Open access • Journal Article • DOI:10.1016/J.RSER.2015.07.037

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Published on: 01 Dec 2015 - Renewable & Sustainable Energy Reviews (Pergamon)

Topics: Energy consumption and Efficient energy use

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Reference:
De Boeck L., Verbeke Stijn, Audenaert Amaryllis, De Mesmaeker L..- Improving the energy performance of residential buildings : a literature review
Renewable and sustainable energy reviews - ISSN 1364-0321 - 52(2015), p. 960-975
Full text (Publisher's DOI): http://dx.doi.org/doi:10.1016/J.RSER.2015.07.037
To cite this reference: http://hdl.handle.net/10067/1268960151162165141

Improving the energy performance of residential buildings: a literature review

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Abstract: Promoting energy efficiency improvements of residential buildings is considered to play an important role in achieving the Kyoto targets. That is because it allows us to reduce energy consumption without curtailing social welfare. It is worth noting that there is an increasing amount of literature on this topic that has been published in recent years. This paper therefore provides an updated review of the literature on improving the energy performance of residential buildings. The set of materials obtained has been examined according to the following topics: area of application and design variables, objectives and performance measures, type of analysis, solution methodology, software tools, case study location and type of building. Apart from trends related to the different topics, opportunities for future research are also presented.

Keywords: energy efficiency; optimization; residential buildings; literature review

1 Introduction

Global CO_2 emissions follow an upward trend and it is presumed that they will keep on growing. Without any further international policies, greenhouse gas (GHG) emissions will rise by 52% from 2005 to 2050, while energy-related CO_2 emissions are expected to climb by 78% (OECD, 2008) [78]. More recent figures from IPCC (2014) [132] indicate that annual GHG emissions continued to increase yearly with 1 gigatonne carbon dioxide equivalent (GtCO2eq) from 2000 to 2010 as compared to 0.4 GtCO2eq from 1970-2010. CO2 emissions from fossil fuel combustion and industrial processes made up about 78% of the total GHG emissions from 1970-2010 and from 2000-2010. Without additional efforts to reduce GHG emissions, they are presumed to keep on growing due to growth in global population and economic activities. The global economic crisis in 2007-2008 has only temporarily reduced emissions (IPCC, 2014) [132]. The increasing international concern related to these high emission levels has led to the Kyoto Protocol, an international treaty setting binding greenhouse gas emissions limitations to the signatories (UNFCCC, 2013) [98]. Promoting energy efficiency improvements is considered to play an important role in achieving these targets because it reduces energy consumption without curtailing social welfare (Kenichi et al., 2012; IEA, 2014) [59, 133].

The final level of energy consumption in the EU-28 for 2012 reached 1104 million tons of oil equivalent (Mtoe), of which 289 Mtoe (26.2%) was attributed to the residential sector (i.e. approximately 2/3 of total energy use in buildings) (European Commission, 2014; Poel et al., 2007) [27, 80]. Residential buildings account for 75% of the total building stock in the EU27 (BPIE, 2011) [117]. Energy in dwellings is mainly consumed by space heating (68,4%) and hot water production (13.6%) (EEA data 2008, climate corrected). The energy used for cooking (3.8%) and electricity for lighting and appliances (14.1%) is far less significant (EEA, 2014) [122]. Improving the energy performance of dwellings could therefore be pointed to as an important opportunity in this energy challenge. Indeed, the building sector has a lot of potential for cost-effective energy savings equivalent to a consumption in the EU of 11% less final energy in 2020 (EU, 2008) [125]. For this purpose the European Commission has launched the Energy Performance of Buildings Directive (EPBD) (2002/91/EC and recast 2010/31/EU). This compilation of general principles and objectives aims to substantially augment investments in energy-efficiency measures within EU buildings, both residential and non-residential.(van Dijk, Wouters et al., 2008) [101]. The EPBD requires member states to implement energy performance certification for existing buildings, inspection of heating and cooling devices and legally imposed performance requirements for new and thoroughly renovated buildings. For the latter, the EPBD recommends all EU member states to employ a methodology for calculating the energy performance of newly constructed buildings, considering at least thermal and insulation characteristics, space and hot water heating, ventilation and air conditioning (HVAC) systems, lighting installations, orientation of the building and indoor climatic conditions (Poel et al., 2007) [80].

In addition to the regularitory approach such as implemented in the EU EPBD, many voluntary building environmental assessment schemes have emerged internationally, such as BREEAM, LEED, SBTool, CASBEE, BEAM Plus and ESGB. These voluntary building environmental assessment schemes cover multiple domains such as transport, waste and water. Some even extend to social and cultural aspects. There is a large variation amongst the building environmental assessment schemes, both on the actual performance criteria of the schemes, the weighting of scores of the multiple performance domains and the scope and organization of the certification systems. This allows to suit the assessment schemes to their respective local contexts, but complicates the benchmarking and comparison of different assessments. (Alyamia et al., 2012; Lee, 2013)[112,136]. The voluntary building environmental assessment schemes have a much broader approach compared to EPBD, but nonetheless energy performance of buildings generally accounts for a significant share of the credits (Lee, 2013) [136]. In this review paper, the focus will be solely on the domain of energy in residential buildings.

In accordance with energy performance legislation and building environmental assessment schemes, several building design optimization studies have been carried out. The optimization methods used in these studies consider both low-emission levels and energy-efficiency performance through modifying different characterics of buildings and in doing so seek to minimize energy consumption and costs (Fesanghary et al., 2012) [28]. Financial limitations and important uncertainties in this retrofit problem, such as climate change, governmental policy change and occupant behaviour, can easily influence the selection between proposed measures and thereby define the success of adjustments. It is certain that the complex whole of interactions between all components of a building and its environment need to be considered in finding the most energy-efficient solution that meets the needs of energy and non-energy related issues such as financial, legal and social factors (Ma et al., 2012) [68].

In recent years, an increasing amount of literature on optimizing energy efficiency in residential buildings has been published. In these studies, different kinds of quantitative models have been developed and examined to find a solution for this optimization problem. Researchers investigated different fields of application such as the building envelope insulation thickness, window characteristics, HVAC systems, etc., utilizing specific constraints and parameters. These methods mostly focus on developing an approach for "designing" the most economically profitable residential building by, for example, minimizing life cycle costs (LCC). This paper will discuss the available literature concerning the extensive range of possibilities for improving the energy efficiency in the residential sector.

Complementary to literature on methods for optimizing energy efficiency in residential buildings, a lot of research on specific parameters influencing the actual energy performance of a building has been published. Despite the advanced energy calculation tools available nowadays, a significant mismatch between predicted energy performance and actual energy consumption of a building is frequently revealed. This is often referred to as the 'performance gap' (De Wilde, 2014; Menezes et al., 2012;) [120, 138]. Apart from modelling errors or faulty construction, this performance gap is largely due do to the substantial impact of several parameters, of which actual values are hard to predict. These parameters include the influence of occupant behavior (Gill et al., 2010; Yu et al., 2010) [128, 142], day lighting control strategies (Bourgeois et al., 2006) [116], uncertainty in material properties and design parameters (Hopfe and Hensen, 2011) [131], and climatic data (Bhandari et al., 2012) [115]. The study of these parameters is not part of this literature review. Nonetheless, these parameters are often implicitly present as boundary conditions in the examined literature. Assumptions on parameters such as climate and occupant behavior can have a big impact on the energy performance of a building, hence interpretation and mutual comparison of research data should be performed with care.

When browsing scientific databases for other available literature reviews concerning optimizing energy efficiency in residential buildings, we were able to find reviews mainly focusing on one specific field (Kaynakli, 2012; Stevanović; 2013; Evins, 2013; Harvey, 2013) [58, 88, 126, 130, 140] within the domain of energy improvement of (residential and/or commercial) buildings. Kaynakli (2012) [58] for instance, reviewed all available literature on determining the optimum thickness of the thermal insulation material of a residential building and its influence on energy demand. More recently, Stevanović (2013) [88] reviewed existing studies on several passive solar design strategies, but both in the case of residential and commercial buildings.

The goal of this literature review is threefold. First of all we aim at providing an updated overview of recent developments in the literature with regard to studies concerning the improvement of building energy efficiency. This review focuses on the literature that explicitly deals with residential buildings only. Non-residential buildings such as offices, shops, industrial buildings and health related buildings often apply specific construction methods and HVAC installations which are tailored to the function of the building. The particular characteristics which are related to the function of a non-residential building – such as increased ventilation rates or high internal heat gains – induce the need for specific design methods depending on the actual function and use of the building. This is out of the scope of this review paper, therefore literature on non-residential buildings will not be taken into consideration. Second, we want to examine this literature from different perspectives in order to classify important information. This should make it possible for researchers who are interested in a specific field to link and compare studies based on several topics. Third, delving into the available literature in great detail enables us to identify trends in this research field and to propose opportunities for future investigation. In section 2, we will outline the structure of this paper and provide a brief description of the following sections. We will end the paper with a section discussing the opportunities for future research followed by a conclusion.

2 Material and methods

This research has been carried out by means of a literature study.
We extensively searched for relevant articles concerning the optimization of energy efficiency in residential buildings in the databases of *Web of Science* and *EBSCO*. In this search procedure we used the following key words "optimization", "energy efficiency", "passive measures", "residential buildings" and "dwellings". Some references in the material used were examined for additional publications. Only literature in English has been examined in order to increase the accessibility of this article. The literature search was also limited to material that was published in or after 2000, because of the growing interest in this field of investigation in concurrence with the emergence of government measures such as the EPBD. This quest has led to a total set of 78 contributions. As can be seen from Table 1, the material almost completely consists of journal articles.

