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# Economic Sustainability Evaluation of Green Residential Projects through Life Cycle Approaches:

## an International Literature Review


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# ABSTRACT

# INTRODUCTION

# Chapter 1 Green residential building



# Chapter 2

# Methodological background: Life cycle thinking

## Chapter 3 Literature selection



## Chapter 4 Conclusion remarks

# ABSTRACT

Global climate change is profoundly affecting the survival and development of human beings, and the construction industry is one of the main sources of greenhouse gas emissions. Residential buildings are the most numerous in the construction market, countries around the world are committed to the development of green buildings for residential uses to reduce energy consumption and greenhouse gas emissions. In many countries, the majority of existing homes are energy inefficient. The development of green, efficient and habitable residential building has become an inevitable trend in the sustainable development of buildings around the world.

Green building construction costs and retrofitting costs are key factors that hinder the promotion of green buildings. The aim of this Master's thesis is to identify how researchers in Europe and China are assessing the costs and environmental benefits of green residential buildings and green retrofitting of residential buildings from a life-cycle perspective, through a literature review.

The research in this thesis is focused on international publications in Europe and China from the period 2010-2022 that provide a comprehensive assessment of green residential buildings or retrofitting initiatives, mainly from a life cycle perspective, using life cycle costing and life cycle assessment, to study the differences and linkages in the use of economic assessment tools in different countries and regions.

41 publications were selected to confirm the feasibility of the integrated application of economic-environmental assessment tools from a life-cycle perspective in green residential buildings and green retrofitting in different international conditions through an initial analysis of the methodology, year of publication, type of publication, and type of case study, and a further analysis of author keywords and year through the use of bibliometric methods in VOSviewer.

# INTRODUCTION

With the development of science and technology, due to the population is increasing, and the energy consumption caused by human activities has a huge impact on the ecosystem. The growing population is also accompanied by a growing construction market. According to statistics, 'Construction industry has been estimated to consume 21 % of global energy consumption in 2040 and operational energy for buildings is expected to increase by 32 % by 2040 due to urbanization in non-OECD countries. Building and construction industry is responsible for resource scarcity, global warming impacts, land use changes and the loss of bio-diversity, which have direct and indirect socio-economic implications.'[1]

Other statistics on EU construction shows. 'Roughly 75% of the EU building stock is energy inefficient. 85-95% of EU buildings are expected to still be standing in 2050.'[2] The European Union is now committed to retrofitting buildings in order to meet the goals of the Paris Agreement, which includes improving the energy efficiency of residential buildings and reducing greenhouse gas emissions.

What's more, the European Union has also introduced a mandatory building renovation directive. 'The Energy Performance Building Directive (EPBD) introduced a new revised directive in 2013 requiring the mandatory introduction of nearly zero energy buildings (nZEBs) in all EU member states. Starting from the end of 2020, all new buildings or those receiving significant retrofit must show a very high energy performance.'[3]

As a result, the topics of green residential building are constantly being emphasized and discussed by academics, and topics on how to design and build green residential building and energy efficiency are constantly being studied by academics. At the same time, academics and real estate practitioners have also noticed that the cost of green residential building and green retrofits may be higher than that of ordinary residential buildings. It is very important to establish a set of economic assessment system and environmental-economic assessment tools for green residential building and green renovation of residential buildings, and approaches like life cycle cost, life cycle assessment, and the concept of cost-optimization are gradually being mentioned and applied.

The aim of this research thesis is to identify how researchers in Europe and China are conducting economic sustainability assessments for green residential building and residential

[1] Janjua Shahana Y., Sarker Prabir K., and Biswas Wahidul K., 'Sustainability Assessment of a Residential Building Using a Life Cycle Assessment Approach', Chemical Engineering Transactions 72 (February 2019): 19–24, https://doi.org/10.3303/CET1972004.
[2] European Commission, 'Factsheet_Buildings_EN (MAKING OUR HOMES AND BUILDINGS FIT FOR A GREENER FUTURE).',Brussels, 15th December 2021.
[3] Paul Moran, John O'Connell, and Jamie Goggins, 'Sustainable Energy Efficiency Retrofits as Residenial Buildings Move towards Nearly Zero Energy Building (NZEB) Standards', Energy and Buildings 211 (15 March 2020): 109816, https://doi.org/10.1016/j.enbuild.2020.109816.

retrofit initiatives from a life cycle perspective, with the ultimate goal of not being an economic assessment but including economic viability, environmental impacts, and social benefits, which can help homeowners gain a more comprehensive understanding of the overall benefits of residential building projects.

This thesis is structured into four chapters, the first of which introduces the basic theories related to green residential building and topics related to sustainability, beginning with a discussion of the idea of sustainability and an introduction to 3R technology and the circular economy, both of which are relevant to the building sector and housing in particular, and which can contribute to the efficient use of resources, the minimization of waste, and the reduction of environmental impacts, thus promoting residential buildings in a more sustainable direction.

The definition, principles and design approaches of green residential building are then presented, as well as the green retrofitting of residential, with a focus on energy-efficient residential retrofitting approaches. Chapter 1 discusses the status of green residential building in Europe. It provides an overview of the European Commission's announcement, discusses relevant laws and regulations, addresses implementation challenges such as cost, surveys the well-known Global Green Building Rating System, and presents European green residential building projects through case studies that illustrate their practical application and effectiveness.

The second chapter introduces life cycle thinking (LCT) and its connection to cost considerations, primarily through life cycle assessment (LCA) and life cycle cost (LCC) methods. In a life-cycle economy, decisions consider environmental, economic, and social impacts across a product's life. LCA evaluates environmental effects, while LCC assesses cost implications. Both methods share frameworks, enabling a holistic sustainability assessment. In architecture, pre-LCC and LCA assessments help developers understand green residential building impacts, aiding collaboration among decision-makers, architects, and construction experts to reduce costs and environmental footprint. Integrating circular economy principles enhances sustainability across industries.

In the third chapter, scientific publications related to life cycle approaches for designing, developing, and retrofitting green residences were collected by database searches using keywords like 'sustainable residence,' 'green housing(residential),' 'green retrofitting,' 'life cycle approach,' 'life cycle cost,' and 'life cycle analysis.' The scope is limited to green residential building and retrofitting, focusing on publications from 2010 to 2022, primarily from Europe and China. All publications are included in a table describing various information about the article. The author of each publication, keywords, country and city of the case, as well as the abstract of the article are presented, and relevant pictures of residential cases used in some of the publications are shown.

In the final chapter the publications collected in the previous chapter were analyzed in a variety of ways and 41 publications were archived through methodological methods, year of publication, type of publication, and case studies methods to examine changes in publications and research trends between 2010-2022. In addition, the literature was analyzed in more depth using bibliometric analysis through the program VOSviewer, such as information on the links between individual publications and the most frequently used author keywords.

# Chapter 1

# Green residential building

# INTRODUCTION

Since the 20th century, the construction industry has advanced rapidly around the world and the environmental problems brought about by social and economic development have made it necessary and urgent to develop green residential buildings. The construction of residential buildings not only consumes a large number of natural resources, but more importantly, has a serious negative impact on the environment.

This chapter introduces the theoretical framework, the definition and the green retrofitting of green residential, examines and discusses the laws and the implementation status of green residential building in Europe.

In the first section, the author will introduce the basic theory of green residential building. Firstly, the author will introduce the origin, concept and development of sustainable development, including its theoretical implications for green residential building. Then author will introduce the 3R technology theory (reduce, reuse and recycle) and show how the 3R technology theory can be applied in the construction of green residential building. Finally, the author will discuss the concept of circular economy, highlighting its application and advantages in the development of green residential building; and how it has been regulated in Europe.

In Section 2 the definition, principles and design tools of green residential building are presented in depth. This section looks at the origins and history of green residential buildings to clarify the concept of green residential buildings and its contribution to environmental sustainability. This is followed by a discussion of the six overarching and interrelated principles of green residential building design, related to environment, energy efficiency, water consumption, quality of life for occupants, durability, cost/benefit ratio, and building materials. Green retrofitting is discussed at last. Renovation and retrofitting are the most crucial part in the construction of green residential building since there are large number of buildings with low energy efficiency no matter in Europe. The approaches about retrofitting focus on energy efficiency and uses or recycling of building materials.

The section 3 is focused on the status of green residential building in Europe. Firstly, the author will introduce the condition of green residential building including the announcement from European Commission. We will then present the relevant laws and regulations to understand the national support and regulatory framework for green residential building in Europe, as well as the biggest resistance to their implementation - the cost; then going on to present some well-known rating systems about green and sustainable building in Europe and around the world. Finally, we will look at some of the green residential building projects implemented in Europe through case studies to demonstrate their application and effectiveness in practice.

## 1.1 The basic theory of green residential building

### 1.1.1 Sustainable Development

Since the 20th century, the construction industry in the world has made rapid progress. The development of green residential building has become very necessary because of the environmental problems brought by social and economic development. Saving resources, protecting the environment and improving the quality of human settlements all remind people to pay attention to the green development of residential.

In 1972, The Limits to Growth was commissioned by the Club of Rome, and its initial presentation took place during the summer of 1971 at international conferences held in Moscow and Rio de Janeiro. 'This document explored the five fundamental elements that shape and, through their interplay, ultimately constrain growth on our planet - namely, population growth, agricultural output, depletion of nonrenewable resources, industrial production, and the generation of pollution.'[1]

During that very year, the Stockholm Declaration emerged as the inaugural environmental proclamation by the United Nations, following the convening of the United Nations Conference on the Human Environment in Stockholm. 'It represented the beginning of a global dialogue on the links between economic growth, environmental pollution and human well-being, and laid the foundation for future global environmental governance.'[2] [3]

The World Commission on Environment and Development (WCED) introduced the notion of Sustainable Development in 1987, from the Brundtland Report. 'The report understands sustainable development as "meets the needs of the present without compromising the ability of future generations to meet their own needs".'[4] It also defines the three pillars of sustainability: social, economic and environmental.

The most basic content of sustainable development is to respect and protect the environment, make rational use of resources, and coordinate the development of all aspects from a long-term perspective. Green residential building meets the different needs of the environment and society, pays attention to the environment in which the house is located, and helps to maintain a high standard of living.

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[1] Meadows, Donella H; Meadows, Dennis L; Randers, Jørgen; Behrens III, William W (1972). 'The Limits to Growth; A Report for the Club of Rome's Project on the Predicament of Mankind.' New York: Universe Books. ISBN 0876631650. Retrieved 26 November 2017.
[2] 'Stockholm Declaration of 1972 Broadly Recognizes Global Environmental Issues', Environment & Society Portal, accessed 11 April 2023, https://www.environmentandsociety.org/tools/keywords/stockholm-declaration-1972-broadly-recognizes-global-environmental-issues.
[3] 'United Nations Conference on the Human Environment | [1972] | Britannica', accessed 11 April 2023, https://www.britannica.com/topic/United-Nations-Conference-on-the-Human-Environment.
[4] WCED, "Report of the World Commission on Environment and Development: Our Common Future", Brundtland Report,1987

### 1.1.2 The 3R Initiative

The principle of reducing waste, reusing and recycling resources and products is often called the "3Rs." Reducing means choosing to use things with care to reduce the amount of waste generated. Reusing involves the repeated use of items or parts of items which still have usable aspects. Recycling means the use of waste itself as resources. Waste minimization can be achieved in an efficient way by focusing primarily on the first of the 3Rs, "reduce," followed by "reuse" and then "recycle." The 3R Initiative aims to promote the "3Rs" (reduce, reuse and recycle) globally so as to build a sound-material-cycle society through the effective use of resources and materials.[5]

There is an enormous potential for application of the 3R initiative in green building environments.

"Reducing" means reducing the discharge of waste and pollutants and preventing and reducing environmental pollution by appropriate methods. "Reusing" means to recycle building materials as many times as possible or in a variety of ways to prevent building materials and materials from becoming building wastes prematurely. "Recycling" is to return construction waste to the production of raw materials for reprocessing into new raw materials.

There will be a huge building trash during the life cycle of residential building, also creating a big burden of the development in environment. Therefore, we should focus on how to reduce the waste emission in the residential design. We can extend the life of the old residential by remodeling and renovating it. In this process, many replacement building materials and components are created. 3R technology is needed to make these materials reusable so that these building materials and components to have no impact on the environment.

[5] 'The 3R Initiative', accessed 11 April 2023, https://www.env.go.jp/recycle/3r/en/outline.html.

### 1.1.3 Circular Economy

Coherently with sustainable development theory and the 3R initiative, circular economy has been widely supported in the built environment.

