler and Moffatt, 2003), the earlier the assessment, the higher is the potential to effectively influence the life cycle performance of the building.

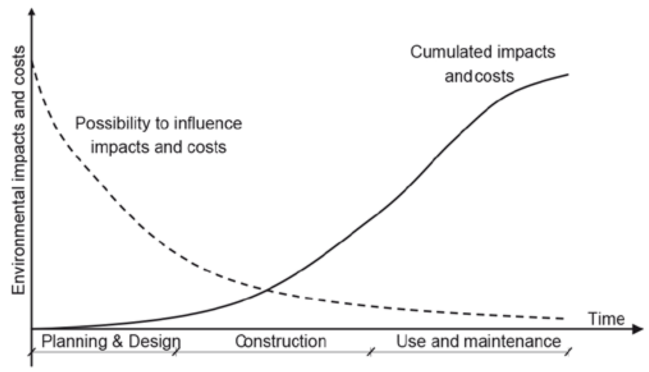

Fig. 1. Influence of design decisions on life cycle impacts and costs (Kohler and Moffatt, 2003)

The aim of this paper is to review, analyze, and compare the methods and tools that are currently used to evaluate housing building retrofits (i.e. energy assessment, life cycle assessment, life cycle cost, multi-criteria optimization methods, etc.), as well as to provide an overview of the main energy-efficient measures applied. The final objective of the paper is to serve as a basis for the development of a sustainability assessment methodology for the evaluation of energy saving measures. To this end, the paper has four chief aims: 1) to provide an overview of housing renovation studies reported so far, comparing the methods, assessment criteria and main energy-efficiency measures; 2) to summarize the main results of the studies; 3) to draw general conclusions on whether sustainability is evaluated in housing retrofitting; and 4) to recommend further developments for sustainability assessment methodologies, including environmental, economic, and social aspects through the life cycle approach.

2. Methods and scope

As mentioned above, the purpose of this paper is to provide an overview of existing housing renovation studies in order to know how sustainability is assessed, by focusing on the state of the art of retrofitting residential buildings. The review is based on a worldwide literature search, sourced mainly by the Scopus database. The research under review covers studies that have analyzed various energy saving measures, works developing assessment methodologies for housing renovation, and macro-scale level research analyzing the potential for energy savings and reducing CO_2 emission in the existing housing stock. Since this topic is still under development, we include not only work reported in peer-reviewed journals, but also studies reported in technical journals, books, conference proceedings and available reports. In order to provide an overview of the research conducted on this topic, works that defined the evaluation method, retrofitting strategies, and the application to a case study were considered. Table 1 summarizes 42 relevant studies identifying the type of housing, assessment criteria and energy-efficiency measures. Housing types have been classified into single-family houses, multi-family houses, and housing stock, which covers macro-scale analysis where the type of housing is not identified. The assessment criteria have been gathered in three groups according to the pillars of sustainability: environmental, economic, and social. Finally, energy-efficiency measures are categorized in the retrofitting of the building envelope, improvement of the building service systems, and implementation of renewable energy. The authors are sorted by the year of the research in order to see whether there has been any development of the criteria of assessment methodologies and the types of retrofitting solutions. The timespan considered to select the relevant literature is post-1980s, where after the first oil crisis a number of studies identified both the opportunities for, and barriers to energy conservation in multi-family houses (Bleviss and Gravitz, 1984, OTA, 1982).

Table 1
Summary of selected research works on housing renovation, classified according to housing type, assessment criteria, and energy-efficiency measures

No	Reference	Country	Housing type			Assessment criteria			Energy-efficiency measures		
			SFH	MFH	HS	Environmental	Economic	Social	Building envelope	Building service systems	Renewable energy
1	Goldman et al. (1988)	US		✓		✓			✓	✓	
2	Cohen et al. (1991)	US	✓			✓	✓		✓	✓	
3	Gorgolewski (1995)	UK		✓			✓		✓	✓	
4	Jaggs et al. (2000)	Greece		✓		✓	✓		✓	✓	✓
5	Goodacre et al. (2002)	UK			✓		✓			✓	
6	Papadopoulos (2002)	Greece		✓			✓		✓	✓	
7	Al-Ragom (2003)	Kuwait	✓			✓	✓		✓		
8	Alanne (2004)	Finland		✓		✓	✓	✓	✓	✓	
9	Gaterell and McEvoy (2005a)	UK	✓			✓			✓		
10	Gaterell and McEvoy (2005b)	UK	✓				✓		✓		
11	Mahlia et al. (2005)	Malaysia			✓	✓	✓			✓	
12	Verbeek and Hens (2005)	Belgium	✓			✓	✓		✓		✓
13	Amstalden et al. (2007)	Switzerland	✓				✓		✓		
14	Martinaitis et al. (2007)	Lithuania		✓			✓		✓	✓	
15	Stovall et al. (2007)	US		✓		✓			✓		
16	Hasan et al. (2008)	Finland	✓				✓		✓		
17	Diakaki et al. (2008, 2010)	Greece			✓	✓	✓		✓	✓	✓
18	Dodoo et al. (2010)	Sweden		✓		✓			✓	✓	
19	Magnier and Haghighat (2010)	Canada	✓			✓		✓	✓	✓	
20	Nemry et al. (2010)	EU-25	✓	✓		✓	✓		✓		
21	Ouyang et al. (Ouyang et al., 2011b)	China		✓		✓			✓		
22	Ouyang et al. (Ouyang et al., 2011a)	China		✓			✓		✓		
23	Asadi et al. (2012)	Portugal	✓			✓	✓		✓		✓
24	Byman et al. (2012)	Sweden		✓			✓		✓	✓	
25	Bin and Parker (2012)	Canada	✓						✓		✓
26	Bojic et al. (2012)	Serbia	✓			✓	✓		✓		
27	Dall'O et al. (2012)	Italy			✓	✓	✓		✓		
28	Häkkinen (2012)	EU-25			✓	✓	✓		✓		
29	Beccali et al. (2013)	Italy	✓			✓			✓	✓	✓
30	Brown et al. (2013)	Sweden		✓		✓	✓		✓	✓	
31	Cellura et al. (2013a)	Italy			✓	✓			✓	✓	✓
32	Desogus et al. (2013)	Italy	✓				✓		✓		
33	Mata et al. (2013b)	Sweden	✓	✓		✓			✓	✓	
34	Paiho et al. (2013)	Moscow		✓		✓			✓	✓	
35	Risholt et al. (2013)	Norway	✓			✓	✓	✓	✓		
36	Vrijders and Wastiels (2013)	Belgium	✓			✓	✓		✓	✓	✓
37	De Angelis et al. (2013)	Italy		✓		✓	✓		✓		
38	Ostermeyer (2013)	France		✓		✓	✓		✓	✓	
39	Assiego de Larriva et al. (2014)	Spain		✓		✓			✓	✓	
40	Antipova et al. (2014)	Portugal	✓			✓	✓		✓		✓
41	Buratti et al. (2014)	Italy	✓			✓			✓		
42	Cetiner and Edis (2014)	Turkey		✓		✓	✓		✓		