[Insert Table 1 about here]

This literature review is divided into several descriptive fields (Stevanović, 2013) [88]. Each of these topics sheds light on all scientific writings from a different point of view. This makes it possible for the reader to identify articles within their field of interest. Six domains can be distinguished:

- *Area of application and design variables (Section 3):* indicates which energy efficiency measure is applied (adjustment of the building's shape, the insulation level, the window type and area, etc.) and in which part of the dwelling it is implemented, such as the roof, the walls, the whole, etc.

- *Objectives and performance measures (Section 4):* describes whether energy related, economic or environmental objectives are considered. These three categories contain specific performance measures such as energy demand, thermal comfort level, life cycle cost, payback period, emission level, etc., that are used to evaluate the implementation of the different design variables.

- *Type of analysis (Section 5):* categorizes the article set into material in terms of single and multi-objective optimization problems, economic analysis, scenario analysis, sensitivity analysis and statistical analysis.

- *Solution methodology (Section 6):* outlines all solution techniques that are applied in the material to optimize the performance measures listed in section 4, such as life cycle assessment (LCA), life cycle cost analysis (LCCA), the payback method, net present value and internal rate of return method, mathematical programming techniques, combinatorial mathematics, a direct search method, heuristics, artificial neural networks, regression analyses and other things.

- *Software tools (Section 7):* lists all software tools used to perform the optimization process that is applied in the set of articles. Table 6 will provide references to the websites of the currently available software tools.

- *Case study location (Section 8):* gives an overview of the case study locations or the countries of which the weather data have been used in the investigation.

- *Type of building (Section 9):* categorises the material according to the case study type of building such as a multi-family residential building, a single apartment, a house (terraced, semi-detached, detached or multi-family) and a simple box model.

Each of the above topics will be briefly discussed in the following sections. These topics will be illustrated based on a selection of the relevant literature and are provided with a table in which all papers are included and classified into different categories. This classification will enable the reader to build upon a specific topic by means of the literature related to a certain field of interest. For some topics apparent trends will be highlighted and discussed by means of graphical illustrations.

3 Area of application and design variables

In the literature set on improving energy efficiency in residential buildings, five major groups of application areas can be distinguished, namely measures concerning the whole building, the construction parts of the envelope (roof, wall, ceiling and floor), windows and shading, HVAC systems and finally, appliances and lighting. These groups are represented in detail in Table 2.

[Insert Table 2 about here]

Table 2 shows that the orientation, infiltration levels and thermal mass of the overall building are frequently taken into account. In the study of Tuhus-Dubrow and Krarti (2010) [93], for example, the energy efficiency optimization of the building shape and other features with respect to the whole building such as the building orientation, thermal mass and infiltration level, are investigated. They consider the widest variety of possible shapes such as rectangle, L-shape, T-shape, H-shape, U-shape, cross, and trapezoid. Two optimization runs were executed, one in which only the shape design variable was allowed to vary, whereas in the second all building features in the study were considered. This type of research gives a better insight into choosing appropriate building shapes when designing more energy-efficient residential buildings. The investigation of Bichiou and Krarti (2011) [10] goes even further by focusing on the selection of optimal building design variables such as building shape, orientation, thermal mass, air infiltration level, etc., and thereupon considers a wide range of HVAC systems so as to create the best possible combination in order to minimize the LCC of the building operations. Audenaert, De Cleyn and Vankerckhove (2008) [9] are the only researchers in the literature set comparing three building types by means of the energy performance and interior climate (EPB) standards in Flanders (Belgium), namely the standard house, the low-energy house and the passive house. They carried out an economic analysis to evaluate the economic viability of the three dwelling types and therefore used specific characteristics concretised in the EPB legislation, while keeping the geometry of the house the same.

As shown in Table 2, the insulation levels of the roof, ceilings, floors and especially the walls are frequently examined in the material collected. The optimisation study by Lollini, Barozzi, Fasano, Meroni and Zinzi (2006) [66] for example, focuses on determining the optimal roof, wall and floor insulation levels of a detached house by means of the net present value and the payback rate, considering economic, environmental and energy issues all to be performance measures. The optima are ascertained both for the component as well as the whole building level in six different Italian climatic zones by using the EC501 software (Edilclima) [20], though only considering the heating season energy performance. Yu, Yang and Tian (2008) [108] consider the individual and simultaneous effects of the exterior wall thermal insulation level and position, the solar radiation absorptance (SRA) of the walls and other design variables of a multifamily residential building insofar as they affect the heating as well as the cooling and total annual energy consumption. It is important to note that many researchers only consider different measures individually, not always taking into account the interactive effects of these adjustments and thus under- or overestimating the synergy outcome. Panayi (2004) [79] anticipates this by determining the impact of a variety of passive measures, such as the insulation levels of roof and wall orientation and thermal mass of a Cypriot dwelling. The study also examines the interactions of those measures and even proceeds to a prioritisation of actions when considering energy savings and costs. Yu, Tian, Yang, Xu and Wang (2011) [107] determine the optimum insulation thicknesses of residential roofs and also take into account the impact that both the surface colour and hence the SRA, as well as the insulation materials, have on this insulation optimum. In their study, Lai and Wang (2011) [62] compared the energy efficiency benefits related to two different roof constructions, namely a metal roof and a "green roof". The latter uses vegetation as an environmentally friendly energy saving feature. The research of Szalay (2008) [89] is the only example in the literature set that considers envelope characteristics such as ceiling heights, the effect of adjacent walls and the number of storeys of the residential buildings and other energy efficiency measures. Realistic ranges were set for these variables describing the geometry of technically feasible buildings, meanwhile considering the energy demand for the whole life cycle.

Table 2 clearly shows that the window types frequently appear in the literature as energy saving measures. The window types are mostly distinguished according to their U-values or heat transfer coefficients, their solar transmittance, the amount of glazing layers and the presence of low-emissivity coatings, etc. The area of windows as in window-to-wall ratio or window-to-floor area, the orientation of windows, the window frame size and utilised materials are considered to a lesser extent. Gasparellaet al. (2011) [35] evaluated the impact of different double and triple glazed windows, the window area and the orientation of the main windowed wall on winter and summer energy needs and peak thermal loads and revealed the most influential design measures. An important aspect in this research is the fact that the authors also considered two individual cases, namely with or without internal heat gains. In the study by Gong, Akashi and Sumiyoshi (2012) [39], passive design measures such as window type, size and orientation together with insulation levels were examined. It is worth noting the presupposed assumption that total internal heat sources are equal to zero, which is clearly not a representative setting for an ordinary residential building. Another piece of research by Jaber and Ajib (2011b) [53] is the only one in the literature set that specifically investigates the influence of four different window types and various possible window areas on the annual heating and cooling demand in three different climate zones.

A lot of studies acknowledge the effect of shading devices on energy consumption, especially shadings on the outer side of the building. Ruiz and Romero (2011), [83] for example, consider building modifications through cooling strategies such as adding external obstacles to create shade. Furthermore, they are the only ones in the literature set to include the effect on thermal energy use by adding lintels to glazing with the aim of reducing the entry of solar radiation into the building. According to their results, the trade-off between changes in cooling and heating energy consumption should always be given due consideration when applying shading devices. Important factors influencing the impact of shadings include the prevailing climate and latitude. Most of the studies in the set considering external shading devices are carried out in climate zones which require a significant share of the cooling energy needed. Nevertheless, countries with an important contribution to heating energy demand can also benefit by eliminating the possible negative consequences related to shadings. Nikoofard, Ismet Ugursal, and Beausoleil-Morrison (2011) [75] are the only ones in the literature set considering the shading effects of neighbouring houses and trees on levels of annual heating and cooling demand from a detached house. In this study, the different orientations, sizes and distances of these contiguous objects were evaluated in four different climate regions in Canada. They pointed out the importance of considering shading effects in the set-up of new neighbourhood developments.

Table 2 shows that for the implementation of HVAC systems as an energy-saving measure, a wide variety of alternative applications is considered. Most studies discuss district heating and the implementation of conventional systems such as natural gas boilers, electric radiator systems, etc., and compare these with solar systems, heat pumps and micro combined heat and power systems (micro-CHP) in terms of energy efficiency and related costs. Alanne, Ahti Salo, Saari and Gustafsson (2007) [2] consider as many as ten different residential energy supply systems in a multi-criteria evaluation, measuring both life-cycle costs and environmental impacts. They even take into account the competitiveness of micro-CHP systems as compared to conventional heating systems. Buoro, Casisi, Pinamonti and Reini (2012) [12] make a distinction between demand and supply side strategies for the energy optimization of dwellings. Demand strategies, on the one hand, concern the subsitution of existent features and technologies by others that are more energy-efficient such as for example an insulation level increase. Supply side strategies, on the other hand, consider systems that are not usually applied and make local production of the whole energy need possible, such as the installation of heat pumps. Their research tries to address the question of whether both energy-saving strategies should be considered as alternatives or whether they have to be employed simultaneously in order to maximize both energy and economic profits.