The circular economy is found on a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of building is extended. Building materials are kept within the economy wherever possible thanks to recycling when buildings reach the end of their life. These can be productively used again and again, thereby creating further value.[6]

Circular economy is a kind of economic model to replace the actual “linear” economy. In a linear economy, natural resources are turned into products that are ultimately destined to become waste because of the way they have been designed and manufactured. This process is often summarized by "take, make, waste".[7] This model relies on large quantities of cheap, easily accessible materials and energy. The circular economy removes the end phase of a product's life cycle and inserts a recycle-use-repair phase.

The figure 1 and figure 2 show the graphic of Linear Economy and circular economy, which indicates the procedure of linear and circular economy.


Figure 1, the graphic of Linear Economy

Source: Author' s re-elaboration from Supply Chain School 'Waste and resource efficiency', accessed 11 April 2023, https://www.supplychainschool.co.uk/topics/sustainability/waste-and-resource-efficiency/.

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[6] 'Circular Economy: Definition, Importance and Benefits | News | European Parliament', 2 December 2015, https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits.
[7] Taylor Brydges, 'Closing the Loop on Take, Make, Waste: Investigating Circular Economy Practices in the Swedish Fashion Industry', *Journal of Cleaner Production* 293 (April 2021): 126245, https://doi.org/10.1016/j.jclepro.2021.126245.


Figure 2, the graphic of Circular Economy

Source: Author' s re-elaboration from Supply Chain School 'Waste and resource efficiency', accessed 11 April 2023, https://www.supplychainschool.co.uk/topics/sustainability/waste-and-resource-efficiency/.

The transition towards CE in Europe is proposed by different economic actors, involving both private companies and public authorities in a virtuous cycle. 'CE primarily emerged in Germany in the early 1976 with the Waste Disposal Act, while at European Community level CE was promoted much later, by means of the Waste Directive 2008/98/EC and more specifically with the Circular Economy Package.'[8]

The "circular economy" has become a primary goal, with a global consensus to reduce the use of non-renewable natural resources and limit carbon emissions, leading to investments in new, more energy-efficient buildings and buildings certified as "sustainable" and "green".[9]

Figure 3 shows the CE model for building. Among them, we can see the application of every links of circular economy in building.

[8] Patrizia Ghisellini, Catia Cialani, and Sergio Ulgiati, 'A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems', *Journal of Cleaner Production* 114 (February 2016): 11–32.
[9] Hamidreza Hasheminasab et al., 'Combination of Sustainability and Circular Economy to Develop a Cleaner Building Industry', *Energy and Buildings* 258 (March 2022)

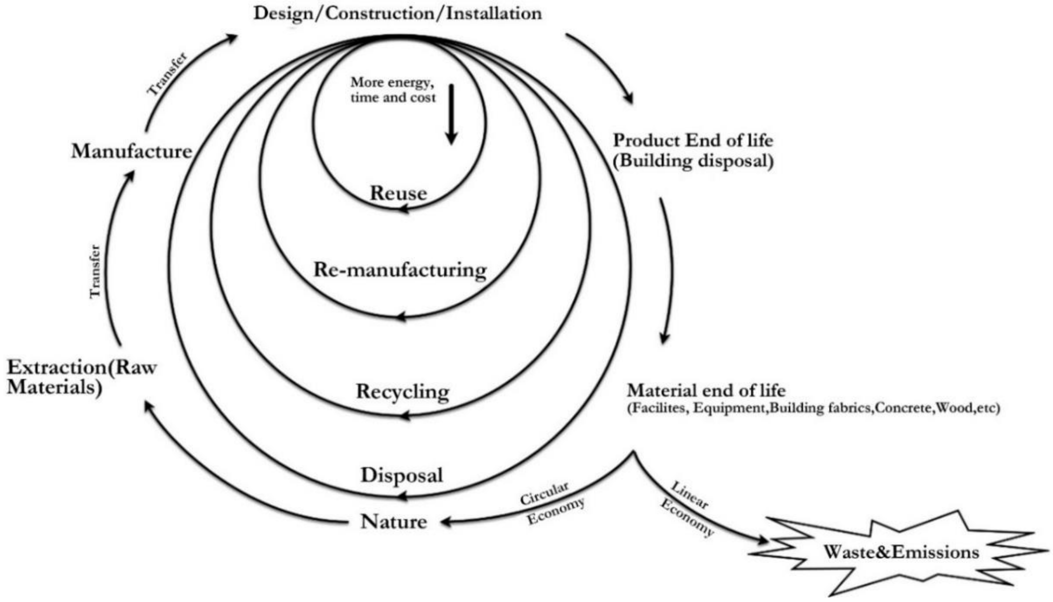


Figure 3 CE model for buildings.

Source: Author' s re-elaboration from Amidreza Hasheminasab et al., 'Combination of Sustainability and Circular Economy to Develop a Cleaner Building Industry', *Energy and Buildings* 258 (March 2022).

Although the building industry is a central target for EU and national Circular Economy (CE) policies, Surveys show that the industry is still in the early stages of developing CE practices. According to the survey in Luxembourg and Gothenburg and article from R.E. Hjaltadottir and P. Hild, [10] the construction industry is still in the early stages of CE practice, and most companies are in the process of positioning and defining the meaning and content of the circular economy. Authors do not find industry-wide practices in firm activities. They find promising developments in individual firms or supply chains, including purchasing for lower waste, CE materials and design using non-virgin materials and using digital tools to increase information transparency.

The article and the survey also highlight two key factors affecting the circular economy. First of all, the government should provide to the building industry the development of guiding principles (e.g. for public procurement) and monitoring procedures (incl. measurements and indicators). Secondly, the system view of the building industry reveals that the lack of collaboration and knowledge transfer within the industry CE, which leading the CE projects in isolated situation and have limited effect outside the project.[11]

Future research should thus focus on understanding the implications for the building industry in transitioning to CE practices. For example, potential CE practices cover suggestions for designing materials for circularity and using reused, up-cycled or recycled materials; and applying digital tools such as BIM to increase the transparency regarding materials used in buildings.

[10] Hjaltadóttir and Hild, 'Circular annveig Edda Hjaltadóttir and Paula Hild, 'Circular Economy in the Building Industry European Policy and Local Practices', *European Planning Studies* 29, no. 12 (2 December 2021): 2226–51, https://doi.org/10.1080/09654313.2021.1904838.in the Building Industry European Policy and Local Practices'. p-1.

[11] Hjaltadóttir and Hild, 'Circular annveig Edda Hjaltadóttir and Paula Hild, 'Circular Economy in the Building Industry European Policy and Local Practices', *European Planning Studies* 29, no. 12 (2 December 2021): 2226–51, https://doi.org/10.1080/09654313.2021.1904838.in the Building Industry European Policy and Local Practices'. p-20

# 1.2 Green residential building

## 1.2.1 The Definition of green residential building

What is green building? According to the White Paper on Sustainability, the Office of the Federal Environmental Executive defines green building as "the practice of 1) increasing the efficiency with which buildings and their sites use energy, water, and materials, and 2) reducing building impacts on human health and the environment, through better siting, design, construction, operation, maintenance, and removal — the complete building life cycle."[12]

Green building is a concept developed by the architectural community in response to the principle of sustainable development. In 1969 Italian architect Paolo Soleri coined the term "Arcology", which consists of the term "architecture" and "ecology". He defined ecological architecture as "Arcologies are architectural organisms of such character and dimensions as to be ecologically relevant." [13]It aims to guide architectural engineering activities from the perspective of sustainable development. In the 1990s, green building design has taken initial shape and become a comprehensive system composed of natural ecology, human construction activities and social economy. Nowadays, each country has established an evaluation system that adapts to its own architectural characteristics.

Europe has been promoting the practice of green residential building since the 1980s. In the 1980s, France carried out large-scale reconstruction work with the improvement of living environment as the main content. In the 1990s, Germany also began to implement the residential policies and measures to adapt to the ecological environment, in order to implement the sustainable development strategy.

Since the beginning of the 21st century, there has been a growing demand for the harmony between construction projects and environment and green residential. Construction projects are also increasingly focused on unified planning and control throughout the project life cycle, from design to recycling. In residential projects, environmental factors should be fully considered and utilized in the planning and design stage, a reasonable labor plan should be formulated, and environment-friendly building materials should be fully utilized in the construction process to minimize the impact on the environment. And make full use of clean energy in daily maintenance to reduce carbon emissions. After demolition, the waste can be sorted for recycling and reuse. Therefore, Chinese scholars defined the green residential building as: 'Green residential building in whole life period is to maximize the save resources, reduce pollution and protection environment, which provide residents comfortable, graceful and healthy living space, and reach the harmonious coexistence with natural.'[14]

[12] New York, N.A.I.M, "White Paper On the Sustainability, Building Design&Construction",2003(11), p-4.
[13] Soleri, Paolo (1973), "The Bridge Between Matter & Spirit is Matter Becoming Spirit; The Arcology of Paolo Soleri," Garden City, New York: Anchor Books, pp. 46, ISBN 978-0-385-02361-0.
[14] Xia Yun Li and Shi Qiang Zhao, 'Research on Construction for Sustainable Residential Based on the Whole Life Cycle', *Advanced Materials Research* 224 (April 2011): 164–69, https://doi.org/10.4028/www.scientific.net/AMR.224.164.

## 1.2.2 The principle and design methods of green residential building

The sustainability of a building involves the following aspects: environment, energy efficiency, water consumption, quality of life for occupants, durability, cost/benefit ratio, and building materials. Green residential building is specifically designed structures that reduce the overall negative impact of the built environment on inhabitant health and the natural environment by:

- 'Efficiency using energy, water land and materials.
- Protecting occupant health and improving employee productivity.
- Reducing waste and pollution from each green building.
- Continuously looking for ways to improve performance.'[15]

High-performance green residential building address sustainable development throughout the building's entire life cycle – from the beginning with the building's site selection and design all the way through to the end of the building's life.

There are six overarching and interrelated principles, noted below: [16]

**Optimize Site Potential.** This principle involves a range of considerations, such as the meticulous choice of appropriate locations, assessment of current edifices and infrastructure, strategic arrangement of roads and residences for optimal solar advantages, positioning of entryways and parking spaces, recognition of potential hazards, and prioritization of precious assets like trees, watercourses, ecological dwellings, and animal sanctuaries necessitating preservation.

**Minimize Energy Use and Use Renewable Energy Strategies.** This principle covers a range of components, such as the importance of substantial reduction in energy usage (achieved through insulation, effective appliances and lighting, and careful consideration of the entire construction design), reducing dependency on non-renewable fuels, incorporating sustainable energy setups such as photovoltaic panels, geothermal heat pumps, and solar water heating whenever viable, and acquiring environmentally friendly energy sources to alleviate the production of greenhouse emissions.

**Conserve and Protect Water.** This principle includes factors like handling site runoff through reduction, control, or treatment methods, creating homes that effectively preserve water for both indoor and outdoor use, and ensuring leak prevention by conducting comprehensive assessments throughout the construction phase.

**Use Environmentally Preferable Products.** This principle covers a range of factors, involving the selection of items derived from reclaimed sources, composed of recycled materials,

[15] 'Basic Information | Green Building | US EPA', accessed 24 April 2023, https://archive.epa.gov/greenbuilding/web/html/about.html.
[16] Sustainable Buildings Industry Council, 'Green Building Guidelines Meeting the Demand for Low-Energy, Resource-Efficient Homes'，the fifth edition, Sustainable Buildings Industry Council, Washington, 2007,p-XI

advocating for the preservation of natural resources, minimizing overall material consumption, showcasing remarkable longevity or limited maintenance needs, undergoing minimal processing, conserving energy and/or water, and/or aiding in the reduction of pollution or waste resulting from operational processes.

**Enhance Indoor Environmental Quality.** This principle incorporates tactics designed to guarantee remarkable acoustic, thermal, and visual attributes, all of which significantly impact well-being, ease, and efficiency. Additional crucial considerations encompass optimizing natural sunlight, introducing suitable ventilation and moisture management strategies, and employing products with minimal or zero VOC (Volatile Organic Compounds) content.

**Optimize Operations and Maintenance Practices.** This principle addresses materials and systems that streamline and minimize operational demands, necessitate less water, energy, and toxic chemicals and cleaners for maintenance purposes, prove cost-effective, and reduce life-cycle costs.

However, not all green residential buildings should be designed in the same way. Different countries and regions have different cultural traditions, climatic characteristics, design styles, lifestyles and social developments, so the design principles and design methods for green residential buildings should be adapted to each situation.