SFH: single-family houses; MFH: multi-family houses; HS: housing stock

Given that the final objective of the paper is to determine the future outlook for sustainable building renovation, an in-depth comparison of a selection of works was conducted, based on the three assessment criteria: environmental, economic, and multi-criteria. Indicators considered by the authors and energy-efficiency measures have been identified and compared. Moreover, the assumptions made in life cycle approaches, mainly in Life Cycle Assessment (LCA) and Life Cycle

Cost (LCC) in terms of lifespan, system boundaries, calculation methods, impact categories, and units (among others) have been compared and discussed. Finally, the different combination methods of life cycle approaches to assess sustainability have been analyzed in order to find both common features and inconsistencies among them. This analysis is reported in section 3. A discussion of the findings is provided in section 4 in order to discuss the future outlook and draw some conclusions regarding these methodologies.

3. Approaches and criteria for the assessment of retrofit alternatives

Tables 2, 3, and 4 summarize illustrative works on the topic of housing retrofitting measures. It is clear that renovation strategies are similar across the works analyzed, whilst, assessment methodologies vary considerably. As previously mentioned, for the purpose of the present review, the research works have been classified according to the evaluation criteria under consideration: environmental (Table 2), economic (Table 3) and multi-criteria assessment (Table 4).

3.1. Environmental assessment

The research works that evaluate retrofitting of residential buildings from an environmental perspective are shown in Table 2. Insulation of the envelope, replacement of windows, and air sealing appear to be the most common passive strategies. Many authors also focus on the improvement of building services, whilst the use of renewable energy still remains low. Energy performance is one of the main topics considered with respect to energy-efficient refurbishment (Goldman et al., 1988, Mahlia et al., 2005). Thus, software tools are widely employed in order to quantify the efficiency of the actions (Assiego de Larriva et al., 2014, Beccali et al., 2013, Bin and Parker, 2012, Buratti et al., 2014, Gaterell and McEvoy, 2005a, Ouyang et al., 2011b, Paiho et al., 2013, Stovall et al., 2007). However, energy consumption, as well as carbon emissions, needs to be considered over the lifespan of a house. In addition to operational energy, embodied energy needs to be taken into account. This is defined as the energy sequestered in buildings and building materials during all processes of production, onsite construction, and final demolition and disposal. When attempting to conduct a deep renovation in order to obtain an energy-efficient building, the introduction of the LCA emphasizes the embodied energy of the building as a key issue that should not be neglected in the evaluation (Cellura et al., 2014). LCA is a systematic approach enabling the quantification of potential environmental impacts of a building over its life cycle, from conception of the structure to the end of its service life, and from raw material extraction to the management of the building's demolition waste. This approach is being increasingly applied in energy-efficient renovation in order to evaluate retrofitting solutions (Dodoo et al., 2010, Bin and Parker, 2012, Beccali et al., 2013, Cellura et al., 2013a).

Table 2
Summary of selected research works on environmental assessment of energy-efficiency measures applied to housing renovation

No	Reference	Country	Indicators	Units	Energy-efficiency measures
1	Goldman et al. (1988)	US	Analysis of measurement data from the database	MBtu/unit kWh/unit	Window retrofits and insulation of water tank Heating controls and system equipment retrofits Installation of low-flow showerheads
9	Gaterell and McEvoy (2005a)	UK	Energy simulation	kWh	Roof insulation Curtains/Insulated shutters Double glazing Cavity wall insulation
15	Stovall et al. (2007)	US	Energy modeling Experimental tests	Energy saving(%)	Wall insulation Air sealing methods for replacement windows
18	Dodoo et al. (2010)	Sweden	LCEA	kWh/m^2	Envelope insulation Ventilation heat recovery Efficient hot water taps
21	Ouyang et al. (2011b)	China	Energy savings $LCCO_2$	kWh kg	Insulation of roof and walls Unfixable curtains or blinds Replacement of windows
25	Bin and Parker (2012)	Canada	LCA EF	gha	Envelope insulation Air sealing Replacement of windows and doors Renewable energy
29	Beccali et al. (2013)	Italy	LCA	GJ	Wall, roof and ground floor insulation PV plant Condensation boiler
31	Cellura et al. (2013a)	Italy	Input-output model combined with LCA	GJ Kt(CO_2)	Envelope insulation Installation of condensing boiler Solar thermal collectors
33	Mata et al. (2013b)	Sweden	Energy use CO_2 emissions	TWh tCO_2/yr	Envelope insulation Replacement of windows Ventilation systems with heat recovery Reductions in the use of hot water Reduction of indoor temperature
34	Paiho et al. (2013)	Moscow	Annual energy consumption	kWh/a kg/a(CO_2)	Envelope insulation Replacement of windows and doors Ventilation Air tightness factor improvement Water consumption
39	Assiego de Larriva et al. (2014)	Spain	LCA	MJ kgCO_2eq	Insulation of floor, walls and roof Replacement of windows New windows and mechanical systems to ensure cross ventilation
41	Buratti et al. (2014)	Italy	Energy simulation (Energy Plus & TRNSYS, with model calibration)	kWh/m^{2}year	Replacement of glazing Innovative package solutions (e.g. innovative glazing systems filled with silica aerogel)

LCEA: Life Cycle Energy Analysis; $LCCO_2$: Life Cycle CO_2; LCA: Life Cycle Analysis; EF: Ecological Footprint; gha: global hectares

3.2. Economic assessment

A variety of typical economic analysis methods can be used to evaluate the cost-effectiveness of retrofitting investments, 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) (Kreith and Goswami, 2008, Krarti, 2011). NPV has been identified as the most widely used technique for optimal building energy assessment, when the future cash flow is taken into account

(Remer and Nieto, 1995). It is the main method for the Life Cycle Cost (LCC) calculation, which is defined as a technique that enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs (ISO 15686-5, 2008).