As can be seen in Table 2, the leading renewable energy technologies considered in the literature set are solar systems and heat pumps, whereas wood stoves and boilers have received less attention. It is important to note the almost complete absence of case study examples considering the implementation of wind turbine systems (see also Encraft, 2009). Kapsalaki, Leal and Santamouris (2012) [55] were the only researchers in the set including three wind turbine systems as well as conventional and solar systems in their research. The study aimed at assisting in the decision making between different energy efficiency solutions by means of the lowest LCC and investment costs. The researchers even included important household appliances and lighting, by comparing a base case with average efficiency systems and a case in which they were all replaced by a high energy-efficient alternative. Nevertheless, the influence of adjusting appliances and lighting is almost always left out of consideration in the literature set, despite the fact that this can have a considerable impact on the energy efficiency of buildings.

In Figure 1a the share of the five main areas of application relative to the total number of papers that were published in a specific year, is shown; Figure 1b shows the absolute numbers. Figures 1a and 1b indicate that apart from 2006 and 2012, appliances and lighting adjustments are not dealt with. Both envelope parts and windows and shading are the most investigated, whereas the attention paid to the other areas show a fluctuating pattern. However, from 2011, we clearly observe a significant increase in studies of HVAC systems reaching a peak in 2013 and at the same time, a significant decrease in papers discussing envelope parts.

[Insert Figures 1a and 1b about here]

4 Objectives and performance measures

The performance measures considered in the literature ought to be optimized in the objective function to find a solution to the energy efficiency improvement problem. Table 3 contains all the performance criteria used in the literature set. Note some criteria are not necessarily part of the objective function in the considered article. The performance measures can be classified into three classes of objectives that are taken into account: energy, economic and environmental issues. The performance measure *energy demand* also includes the measuring of *energy savings*. The latter could, for example, just as well be situated in the class of environmental or economic objectives, because of the positive effect it can have on the environment as well as on economic performance. Nevertheless we decided to classify this performance measure under the energy objectives section in order to be consistent throughout the whole literature set. The reason for doing this, is that the papers in question did not always report on the environmental impact these energy savings entailed or it was not apparent whether these savings were used to underline the possible enhancement of economical benefits. Only explicit influences on environmental matters were thus placed in the environmental objectives group. Although we aimed at reducing the number of performance measures as much as possible by grouping them into more wide-ranging concepts, Table 3 illustrates that the literature set still encompasses a large variety of different criteria, all of which aim at evaluating and optimizing possible applications in order to improve the energy efficiency of residential buildings.

[Insert Table 3 about here]

The first series of performance measures are related to energy issues. As can be seen in Table 3, the energy demand measure is the one most taken into account in this group, whilst thermal comfort level as a benchmark gained some attention in the most recent years. Magnier and Haghighat (2010) [69] for instance, used their methodology for the optimization of both thermal comfort and energy consumption in a residential building by evaluating envelope design features and HVAC system-related variables. The study acquired dozens of possible house designs with different trade-offs between these two measures. Asadi, da Silva, Antunes and Dias (2012a) [6] add a third objective function, namely the minimization of the retrofit or overall investment cost of the building used in order to choose the most appropriate retrofit action and to this end consider different roof and wall insulation materials, window types and solar systems. The category “other” contains papers using indices (“evaluation of energy and thermal performance” (EETP) (Yu et al., 2009b) [110], “energy performance difference between housing units” (EDH) (Yao, 2012) [106] and “energy utilization index” (EUI) (Gagliano et al., 2013) [127]) or indicators (health impact indicators (Risholt et al, 2013) [118] and home quality indicators (Das et al., 2013) [141]).

The economic objectives category consists of widest range of performance measures and is used the most in the literature set as compared to the energy and environmental classes. Among others, Yu, Yang, Tian and Liao (2009a) [109] divide the life cycle cost into three slightly distinct but related concepts, namely life cycle savings (LCS), life cycle total costs (LCC or LCT) and life cycle energy savings costs. LCC can be defined as the sum of all the costs related to an energy delivery system, such as for example energy consumption and building retrofit expenses over the lifetime of a building. The difference between the LCC of a retroffited building and that of a non-retroffited residence equalizes LCS. In other words, LCS is the difference value between the life cycle energy savings costs and the retrofit payout. Yu et al. (2009a) [109], for example, search for the optimal insulation thicknesses of walls for different insulation materials, climate zones, surface colours and orientations by minimizing LCC or maximizing LCS. The research by Hamdy, Hasan and Siren (2011) [43] only considers the minimization of investment costs for the design of low-emission dwellings. Others apply the annual energy use costs or annual costs for owning, maintaining and operating the components of the adjusted residential building in their optimization study. Joelsson and Gustavsson (2009) [54] reduce annual heating costs by implementing several building features in combination with the conversion to alternative heating systems. In the study by Ren, Gao and Ruan (2009) [82] the objective is to minimize the annual cost of photovoltaic (PV) systems which includes the PV investment cost, maintenance cost and utility cost, subtracting the earnings from selling the electricity surplus. In their search for the economically most profitable combination of energy saving insulation measures in the residential sector, Audenaert, De Boeck and Roelants (2010) [8] used three profitability criteria, that is the payback period, net present value (NPV) and internal rate of return (IRR). The payback period is the exact time needed to recover the initial investment costs. NPV stands for the value an investment generates during its lifespan, whereas the IRR is the discount rate at which an investment has an NPV of zero (Brealey et al. (2008)) [11]. Although NPV is a suitable approach for the calculation of LCC, we decided to treat it separately given that many articles did not emphasize whether this method was used or not. As can be seen in Table 3, the payback period is frequently used as an additional performance measure, though it is not always included in the objective function.

When taking environmental issues into account, the literature in question either executed a complete life cycle analysis on the environmental impact of some energy saving strategies or evaluated the mitigation potential of CO_2, SO_2 or other greenhouse gas emissions. In the research by Dorer and Weber (2009) [17] for example, the environmental benefits of the micro-cogeneration technology are studied only by looking at the effect on CO_2-equivalent emissions. Anastaselos et al. (2011) [4] strongly emphasized the recycling potential throughout the assessment of thermal insulation solutions. In their extensive analysis, they carried out an environmental impact assessment based on the life cycle assessment (LCA) methodology, which links specific actions to environmental impacts such as climate change and acidification. Since these categories are also related to emissions, they eventually make it possible to calculate the whole environmental impact based on the relevant emissions.

In Figure 2a the share of energy, economical and environmental objectives relative to the total amount of objectives that were considered in a specific year is shown; Figure 2b shows the absolute numbers. Figure 2a shows that apart from 2007, only a small proportion deals with environmental objectives from 2009 on. Both energy and economical objectives have always taken up a prominent position. However, we observe an increasing number of papers taking into account energy objectives from 2009 on and a decreasing number of papers dealing with economical objectives since 2011. Only a few articles took into account all three objectives. Alanne et al. (2007) [2] for instance, formulated the selection process between residential energy supply systems as a multi-objective optimization problem in which they address life cycle costs, energy consumption and emissions related to global warming and acidification.

[Insert Figure 2a and 2b about here]

5 Type of analysis

This section distinguishes between different types of analysis that were applied throughout the literature to evaluate the presupposed performance measures. The classification was carried out by looking at the main types of analysis the material used. Notwithstanding the fact that we aim at making a clear distinction between the various approaches used, we emphasize the fact that most categories can overlap or can be executed in tandem with one another. In particular, the category "economic analysis" is almost always applied in combination with optimization, sensitivity analysis or scenario analysis. That is why we will not discuss this category seperately in what follows.

[Insert Table 4 about here]

As can be seen in Table 4, a sensitivity analysis and scenario analysis are predominantly carried out in addition to one of the other types of analysis. Instead of focusing on, for instance, a traditional optimization problem, researchers might also integrate a sensitivity analysis in orderto illustrate uncertainty in output that can be attributed to the uncertainty of changes in input factors. Marszal and Heiselberg (2011) [70] for example, sought the cost-optimal balance between the application of several energy efficiency measures and the implementation of renewable energy technologies, that is to say solar systems and heat pumps. Firstly, a single criteria optimization was executed in the form of a LCC analysis. Subsequently the robustness of the analysis was verified by a sensitivity analysis through the modification of several parameters such as the price of the photovoltaic panels, household electricity consumption, the real interest rate and the lifetime of the building.
As indicated in Table 4, the literature provides several contributions in which scenario analyses are included. Material situated in this category focuses on the impact of changing the residential building setting under study and therefore compares these multiple scenarios in relation to the performance measures. In the research by Jaber and Ajib (2011a) [52] for instance, the main aim was to determine the optimal insulation thickness of a selected residential building. For this purpose, three scenarios were tested with different combinations of insulation thicknesses for walls and ceilings and consequently were compared to one another in terms of LCC and energy consumption.

In the literature concerning the energy efficiency improvement of residential buildings, the optimization approaches can be broken down into single and multiple objective problems based on the number of performance measures that ought to be optimized. As shown in Table 4, those papers that use one performance measure and those taking into account more criteria, are almost equally distributed. Griego et al. (2012) [40] perform a single criteria optimization using LCS as an economic performance measure and at the same time employ an economic analysis to evaluate several energy efficiency measures. An example of a single criteria optimization technique that is applied twice is provided by Znouda et al. (2007) [111]. They determine the optimal building configuration by considering the LCC and energy consumption as performance measures in two seperate optimizations, but using the same developed algorithm. As a result an optimization solution in terms of energy savings and another regarding monetary savings is obtained. A multi-criteria method is, for example, deployed by Fesanghary et al. (2012) [28], which simultaneously aims at minimizing the LCC as well as the CO_2-equivalent emissions related to several building envelope parameters. Tuhus-Dubrow and Krarti (2010) [93] also consider a multi-objective approach in optimizing some building envelope features, but combine the minimization of the LCC and energy use.