### 1.2.3 Green retrofitting

According to the '2022 Global Status Report for Buildings and Construction', 'Operational energy demand in buildings (such as space heating and cooling, water heating, lighting and cooking) has grown to around 135 EJ, which is an increase of around 4 per cent from 2020 and exceeds the previous peak in 2019 by over 3 per cent. Related to energy demand, the global buildings sector $CO_2$ operational emissions have also rebounded from 2020 by about 5% to a level of around 10 $GtCO_2$. This increase in emissions exceeds the pre-pandemic all-time high in 2019 by 2%.'[17]

As the pandemic wanes and the global economy recovers, households and business economies will return to their previous levels of energy use, if not higher. 'The energy intensity of buildings, representing the total final energy consumption per square meter. According to the estimation of International Energy Agency (IEA), to achieve the needed pathway toward net zero carbon, the intensity needs to drop by around 35%, from current 150 $kWh/m^2$ to around 95 $kWh/\ m^2$. To do so, alongside decarbonization of the grid, the building renovation rate must increase to 2.5% per year (or 10 million dwellings per year) by 2030 in developed economies.'[18]

To achieve this goal, EU currently faces a huge challenge in building renovation. 'Currently, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient. Each year only 0.4-1.2% of the building stock is renovated.'[19]

Figure 4 represents the analysis for the average age of existing buildings, based on the data published in the 2011 Census Hub[20] of EUROSTAT, updated by down-scaling the national constructions after 2011, taken from the Building Stock Observatory[21] of the EC.'

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[17] United Nations Environment Programme (2022). 2022 Global Status Report for Buildings and Construction: Towards a Zero‑emission, Efficient and Resilient Buildings and Construction Sector. Nairobi, p-18.

[18] United Nations Environment Programme (2022). 2022 Global Status Report for Buildings and Construction: Towards a Zero‑emission, Efficient and Resilient Buildings and Construction Sector. Nairobi, p-18.

[19] Antonella Valitutti and Salvatore Roberto Perricone, 'The Application of Minimum Environmental Criteria (CAMs) Construction and Sustainable Transformation of Public Building Stock', in *WORLD HERITAGE AND LEGACY: CULTURE, CREATIVITY, CONTAMINATION*, ed. A. Ciambrone, vol. 4, Architecture Heritage and Design (17th International Forum on World Heritage and Legacy: Culture, Creativity, Contamination, Roma: Gangemi Editore S P A, 2019), 444–50, https://www.webofscience.com/wos/woscc/full-record/WOS:000561109000049.

[20] 'Census 2011', accessed 2 May 2023, https://ec.europa.eu/statistical-atlas/viewer/?config=census.json&.

[21] 'EU Building Stock Observatory', accessed 2 May 2023, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/eu-building-stock-observatory_en.

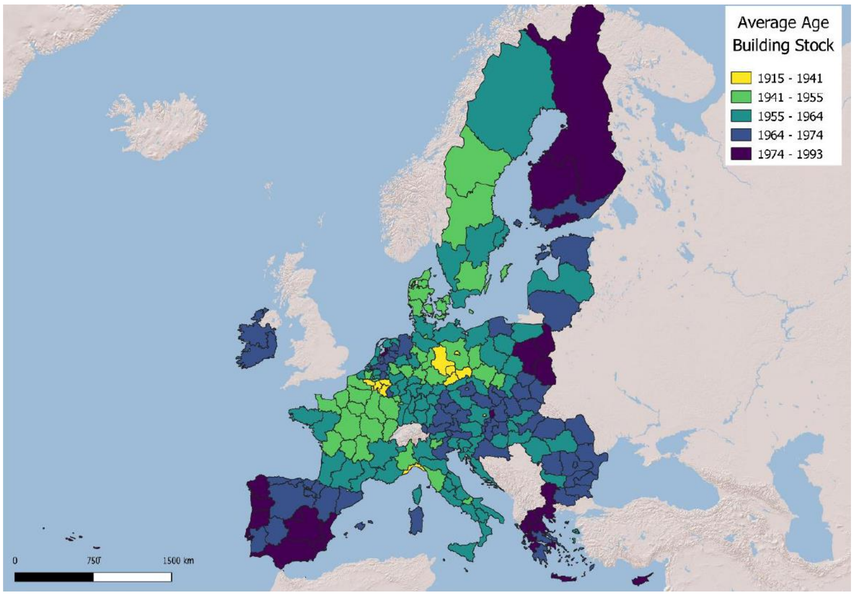


Figure 4 Average age of building stock at NUTS2 level (JRC elaborations on CENSUS HUB data).

Source: European Commission. Joint Research Centre., *Building Energy Renovation for Decarbonisation and Covid-19 Recovery: A Snapshot at Regional Level.* (LU: Publications Office, 2020), https://data.europa.eu/doi/10.2760/08629, p-11.

The graph shows that the average age building stock in most of Europe was between 1941 and 1964. During this period, most of the buildings built were extremely energy inefficient.

Nowadays, construction activities in Europe are dominated by green retrofitting, as well as energy-efficient and low carbon building design.

The definition of green retrofitting is 'Upgrade at an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, improve comfort and quality of space in terms of natural lighting, air quality and noise, all done in a way that it is financially beneficial to the owner'[22]

Smaller projects can also be included in green retrofitting, no need for complete retrofitting of the original building. Some projects of green retrofitting are as follows:

**Integrated design**: Integrated design principles are central to green retrofits. Unlike the conventional approach where architects, engineers, and contractors operate independently, integrated design mandates the convergence of all three disciplines into a cohesive team effort. 'The design solutions are often constrained by the existing site, this could relate to the orientation and geometry of the existing building form, the size of the site, or the installation requirements of the existing and proposed mechanical systems. To ensure sustainable, effective, and cost-efficient solutions, project teams must consider all aspects from the start.'[23]

[22] Tantau, Adrian, and Maria Alexandra Maassen. "Business Models for Green Retrofitting." Retrofitting for Optimal Energy Performance, edited by Adrian Tantau, IGI Global, 2019, pp. 1-27. https://doi.org/10.4018/978-1-5225-9104-7.ch001

[23] Bu, Shanshan; Shen, Geoffrey (2013). "A Critical Review of Green Retrofit Design". Iccrem 2013. pp. 150–158. doi:10.1061/9780784413135.014. ISBN 9780784413135.

**Occupant behavior**: The wrong behaviors of occupants have considerable impact on building energy performance, to ensure that energy efficiency measures reach their full design potential, green retrofitting involves training occupants in sustainable practices for using the building system that interact with them. 'The first lever of energy efficiency is a proper energy-education of users.'[24]

**Light retrofit**: This involves a comprehensive or partial lighting retrofit, which typically entails the substitution of older, less efficient lightbulbs in a structure with newer and more energy-efficient alternatives. 'LED bulbs are often preferred over incandescent bulbs because they are more efficient. Lighting retrofits can also include implementing new lighting controls like occupancy sensors, daylight sensors, and timers. When correctly implemented, these controls can reduce the demand for lighting.'[25]

**HVAC retrofit**: It mainly involves replacing older, less efficient HVAC systems with more efficient HVAC equipment that uses less electricity. 'According to the statistics, heating, ventilation, and air conditioning (HVAC) account for around 50% of a building's operating energy consumption, and HVAC retrofits can account for 40-70% of energy savings'[26] 'newly sealed houses, heat recovery ventilation systems are used to exchange old, damp air in the room; more efficient water heaters are used to power the heating system, old boilers are replaced with newer ground or air source heat pump systems, etc.'[27]

**Building envelope retrofits:** The building envelope is the key to whether the building can meet the energy saving standard. If the thermal solution of the building envelope are not able to achieve the standard of green building rating systems, costing money on energy for cooling and heating and adjusting the air inside building, however, the air will be leaked from the through poorly insulated windows and envelopes.

**Window retrofits:** Windows have a great impact on the insulation efficiency of the envelope, so window renovation is a key area of green renovation. 'Window retrofits refer to decreasing overall window U-factors through adding glass layers, surface coatings, or altering the gas mixture in the glazing units.'[28] These gas mixtures are usually inert gases.

**Green roof retrofits:** There are many environmental benefits on green roofs, here are as follows: 'reduction of energy demand for heating and cooling, mitigation of urban heat island, reduction and delay of storm water runoff, improvement in air quality, replacement of displaced landscape, enhancement of biodiversity, provision of recreational and agricultural spaces, and insulation of

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[24] F.Ascione, N.Bianco, ed, "The role of the occupant behavior in affecting the feasibility of energy refurbishment of residential buildings: Typical effective retrofits compromised by typical wrong habits". Energy and Buildings. 223: 110217. doi:10.1016/j.enbuild.2020.110217

[25] Gordon Lowry (2016). "Energy saving claims for lighting controls in commercial buildings" (PDF). Energy and Buildings. 133: 489–497. doi:10.1016/j.enbuild.2016.10.003.

[26] Luis Pérez-Lombard, José Ortiz, Christine Pout, 'A review on buildings energy consumption information', Energy and Buildings, Volume 40,Issue 3, 2008, Pages 394-398, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2007.03.007.

[27] 'Green Retrofit', in *Wikipedia*, 29 January 2023, https://en.wikipedia.org/w/index.php?title=Green_retrofit&oldid=1136215333.

[28] Denver Jermyn and Russell Richman, 'A Process for Developing Deep Energy Retrofit Strategies for Single-Family Residential Typologies: Three Toronto Case Studies', *Energy and Buildings* 116 (March 2016): 522–34, https://doi.org/10.1016/j.enbuild.2016.01.022.

a building for sound.'[29] It is necessary to consider the strength of building roof or the existing building roof whether it can be bear the corresponding structural strength, when designing a green roof. Therefore, the structure of the building needs to be evaluated or re-waterproofed.

**Passive design:** Passive design emerges as a pivotal approach for green retrofitting. It orchestrates the inherent characteristics of both the building and its surroundings to fulfill the building's essential requirements, encompassing aspects, 'Passive design is a design strategy that uses the objective conditions of the building and landscape to provide the functions needed by the building, such as heating, cooling, lighting, ventilation, electricity, etc. The shape of the building is also designed to create a microclimate, collecting heat or funnel breezes to warm up in winter or cool down in summer.'[30] It is crucial to take passive design into consideration for green retrofitting. 'For example, adjusting the unsuitable windows if they absorb less sunshine in winter but more sunshine in summer.'[31]

[29] Fabricio Bianchini and Kasun Hewage, 'How "Green" Are the Green Roofs? Lifecycle Analysis of Green Roof Materials', *Building and Environment* 48 (February 2012): 57–65, https://doi.org/10.1016/j.buildenv.2011.08.019.
[30] 'Green Retrofit'. in *Wikipedia*, 29 January 2023, https://en.wikipedia.org/w/index.php?title=Green_retrofit&oldid=1136215333.
[31] Hootman, Thomas (2013). 'Net zero energy design : a guide for commercial architecture.' John Wiley & Sons. ISBN 978-1-118-34848-2. OCLC 775591941.

## 1.3 Green residential building in Europe

### 1.3.1 The status of green residential building in Europe

The expansion of the green building industry in Europe is attributed to a number of governmental policies implemented by European nations, as well as the European Union's policy framework aimed at promoting the growth of eco-friendly and sustainable residential. 'The Europe green building market is expected to grow from US$ 54.1 billion in 2021 to US$ 122.61 billion by 2028; it is estimated to grow at a CAGR of 12.4% from 2021 to 2028.'[32]

In 2020, the European Commission announced 'A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives'[33] The aim is to increase the yearly energy renovation rate of both residential and non-residential buildings by 2030, with a target of doubling the current rate. Additionally, there is a focus on promoting extensive energy renovations. To achieve this objective, it is necessary to bring together all stakeholders and resources, with the ultimate goal of renovating 35 million building units by 2030. It is crucial to sustain this accelerated pace of renovation, even beyond 2030, to attain climate neutrality across the EU by 2050.