Table 3
Summary of selected research works on economic assessment of energy-efficiency measures applied to housing renovation

No	Reference	Country	Indicators	Energy-efficiency measures
3	Gorgolewski (1995)	UK	SIR	Insulation Different glazing Ventilation control Different boilers District heating
5	Goodacre et al. (2002)	UK	Cost-benefit analysis	Upgrading heating and hot water energy efficiency
6	Papadopoulos (2002)	Greece	NPV	Insulation of envelope Improvement of heating systems
10	Gaterell and McEvoy (2005b)	UK	BCR	Roof insulation Curtains/Insulated shutters Double glazing Cavity wall insulation
13	Amstalden et al. (2007)	Switzerland	DCF(NPV+IRR+PBP)	Envelope insulation Replacement of windows
14	Martinaitis et al. (2007)	Lithuania	CCE	Insulation of walls and roof Replacement of windows Renovation of building service systems
16	Hasan et al. (2008)	Finland	LCC(NPV)	Envelope insulation Glazing improvement
22	Ouyang et al. (2011a)	China	LCC	Insulation of roof and walls Unfixable curtains or blinds Replacement of windows
24	Byman et al. (2012)	Sweden	NPV	Insulation of envelope Replacement of windows and doors Airtightness Ventilation systems with heat recovery Improvement of heating systems
32	Desogus et al. (2013)	Italy	NPV	Wall and roof insulation Replacement of windows

LCC: Life Cycle Cost; SIR: Savings-to-Investment Ratio; NPV: Net Present Value; BCR: Benefit-Cost Ratio; DCF: Discounted Cash Flow; IRR: Internal Rate of Return; PBP: Payback Period; CCE: Cost of Conserved Energy.

Research works that evaluate retrofitting of residential buildings from an economic perspective are introduced in Table 3. Different cost-benefit methods are used according to the scope of the study. Gorgolewski (1995) described a method of identifying an optimum strategy for renovating a dwelling in a typical 12-storey large-panel system-built block in the West London. Energy savings were calculated using the energy model BREDEM 8 (BRE, 1994). A life cycle costing procedure enabled the measures to be ranked in order of decreasing cost effectiveness, indicating which measures should be given priority. A cost-benefit analysis framework has also been used to assess the potential scale of some energy saving renovation measures (Amstalden et al., 2007, Goodacre et al., 2002, Papadopoulos et al., 2002). Gaterell and McEvoy (2005b) investigated the impact of the uncertainty of external environmental and social costs on the relative performance of a range of insulation measures applied retrospectively to an existing residential dwelling. Social costs arise when any costs of production or consumption are passed on to third parties, such as future generations or society in general (Hohmeyer, 2002). Hasan et al. (2008) analyzed the minimization of LCC for a single family detached house, by combining simulation and optimization. In the same vein, Desogus et al. (2013) compared the cost effectiveness of the two retrofit scenarios for the improvement of the fabric thermal performance of stone masonry buildings located in Cagliari, Italy. Byman and Jernelius (2012) evaluated the renovation of various multi-family blocks in Sweden in order to learn from successful examples. In all the refurbishment projects studied, major energy-efficiency improvements were achieved, reducing energy use by half or more. However, they found that, depending on the economic parameters defined (interest rate, growth of energy price, and lifespan) it was not always profitable to halve energy use in apartment buildings. In order to address this issue, the IEA ECB Annex 56 project (Ott et al., 2014), which is under development, aims at developing a new methodology for the cost effective renovation of existing buildings, using the right balance between energy conservation and efficiency measures on the one hand, and measures and technologies that promote the use of renewable energy on the other. An in-depth analysis of the parameters considered in cost-effectiveness methodologies used in housing retrofitting initiatives, including the life cycle approach, is presented in section 3.4.2.

3.3. Multi-criteria assessment

Multi-criteria analysis methodologies have been increasingly developed in order to achieve sustainable assessment, and whilst economic and environmental impacts are generally considered, social impacts - which are consequences of positive or negative pressures on social endpoints i.e. the well-being of stakeholders (UNEP, 2009) - are still put aside (Table 4). Gero et al. (1983) were among the first authors to propose a multi-criteria (MC) model to be used at the process of building design in order to explore the trade-offs between building thermal performance and other criteria such as capital cost and usable area of the building.

More recently, other researchers have also applied MC techniques for the evaluation of retrofitting scenarios (Alanne, 2004, Jaggs and Palmer, 2000, Rey, 2004). Verbeeck and Hens (2005) discussed economically feasible ways of choosing between insulation measures, better glazing, and renewable energy systems such as solar collectors and PV cells. The impact of these measures on energy consumption and greenhouse gas emissions was assessed through a life cycle inventory of the primary energy consumption and the CO_2 emissions from a cradle to grave perspective, while the economic impact was assessed through the total net present value.