The final category in Table 4 contains those papers that incorporated a statistical analysis in their research, which was employed as a way of conducting a sensitivity analysis. Morrissey and Horne (2011) [74] for example, carried out a sensitivity analysis using a multiple regression. This type of analysis indicated to what degree the final calculated NPV of an energy efficiency investment was significantly related to the capital cost, energy savings and changes in the residual house market value.

6 Solution methodology

The literature on improving the energy efficiency of residential buildings applies a wide variety of solution techniques, as can be observed from Table 5. The solution methodologies can be clearly linked to Table 4. Sensitivity, scenario and economic analyses use life-cycle assessment (LCA) and capital budgeting techniques. The optimization and economic analyses correspond with mathematical programming, heuristics, artificial neural networks, direct search and combinatorial mathematics. The statistical analysis is executed by regression analysis. Moreover, most of the articles link these methods with building energy simulations. The table indicates that a great deal of the material utilizes capital budgeting methods and heuristics in order to find solutions to problems. The use of optimization methods can be located in the early adoption stages where researchers are concerned. Parametric studies, on the other hand, function as an elementary form of optimization in which parameters are optimized while keeping others at a constant level. Though they do not necessarily yield a globally optimal solution, such procedures can provide a locally optimal solution (Stevanović, 2013) [88]. We refer the interested reader to Foucquier et al. (2013) [32] for an extensive review of research work analysing building modelling and energy performances prediction.

[Insert Table 5 about here]

LCA is one of the solution methodologies used in the literature (see Table 5). This technique deals with the assessment of the environmental aspects of, and possible impacts related to, a product throughout its life cycle. In this analysis, the relevant in- and outputs of a system are formulated, after which the possible environmental impacts related to these in- and outputs are evaluated. The LCA technique can be directly employed in the residential building sector. However residential buildings possess many characteristics which can complicate the application of LCA methods, such as the uncertain lifespan of a building and the actors involved (International Energy Agency, 2001) [51]. Dylewski and Adamczyk (2011) [18] for example, implement this LCA method in a correct manner by implementing four successive stages, namely goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and the interpretation stage. By means of LCA, they determined the environmental costs and profits of a thermal insulation project with regard to building external walls. In the study of Citherlet and Defaux (2007) [14], the LCA was carried out to evaluate and compare the environmental impacts of three variants of a family house. As for products guaranteed to last a long time, the life cycle of a building consists of multiple phases, which all need to be incorporated into the assessment. Owing to the complexity of residential buildings, Gustavsson and Joelsson's (2010) [42] analysis only included production and operation phases and excluded on-site construction and the demolition and renovation phases of the building. By definition, the LCA approach necessitates the identification of all these phases in order to provide a comprehensive view of the total environmental impact.

Table 5 demonstrates that a large number of articles apply capital budgeting methods. The desired outcome of such capital budgeting processes is the ability to select an optimal portfolio of investments from a set of presupposed alternatives. This ultimate portfolio makes the greatest contribution to the achievement of the decision maker's goals (Gass and Harris, 2000) [36]. Saari et al. (2012) [84] for instance, analyse the financial viability of several energy-saving design options by only using the payback period method that calculates the time needed to recover the investment costs of the energy efficiency measures applied. This can provide misleading outcomes, since the payback rule ignores cash flows generated after the cutoff date. In the study by Audenaert et al. (2010) [8] three economic profitability criteria are utilized in their quest for the most profitable combination of insulation in the facade, roof, floor and glazing systems. This study examines the payback period, the net present value (NPV), and the internal rate of return (IRR). Although the NPV method leads to better energy efficiency investment decisions than other methods, it is also advisable to use supplementary measures such as payback and IRR (Brealey et al., 2008) [11]. Another important and frequently applied tool for evaluating residential building design alternatives is life cycle cost anaysis (LCCA). When energy conservation projects increase, either the initial investment costs of new dwellings increase or they require retrofit expenditures. LCCA can determine whether these applications are economically justified (Fuller and Petersen, 1996) [34]. Uygunoğlu and Keçebaş (2011) [100] for example, carry out an LCCA in order to estimate the optimum thickness of different types of construction masonry blocks, including both the material costs and energy consumption. In the study by Hasan et al. (2008) [45], the absolute life cycle cost (LCC) was not calculated, but instead the difference between the LCC of different cases and the LCC of the reference case was calculated. Owing to this, there is no need to consider the costs of all building components, but only those related to the differences that originate from the variation of parameters between the reference case and any other investigated design.

Up to now, mathematical programming methods appear to have been applied hardly at all in the literature on energy improvement of residential buildings, as can be seen from Table 5. All the articles that used such solution techniques were published in or after 2007, a fact that might indicate growing interest in applying these methods. We indeed observe from Figure 3b (see infra) a slightly increasing number of papers applying these techniques from 2007 till 2012. However in 2013, this positive trend is stopped. These accurate methods guarantee the optimal solutions for the problem at hand. Some articles develop their models based on linear programming (LP), a mathematical modelling technique where both the objective function and the constraints are linear funtions (Gass and Harris, 2000) [36]. In their study, Milan et al. (2012) [73] developed an LP model for the optimization of a 100% renewable energy supply system. Their aim is to minimize the overall costs for the sizing of

three energy supply systems,namely a photovoltaic module, a solar thermal collector and a ground source heat pump. These costs depend on three design variables that represent the specific capacities of the considered technologies.
Two articles in the set (see Table 5), written by the same authors, utilized a multi-objective optimization model that was tackled by a Tchebycheff programming technique. The decision model was rearranged by aggregating multiple objective functions. In this method, weighting vectors are used that represent the weight of each objective, which can be altered to acquire distinct compromise outcomes (Asadi et al., 2012b) [7]. First, an ideal objective function vector is determined, after which the weighted distance from this vector to the feasible region is minimized. This method has the ability to generate multiple solutions at each iteration, which are presented to the decision maker who then selects the preferred one (Miettinen, 1999) [72]. Asadi et al. (2012b) [7] for example, use Tchebycheff programming to quantitatively assess technology choices in a building retrofit case, aiming to minimize retrofit costs while maximizing energy savings. In another building retrofit case study, a third objective function for minimizing thermal discomfort hours was added on top of the previous two and solved by the same method (Asadi et al., 2012a) [6].
A third mathematical programming method used is mixed-integer programming (MIP) in which the constraints and the objective function are linear, but at least one of the optimization variables is either binary and/or takes on an integer value (Gass and Harris, 2000) [36]. In the study by Wakui and Yokoyama (2011) [105] for example, a MIP model is formulated to identify the optimal sizing of a residential gas engine cogeneration system for the power interchange operation in a housing complex. It seeks to minimize the total primary energy consumption of the intended residences and therefore the authors analyzed the energy-saving effect of the optimal operation patterns for different system scales.

As shown in Table 5, heuristic methods are also applied in a considerable number of papers. The harmony search (HS) algorithm is a recently developed optimization method, which was conceptualized using the musical improvisation process of composing a perfect state of harmony Lee and Geem (2005) [64]. This process can be considered analogous to the optimization process to find a global solution for an objective function. The HS method regards a solution as a melody, that is to say a combination of building components, which has a fitness reflected by the objective function value. Fesanghary et al. (2012) [28] are the only researchers in the literature set that have explored this promising application of HS for improving energy efficiency in residential buildings. They presented a multi-objective optimization problem to minimize both the LCC and CO_2-equivalent emissions. Initially, random values of the design parameters considering building envelope elements and glazing types were assigned. Based on the obtained simulation results of this first melody, the HS algorithm defines new values for the design variables at random, or in the case of later simulations by using the best values stored in the harmony memory. Subsequently new simulations are carried out. This searching process gradually approaches the optimal value and is continued until the maximum of iterations has been reached.
Anderson et al. (2006) [5] discuss the use of the BEopt (NREL, 2013) [76] software tool (see Table 6, section 7) that applies a sequential search technique to identify the most cost-effective energy efficiency strategies leading to net zero energy residential buildings. In their study, the sequential search algorithm starts by individually evaluating all available improvement options in an initial building design. Based on the steepest slope of the total annual cost in relation to the source energy savings, an optimal design option is chosen. Thereupon, the optimal design variable is removed from the search space, after which a new simulation run is executed for the remaining measures in order to find the next optimal point. This search process is continued until the optimal package of measures is found. The study

by Ihm and Krarti (2012) [49] also aims at identifying optimal sets of energy efficiency measures while reducing LCC by means of a sequential search optimization. Moreover, the results obtained from this method were then compared to those of a brute-force search method. The latter is an exhaustive search, often used as a validation method, that assesses all possible candidate solutions and therefore is characterized by high computational efforts (Hasan et al., 2008) [45].

As can be seen from Table 5, several researchers employ evolutionary algorithms to simultaneously optimize various objectives. The idea behind these evolutionary computation techniques is to replicate natural phenomena Gass and Harris (2000) [36]. Verbeeck and Hens (2007) [103] for instance, optimize their multi-objective problem with a genetic algorithm and the Pareto-concept. The algorithm starts from a population which consists of individuals or chromosomes that represent candidate solutions. These chromosomes depict parameter sets, such as insulation thickness, glazing type, glazing area, etc., joined together in a string of values. The quality of these solution chromosomes is indicated by their fitness, which in this case depends on its energy consumption, NPV and emission level. Based on their fitness, chromosomes are selected from the population chosen at the beginning, after which they go through a recombination and mutation phase. This iteration ultimately leads to a new and better population and is repeated until the presupposed number of iterations has been gone through. During the optimization process, the Pareto concept deduces the trade off between all objectives by seeking non-dominated solutions.