A particular study offers insights into the status of European Union (EU) member countries' application of European policies concerning building energy efficiency. The study also highlights the utilization of financial initiatives and incentives aimed at fostering an energy-efficient built environment. 'It is shown that more than 70% of Member States have transposed the EU Energy Performance of Building Directives and all of them have activated plans or programs to finance the building energy renovation, mainly in the residential sector.'[34]

As European nations embrace greener paradigms, the region has evolved into a crucible of pioneering advancements encompassing energy-efficient technologies, resource-sensitive designs, and sustainable construction methodologies. This dynamic milieu fosters a collaborative synergy among architects, engineers, developers, and policymakers, propelling the creation of edifices that seamlessly amalgamate practicality with ecological mindfulness. 'A few examples of these buildings are Cube in Germany, the Edge in the Netherlands, and Bloomberg in the UK. These green buildings are building a positive influence on the green building market in Europe by creating avenues for innovation and setting the trends for the green building market worldwide. For example, The Edge is renowned worldwide for its use of IoT, photovoltaic, and LED technologies, among other advanced technologies, to measure and attain energy efficiency.'[35]

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[32] Business Market Insights, 'Europe Green Building Market Forecast to 2028 - COVID-19 Impact and Analysis by Product Type (Insulation, Roofing and Siding, Interior Products, Building Systems, and Others) and Building Type (Residential and Non-residential)', TIPRE00026816, Jan 2022.

[33] EUROPEAN COMMISSION (2019). 'Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives.' Brussels.14 October 2020.

[34] Fabrizio Ascione et al., 'Improving the Building Stock Sustainability in European Countries: A Focus on the Italian Case', *Journal of Cleaner Production* 365 (September 2022): 132699, https://doi.org/10.1016/j.jclepro.2022.132699.

[35] Business Market Insights, 'Europe Green Building Market Forecast to 2028 - COVID-19 Impact and Analysis by Product Type (Insulation, Roofing and Siding, Interior Products, Building Systems, and Others) and Building Type (Residential and Non-residential)', TIPRE00026816, Jan 2022.

Most buildings in Europe are poorly insulated, 'In the EU, 23 % of homes were constructed before 1945, and 26 % were constructed between 1945 and 1969, according to 2014 figures. That means 49 % of homes were built before 1970. Only 23 % were built after 1990.'[36] Consequently, all individuals within these nations are confronted with substantial expenses associated with renovations.

Currently the cost of retrofitting buildings is the biggest resistance to the implementation of green residential building renovation in Europe. 'According to ANCE, the Italian national building association, meeting the objectives of the green building pact will require upgrading approximately 1.8 million residential buildings at an estimated cost of €400 billion over the next decade. Moreover, an additional €190 billion will be necessary to ensure that commercial properties comply with the required standards.' [37]

In response to the growing green building market, certification and rating mechanisms for evaluating sustainable buildings have emerged in various countries. These tools assume a pivotal function, aiding developers and proprietors in readily discerning the most fitting category of eco-friendly building practices.

Presented below are a selection of the most renowned rating systems, acknowledged both within Europe and across the world:

**LEED: '**LEED is a third-party certification program established by the United States Green Building Council (USBGC). LEED is a framework that enables building owners and operators to identify and implement practical and measurable green building design, construction, and operations and maintenance solutions. The intent behind the creation of LEED was to have a common standard of measurement, and promote integrative, whole building design practices. LEED has now developed into a comprehensive system of interrelated standards covering all aspects of the development and construction process. It has revolutionized the marketplace as the world's premier benchmark for design, construction, and operation of high-performance green buildings.'[38] Projects with LEED certification spread over 140 countries.

**WELL: '**The WELL Building Standard (WELL) is currently one of the most comprehensive building certification programs that aim to enhance the health and well-being of building occupants. WELL certification made its debut with the launch of the first version of WELL (WELL v1) in 2014. WELL v1 features fall within seven WELL concepts: Air, Water, Nourishment, Light, Fitness, Comfort, and Mind.'[39] The WELL is primarily concerned with the

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[36] Servet Yanatma, 'Europe's energy crisis in data: Which countries have the best and worst insulated homes?', euronew. green, Published on 09/12/2022 - 07:00. https://www.euronews.com/green/2022/12/09/europes-energy-crisis-in-data-which-countries-have-the-best-and-worst-insulated-homes.

[37] Angela Symons, 'The EU green buildings plan aims to slash emissions - but this European country isn't happy', euronew. green, Published on 06/02/2023 - 13:43, https://www.euronews.com/green/2023/02/06/the-eu-green-buildings-plan-aims-to-slash-emissions-but-this-european-country-isnt-happy#:~:text=Italy's%20national%20building%20association%20ANCE,required%20standards%2C%20it%20has%20forecast.

[38] Jin Ouk Choi et al., 'LEED Credit Review System and Optimization Model for Pursuing LEED Certification', *Sustainability* 7, no. 10 (October 2015): 13351–77, https://doi.org/10.3390/su71013351.

[39] Nasim Ildiri et al., 'Impact of WELL Certification on Occupant Satisfaction and Perceived Health, Well-Being, and Productivity: A Multi-Office Pre- versus Post-Occupancy Evaluation', *Building and Environment* 224 (1 October 2022): 109539, https://doi.org/10.1016/j.buildenv.2022.109539.

health and well-being of its occupants

**Green Globes:** 'Green Globes is the first web-based environmental assessment, education and rating system, which is produced by the ECD Energy & Environment Canada Ltd. Seven areas are included in the assessment tool, namely Project Management, Site, Energy, Water, Materials & Resources, Emissions, and Indoor Environment.' [40] Unlike LEED, Green Globes has no prerequisites.

**DGNB: '**The German Sustainable Building Council (DGNB) is the German and international knowledge platform for sustainable building and provides the world's most advanced sustainable building certification system. Its aim is the planning and assessment of sustainable buildings and districts. With more than 2800 pre-certified or certified projects worldwide.'[41] Meanwhile, DGNB is also the largest sustainable architecture network in Europe.

**Miljöbyggnad: '**This is the Swedish national sustainable building certification system and by far the most popular one, with 547 certified buildings and 659 preliminarily certified buildings across the country. It is owned and managed by the Swedish Green Building Council (SGBC) and was adapted to the Swedish climate and construction environment, rooted in the national construction and sustainability regulation context.'[42] Unlike LEED, Miljobyggnad focuses on building and construction and is complementary to Swedish regulations

**ITACA PROTOCAL:** In 1996, within the Italian regions, an altruistic organization known as ITACA, which stands for "Institute for Innovation and Transparency in Procurement and Environmental Compatibility," was established. This non-profit association aimed to promote transparency, continuous improvement, and the certification of contractual practices. 'The buildings are classified according to their level of sustainability. There are 37 credits, divided into 19 categories, distributed in turn in five thematic areas. Site quality, resource consumption, environmental load, indoor environmental quality, and service quality. The output of the activity conducted for the calculation of the performance score is an "evaluation report", carried out on a single building and its external area of relevance, containing the results of the evaluation with respect to the set of criteria taken into consideration.' [43]

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[40] Zezhou Wu et al., 'A Comparative Analysis of Waste Management Requirements between Five Green Building Rating Systems for New Residential Buildings', *Journal of Cleaner Production* 112 (20 January 2016): 895–902, https://doi.org/10.1016/j.jclepro.2015.05.073.
[41] Anna Braune, 'DGNB Framework for "Carbon-Neutral Buildings and Sites"', in *IMPROVING ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS AND SMART COMMUNITIES*, ed. P. Bertoldi, Springer Proceedings in Energy (10th International Conference on Improving Energy Efficiency in Commercial Buildings and Smart Communities (IEECB and SC), Cham: Springer International Publishing Ag, 2020), 45–52, https://doi.org/10.1007/978-3-030-31459-0_4.
[42] Mara Forsberg and Clarice Bleil de Souza, 'Implementing Regenerative Standards in Politically Green Nordic Social Welfare States: Can Sweden Adopt the Living Building Challenge?', *Sustainability* 13, no. 2 (January 2021): 738, https://doi.org/10.3390/su13020738.
[43] Giuseppe Iiritano et al., 'ITACA PROTOCOL: A POSSIBLE PATH TO SUSTAINABILITY IN THE GOVERNANCE OF THE BUILDING PROCESS' (SUSTAINABLE CITY 2021, Bilbao, Spain, 2021), 111–22, https://doi.org/10.2495/SC210101.

## 1.3.2 Regulation & Legislation

This section provides on introduction of regulation and legislation from EU countries in terms of building energy efficiency. 'It is shown that more than 70% of Member States have transposed the EU Energy Performance of Building Directives and all of them have activated plans or programs to finance the building energy renovation, mainly in the residential sector.'[44]

From 2002, the EU began to gradually introduce mandatory standards on the energy performance of buildings, starting with directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. 'The objective of this Directive is to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness.'[45]

This directive includes 17 articles about the general framework for a methodology of calculation of the integrated energy performance of buildings and requirements of energy performance for both new buildings and existing buildings; the energy certification of buildings and so on. The New Approach Directive makes the technical regulations of the member states gradually converge, thus accelerating the harmonization process of the EU technical regulations.

In terms of technical building regulations, in 2010, the EU adopted the new Energy Efficiency in Buildings Directive EPBD (2010/31/EU)[46], replacing the former EPBD (2002/91/EC).

In the 2002/91/EC Directive, Article 3 of the EPBD recast focuses on implementing a methodology for determining the energy efficiency of buildings, with a more comprehensive explanation compared to the previous Directive. Annex I, which implements Article 3, provides additional detailed guidelines, including the requirement for prior calculation of annual energy consumption, heating and cooling energy requirements, energy performance indicators, and a numerical indicator for primary energy usage.

A revised version of the EPBD was published in 2018. This revised version emphasizes the roles of the EPB standards. 'EU Member States are encouraged to consider applicable standards, in particular from the list of EPB standards. The EPBD aims to promote the improvement of the energy performance of buildings within the European Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. (Article 1).'[47]

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44 Fabrizio Ascione et al., 'Improving the Building Stock Sustainability in European Countries: A Focus on the Italian Case', *Journal of Cleaner Production* 365 (September 2022): 132699, https://doi.org/10.1016/j.jclepro.2022.132699.

45 EU Commission and Parliament Directive 2002/91/EU, 2003. Of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings. Off. J. Eur. Union. Available at: https://eur-lex.europa.eu/LexUriSer v/LexUriServ.do?uri=OJ:L:2003:001:0065:0071:EN:PDF.

46 'Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast)', 153 OJ L § (2010), http://data.europa.eu/eli/dir/2010/31/oj/eng.

47 'The Energy Performance of Buildings Directive (EPBD) — EPB Standards — EPB Center | EPB Standards', accessed 17 May 2023, https://epb.center/epb-standards/energy-performance-buildings-directive-epbd/.

Not all EU countries have translated EPBD updates into national legislation, but they all promote incentives for building energy efficiency retrofits. A schematic summary of the EPBD implementation status and the financial incentives and funding programs for some European Countries is reported in figure 5.

| European country | Implementation of EU Directive 2018/844 | Funding programs and financial initiatives to improve building energy efficiency |
|---|---|---|
| Austria | OIB Guideline 6 (further recast under preparation for 2023). | Financial incentives for single-family households are provided since 2009. The big renovation campaign: "Sanierungscheck" from 2016 and "Raus-aus-dem- ¨ Ol" for thermal and energetic retrofit of buildings were introduced. In addition, several subsidies in the form of grants or loans are available for regeneration according to the province (Subsidies and financing for residential)[48]. |
| Belgium – Brussels Capital Region | Energy performance of buildings (EPB) regulation. The ordinance for the Brussels Air, Climate and Energy Code (COBRACE) has implemented Directive 2010/31/EU1 and Directive 2018/844/EU. | Since 2004, energy premiums are given for renovation works. From January 2022, the "RENOLUTION-premies 2022" has been introduced by merging all the previous bonuses for energy renovation and façade enhancement (RENOLUTION-premies 2022, 2022)[49]. |
| Denmark | In 2019 Law No. 1590 was amended to introduce the prescriptions of Directive 2018/844/EU in Danish regulation. | The tax-deduction schemes for private buildings are: the "BetterHouses"("BetterHouses" funding program)[50] initiative to support cost-optimal energy saving and the "Building scheme" ( Building scheme) which is a grant given to the owners of a building with the greatest energy-saving potential. For the industrial sector, there is the "Competitive subsidy scheme related to private enterprises" (Competitive subsidy scheme related to)[51]. New subsidy schemes were opened starting in 2021. |
| Finland | Directive 2018/844 EU was transposed into Law 733/2020, which introduces the automation control and local recharging points for electric vehicles in the building projects. A reference Law about energy efficiency and technical systems in buildings, which comply with EPBD Directives, is the Decree of the Ministry of the Environment 718/2020. | The government supports the improvement of the building energy performance through Decree 1341/2019 which provides for a state grant for the energy renovation of residential buildings for the period 2020–2022. This subsidy program was set by the Ministry of Environment and is available for small houses or public and private buildings (Valtioneuvoston asetus asuinrakennusten energia, 2020)[52]. |
| France | The current regulation about energy performance, which transpose the EPBD requirements, is the RT 2012 "R´ eglementation Thermique 2012" (RT2012), but from 2020 the RE2020 "R ´ eglementation environnementale 2020" was prepared. | From September 2020, France has established new objectives in the stimulus plan, giving prominence to the energy-efficient renovation of buildings: 4 billion euros has been devoted to the refurbishment of public buildings. Until 2019, the financial support for energy renovations was a tax deduction[53] |
| Germany | Directive 2018/844 was implemented into the Law to standardize energy saving (GEGEG) in 2020 and Building Electromobility Infrastructure Act (GEIG) in 2021. | To promote energy saving in buildings and to encourage investments in the building sector the Federal Ministry for Economic Affairs funded the "Energy Efficient Refurbishment" program (Energy Efficient Refurbishment)[54]. Energy efficiency measures for residential buildings are eligible for funding in the |