With respect to a discussion of methodological approaches, some authors have analyzed the application of various frameworks. Diakaki et al. (Diakaki et al., 2008, 2010) investigated the feasibility of applying multi-objective optimization techniques, which is a scientific area that offers a wide variety of methods with great potential for resolving complicated decision problems (Munda, 2005), to the problem of improving energy efficiency in buildings. Juan et al. (2009) developed a genetic algorithm-based decision support system for housing condition assessment that suggests optimal refurbishment actions that take into account the trade-off between cost and quality. Magnier and Haghighat (2010) applied the GAINN approach for the optimization of thermal comfort and energy consumption in a residential house. This approach first used a simulation-based Artificial Neural Network (ANN) to characterize building behavior, and then combined this ANN with a multi-objective Genetic Algorithm (NSGA-II) for optimization. Chantrelle et al. (2011) developed a new tool, MultiOpt, for the multi-criteria optimization of renovation operations, with regard to building envelopes, HVAC systems, and control strategies. MultiOpt was based on an existing optimization method, NSGA-II, considering four criteria: energy consumption, cost, life-cycle environmental impact, and thermal comfort.

Asadi et al. (2012) presented a multi-objective optimization model to quantitatively assess technology choices in a building retrofit project. Bojic et al. (2012) studied the possibilities of decreasing energy consumption in a thermally non-insulated old house in Belgrade, Serbia. By using EnergyPlus (US Department of Energy, 2015), the conditioned space inside the old and refurbished houses was simulated for the single and combined refurbishment measures. The results obtained were analyzed in terms of energy savings, investment, and investment return. Brown et al. (2013) proposed a method for assessing renovation packages drawn up with the goal of increasing energy efficiency. The method included calculation of bought energy demand, life cycle cost analysis, and assessment of the building according to the Swedish environmental rating tool (Malmqvist et al., 2011).

Table 4

Summary of selected research works on multi-criteria assessment of energy-efficiency measures applied to housing renovation

No	Reference	Country	Indicators			Energy-efficiency measures
			Environmental	Economic	Social	
2	Cohen et al. (1991)	US	Analysis of metering data	Actual installation costs		Insulation of ceiling, walls and foundations Replacement of windows Heating system retrofits
4	Jaggs et al. (2000)	Greece	Improved indoor environmental quality Optimization of energy consumption	Cost effectiveness		Insulation of walls and roof Double glazed windows New boiler Solar panels
7	Al- Ragom (2003)	Kuwait	DOE-2.1E	Simple payback method		Wall and roof insulation Change of glazing system Decrease of window area
8	Alanne (2004)	Finland	Environmental value	Investment cost	Functionality	Insulation of walls and roof Replacement of windows Heat recovery in ventilation Decrease of indoor temperatures Economizer jets in water fittings
11	Mahlia et al. (2005)	Malaysia	Simple energy calculation	Cost-benefit analysis		Replacement of incandescent lamps by compact fluorescent lamps (CFL)
12	Verbeek and Hens (2005)	Belgium	LCI (Primary energy + CO_2 emissions)	NPV		Insulation Glazing improvement Solar collectors and PV cells
17	Diakaki et al. (2008, 2010)	Greece	Global annual primary energy consumption CO_2 emissions	Investment cost		Wall insulation Windows replacement Improvement of building services Solar collectors
19	Magnier and Haghighat (2010)	Canada	Energy savings (ANN+TRNSYS)		Thermal comfort	Glazed area Orientation of windows Thermal mass HVAC optimization
20	Nemry et al. (2010)	EU-25	LCA	NPV IRR		Replacement of windows Insulation of walls and roof New sealing
23	Asadi et al. (2012)	Portugal	Energy savings (TRNSYS)	Retrofit cost (GenOpt)		Insulation of walls and roof Replacement of windows Solar thermal collectors
26	Bojic et al. (2012)	Serbia	Energy savings (Energy Plus)	Investment Investment return		Insulation of walls and ceiling New partition below the old ceiling
27	Dall'O et al. (2012)	Italy	Energy savings	Inversion cost Annual savings		Insulation of walls and roof Replacement of windows New sealing
28	Häkkinen (2012)	EU-25	Simulation Footprint	LCC		Insulation of walls
30	Brown et al. (2013)	Sweden	Energy demand MB	LCC		Insulation of walls, roof and foundations Replacement of windows Improvement of heating and mechanical ventilation systems
35	Risholt et al. (2013)	Norway	Energy demand	LCC	Home qualities	Insulation of walls Windows replacement
36	Vrijders and Wastiels (2013)	Belgium	LCA	LCC		Insulation of roof and walls Replacement of windows Improvement of heating and hot water production PV panels
37	De Angelis et al. (2013)	Italy	LCA	LCC		Insulation of roof and walls Replacement of windows
38	Ostermeyer (2013)	France	LCA	LCC		Insulation of roof and walls Replacement of windows Improvement of heating and mechanical ventilation systems
40	Antipova et al. (2014)	Portugal	LCA	Cost (investment+energy consumption)		Insulation of walls and roof Replacement of windows Solar thermal collectors
42	Cetiner and Edis (2014)	Turkey	LCA	LCC		Insulation of building envelope Replacement of windows

NPV: Net Present Value; LCI: Life Cycle Inventory; LCA: Life Cycle Assessment; IRR: Internal Rate of Return; MB: Swedish environmental rating tool; LCC: Life Cycle Cost.

Risholt et al. (2013) evaluated the sustainability of two nearly-zero energy renovation strategies in a Norwegian detached house. They proposed an iterative method for sustainability analysis, including energy and technical performance after renovation, life cycle cost, and homeowner preferences. Vrijders and Wastiels (2013) evaluated the renovation of a building in Belgium considering different scenarios through the LCC and LCA methodologies. In this case, cost efficiency and environmental impacts were compared separately. In Northern Italy, De Angelis et al. (2013) analyzed a multi-story residential building in order to evaluate various renovation alternatives, defining a practical LCA and LCC-based method. With a broader scope, Ostermeyer et al. (2013) proposed a multidimensional Pareto optimization methodology, using LCC and LCA. According to the Pareto principle, the options from the considered population of alternatives are optimal (non-dominated) if there is no other option that improves one objective without simultaneously worsening at least one other objective (Marler and Arora, 2004). It was used to analyze a case study from an EU project named BEEM-UP in which solutions for large-scale uptake of refurbishment strategies were developed. Cetiner and Edis (2014) defined an environmental and economic sustainability assessment method to evaluate the effectiveness of existing residential building retrofits for reducing their heating energy consumption, and the resulting emissions. The proposed method was based on the life cycle assessment method, and evaluated the environmental and economic sustainability performance of building envelope retrofits.