The study by Magnier and Haghighat (2010) [69] is the only one considering a multiobjective genetic algorithm that was preceded by a simulation-based artificial neural network for the optimization of thermal comfort and energy consumption in residential buildings. This neural network, based on the operation of the central nervous system, is composed of neurons that are interconnected. The input layer of the network consists of neurons representing the design parameters, while the output layer contains the performance measures. The integration of these two methods is still widely unexploited and therefore has seldom been used in energy efficiency optimization studies of buildings. As the authors state, time-consuming genetic algorithms conjoined with neural networks that are able to provide fast evaluations of the building performance can save an enormous amount of computation time.

In the study by Tuhus-Dubrow and Krarti (2009) [92], three optimization tools, the sequential search technique, the genetic algorithm and the particle swarm technique, are individually applied to design a building envelope that minimizes energy use costs. They are then compared with each other in terms of accuracy and efficiency. As is the case for genetic algorithms, the particle swarm method works with a solution set called a population, in which each potential solution is represented by a particle. This algorithm is based on the behavior known as synchronous flocking, in which every particle has a velocity with which it explores hyperspace, or in this case the cost function, accelerating towards optimal solutions (Kennedy and Eberhart, 1995) [60].

In their search for the optimal values of energy efficiency measures obtained by minimizing LCC, Hasan et al. (2008) [45] apply a hybrid algorithm that initially executes a particle swarm optimization and subsequently applies the Hooke-Jeeves direct search algorithm.

Gong et al. (2012) [39] are the only ones in the literature set that integrated the orthogonal and the listing method in order to explore the total energy consumption reduction by optimizing energy efficiency design measures. The orthogonal method is able to determine the significance of all design parameters and their mutual interactions, and can define the preferable level of each variable. Subsequently, the listing method runs through all parameters one by one to further refine their optimal value, while keeping all other variables unchanged. The authors state that this method was chosen as it can define the preferable level and significance of design variables without the need for advanced computer programming knowledge.

As can be seen in Table 5, regression analysis is used in some of the material to perform a sensitivity analysis. Nevertheless, this method does not aim at formulating a general model, but is conducted in order to indicate the degree to which particular independent variables contribute to the values of the performance measures (Morrissey and Horne, 2011) [74]. Gasparella et al. (2011) [35] for instance, investigate the impact of different window types, sizes and orientations on the building performance by means of a building simulation tool (see Section 7). Thereafter, a multiple regression analysis was applied to validate the obtained simulation results by identifying the most influential parameters such as for example, glazing solar transmittance, on thermal loads and energy needs.

The category of "other" refers to those parts of the literature set that employed method(s) that cannot be classified into one of the other groups in Table 5. These studies almost always chose to carry out the necessary computations by means of dynamic building simulation programs, numerical computation programs, or simply did not specifically state which solution technique was utilized. All software tools used in these articles and those of the other categories, will be further discussed below in Section 7.

In Figure 3a, the share of the five most used solution technique categories relative to the total amount of material published in a specific year is presented; Figure 3b shows the absolute numbers. Artificial neural networks, direct search, and combinatorial mathematics are left out because only a few articles apply these methods. Figure 3a shows that capital budgeting techniques take up a prominent position in most years. In 2012 however, the share of mathematical programming techniques showed an increase.

[Insert Figure 3a and 3b about here]

7 Software tools

The literature set on evaluating the energy efficiency of residences exhibits a wide range of software tools used. As shown in the first category in Table 6, the majority of the articles carried out a building energy simulation and therefore utilized the appropriate program(s). Building simulations play an important role in determining the optimal design variables, since the building's response to these new features can be highly sensitive to local climate factors (Stevanović, 2013) [88]. The major tools in the building energy field are whole-building energy simulation programs that consider key performance indicators such as energy demand and costs (Crawley et al., 2005) [15]. The table shows that in some cases software programs were used to implement parametric studies, optimizations and various other issues. The other things were then classified in the second category “others”.

Owing to the extensive reach of the building design space, solely applying a trial-and-error approach is not enough to ensure high-level performance. Therefore it becomes inevitable to couple a solution methodology with a simulation engine in order to find the optimal design strategy for a given location (Stevanović, 2013) [88]. The simulation tools in the literature were used a few times in combination with other programs to perform, for example, an additional optimization study, which indicates that this type of combined research still finds itself at an early stage, but it is assumed that it will grow in the future. Nevertheless, not all the studies stated explicitly whether they had carried out a building simulation or which tool they used, and this made it impossible to indicate a clear growing trend in this coupling technique.

[Insert Table 6 about here]

Almost all the building simulation tools enumerated in Table 6 can be found in the directive provided by the U.S. Department of Energy (2013a) [94], which provides information on more than 400 tools. Therefore we refer the interested reader to this internet source for an extensive overview of the available simulation tools for buildings, making it easy to compare them with each other. In what follows, we will highlight the most applied tools in the literature set, that is TRNSYS, EnergyPlus, DOE-2, IDA ICE, MATLAB (and GenOpt), and give a brief discription of the purpose for which they were used (EQUA Simulation AB, 2013; Hirsch, 2009a; Lawrence Berkeley National Laboratory, 2011; The MathWorks, 2013; Thermal Energy System Specialists, 2013; U.S. Department of Energy, 2013b) [23, 46, 63, 90, 91, 95].

In the literature set, the TRNSYS tool was implemented the most. In their design optimization study for combined solar and pellet heating systems, Fiedler et al. (2007) [29], for example, chose this energy simulation software because of its component based approach. The authors stated that it was the only tool available that made use of adjustable system models to generate the necessary pellet and solar combisystem for their optimization. They coupled this energy simulation tool with the generic optimization program GenOpt. This dual process initially starts with the description of the building features, the input templates and the objective function in GenOpt. To perform the optimization, GenOpt automatically starts to write the input files for the simulation program, runs a simulation and based upon the results it defines new input files for the next simulation run. This process is reiterated until the optimal function is found (Lawrence Berkeley National Laboratory, 2011) [63].

Alanne et al. (2010) [3] used the IDA ICE platform in their search for an optimal integration of Stirling engine-based micro-cogeneration systems into residential buildings. The authors chose this simulation software because it provides highly advanced dynamic simulations for heat transfer and airflows in buildings. They implemented the micro-cogeneration engine in the software program and thereupon comparatively validated the results with the use of TRNSYS and EnergyPlus.

The DOE-2 software is widely recognized as the industry standard according to the U.S. Department of Energy (2013a) [94]. Ihm and Krarti (2012) [49], for instance, apply this tool in the simulation environment in order to describe building energy performance in a detailed manner. They also linked the DOE-2 simulation software to an optimization engine in order to determine the cost-effective residential building design that maximizes energy efficiency. However, the optimization tool used was not mentioned in the text. The study by Tuhus-Dubrow and Krarti (2010) [93], already mentioned in Section 3, implemented DOE-2 for the whole-building energy simulation together with MATLAB for the genetic algorithm optimization in the simulation environment.

8 Case study location

In the search for energy efficiency improvement in residential buildings, the case study location together with its prevailing climate plays an important role. Suitable building energy strategies can vary enormously across countries, especially for those situated in distinct climate zones. Energy efficiency improvement measures in cold climates are different from those of hot ones, showing that design measures are different for each type of weather (Ochoa and Capeluto, 2008) [77]. Keeping this thought in mind, an overview of all the countries in which the case studies were carried out or for which the weather data was used in the simulation, is given in Table 7. This list gives the reader the chance to consult the material that suits the location he or she is interested in.
[Insert Table 7 about here]

As can be seen from Table 7, locations in China have been investigated the most by the literature set, followed by locations in Sweden, Finland, Belgium and the USA. It is notabule that there is an almost complete absence of studies in Australia. When considering five continents as main categories, one can see that most case study locations were situated in Europe, followed by countries in Asia and America.

[Insert Figure 4a and 4b about here]

Figure 4a represents the number of articles per case study location relative to the total number of publications in a specific period since 2000; Figure 4b shows the absolute numbers. Figures 4a and 4b show that in every publication year, most case studies used data from European countries with a clearly increasing share from 2009 till 2013 up to the level of 2007. The same trend can be observed from Figure 4b (except for 2012 which shows a small decrease in the number of papers applied to the European countries). Although Asian countries have been clearly present in recent years, their presence showed a sharp decrease in 2013. Their significant share before 2013 probably indicated a growing level of attention paid towards energy efficiency measures in this continent. Indeed, from 1971 to 2004, more than 60 percent of CO_2 emissions increase from residential buildings came from developing countries in Asia. The persistent growth in building construction in Asia, and the fact that the marginal cost of increasing building's energy efficiency is lowest in the construction phase of new buildings, can create real opportunities in lowering energy consumption by integrating energy-efficient measures and new technologies (United Nations Development Programme, 2010) [99].

In only three papers, namely Gasparellaet al. (2011) [35], [53] and [55], did the study consider more than one climate zone in a similar simulation setting. These scientific investigations correspond to the growing need for insights concerning the influence of climatic conditions in selecting the most suitable energy measures. Kapsalaki et al. (2012) [55] for instance, carried out their analysis for three climate scenarios, namely Stockholm (Sweden), Lisbon (Portugal) and Iraklion (Greece), with the aim of selecting the most economically efficient Net Zero Energy Building design solutions for each country.