[48] 'Subsidies and Financing in the Federal Provinces', oesterreich.gv.at - Österreichs digitales Amt, accessed 17 May 2023, https://www.oesterreich.gv.at/en/themen/bauen_wohnen_und_umwelt/wohnen/2.html.
[49] 'Publications', *Homegrade* (blog), accessed 17 May 2023, https://homegrade.brussels/publications/.
[50] 'Energirenovering med BedreBolig', Energistyrelsen, 2 October 2014, https://old.sparenergi.dk/forbruger/vaerktoejer/bedrebolig.
[51] Competitive subsidy scheme related to private enterprises". Available online at: https ://ens.dk/ansvarsomraader/energibesparelser/virksomheder/erhvervstilskud-til energieffektiviseringer.
[52] Valtioneuvoston Asetus Asuinrakennusten Energia-Avustuksista Vuosina 2020–2022 (1341/2019). Available online at: https://www.finlex.fi/fi/laki/alkup/2019/ 20191341.
[53] Efficiency in France. Available online at: https://www.french-property.com/guides/ france/building/renovation/energy-conservation/.
[54] Energy efficient refurbishment" programme. Available online at: https://www.kfw. de/inlandsfoerderung/Privatpersonen/Bestehende-Immobilie/F%C3%B6rderprod ukte/Energieeffizient-Sanieren-Kredit-(151-152)/?redirect=647750.

| | | |
|---|---|---|
| | | form of tax deductions (Steuerliche F ¨ o rderung energetischer Geb ¨ a udesanierungen)[55]. During the COVID-19 a CO2 renovation program |
| Italy | Legislative Decree No. 48/2020 aligns the Italian legislation on the energy performance of buildings with the new European rules envisaged by the EU Directive 2018/844. | Italy has introduced different measures to incentive the building renovations in the form of tax deductions: a renovation bonus "Bonus ristrutturazioni", an energy refurbishment bonus "Ecobonus" and a bonus for anti-seismic interventions "Sisma-Bonus", a bonus for the restoration of external facades "Bonus Facciate" and finally, the "Superbonus" in response to the COVID-19, from July 2020 to December 2022 and in some cases to 2023 (Italian Superbonus)[56]. |
| The Netherlands | From March 2020, the government has presented a long-term renovation strategy to implement Directive 844/2018. | At the national level, the national heating fund "Nationaal Warmtefondsis" is at the disposal of homeowners, schools, or associations of homeowners, to finance energy-saving measures in the form of loans (Financing sustainability in Netherlandsd)[57]. In addition, subsidies for sustainable heat measures (solar water systems, heat pumps pellet stoves, or biomass energy) and thermal insulation are available as grants for the owner. Single municipalities have also their grant systems. |
| Sweden | In May 2019, the Swedish National Board of Residential, Building, and Planning started to investigate how to introduce the new requirements of Directive 844/2018 into national legislation and proposed the Report 2019:15 "New requirements for recharging infrastructure for rechargeable vehicle". In 2020 amendments entered into force in the Swedish Planning and Building Act (2010:900) and Planning and Building Ordinance (2011:338). | A tax deduction is granted for the work of repair or refurbishment of dwellings for a maximum of 75′ 000 SEK per person/year (Root deductions for houses in, 1163)[58]. |
| Spain | The Basic Energy-Saving Document of the Technical Building Code (CTE-DB-HE, 2006) is currently under revision to implement Directive 844/2018. | MITMA State Residential Plan 2018–2021 has promoted energy efficiency and sustainability in residential. Starting from 2021, with a recovery plan after the COVID-19 pandemic, the "programa PREE 5000" was published to support energy refurbishment of buildings with a percentage grant commeasured to the type of intervention (PREE 5000)[59]. |

Figure 5 A schematic summary of the EPBD implementation status and the financial incentives and funding programs for some European Countries.

Source: Author's re-elaboration from Fabrizio Ascione et al., 'Improving the Building Stock Sustainability in European Countries: A Focus on the Italian Case', *Journal of Cleaner Production* 365 (September 2022): 132699, https://doi.org/10.1016/j.jclepro.2022.132699.p-4.

According to the investigation and research of Fabrizio Ascione et al, 'More than 70% of EU Countries have implemented Directive 2018/844 into national legislation (figure 6), and some of the Countries that have not yet transposed it, have started implementation processes. In any case, all MSs have promoted initiatives and incentives to finance the improvement of building energy efficiency. At least 6 Countries have improved or incremented their financing initiatives to promote building energy efficiency in 2021, after the onset of the COVID-19 pandemic.'[60]

[55] Steuerliche F ¨ orderung energetischer Geb ¨ audesanierungen. Availabe online at: https ://www.deutschland-machts-effizient.de/KAENEF/Redaktion/DE/Foerderprog ramme/steuerliche-foerderung-fuer-energetische-gebaeudesanierung.html.
[56] Italian Superbonus. Available online at: https://www.agenziaentrate.gov.it/portale/ web/guest/superbonus-110%25.
[57] Financing sustainability in Netherlandsd. Available online at: https://www.energ iebespaarlening.nl/.
[58] Root deductions for houses in Sweden. Available online at: https://www.skatteverket.se/ foretag/skatterochavdrag/rotochrut/gerarbetetratttillrotavdrag.4.5c1163881590be 297b5173bf.html.
[59] PREE 5000. Rehabilitaci´ on energ´ etica de EDIFICIOS EN MUNICIPIOS de reto demogr´ afico- ESPAGNA. Available online at: https://www.idae.es/ayudas-y-financi acion/para-la-rehabilitacion-de-edificios/programa-pree-5000-rehabilitacion.
[60] Fabrizio Ascione et al., 'Improving the Building Stock Sustainability in European Countries: A Focus on the Italian Case', *Journal of Cleaner Production* 365 (September 2022): 132699, https://doi.org/10.1016/j.jclepro.2022.132699.

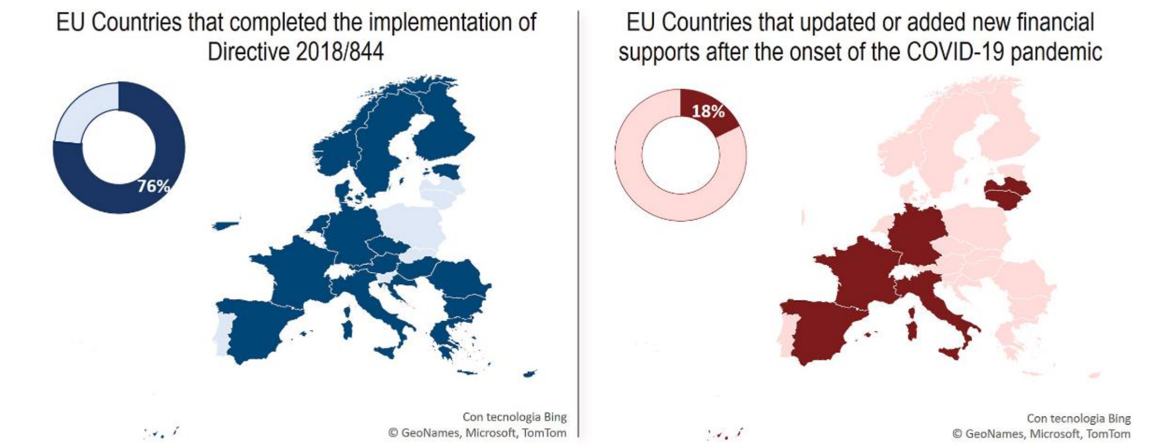


Figure 6 The level of implementation of Directive 2018/844 and the update of financial support after the onset of the COVID-19 pandemic, in Europe.

Source: Author's re-elaboration from Fabrizio Ascione et al., 'Improving the Building Stock Sustainability in European Countries: A Focus on the Italian Case', *Journal of Cleaner Production* 365 (September 2022): 132699, https://doi.org/10.1016/j.jclepro.2022.132699. p-6.

## 1.3.3 Case studies

Here are some examples of excellent green residential buildings in Europe.

Author will focus on describing the various green design approaches for these green residential buildings

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**Savonnerie Heymans, Brussels, Belgium.**

This building is located in Brussels, Belgium, 'There are 42 sustainable accommodations of different types including studios, 1 to 6-bedroom apartments, lofts, duplexes and Maisonettes. Although a 100% public residential scheme, thanks to the diversity of its program the Savonnerie Heymans provides a variety of spaces echoing the diversity of the people living in the very heart of Brussels. Glass-enclosed bioclimatic loggias characterize the entire complex, providing an effective acoustical and thermal barrier but also providing a sense of privacy.' [61]

Figure 7 is the facade design of Savonnerie Heymans.

Figure 7 The building design of Savonnerie Heymans

Source : 'Savonnerie Heymans / MDW Architecture', ArchDaily, 27 March 2012, https://www.archdaily.com/220116/savonnerie-heymans-mdw-architecture?ad_source=search&ad_medium=projects_tab.

The glass-enclosed bioclimatic loggias provide each residential unit with a state-of-the-art acoustical and thermal barrier requiring no expensive/complicated services to run and lowering considerably energy consumption. The Loft building has been treated one step further as thanks to super-tight insulation, the building is now considerate "Passive" and requires less than 15 Kw per square meter per year to heat.

[61] 'Savonnerie Heymans / MDW Architecture', ArchDaily, 27 March 2012, https://www.archdaily.com/220116/savonnerie-heymans-mdw-architecture?ad_source=search&ad_medium=projects_tab.

The scheme was intentionally developed around the concepts of sustainable development and relies on low-serviced buildings. The glass-enclosed bioclimatic loggias provide each residential unit with a buffer acting as a state-of-the-art insulation tool lowering considerably energy consumption and protecting from the city center noises. They also allow sharing the variety of arrangements of the semi outdoor space of each individual unit.

Figure 8 The interior design of Savonnerie Heymans

Source：'Savonnerie Heymans / MDW Architecture', ArchDaily, 27 March 2012, https://www.archdaily.com/220116/savonnerie-heymans-mdw-architecture?ad_source=search&ad_medium=projects_tab.

The Lofts is a passive building while the rest of the complex is low-energy rated. Beside the bioclimatic loggias, the scheme also features a collective heating system for the entire site (cogeneration), sanitary hot water heated by 60m² of solar panels, rainwater harvesting for toilets, maintenance and gardens and natural materials for insulation (hemp fibers, expanded cork etc.). Whenever possible, existing buildings and structures have been retained and reused.

**Bondy, Saints, France**[62]

This effort was a component of the urban revitalization strategy for the Saints district. 'The building replaced an outdated high-rise complex with a sustainable social residential solution. It's not just the timber-clad that provides a natural feel for residents and onlookers. Each unit also contains a terrace, balcony, or garden. There are also solar arrays and rainwater collection systems to keep costs down and minimize the impact on the planet.'[63]

[62] 'BONDY / Guérin & Pedroza architectes', ArchDaily, 30 August 2013, https://www.archdaily.com/421933/bondy-guerin-and-pedroza-architectes.
[63] habitat_ehf, '7 Sustainable Residential Designs: Passivhaus in Western Europe', *Europe Residential Forum 2021* (blog), 8 June 2022, https://europeresidentialforum.eu/7-sustainable-residential-designs-passivhaus-in-western-europe/.

To respond to various requests of the programme, the architects have opted for an architecture that is simple in that they went for a well-tried bioclimatic design. Passers-by and people living in the neighborhood enjoy the sight of façades covered with a plain coating and wood, a soothing material, like the ground floor gardens may be. The sliding shutters animates the four sides of the building, depending on the weather and the time of the day.