3.4. The role of the life cycle approach in housing renovation

3.4.1. Life Cycle Assessment (LCA)

LCA was initially developed for industrial products in the 1970s. Its first application in the building sector was concerned only with energy issues (Kohler, 1986). Over recent decades, the relevance of considering environmental-related product information by LCA has been broadly recognized (Beccali et al., 2013). Some building LCA studies focus on materials (Nicoletti et al., 2002, Bolin and Smith, 2011, Audenaert et al., 2012) or only address the production phase of a building (González and García Navarro, 2006, Asif et al., 2007, Zabalza Bribián et al., 2011). Nevertheless, a LCA of a building is a complex task due to several factors, including the long lifespan (often more than 50 years), the number of involved stakeholders, and the singularity of each building. When the energy performance of a building improves because of retrofit measures, additional materials and components are applied, resulting in higher embodied energy (Chen et al., 2001). Thus, when assessing environmental impacts throughout the life cycle, it is critically important to consider both the embodied energy of the retrofit measures and the post-retrofit building energy consumption.

LCA follows the ISO standards 14040 (2006) and 14044 (2006). The main assumptions of life cycle assessment for the retrofitting of residential buildings are described in Table 5. The functional unit is not included, since it was mentioned in only 4 studies. Nemry et al. (2010) defined it as "the use of $1m^2$ of the building's living area over the period of one year". The selected functional unit for the LCA study performed by Beccali et al. (2013) was the assessed building. De Angelis et al. (2013) specified it as "1 m^2 of living area". Finally, Assiego de Larriva et al. (2014) described it as "the energy needed (MJ) to ensure the conditions of comfort with in the dwellings during one year". The considered service life differs from 20 to 60 years, being 50 years the most representative. The most common system boundaries adopted are “cradle-to-grave”. A wide variety of impact categories have been found in environmental assessments. Global warming potential is addressed in 33% of the papers reviewed, followed by cumulative energy demand, (25%), acidification potential (25%), and eutrophication potential (25%).

Table 5
Information considered in the LCA for the retrofitting of residential buildings (including multi-criteria assessment methodologies)

No	Reference	Country	Lifespan (yr)	System boundaries	Calculation method	Impact categories	Units
12	Verbeek and Hens (2005)[1]	Belgium	30	Cradle-to-grave	Life cycle inventory	Primary energy consumption	kWh/year
						CO_2 emissions	ton/year
18	Dodoo et al. (2010)	Sweden	50	Cradle-to-grave		Net primary energy use	kWh/m^2
20	Nemry et al. (2010)[1]	EU-25	40	Cradle-to-grave	CML 2001	Primary energy (PE)	MJ/m^{2}a
						Acidification Potential (AP)	%
						Eutrophication potential (EP)	%
						Global warming potential (GWP)	kgCO_{2eq}/m^{2}a - %
						Ozone layer Depletion Potential (ODP)	%
						Photochemical Ozone Creation Potential (POCP)	%
21	Ouyang et al. (2011b)	China	20	Construction + Use phase	Simple LCCO_2 method	Annual energy savings	kWh/a & kWh/(m^2 a)
						CO2 emissions reduction	kgCO_2
25	Bin and Parker (2012)	Canada	50	Cradle-to-grave	Footprint methodology	Embodied Energy (EE)	kWh
						Embodied Carbon (EC)	kgCO_2e
						Ecological Footprint (EF)	gha
29	Beccali et al. (2013)	Italy	50	Cradle-to-grave	Cumulative Energy Demand (CED) Method (Primary energy requirement)	Cumulative Energy Demand (CED)	GJ
						Global Warming Potential (GWP)	kgCO_{2eq}
						Ozone Depletion Potential (ODP)	kgCFC_{11eq}
						Acidification Potential (AP)	kgSO_{2eq}
						Eutrophication Potential (EP)	kg$PO_4^{3-}{}_{eq}$
						Photochemical Ozone Creation Potential (POCP)	kgC_2H_{4eq}
36	Vrijders and Wastiels (2013)[1]	Belgium	60	Construction + Use phase	ReCiPe Endpoint (H) / Europe ReCiPe H/A	Pts (ReCiPe)	Pts
37	De Angelis et al. (2013)[1]	Italy	50	Use phase		Cumulative Energy Demand (CED)	MJ/m^2
						Golbal Warming Potential (GWP)	kgCO_{2eq}/m^2
38	Ostermeyer (2013)[1]	France	30		ReCiPe H/A	ReCiPe H/A	
						IPPC 100	
						CED	
39	Assiego de Larriva et al. (2014)	Spain	20[2]	Gate-to-grave		Gross energy requirement (GER)	MJ/FU
						Global Warming Potential (GWP)	kg$CO_{2eq.}$/FU
40	Antipova et al. (2014)	Portugal		Cradle-to-gate	CML 2001	Climate change	kg CO2-Eq
						Human toxicity	kg 1,4-DCB-Eq
						Aquatic toxicity	kg 1,4-DCB-Eq
						Terrestrial toxicity	kg 1,4-DCB-Eq
						Eutrophication (EP)	kg NOx-Eq
						Acidification (AP)	kg SO2-Eq
42	Cetiner and Edis (2014)[1]	Turkey	50	Cradle-to-grave	$NR_{i,j}=(NI_i-NI_j)x100/NI_i$	Eco-indicator point (eco-point)	Eco-points (NI)

NR: environmental performance; NI: environmental impacts; i: building type; j: retrofit alternatives.

[1] Authors considering LCA as a part of multi-criteria assessment.

[2] The lifespan considered for the building is 50 years. It was built in 1983 and the renovation was done in 2013. The remaining lifespan is 20 years.