9 Type of building

Besides the development of a solution technique for an energy improvement problem, researchers in most cases provide a thorough trial phase in which they demonstrate the applicability of their research. As depicted in Table 8, a variety of building types are considered in the literature set with the aim of improving their energy efficiency level.

Ultimately, four main categories can be distinguished: multi-family residential buildings, single apartments, houses and a simple box model.

[Insert Table 8 about here]

Several studies based their case study on multi-family residential buildings, which comprise all sorts of apartment blocks. The reason for this is that no clear distinction could be made between small or large apartment buildings, because not all studies indicated the total number of flats that were located within the investigated building or only stated the number of storeys present. Some research papers focused their investigation on single apartments. These studies only took into consideration the effect of energy efficiency measures on one part of a whole building or else looked at all the flats in the building but did so separately. By so doing, the interactive effects that these dwellings encounter in an apartment building are hardly taken into account. Cheung, Fuller and Luther (2005) [13] for example, examined the influence of passive design strategies on the energy consumption of eight flats of a typical floor in a residential block. The researchers did not take into account interzonal thermal exchanges between the apartments and merely treated them separately.
Table 8 clearly indicates that most of the studies use houses as case study objects. This category can be divided into terraced, semi-detached, detached and multi-family houses. Detached houses capture the largest share both in comparison with multi-family residential buildings and single apartments and also as compared to the other housing types. In 2011, 40.9% of the European population lived in flats, whereas 58.3% lived in houses, 34.7% in detached and 23.6% in semi-detached dwellings or terraced houses. (European Commission, 2011) [26]. Therefore, the major focus on houses and more specifically on detached homes is conducive to the improvement of the overall energy efficiency of the housing market. The multi-family house category represents only two cases in which multiple houses were attached and formed a residential block (Dorer and Weber, 2009; Lai and Wang, 2011) [17, 62]. This type of dwelling thus differs from the multi-family residential building, because the former consists of houses, whereas the latter is constructed out of apartments.

As can be seen in Table 8, one paper utilized a *simple box model* as a case study object. This box model acts as an extremely simplified version of a dwelling and is used to simulate indoor thermal conditions. Gong et al. (2012) [39] utilized this single room model in the shape of a box to determine an optimal design of passive measures. Nevertheless, the researchers acknowledge the need for more complex multi-room models.

10 Opportunities

Technological progress and the development of new building techniques makes it possible in the near future to construct all new dwellings in line with a net zero energy goal. The biggest challenge, however, is to thoroughly carry out cost-efficient building retrofit projects, as the existing building stock accounts for the largest contribution to global energy consumption. This is however a difficult task, as residential buildings and their environment are a complex whole influenced by economic, environmental and social aspects, among others. All imaginable actors and their mutual interactions can therefore have a significant impact on the energy efficiency performance of residences. The focus of research should thus be primarily on the selection process for retrofit measures. The difficulty with this multi-objective problem, is the high number of design measures and constraints that have to be considered in order to optimize the presupposed and often competing objectives in the best possible way. That is why many previous studies investigated this problem by means of simulations and only treated distinct parts of the problem rather than using a global approach. The development of detailed building energy simulation software made it possible to implement a series of parametric studies in order to evaluate the impact of design parameters on the energy efficiency of the building, though most of the time they left out important parameters and/or interactive effects. So it is clear that the case study settings used in the material did not fully comply with reality and are simplified by, for example, leaving all heat sources out of consideration, simulating only small living spaces, and so on. The application possibilities of these performance-based simulation packages are thus still limited and imperfect to some extent when it comes to their use in real world projects. The development of new calculation and evaluation methods should therefore consider the possibility of examining the residential building as a complete system instead of approaching individual components.

Recent studies on improving the energy efficiency of residential buildings are mostly based on mathematical programming methods and heuristics. Such techniques, when compared to simulation packages, frequently have the ability to consider the modelling of the whole building and are also appropriate for defining the right trade-off between energy efficiency measures and supply system options. Nevertheless, using these tools for exploring the large number of design options, including conventional energy saving measures and all HVAC and renewable energy systems, involves considerable computational effort and requires the necessary mathematical knowledge. In future studies, researchers should aim at developing more flexible and user-friendly solution techniques or experiment by combining several methods, such as for example the conjunction of genetic algorithms with neural networks (see Section 6). These combinations could considerably reduce the computation time and thus carry out fast evaluations of the building performance.

Although the investigation data utilized in the literature is mostly based on real data collected from prototype reference buildings and not on theoretical data, almost no implementation in practice was carried out. This seems rather contradictory as the amelioration of energy efficiency in residences ought to be a practical problem. One research opportunity could therefore be the setting up of simple and user-friendly applications of the developed optimization method, which would enable home owners to apply the designed tool to their own case.

As clearly indicated in Section 4, a sizable number of studies have searched for energy improvement measures with a clear focus on the economic perspective. It would be interesting to find the optimal designs of buildings by means of a method that incorporates the prevailing subsidies and possible subsidy changes at country-level. This would make it possible to define the best possible solution regarding the impact on the private economy of the house owner. Though mostly considering economic effects, previous research barely took into account the societal climate change effect. It is self-evident that moving towards the construction of only low-energy buildings will reduce the total energy consumption and therefore emissions. Nevertheless, when making decisions on building construction or retrofitting to lower the overall energy demand, researchers should also pay attention to the reduction in emission levels, particularly when the energy originates from fossil fuels.

The lack of necessary detailed weather data in some cases makes it impossible to carry out the analysis in specific geographical locations. Therefore, much more effort should be made to acquire a more complete and specific weather database. Future research might be interested in determining the optimal design in all possible climate conditions and in mapping the most recommended passive design measures for all climate zones (Gong et al., 2012) [39]. Most of the reviewed studies also had difficulties finding suitable optimal energy efficiency solutions both for winter and summer weather conditions. Researchers mainly focused on one season, which can be unsuitable for others. Future research could focus more on the specific trade-off that has to be made between winter and summer energy consumption and could search for global energy efficiency solutions.

11 Conclusion

The promotion of energy efficiency improvement applications in residential buildings will undoubtedly play an important part in achieving energy efficiency and carbon reduction targets. Both regulatory actions such as EU Energy Performance of Buildings Directive and voluntary building environmental assessment schemes enforce attention to the energy efficiency of newly constructed or renovated buildings. In recent years, an increasing amount of scientific literature on optimizing energy efficiency in residential buildings has been published. These studies have been developing and examining different research methods in order to find a solution to this optimization problem. Researchers therefore investigated different fields of building applications by evaluating their effect on specific performance variables.

This paper provides an extensive literature review that encompasses the recent developments in the research field concerning the improvement of energy efficiency in residential buildings. The literature is classified by means of the following important topics: area of application and design variables, objectives and performance measures, type of analysis, solution methodology, software tools, case study location and type of building. This literature review does not encompass the study of specific parameters influencing the actual energy performance of a building such as climate, occupant behavior and uncertainty in material properties and design parameters. Although not explicitly discussed in the literature review, these parameters are often implicitly present as boundary conditions in the examined literature. Within some fields, we are able to identify the most significant trends in research. Both windows and shading on the one hand and envelope parts on the other hand have always taken up a prominent position. However, the latter showed a decreasing trend during the last three years in favor of a significant increase in studies of HVAC systems. Although energy and economical are the most used objectives, there is a recent trend in more papers dealing with energy objectives and less papers with economical objectives. To reach those objectives, capital budgeting techniques have been used extensively throughout the years. However, the share of mathematical programming techniques has gained more attention in recent years. Most papers are applied to European countries. And the number of countries within Europe focusing on energy performance extends rapidly. Although Asian case studies have been clearly present the last half decade, they showed a sharp decrease in 2013.

The literature review touches on the imperfections of past studies and in so doing highlights some important future research opportunities. Researchers should, for example, focus more on building retrofit projects. The development of new solution techniques should consider the possibility of examining the residential building as a whole instead of approaching individual components, and should be more flexible and user-friendly. Another opportunity would be the setting up simple and user-friendly applications of solution techniques which have been developed. This would enable home owners to apply the designed tool. Researchers should also pay more attention to the societal climate change effect of new building construction or retrofitting projects. Furthermore, it would be interesting to determine the optimal design for all possible climate conditions and to map the most recommended passive design measures for all climate zones. Ultimately, the specific trade-off between winter and summer energy consumption should be taken into account so as to find suitable energy efficiency solutions.