The building follows the norm of the green building standard called the BBC (low energy building) and has a 45 kWh/m2/year, that is 5 kW less that the level expected by the label. The building is compact and let the sunshine in so that its energy efficiency is good and ensures the inhabitants' well-being. The exterior insulation reduces any thermal loss. Following a bioclimatic concept, all the flats can be naturally cross-ventilated. For a better summer comfort, the balconies bring shade and coolness. So do the wooden sliding shutters. In the sun heats the flats for free. These environmental devices are completed with 34 solar thermal collectors (75 square meters) placed on the roof. They produce hot water. And for who can enjoy gardening, they can use the rainwater collected on the roofs.

Figure 9 The building design of Bondy.

Source: 'BONDY / Guérin & Pedroza architectes', ArchDaily, 30 August 2013, https://www.archdaily.com/421933/bondy-guerin-and-pedroza-architectes.

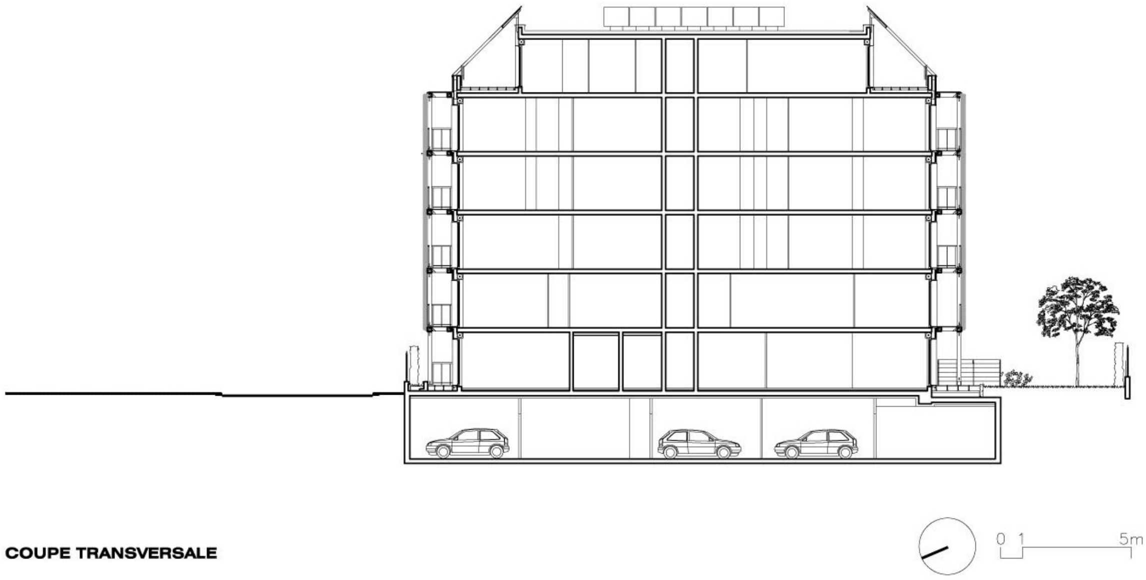


Figure 10 The section of Bondys

Source: 'BONDY / Guérin & Pedroza architectes', ArchDaily, 30 August 2013, https://www.archdaily.com/421933/bondy-guerin-and-pedroza-architectes.

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# Chapter 2

# Methodological background:

# Life cycle thinking

# INTRODUCTION

This chapter deals with life cycle thinking and the concept of cost. And based on the principle of LCT two main calculation methods, life cycle assessment (LCA) and life cycle cost (LCC). These are the two most frequently used approaches in the literature of this work.

In a life-cycle economy, all decisions are based on an analysis of their consequences for the entire life cycle, including the environmental, economic and social spheres. 'Life cycle assessment looks at the potential environmental impacts of resource extraction, transport, production, use, recycling and disposal of products; Life cycle costs are used to assess the cost impact of this life cycle. They all have similar methodological frameworks and objectives that can be combined to make it possible to move towards a holistic sustainability assessment.' [64]

In architecture industry, developers and architects can know the environmental impact, initial costs, operational maintenance, and demolition costs of a green residential building through pre-LCC and LCA assessments. With the support of effective information, decision makers would corporate with architects, construction engineers and operations and maintenance personnel to find ways to replace or reduce the life-cycle costs and environment impact of green residential building.

The principle of life cycle thinking integrating circular economy also includes the principle of sustainability in many aspects and industries.

[64] UNEP/ SETAC Life Cycle Initiative, "Life Cycle Approaches-The road from analysis to practice",2005, p-15

## 2.1 The concepts of life cycle thinking

Since the beginning of the 21st century, life cycle thinking has been developed and applied to all walks of life, especially when the trend of sustainable development is becoming more and more popular. 'The precursors of Life Cycle Thinking emerged in the late 1960s and early 1970s from concerns about limited natural resources, particularly oil. Since the 1970s, needs have changed and techniques have improved. Life Cycle Thinking has become a key complementary tool in policy and decision making, both in government and business.'[65]

The definition of Life Cycle Thinking is 'a framework that considers a holistic view of a product, process, or service from production through to consumption or use to end-of-life.'[66] Through the adoption of life cycle perspective, both entities and individuals can pinpoint chances to mitigate adverse impacts and amplify positive contributions throughout each phase. This methodology nurtures the growth of sustainable behaviors by prompting contemplation of enduring outcomes and fostering the adoption of tactics that curtail waste, safeguard resources, and alleviate broader environmental and social pressures.

LCT primarily aims to curtail a product's resource consumption and environmental emissions, while concurrently enhancing its socio-economic performance across its entire life cycle. 'This may facilitate links between the economic, social and environmental dimensions within an organization and through its entire value chain.'[67]

In order to effectively achieve the sustainability of green residential endeavors, it is imperative to embrace an expansive and comprehensive life cycle approach. This entails the adoption of life cycle thinking as a foundational methodology for the sustainable advancement of the real estate industry. Employing life cycle assessment tools serves as a mechanism for evaluating the economic sustainability of both new constructions and the refurbishment of residential structures. It is worth noting that the decisions and measures implemented at each juncture of a residential unit's life cycle, encompassing design, construction, utilization, maintenance, and eventual demolition, carry profound ramifications for its long-term trajectory and overall viability.

According to Maurizio Nicolella, 'To design sustainably according to the LCT approach, it is therefore necessary to pursue the following objectives from the design phase to the decommissioning phase:

- Minimize the use of resources;
- Choose energy resources and materials with less impact;
- Optimize the useful life of the building;
- Extend the life of materials;

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[65] European Commission. Directorate-General for the Environment and European Commission. Joint Research Centre, *Making Sustainable Consumption and Production a Reality: A Guide for Business and Policy Makers to Life Cycle Thinking and Assessment* (LU: Publications Office, 2010), https://data.europa.eu/doi/10.2779/91521. P.7

[66] 'Life Cycle Thinking • Plastics Europe', *Plastics Europe* (blog), accessed 20 March 2023, https://plasticseurope.org/sustainability/circularity/life-cycle-thinking/.

[67] 'What Is Life Cycle Thinking? - Life Cycle Initiative', 7 December 2012, https://www.lifecycleinitiative.org/activities/what-is-life-cycle-thinking/, https://www.lifecycleinitiative.org/activities/what-is-life-cycle-thinking/.

- Facilitate disassembly.'[68]

(Per progettare in chiave sostenibile secondo l'approccio LCT occorre dunque perseguire, dalla fase di progettazione alla fase di dismissione, i seguenti obiettivi:

- minimizzare l'uso delle risorse;
- scegliere risorse energetiche e materiali con minor impatto;
- ottimizzare la vita utile dell'edificio;
- estendere la vita dei materiali;
- facilitare il disassemblaggio.)

Figure 1 shows the conceptual diagram of building material life cycle. Arrows represent building material sources (blue) and both general (black) and circular (green) material life cycle processes and value chains.

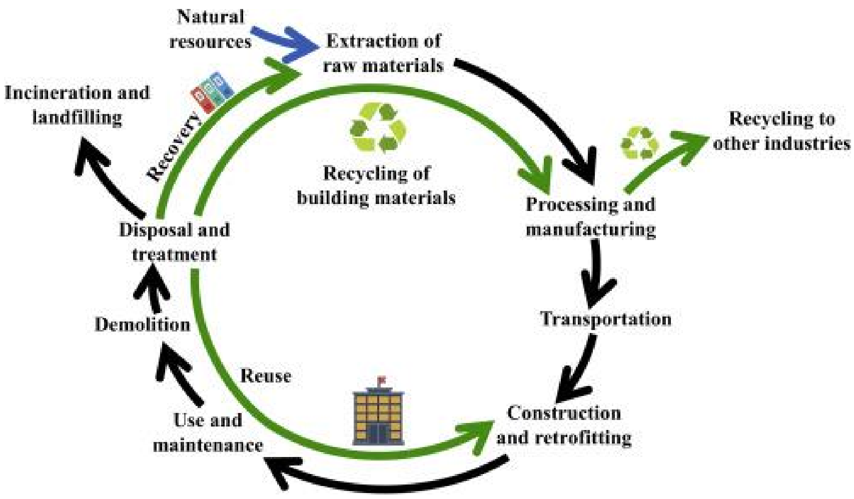


Figure 1, Conceptual Diagram of Building Material Life Cycle.

Source: Beijia Huang et al., 'A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials', *One Earth* 3, no. 5 (November 2020): 564–73, https://doi.org/10.1016/j.oneear.2020.10.010.p-566.[69]

[68] Maurizio Nicolella, 'Verso una "sostenibilità programmata': valutazioni LCA e LCC per la progettazione di coperture piane', 2018.P.3
[69] Beijia Huang et al., 'A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials', *One Earth* 3, no. 5 (November 2020): 564–73, https://doi.org/10.1016/j.oneear.2020.10.010.p-566.

## 2.2 The concepts of cost

Understanding the distinction between cost and expense is crucial for effective financial management and accurate reporting. 'Cost and expense, these two terms are often used incorrectly or interchangeably. Cost is a measure of resource consumption related to the demand for jobs to be done, whereas expense is a measure of spending that relates to the capacity provided to do a job.'[70]

ISO 15686[71] is a regulatory framework and policy relating to costs during the building life cycle process. In ISO 15686, the definition of the Whole life cost is "all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements." According to Fregonara E, the definition of cost is "the foundation of construction, management and building life cycle processes" [72].

For enhanced precision in assessing the comprehensive expenses associated with building construction, it is recommended to meticulously categorize and differentiate the various components of construction-related expenditures. 'Building-related costs usually fall into the following categories:

- Initial Costs—Purchase, Acquisition, Construction Costs.
- Fuel Costs
- Operation, Maintenance, and Repair Costs
- Replacement Costs
- Residual Values—Resale or Salvage Values or Disposal Costs
- Finance Charges—Loan Interest Payments
- Non-Monetary Benefits or Costs'[73]

Life cycle costs are the expenses associated with constructing and operating a building, or the costs incurred by an asset to achieve desired performance over its life cycle. The full life cycle cost includes land, income generated by the building, support fees for activities within the building and other costs, covering all the initial and future types of costs on the time scale. The construction industry is best able to provide expertise in life-cycle costs that clients can use to determine their entire life-cycle costs.

The definition of global cost is "sum of the present value of the initial investments costs, annual running costs and replacement costs (referred to the starting year) as well as disposal costs if applicable" [74]. It can be applied with all infrastructure and building types. Two calculation methods are provided in EN 15459, global costing method and annuity method.

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[70] Jan Emblemsvåg, *Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks* (Hoboken, N.J: Wiley, 2003).
[71] ISO (2017) ISO 15686-5:2017 Buildings and Constructed Assets – Service Life Planning – Part 5: Life-cycle costing.
[72] Fregonara E, 'Evaluation Sustainability Design. Life Cycle Thinking and international orientations.', Milano, FrancoAngeli, 2017, p-9
[73] 'Life-Cycle Cost Analysis (LCCA) | WBDG - Whole Building Design Guide', accessed 26 April 2023, https://www.wbdg.org/resources/life-cycle-cost-analysis-lcca.
[74] (Committe Europeen de Normalisation) document, Energy performance of buildings – Economic evaluation procedure for energy systems in buildings, Standard EN 15459:2007, Brussels, CEN, 2007.p-31

The following is the calculation of global cost and formula. 'All the costs refer to the starting year by applying an appropriate present value factor. The whole cost is determined by summing up the global costs of initial investment costs, periodic and replacement costs, annual costs and energy costs and subtracting the global cost of the final value. Calculation of global cost considers the initial investment $C_I$ and for every component or system j the annual costs for every year i (referring to the starting year) and the final value.' [75] The global cost demonstrates a direct connection with the calculation period τ, and its representation can be formulated as follows:

$$C_G(\tau) = C_I + \sum_j \left[ \sum_{i=1}^{\tau} \left( C_{a,i}(j) \cdot R_d(i) \right) - V_{f,\tau}(j) \right]$$

Where:
$C_G$ (τ)= the Global Cost, referred to in the initial year $\tau_0$;
$C_I$= for initial investment costs;
$C_{a,i}$ (j)= the annual cost at year i, for the j component (including running costs and the periodic or replacement costs);
$R_d$ (i)= the discount factor at year;
$V_{f,\tau}$(j)= the final value of the j component at the end of the calculation period (referred to the initial year $\tau_0$);

The discount factor $R_d$ may be expressed as:

$$R_d = \frac{1}{(1 + R_r)^P}$$

Where $R_r$ is the real discount rate, and p is the reference period.[76]

Figure 2 illustrates how a selection of type of costs take place during the calculation period.