LCA has been used to perform optimization studies, but the assumptions regarding occupants' behavior (e.g. thermostat set point temperature, water consumption etc.) are generally not described, whereas occupant behavior is directly related to the energy use of the building (Guerra Santin et al., 2009, Guerra-Santin and Itard, 2010, Mullaly, 1998, Owens and Wilhite, 1988, Seligman et al., 1978, Steg, 2008). Several studies have shown that occupant behavior may vary to such an extent that the resultant building energy use differs by a factor of two or more (Baker and Steemers, 2000, Steemers and Yun, 2009). Galling et al. (2013) found that the theoretical heating energy savings being achieved in Germany were around 33%, while post-renovation heating energy savings based on measured consumption were likely to be 25%. Because of the relevance of user behavior for energy consumption, Peuportier et al. (2013) developed an approach that incorporated a sensitivity study regarding the influence of occupants on energy use, along with other environmental issues.

The consensus to date has been that the majority of life cycle energy and carbon impacts are accrued during the use phase (Gustavsson and Joelsson, 2010, Russell-Smith et al., 2015). Keoleian et al. (2000) found a wide distribution of effects accruing from all stages of the life cycle of a residential building, with most of them emerging from the use phase. Sartori and Hestnes (2007) found significant impacts throughout the life cycle of constructed facilities, with a strong correlation between total life cycle energy consumption and operating energy consumption. However, after retrofitting a building, the energy use decreases, but this is accompanied by an increase in use of materials, which increases the demands on production energy. Therefore, the embodied energy of building materials increases, and the energy use in the operation phase is comparable to those of other phases (Ardente et al., 2011). Cellura et al (2013b) demonstrated that, in the assessment of the energy and environmental benefits arising from a specific implemented policy or action, it is of primary importance to compute, in addition to the direct energy saving arising from the implemented measure, the indirect energy consumed to implement this measure. Thus, the project IEA EBC Annex 57 (2014) is attempting to develop guidelines for both evaluating and reducing the embodied energy and CO_2 emissions resulting from building construction.

3.4.2. *Life Cycle Cost (LCC)*

LCC has its origins in the US Department of Defense in the mid-1960s (Epstein, 1996). In the mid-1980s, attempts were made to adapt LCC to building investments (Bennett and Norman, 1987). Recently, several research projects have been conducted with the aim of finding the optimal energy strategy for housing refurbishment, using LCC to give an indication of the financial benefits over the life of the measures (Amstalden et al., 2007, Brown et al., 2013, Cetiner and Edis, 2014, Desogus et al., 2013, Gorgolewski, 1995, Hasan et al., 2008, Ostermeyer et al., 2013, Papadopoulos et al., 2002, Risholt et al., 2013, Verbeeck and Hens, 2005, Vrijders and Wastiels, 2013). The municipality of Växjö decided to calculate life cycle costs as the basis for the selection of energy-efficiency measures of their buildings. To do so, the model Belok LCC - a tool for cost and energy calculations for alternative investments - was developed (Gustavsson, 2012). The approach taken by Amstalden et al. (2007) is based on the logic that economically optimal design interventions minimize the sum of construction and operating expenses (energy costs accrued from space conditioning) over the lifetime of the building. LCC has also been applied to identify opportunities for improvements in the current housing stock (Cuéllar-Franca and Azapagic, 2013, Morrissey and Horne, 2011, Nemry et al., 2010). For example, Cuéllar-Franca and Azapagic (2013) found from the LCC analysis of the UK housing stock that use stage was responsible for the majority (52%) of the costs, largely from the use of energy. The construction stage contributed 35%, while end-of-life activities were responsible for 13% of the total costs. Therefore, these areas were identified as those that need to be targeted for reducing the housing life cycle costs. For example, making the existing houses more energy-efficient through improved insulation, and the use of energy-efficient appliances and lighting would not only reduce energy bills but also environmental impacts, since the use stage was also the hot-spot for most impact categories.

Table 6 includes the main considerations adopted in the assessment of LCC in energy-efficient retrofit investments. With respect to calculation methods, net present value (NPV) was conducted in 56% of the papers reviewed, followed by payback period (31%), and internal rate of return (25%). Note that NPV is the normal measure used in LCC analysis, although others are available, including payback period, net savings (NS), saving-to-investment ratio (SIR), internal rate of return (IRR), and annual cost (AC) or annual equivalent cost (AEC) (ISO 15686-5, 2008). A classification into cradle-to-gate and cradle-to-grave is rather unusual in LCC studies. They are typically conducted from the perspective of a specific economic decision maker (e.g., producer, consumer, supply chain) (Dhillon, 1989). Accordingly, LCC studies focus mainly on the life cycle phases where monetary effects occur that are relevant for the respective decision maker. This is strongly reflected in the information presented in Table 6.

It is recognized that the lifespan applied in LCC can significantly alter economic and environmental outcomes (Aktas and Bilec, 2012, Mequignon et al., 2013a). Typically, the longer the life of the house is, the lower the environmental impacts and the greater the economic benefits are (Moore and Morrissey, 2014). However, there is no universal standard for what the lifespan of a building should be. Given that lifespan is considered to represent a long period of time (from 30 to 100 years, or more), the timing of cost and benefit flows is important. A common technique to reflect this is the use of discounting. The time value of money - expressed as a discount rate - depends on inflation, cost of capital, investment opportunities, and personal consumption preferences (Pike and Dobbins, 1986, Perkins, 1994, Kirk and Dell'Isola, 1995). The selection of an appropriate discount rate is often raised in criticisms of LCC analysis of minimum housing standards, and more broadly in the evaluation of environmental cost–benefit analysis (Moore and Morrissey, 2014). Hasan et al. (2008) found, through a sensitivity analysis, that the ranking of the best construction solutions they established was valid for a maximum real interest rate of 4% and if the real interest was higher, the preferred solution they had previously found was not feasible. According to the guidelines given by the European Commission (2012), a higher real discount rate (typically higher than 4%) will reflect a purely commercial, short-term approach to the valuation of investments. A lower rate (typically ranging from 2% to 4%) will more closely reflect the benefits that energy-efficiency investments bring to building occupants over the entire lifetime of the investment.