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Table 1: Material in the literature set, classified by publication period and document type

	2000-2005	2006	2007	2008	2009	2010	2011	2012	2013	total
conference article		1			1		1			3
journal article	4	1	8	5	5	8	16	14	14	75
total	4	2	8	5	6	8	17	14	14	78

Table 2: Area of application and design variables

building	
shape	[10, 31, 89, 92, 93, 111]
orientation	[5, 10, 16, 31, 35, 49, 52, 55, 79, 92, 93, 106, 109]
infiltration level	[5, 10, 31, 40, 43, 44, 49, 55, 57, 86, 92, 93]
thermal mass	[5, 10, 13, 16, 31, 55, 69, 79, 92, 93, 111]
floor area and volume	[86, 89]
number of storeys	[89]
building type	[9, 14]
envelope parts	
roof	
insulation	
insulation level	[8, 10, 14, 16, 30, 39, 40, 42, 43, 44, 45, 49, 66, 70, 79, 86, 93, 102, 103, 107, 110, 111, 114, 127, 135, 139, 141]
insulation material	[4, 6, 7, 40, 107, 127, 139]
surface colour and SRA	[40, 107, 110]
construction materials and layer distribution	[28, 62, 79, 93]
slope	[89]
thermophysical properties	[129]
Wall	
insulation	
insulation level	[5, 8, 10, 13, 14, 16, 18, 28, 30, 33, 39, 40, 41, 43, 44, 45, 49, 52, 54, 55, 57, 66, 70, 74, 79, 83, 86, 87, 92, 93, 96, 97, 102, 103, 106, 108, 109, 110, 111, 114, 134, 135, 139, 141]
insulation material	[4, 6, 7, 18, 28, 40, 96, 109, 134, 139]
insulation position	[79, 108, 134]
surface colour and SRA	[13, 83, 87, 106, 108, 109, 110]
construction materials and layer distribution	[18, 28, 89, 93, 100, 134]
thickness	[39, 79]
adjacent walls	[89]
thermophysical properties	[129]
ceiling	
insulation	
insulation level	[5, 28, 52, 74, 92, 135]
insulation material	[28]

height	[89]
floor	
insulation	
insulation level	[8, 10, 14, 41, 42, 43, 44, 45, 54, 57, 66, 70, 86, 92, 93, 102, 103, 114, 139, 141]
insulation material	[4, 45]
windows and shading	
windows	
window type	[5, 6, 7, 8, 10, 13, 14, 16, 28, 30, 31, 33, 35, 39, 40, 41, 42, 43, 44, 45, 49, 53, 54, 55, 57, 62, 70, 74, 79, 86, 87, 92, 93, 102, 103, 106, 108, 110, 111, 135, 139, 141]
window area	[5, 10, 13, 30, 35, 39, 49, 52, 53, 55, 57, 69, 83, 89, 92, 93, 108, 111, 135]
window frame	[16, 83, 86, 89, 103]
window orientation	[39, 53, 111]
shading device	
internal shading	[44, 55, 103, 106, 108]
external shading	[5, 10, 13, 30, 31, 35, 39, 40, 43, 44, 52, 55, 62, 74, 75, 83, 103, 108, 110, 111, 134]
HVAC systems	
district heating	[2, 12, 42, 43, 44, 54, 70, 86, 127, 135]
conventional systems	[2, 5, 10, 12, 14, 18, 37, 41, 42, 43, 44, 49, 55, 84, 86, 102, 103, 114, 119, 135, 141]
wood boiler and stove	[2, 29, 37, 41, 54, 86, 139]
solar systems	[2, 5, 6, 7, 12, 14, 29, 40, 42, 44, 55, 61, 70, 73, 82, 84, 86, 102, 103, 114, 127, 135, 141]
heat pumps	[2, 10, 12, 14, 17, 18, 37, 41, 42, 43, 44, 54, 55, 61, 70, 73, 84, 86, 103, 113, 119, 123, 135, 137, 141]
wind turbines	[55]
micro CHP systems	[2, 3, 12, 17, 103, 105, 121, 135]
natural ventilation systems	[103, 118, 119]
mechanical ventilation systems and ERV	[14, 43, 44, 45, 65, 84, 86, 103, 119, 135, 141]
appliances and lighting	
appliances	[5, 49, 55]
lighting	[5, 49, 55]

Table 3: Objectives and performance measures

energy related objectives	
energy demand	[2, 3, 4, 6, 7, 14, 16, 17, 29, 30, 33, 35, 37, 41, 42, 44, 49, 52, 54, 57, 61, 62, 65, 69, 79, 83, 86, 87, 89, 93, 103, 105, 106, 108, 111, 113, 114, 118, 121, 129, 134, 135, 139, 141]
thermal comfort	[6, 30, 69, 118, 129]
thermal load	[13, 31, 35, 39, 75]
other	[106, 110, 118, 127, 141]
economic objectives	
life-cycle cost	
LCS	[3, 31, 40, 44, 96, 97, 100, 107, 109]
LCC	[2, 4, 10, 28, 45, 49, 52, 53, 55, 57, 70, 74, 93, 107, 109, 111, 119, 141]
investment cost	[6, 7, 37, 43, 55, 79, 84, 102, 103]
annual (energy) cost	[5, 12, 41, 54, 82, 92]
NPV	[8, 9, 18, 37, 66, 73, 74, 103, 113, 121, 123, 137, 139]
IRR	[8, 121]
payback period	[3, 8, 9, 31, 53, 66, 82, 84, 96, 97, 100, 107, 109, 121, 134, 139]
environmental objectives	
life cycle environmental impact	[4, 14, 18, 114, 119]
emission level	[2, 3, 12, 14, 17, 28, 29, 37, 41, 42, 43, 54, 82, 83, 86, 103, 113, 121, 123, 139]

Table 4: Type of analysis

economic analysis	[2, 3, 8, 9, 10, 18, 31, 40, 44, 45, 49, 52, 53, 55, 57, 66, 70, 74, 82, 84, 93, 96, 97, 100, 102, 103, 107, 109, 113, 123, 134, 137, 139, 141]
sensitivity analysis	[3, 9, 12, 29, 35, 41, 42, 43, 44, 49, 55, 62, 66, 70, 74, 82, 89, 93, 97, 103, 107, 110, 123, 139]
scenario analysis	[4, 8, 14, 17, 30, 35, 37, 40, 42, 52, 54, 70, 74, 83, 84, 86, 106, 107, 113, 114, 119, 127, 134, 135, 137, 139, 141]
optimization	
single objective	[5, 10, 12, 13, 16, 31, 33, 39, 40, 45, 52, 53, 61, 62, 65, 70, 73, 74, 75, 82, 87, 92, 96, 97, 100, 102, 105, 108, 110, 111, 121]
multi-objective	[2, 3, 4, 6, 7, 8, 17, 18, 28, 29, 30, 35, 37, 41, 42, 43, 44, 49, 54, 55, 57, 66, 69, 79, 83, 86, 93, 103, 106, 107, 109, 118, 119, 121, 129]
statistical analysis	[35, 74, 82, 89, 110]

Table 5: Solution methodology

LCA	[4, 14, 18, 42, 66, 89, 102, 114, 119]
capital budgeting	
payback method	[3, 8, 9, 66, 82, 84, 107, 121, 134, 139]
NPV	[8, 18, 66, 74, 102, 103, 113, 121, 123, 137, 139]
IRR	[8, 121]
LCCA	[10, 31, 44, 45, 49, 52, 53, 55, 57, 70, 74, 93, 96, 97, 100, 107, 109, 119]
mathematical programming	
linear programming	[2, 73, 82]
Tchebycheff programming	[6, 7]
mixed integer programming	[12, 105]
heuristics	
harmony search	[28]
sequential search	[5, 10, 40, 49, 92, 93]
brute-force search	[45, 49]
genetic algorithm	[10, 43, 44, 69, 92, 93, 103, 111, 129]
particle swarm method	[10, 45, 92, 93, 129]
artificial neural network	[69, 129]
direct search (Hooke-Jeeves)	[29, 45]
combinatorial mathematics	
orthogonal method	[39]
listing method	[39]
regression analysis	[35, 74, 82, 89, 110]
other	[3, 4, 13, 16, 17, 30, 31, 33, 37, 41, 54, 61, 62, 65, 75, 79, 83, 86, 87, 97, 106, 108, 113, 118, 119, 121, 127, 135, 141]

Table 6: Software tools

building simulation	
TRNSYS [91]	[3, 6, 13, 16, 17, 29, 31, 35, 44, 52, 53, 61, 69, 103, 114, 129, 134]
EnergyPlus [95]	[3, 4, 5, 28, 33, 40, 65, 83, 87, 113, 137]
DOE-2 [46]	[5, 10, 49, 93, 109]
IDA ICE [23]	[3, 43, 44, 45, 84]
eQUEST [47]	[62, 107, 108, 110]
Pvsyst [81]	[14, 70]
EPB software [104]	[8, 9]
Enorm 1000 [24]	[41, 54]
ESP-r [22]	[3, 75]
Lesosai [19]	[14]
Polysun [50]	[14]
IDA ESBO [25]	[44]
DEROB-LTH [67]	[86]
TAS [21]	[79]
EC501 [20]	[66]
DeST-h	[106]
THERB	[39]
AccuRate	[74]
SIMEDIF	[30]
LabVIEW	[123]
CONTAM	[118]
Design builder	[127, 139]
others	
MATLAB [90]	[6, 7, 55, 92, 93, 96, 97]
GenOpt [63]	[6, 29, 69, 92, 129]
BEopt [76]	[5, 40, 92]
ENSYST [56]	[41, 42, 54]
CPLEX [48]	[73, 105]
Microsoft Excel [71]	[8, 89, 123]
SimaPro [85]	[18]
CHEOPS [38]	[111]
WinPre [1]	[2]
VERBR 2.6	[102]
not specified	[12, 37, 57, 82, 100, 119, 121, 141]