Where:
Point 1 is $t_{rc}$ means Calculation period (50 years for example).
Point 2 is $CO_{inv}$ means Investment cost.
Point 3 is $CO_{run}$ means Running costs.
Point 4 is $CO_{repl}$ means Replacement costs.

[75] Becchio, Cristina & D, GUGLIELMINO & Fabrizio, Enrico & Filippi, Marco. (2011). 'Whole cost analysis of building envelope technologies according to the European Standard' EN 15459. 291-306.
[76] (Committe Europeen de Normalisation) document, Energy performance of buildings – Economic evaluation procedure for energy systems in buildings, Standard EN 15459:2007, Brussels, CEN, 2007.p-31

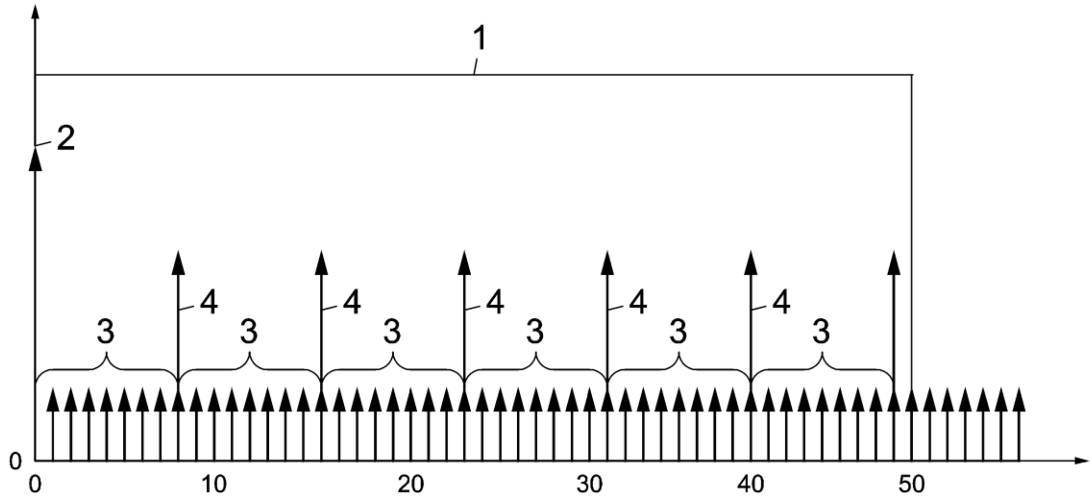


Figure 2

Source: Author's re-elaboration from '(Committe Europeen de Normalisation) document, Energy performance of buildings – Economic evaluation procedure for energy systems in buildings, Standard EN 15459:2007, Brussels, CEN, 2007, p-31'

### 2.2.1 The concept of cost optimal

The cost-effectiveness of construction projects is expected to focus on ways to both improve energy efficiency and significantly reduce costs. 'Cost-optimal level means the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where the lowest cost is determined taking into account energy- related investment costs, maintenance and operating costs including energy costs and savings.' [77]

Following this, cost-optimal computations have been progressively integrated across European nations in accordance with the Directive. These calculations are gaining increasing recognition among individual designers, investors, and practitioners. Notably, the European Standard EN 15459-1:2017 has emerged as the principal point of reference in Europe for assessing life cycle costs (LCC) pertaining to energy-efficient interventions within the realm of building structures.

The Energy Performance of Buildings Directive (EPBD) assumes a pivotal role in shaping the implementation of cost-optimized strategies. 'The EPBD recast now requests that Member States shall ensure that minimum energy performance requirements for buildings are set "with a view to achieving cost-optimal levels". The cost optimum level shall be calculated in accordance with a comparative methodology.'[78]

As this directive gains traction and its principles become ingrained in national policies, the integration of cost-optimal considerations into building energy regulations is expected to not only enhance energy efficiency but also contribute to broader sustainability goals.

Sustainable and green buildings' minimum performance criteria should be established within the domain of the curve (as depicted in Figure 3) where the most favorable energy and environmental outcomes are achieved at a minimized expense. This has the potential to yield improvements surpassing existing requisites while incurring equivalent or lesser overall expenditures. 'Societal priorities may also lead to setting minimum requirements that are stricter than the private cost-optimal, as for example to the left of the "Best practice" field in Figure 3.'[79]

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[77] 'cost-optimal level Definition', Law Insider, accessed 2 May 2023, https://www.lawinsider.com/dictionary/cost-optimal-level.
[78] European Council for an Energy Efficient Economy, 'Cost optimal building performance requirements', Sweden, 2011, p-2.
[79] European Council for an Energy Efficient Economy, 'Cost optimal building performance requirements', Sweden, 2011, p-7.

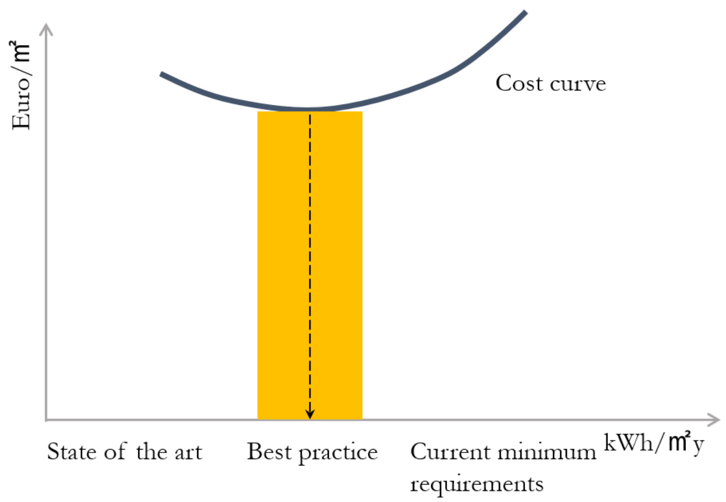


Figure 3, Position of minimum performance requirements

Source: Author's re-elaboration from European Council for an Energy Efficient Economy, 'Cost optimal building performance requirements', Sweden, 2011, p-8.

## 2.3 Life Cycle Assessment (LCA)

### 2.3.1 Origins, definitions and references

The concepts of LCA first emerged in the 1960s. …The ISO 14040 series provides a technically rigorous framework for carrying out LCAs. Since the release of the 14040 series, a rapidly growing number of LCA studies have been published.' [80]

LCA, being a robust technological tool, holds the capacity to address and harmonize environmental concerns, thereby offering informative insights to facilitate strategic decision-making. In recent years, there has been a growing recognition among the general populace, governmental entities, and various sectors regarding the maturation of Life Cycle Assessment (LCA) concepts and their integration into environmental policy frameworks. This acknowledgment also extends to the incorporation of LCA into management systems.

According to the standard UNI EN ISO 14040:2006, the definition of Life Cycle Assessment is

> "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle."[81]

Thus, LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave).

[80] United Nations Environment Programme UNEP (2011), 'Towards a Life Cycle Sustainability Assessment: Making informed choices on products.'p-6.
[81] International Organization for Standardization, ISO 14040:2006, 'Environmental Management - Life Cycle Assessment - Principles and Framework', ISO/TC 207/S05, International Organization for Standardization, Geneva, Switzerland, 2006.

## 2.3.2 Methodological framework

There are four phases in an LCA study (Figure.4):
a) the goal and scope definition phase,
b) the inventory analysis phase,
c) the impact assessment phase,
d) the interpretation phase.

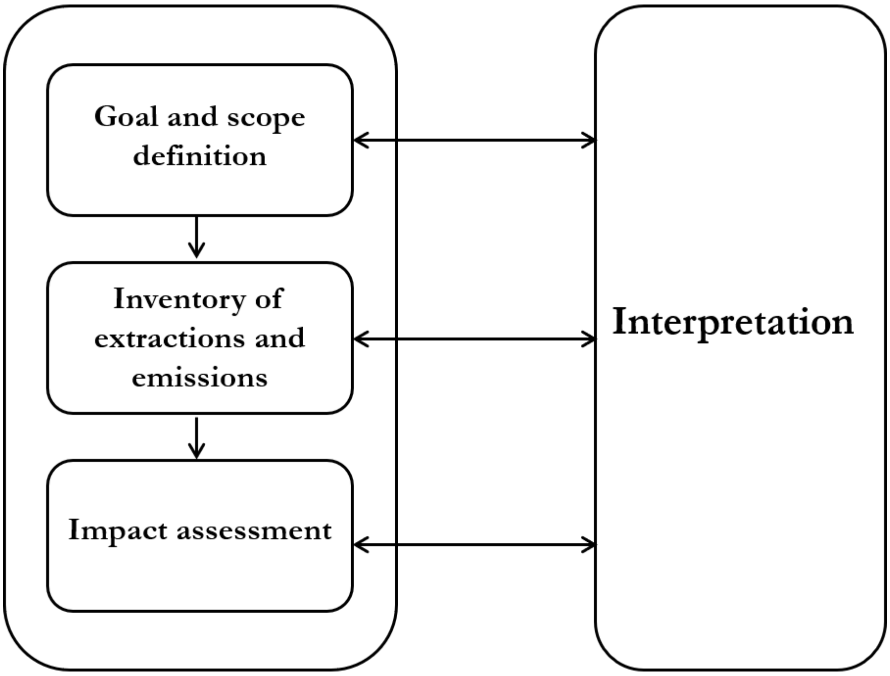


Figure 4, the four phases of LCA.
Source: auther's re-elaboration from UNEP/ SETAC Life Cycle Initiative, "Life Cycle Approaches-The road from analysis to practice",2005, p-15

**Phase 1 State goal and scope of study**

First, the goal and scope of the study must be stated explicitly. This provides the context for the assessment and explains to whom and how the results are to be communicated. This step includes the detailing of technical information – such as defining the functional unit, the system boundaries, the assumptions and the (de)limitations of the study, the impact categories and the methods that will be used to allocate environmental burdens in cases where there is more than one product or function.

**Phase 2 Inventory of resources and emissions**
In the second phase, all emissions released into the environment and resources extracted from the environment along the whole life cycle of a product are grouped in an inventory. The inventory is a list of elementary flows as shown in Figure 5.

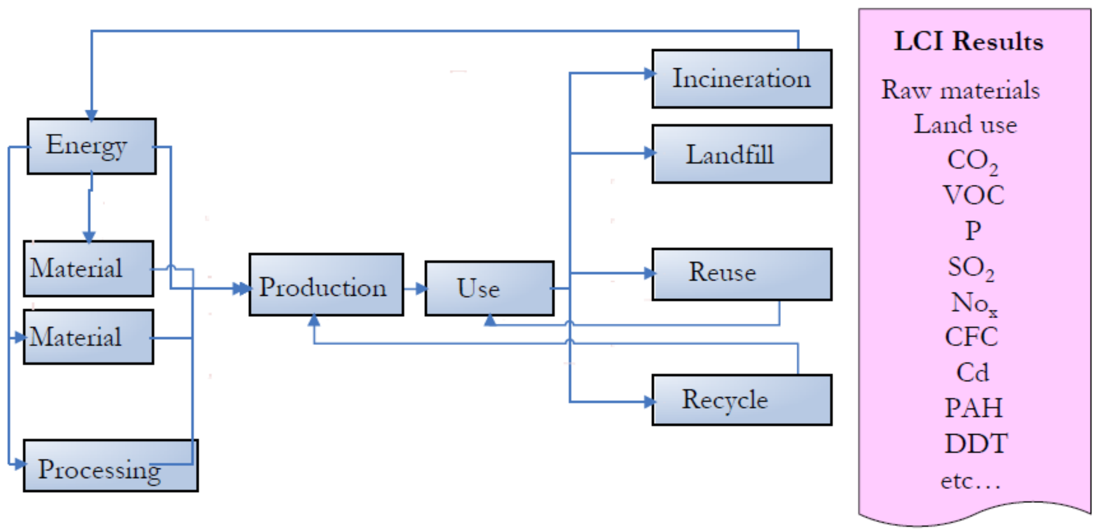


Figure 5, Flows of information needed for a life cycle inventory.