Table 6
Information considered in the LCC for the retrofitting of residential buildings

No	Reference	Country	Lifespan (yr)	System boundaries	Impact categories	Real interest rate	Nominal interest rate	Inflation rate	Energy price increase	Energy policy instruments
3	Gorgolewski (1995)	UK	30	Investment + use phase	SIR Net benefit (£) Cumulative net benefit (£)	4%	-	-	0%	Not considered
6	Papadopoulos (2002)	Greece	50	Investment + use phase	DBP (years) SIR	6%	-	-	Sensitivity analysis on energy prices, covering a range of 40% variation	No tax reduction or any other form
10	Gaterell and McEvoy (2005a)	UK	47	Investment + use phase	BCR	6%	-	-		Not considered
12	Verbeek and Hens (2005)[1]	Belgium	30	Investment + use phase	Investment (€) Yearly energy cost (€/year) Total net present value (€) Payback time (year) Investment/ton yearly avoided CO_2 (€/ton)	5%	-	0%	2%	Not considered
13	Amstalden et al. (2007)	Switzerland	40	Investment + use phase	NPV IRR PBP	3.5%	-	-	4 scenarios to cover future oil prices 4 scenarios to postulate a dynamic development of fuel oil price, such as 1.5% and 2.5% per year.	Subsidies Income tax deduction Carbon tax
16	Hasan et al. (2008)	Finland	20; 50	Investment + use phase	dLCC (€) dOC (€) dIC+dRC (€)	4,90%; 2,94%	7%; 5%	2%	1%; 5%	Not considered
20	Nemry et al. (2010)[1]	EU-25	40	Investment + use phase	NPV IRR	4%	-	-	2%	Not considered
21	Ouyang et al. (2011b)[1]	China	40	Investment + use phase	NPV IRR		6%	3%	Annual energy savings: 2% Electricity price: 2%	Not considered
24	Byman et al. (2012)	Sweden	50	Investment + use phase	NPV	5% 4,25%	-	-	0% 4%	Not considered
30	Brown et al. (2013)[1]	Sweden	50	Investment + use phase	LCC	5%	-	1.2%	Electricity: 2% District heating: 1.4%	Not considered
32	Desogus et al. (2013)	Italy	30	Investment + use phase	IROR NPV PBT	5%	-	-	0%	A55% public financing spread over the first 10 years.
35	Risholt et al. (2013)[1]	Norway	30	Investment + use phase	LCC (NPV) PBT	4%	-	2%	5%	Financial support from Enova
36	Vrijders and Wastiels (2013)[1]	Belgium	30	Investment + use phase	Investment cost (€) NPV (€)	1.96%	-	-	2.25%	The influence of financial incentives is taken into account
37	De Angelis et al. (2013)[1]	Italy	50	Investment + use phase + demolition	Cost	0%	-	-	0%	Not considered
38	Ostermeyer (2013)[1]	France	30	Investment + use phase	LCC_{TFA}	5%	-	2%	5%	Not considered
42	Cetiner and Edis (2014)[1]	Turkey	50	Investment + use phase	CR CI	6.71%			0%	Not considered

SIR: Savings-to-Investment Ratio; PV: Present Value; DBP: Depreciated Payback period; NPV: Net Present Value; DCFs: Discounted Cash Flows; BCR: Benefit Cost Ratio; IRR or IROR: Internal Rate of Return; PBP/PBT: Payback Period; dLCC: difference in Life Cycle Cost; dOC: difference in Operating heating energy Cost; dIC+dRC: difference in Investment Cost including associated Replacement Cost; TFA: Treated Floor Area; CR: economic performance; CI: economic impact.

[1] Authors considering LCC as a part of multi-criteria assessment.

Assumptions concerning the future energy price notably affect the outcome of the investment analysis of energy-efficient retrofitting. Investors frequently assume that the average energy price remains constant during the time of amortization of the investment and that past prices can be used to predict future costs. However, given the increasing global energy demand and that the supply of cheap fossil fuels is imminently expected to reach a maximum (Campbell, 2002, Greene et al., 2006, IEA, 2004), this optimistic speculation is no longer economically sound. In the analyzed works, energy price increase differs from 1 to 5%. Papadopoulos (2002) performed a sensitivity analysis on energy prices, covering a range of 40% variation, whereas Amstalden et al. (2007) proposed 4 scenarios to cover future oil prices and a further 4 scenarios that assume a dynamic development of fuel oil price. Next to the actual installation costs, the profitability from the investor's perspective is influenced by various other factors such as subsidies and income tax deductibility, which are offered in many countries, or by levies on energy use or CO_2 emissions.

Another effect that requires consideration is the future development of investment costs of energy-efficiency measures. During the course of applying a new technology, the price of the technology usually decreases, due to economies of scale or learning effects. This is commonly described by the experience curve concept (IEA, 2000, Jakob and Madlener, 2004). Jakob et al. (2002) estimated the potential for decreasing the cost of energy conserving measures in buildings by investigating cost decrease curves of the past. In their analysis, they included the potential for technical progress, the extent of future application of energy-efficiency measures, and assumptions about future labor and energy costs.

3.4.3. Environmental and economic optimization

Integrated economic and environmental decision-making is a subject of growing importance in the assessment of renovation solutions. In this regard, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are promising instruments for the modeling and calculation of the respective effects (Bierer et al., In press, Optis and Wild, 2010). However, they have been developed quite independently, and so there are differences in terminology, framework, and calculation rules. In the present review, some inconsistencies were found when LCA and LCC where conducted in the assessment of retrofitting solutions. System boundaries differed in some research studies (Cetiner and Edis, 2014, Nemry et al., 2010). In particular, whilst LCA studies used a cradle-to-grave classification, LCC studies, considered only investment and use phase costs. Table 7 presents different ways of combining LCA and LCC in order to optimize the energy performance of housing. The work of Allacker and De Troyer (2013) has been included, as they developed an interesting methodology in order to optimize the Belgian housing typologies.