Table 7: Case study location

Europe	
Sweden	[29, 41, 42, 54, 55, 61, 86]
Finland	[2, 3, 43, 44, 45, 84]
Belgium	[8, 9, 37, 102, 103, 119]
Italy	[12, 35, 66, 87, 113, 114, 127, 137]
Portugal	[6, 7, 55]
Greece	[4, 55, 134]
Denmark	[70, 73]
Switzerland	[14, 17]
Cyprus	[31, 41, 79]
Spain	[16, 83]
France	[35, 129]
Poland	[18]
Germany	[53, 135]
Hungary	[89]
The Netherlands	[135]
UK	[118, 139]
Norway	[141]
Asia	
China	[13, 39, 65, 106, 107, 108, 109, 110]
Turkey	[57, 96, 97, 100]
Japan	[82, 105]
Jordan	[52, 53]
Taiwan	[62]
United Arab Emirates	[33]
Iran	[121]
America	
USA	[5, 10, 28, 92, 93, 123]
Canada	[69, 75]
Mexico	[40]
Argentina	[30]
Africa	
Tunisia	[49, 111]
Australia	[74]

Table 8: Type of building

multi-family residential building	[4, 13, 16, 42, 70, 86, 87, 89, 106, 107, 108, 110, 113, 121, 127, 135, 137]
single apartment	[13, 65, 79, 103, 118, 134]
house	
terraced house	[8, 42, 89, 102, 103, 139]
semi-detached	[6, 8, 33, 43, 44, 69, 103]
detached	[8, 14, 30, 31, 37, 41, 42, 45, 49, 52, 54, 55, 66, 74, 75, 79, 83, 84, 86, 89, 92, 102, 103, 105, 111, 114, 118, 119, 129, 141]
multi-family house	[17, 62]
not specified	[2, 3, 5, 9, 10, 12, 17, 18, 28, 29, 35, 40, 53, 57, 61, 73, 82, 93, 96, 123]
simple box model	[39]
not specified	[97, 100, 109]

Figure 1a: Share of the five main areas of application relative to the total number of articles per period

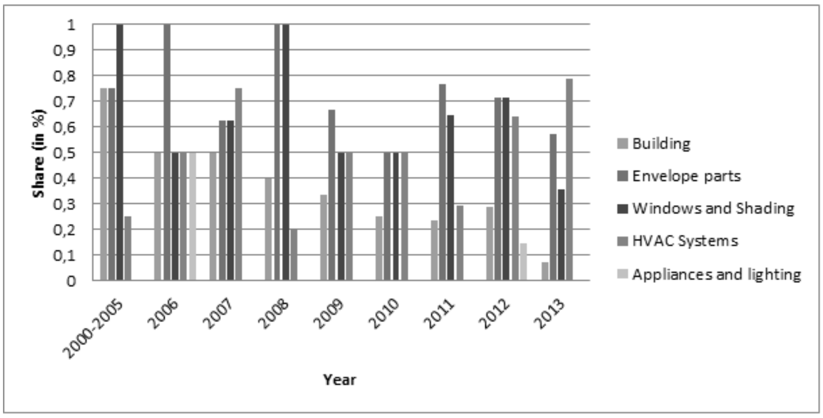

Figure 1b: Total number of articles of the five main areas of application per period

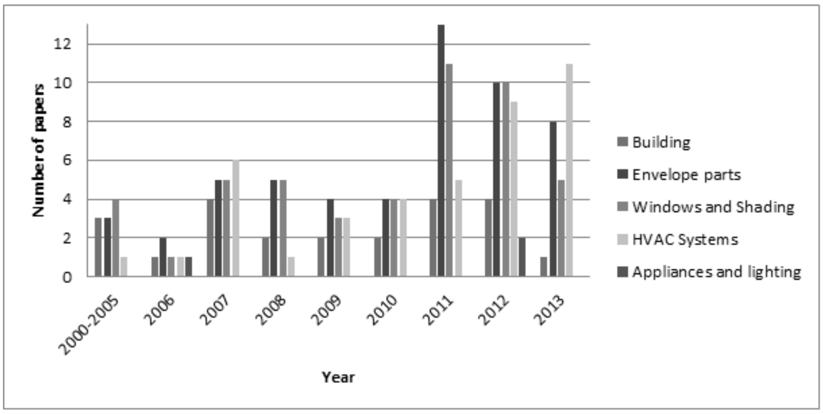

Figure 2a: Share of environmental, economical and energy objectives relative to the total number of articles per period

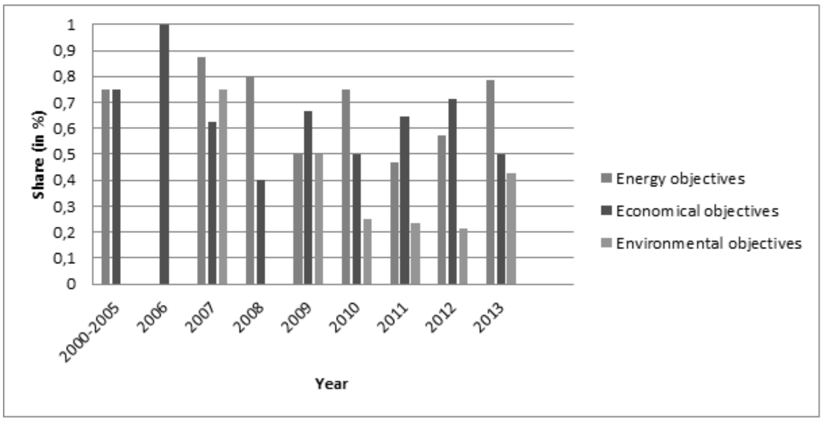

Figure 2b: Total number of articles of environmental, economical and energy objectives per period

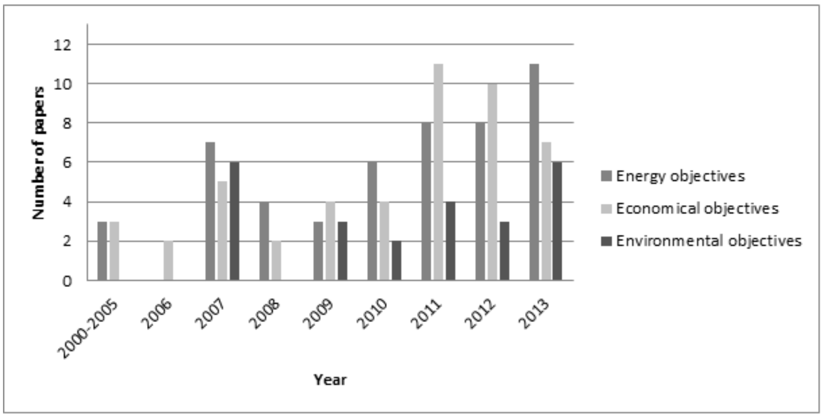

Figure 3a: Share of the five largest solution technique categories relative to the total number of articles per period

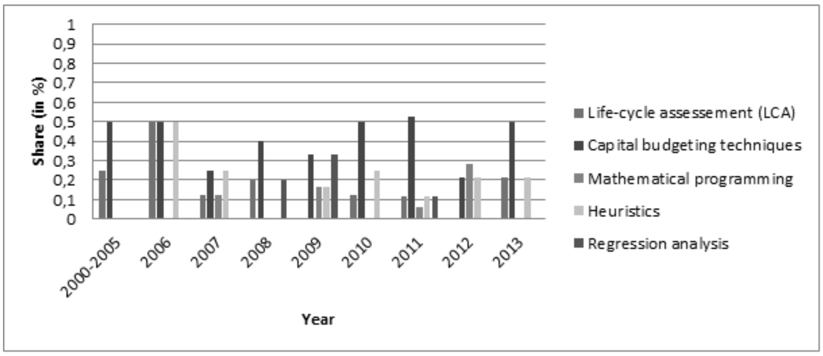

Figure 3b: Total number of articles of the five largest solution technique categories per period

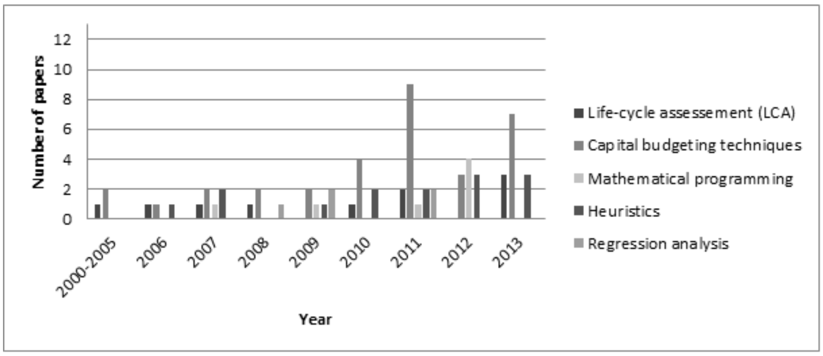

Figure 4a: Number of articles relative to the total number of publications per case study location since 2000

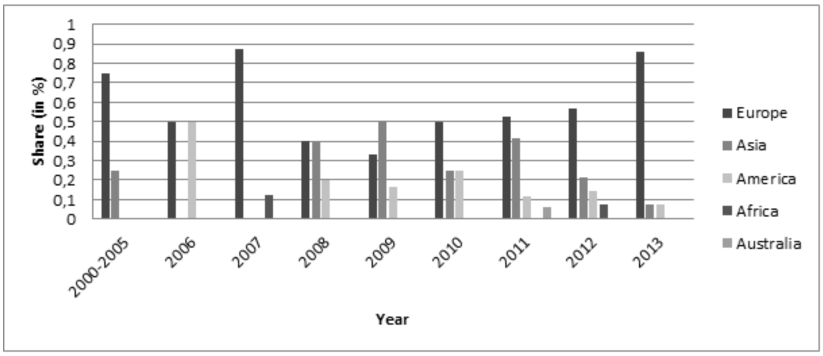

Figure 4b: Total number of articles per case study location since 2000