Table 7
Environmental and economic optimization of energy-efficiency strategies in residential buildings

No	Reference	Country	Lifespan (yr)	Environmental impacts	Economic impacts	Optimization method
	Allacker and De Troyer (2013)	Belgium	60	External cost (€/m^2) External initial cost (€/m^2)	Life cycle cost (€/m^2) Initial cost (€/m^2)	Pareto optimization
37	De Angelis et al. (2013)	Italy	50	Cumulative Energy Demand (MJ/ m^2) CO_{2eq} emissions (kgCO_{2eq}/m^2)	Life cycle cost (€/m^2)	Pair-wise ranking method
38	Ostermeyer (2013)	France	30	ReCiPe (%) CED (%) IPCC (%)	Life cycle cost (%)	Pareto optimization
42	Cetiner and Edis (2014)	Turkey	50	NR	CR	Weighted-sum method

NR: environmental performance; CR: economic performance

4. Discussion

A review of the literature has revealed that the various retrofitting strategies employed in sustainable housing renovation appear to be broadly similar. Results showed that envelope insulation, window replacements, and air sealing are the most common strategies under consideration. However, this does not mean that the most preferred insulation material and thickness for a certain element, i.e. facade, would be the same using different assessment methodologies. When the energy demand of a building is reduced due to retrofitting, the importance of the materials increases. Moreover, the high reduction of energy consumption is not always profitable from a financial perspective (Byman and Jernelius, 2012). LCA and LCC should be used to find the most preferred solutions from an environmental and economic point of view by searching for optimal solutions. To this end, the Pareto Optimization method was found to be a useful approach.

When combining LCA and LCC, discrepancies found in the results do not appear to be problematic. System boundaries, as well as the functional unit, should be equally defined for both environmental and economic assessment, as they are common aspects (Allacker, 2012). A limitation found in the environmental and economic optimization is the different ways of weighting and normalizing environmental impacts in order to have a single score value which can be easily compared with financial results. A multiplicity of individual impact scores is rarely a good basis for decision-making. Although the CEN-TC/350 working group has defined the most appropriate environmental impact indicators at both product and building level (CEN, 2011, CEN, 2012), more studies are needed for the application of an integrated and transparent aggregation method. This is particularly important for progressing towards a comprehensive assessment of life cycle sustainability.

In order to minimize limitations and uncertainties in the life cycle approach, it is necessary to conduct sensitivity analyses of lifespan, occupant behavior, discount rate and growth of energy price. It is recognized that the lifespan applied in LCA and LCC can significantly alter economic and environmental outcomes (Aktas and Bilec, 2012, Mequignon et al., 2013b). Moore and Morrisey (2014) found, from a sensitivity test, that by extending residential building lifespan from 40 years, which is currently used in Australia, to 80 years, economic benefits to the household increased by more than six times. Several authors demonstrated that occupant behavior has a major influence on final energy consumption, this being the main reason underlying the significant gaps between actual and predicted energy use (Baker and Steemers, 2000, Bühring and Kiefer, 2002, Haas and Biermayr, 2000, Steemers and Yun, 2009, Sunikka-Blank and Galvin, 2012). There are assumptions about occupant behavior, particularly within the energy modeling tools, which may not reflect actual behavior, or future changes to behavior. Some studies have shown that targeting occupant behavior can lead to improved energy-efficiency outcomes of up to 40% (Abrahamse et al., 2005, Benders et al., 2006). Although this should be considered in both LCA and LCC, none of the studies compared in tables 5 and 6 have taken it into account. More research is therefore needed on ways of reducing the gap between real and predicted energy use, which has a significant impact on the final results.

With regard to uncertainties in LCC, the results found by Moore and Morrisey (2014) revealed that the selected discount rate had a significant impact on the net present value. Overall, the lower the discount rate the greater the net present value is (Hasan et al., 2008, Moore and Morrissey, 2014). The future price of energy is also relevant. Results are better for a future scenario of high energy prices than for a low energy price future. Hasan et al. (2008) found that a higher reduction in LCC was obtained in cases that had both a higher escalation of electric energy price and a higher lifespan.

The idea of sustainability as defined by the triple-bottom approach and its three dimensions of sustainability are not visible in the building sector (Ostermeyer et al., 2013). Most importantly, Life Cycle Sustainability Assessment (LCSA) is still weak and relatively rare, meaning that a whole pillar is often excluded from consideration in many assessments (Dreyer et al., 2006, Kaatz et al., 2006, Reitinger et al., 2011). Although few papers considered LCA and LCC simultaneously, none of the papers reviewed considered Social Life Cycle Assessment (S-LCA), which is a method that can be used to assess the social and sociological aspects of products, and their actual and potential positive and negative effects throughout the life cycle. This looks at the extraction and processing of raw materials, manufacturing, distribution, use, reuse, maintenance, recycling and final disposal (UNEP, 2009). The application of S-LCA is still difficult, as it still remains unregulated. For future work, the development of suitable indicators should be promoted in order to solidly implement the use of this method in the building sector (Kloepffer and Renner, 2008).

5. Conclusions and future outlook

This paper presents a critical review of the work related to energy-efficiency strategies, and discusses the sustainability assessment methods applied in building retrofits, summarizing illustrative works in Tables 1, 2, 3, 4, 5, 6 and 7. The results showed that envelope insulation, window replacements, and air sealing are the most common strategies under consideration. However, the results highlighted the need to apply a life cycle approach in order to find optimal retrofitting solutions and the real improvement potential of housing renovation. Further work should focus on the development of a methodology to assess retrofitting strategies from the environmental and economic life cycle approach.

The key points that have been highlighted from the results should be integrated into methodology. In order to avoid inconsistencies, functional unit as well as system boundaries should be equally defined for LCA and LCC. Furthermore, sensitivity analysis is critical for reducing uncertainties. Although CEN-TC/350 (2011, 2012) recommends mid-point impact indicators for the LCA, a multiplicity of individual impact scores hinders the possibility of combining these with financial indicators. Aggregation and weighting methods were used in all the cases analyzed in Table 7.

However, they were all different. As highlighted in the discussion, more research is needed for the application of harmonized and transparent aggregation methods.

Finally, the social dimension is still underdeveloped, and none of the reviewed studies considered S-LCA. Further research is required in order to define the methodology and the impacts of this pillar, as well as to incorporate it into life cycle sustainability assessment (LCSA). This would represent a significant step forward in meeting the strong need for an integrated methodology that takes into account environmental, economic, and social impacts from a life cycle perspective.

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