Source: United Nations Environment Programme UNEP (2011), 'Towards a Life Cycle Sustainability Assessment: Making informed choices on products'. p-7.

**Phase 3 Life cycle impact assessment: Translate results into environmental impacts.**

In the third phase – life cycle impact assessment (LCIA) – the LCI results or indicators of environmental interventions are translated, with the help of an impact assessment method, into environmental impacts. This phase is divided into four main steps.

1. Classification of impact categories.
2. Characterization of each substance through a weighted average of inputs and outputs, combined with the impact on the particular environmental problem.
3. Normalization of the values relative to a reference value.
4. Valuation of the environmental impact of the product by means of a numerical factor.

**Phase 4 Interpretation**

This is necessary for identifying, quantifying, checking and evaluating information from the results of the LCI and/or the LCIA. it is introduced by ISO 14043. It combines the results of LCI and LCIA with the pre-established goals of the first step and is

1. Ending with a single number or environmental index in which each environmental issue is weighted according to its importance.
2. A simple and straightforward comparison of different products or scenarios.
3. For the results of the LCA, together with all the options and assumptions made in the analysis, are evaluated and an overall conclusion is drawn.[82]

The notable advantage inherent in LCA lies in its comprehensive nature, not only embracing all pertinent environmental considerations, but encompassing the entirety of the production-

[82] United Nations Environment Programme UNEP (2011), 'Towards a Life Cycle Sustainability Assessment: Making informed choices on products.' p-9.

consumption-waste management continuum from inception to disposal. 'The comparisons of different ways to fulfil one function therefore is in principle encompassing, and LCA may be regarded as the most suitable tool for this purpose. This includes all types of analysis of chains that are defined in reference to the fulfilment of a specific function: spotting the main problematical points in a chain, deriving options for chain improvement, optimizing a chain, comparing alternative chains, etc.'[83]

[83] UNEP/ SETAC Life Cycle Initiative, "Life Cycle Approaches-The road from analysis to practice",2005, p-23

# 2.4 Life Cycle Costing (LCC)

## 2.4.1 Origins, definitions and references

Life cycle costing (LCC) is originated in the early seventies to support the purchase of expensive military equipment for the US Department of Defense. It is a methodology used to assess the comprehensive expenses associated with a product, process, or activity throughout its entire lifecycle. Typically employed in the decision-making process for designing and developing products, processes, and activities, LCC takes into account all the costs incurred from inception to retirement.

An analysis utilizing Life Cycle Costing (LCC) consistently encompasses all internal expenditures occurring over the lifespan of the subject in question. Typically, this evaluation does not account for external expenses. Internal costs encompass traditional expenditures like product costing and performance evaluation, as well as less tangible, concealed, and indirect corporate expenses such as environmental permitting, licensing, reporting, and waste handling. External costs refer to those for which the company, at a given point in time, bears no responsibility, as neither the market nor regulations assign such costs to the firm.

The tool is defined by Standard ISO 15686-5:2008, revised by ISO 15686-5:2017.

The definitions are as follow, "a technique which enables the systematic appraisal of life cycle costs over a period of analysis; an approach for the quantification of costs and benefits with particular reference to component costs during the entire life cycle of the building, so that it can support the decisions between project design solutions/components/specific materials based on the criteria of efficacy and economic efficiency; it is a technique for the economic evaluation of a new construction or an existing asset taking into account both immediate and long-term costs and benefits." [84]

Life cycle cost analysis considers all stages of the life cycle from 'cradle to grave', including Briefing, Planning, Design, Construction, Use - Maintenance - Adaptation, End of life - Disposal. Adaptation, End of life - Disposal. Figure 6 shows the components of LCC, pre-acquisition costs, post-acquisition cost and external cost, as well as direct and indirect costs.

Figure 6 presents the cost components of LCC.

[84] International Organization for Standardization, ISO 15686-5:2017, 'Buildings and constructed assets - Service-life planning', Part 5: Life Cycle Costing, ISO/TC 59/CS 14, International Organization for Standardization, Geneva, Switzerland, 2017.

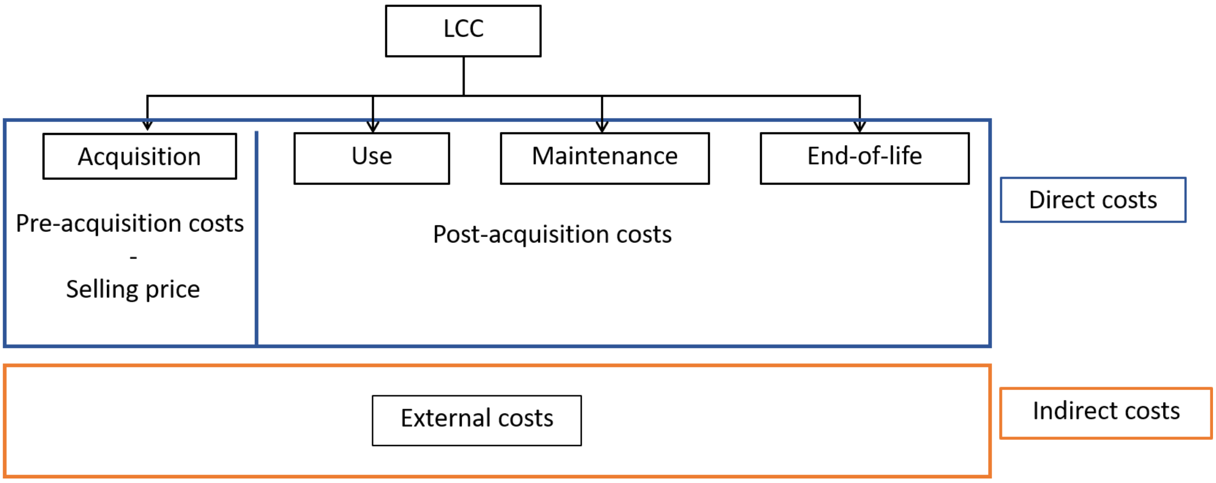


Figure 6 The costs components of LCC

Source: author's re-elaboration from European Commission 'Life cycle costing calculation tool. Pdf', accessed 31 May 2023, https://ec.europa.eu/environment/gpp/pdf/09_06_2015/Life_cycle_costing_calculation_tool.pdf.p-4.

Today, different "flavors" of LCC exist for different industrial sectors and products, to meet the needs of different sustainability assessments. There are three different types of LCC according to The Society of Environmental Toxicology and Chemistry (SETAC):

1. Conventional LCC incorporates private costs and benefits, which is the life cycle cost analysis method described in this chapter.

2. The Environment LCC takes into account the external costs and benefits associated with being privatized. For example, if a new carbon tax is to be implemented in the future, or if subsidies are to be provided for hiring unskilled workers over the next two years, the LCC will reflect these costs and benefits in its calculations.

3. Social LCCS, in which all private and external costs and benefits are monetized.[85]

In the past several years, the theoretical system of LCC has been continuously enriched and improved through the explorations of scholars from various countries. So far, the LCC theory has been gradually applied to the cost management of modern engineering projects. At present, the whole life cycle cost theory has been widely used in the field of construction. Harding. A, Lowe. D. Jet al believed that 'engineering construction should combine design with cost management, and carry out cost management of the whole life cycle from planning, design, operation to scrapping stage.' [86] I.F.Weustink, E.Eustink proposed that 'the whole life cycle cost estimation of construction products should be carried out in the early stage of development, and the whole life cycle cost control was achieved by establishing a cost estimation framework'.[87]

[85] United Nations Environment Programme UNEP (2011), 'Towards a Life Cycle Sustainability Assessment: Making informed choices on products.' p-14

[86] Harding A L D J." Implementation of annual network model for the comparison of the cost of different procurement routes[J]." Proceedings of the 15th ARCOM. 1999, 60.

[87] Weustink, I.F & Brinke, E (2000). "Generic framework for cost estimation and cost control in product design. Journal of Materials Processing Technology". 103. 141-148. 10.1016/S0924-0136(00)00405-2.

Dimitri V. Val and Mark G. Stewart studied the cost of construction projects in the United States and found that the early stage of a project plays an important role in the whole life cycle, especially in the decision-making and design stages of the project.[88]

In China, Wang Wei et al begin from the concept, classification and research significance of the LCC in production, in-depth analysis of the key points of cost management in each stage of life cycle and the corresponding cost management methods, and combined with conditions in China put forward suggestions to adapt to the development of construction projects in China.[89] Dong Shibo combined foreign advanced methods and concepts of full life cycle cost management with China's national conditions, trying to explore effective ways and methods of full life cycle cost control of engineering construction projects.[90]

### 2.4.2 The calculation of LCC

The use of life cycle cost (LCC) analysis is common in studies focusing on the economic impact of energy retrofit alternatives in the building industry. According to Sergio Copiello, The LCC methodology has a long-established framework and can be seen as a specialized form of cost-benefit analysis that specifically concentrates on a project or program's cost components. What sets it apart is its unique emphasis on accounting for all relevant costs over the entire lifespan. In the context of the construction industry, 'the LCC model may be expressed as follows:

$$LCC = BC + MC + OC$$

Where:
LCC = Life-cycle cost
BC= Building cost
MC= Management cost
OC=Operating cost

Supplementary handling is necessary for recurrent cost components. Given their recurring nature in the future over a period n, maintenance and operational expenses should be computed as present values utilizing the discount rate r. The equation can also be written like:

$$LCC = BC + \sum_{i=1}^{n} \frac{(MC + OC)}{(1 + r)^i}$$

Where:
i=the number of year
r=Discount rate

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[88] Dimitri V. Val and Mark G. Stewart, 'Decision Analysis for Deteriorating Structures', *Reliability Engineering & System Safety* 87, no. 3 (March 2005): 377–85, https://doi.org/10.1016/j.ress.2004.06.006.
[89] W. Wei, W. Lin. 'chanpin shengming zhouqi chengben guanli yanjiu [Research on Product Lifecycle Cost Management]'. Productivity Research,2008(14):145-147.
[90] Shibo Dong, 'Jianshe Xiangmu Quanshegnming Zhouqi Chengben Guanli, [Whole Life Cycle Cost Management of Construction Projects] '(*China Electric Power Press, 2009*), https://books.google.it/books?id=gF06QwAACAAJ.

If energy retrofits are considered for inclusion in the life cycle costing calculation, let us define the following inputs. Icj are the investment costs to implement each of the j scenarios, assumed incurred at time 0. The period of analysis n is considered equal to the useful life of the works (30 years). Hence, the maintenance costs (Mcj) are assumed to be equal to zero. The operating costs (Ocj) are limited to the energy expenses, given by the product of the energy requirement subsequent to the implementation of works (qj) and the energy price (p). Accordingly, the previous equal becomes:

$$LCC_j = Ic_j + \sum_{i=1}^{n} \frac{(q_j * p) * (1+e)^i}{(1+r)^i}$$

Where:
e=Energy inflation rate.
LCCj is suitable to be used both for ranking purposes and as a decision criterion: the minimum overall cost during the whole useful life characterizes the preferred scenario.'[91]

### 2.4.4 LCC methodologies

'Activity-Based Life-Cycle Costing (LCC) is an approach that was developed from the more comprehensive Activity-Based Cost and Environmental Management approach that Professor Bert Bras and Jan Emblemsvåg developed in the latter half of the 1990s. Activity-Based LCC, however, has an improved structure and is more comprehensive with respect to costs.'[92]

Here are the steps of the Activity-Based LCC methods.

**Step 1: Define the scope of the model and the corresponding cost objects.**

The scope should include as a minimum the objectives of the model, its system boundaries, and its perspective. It is crucial to define the objectives of the model because this determines whether model should build a back-casting model or a simulation/forecasting model.

**Step 2: Obtain and clean bill of materials for all cost objects.**

For LCC cost accounting models, it is important to assure that the existing costing system does not overhead costs with direct costs in the Bill of Materials. If they are mixed, the Bill of Materials must be cleansed for overhead costs and must be transferred back to respective overhead accounts or to new accounts needed for the analysis. This objective is aimed for reducing cost assignment distortion.

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[91] Sergio Copiello, Laura Gabrielli, and Pietro Bonifaci, 'Evaluation of Energy Retrofit in Buildings under Conditions of Uncertainty: The Prominence of the Discount Rate', Energy 137 (15 October 2017): 104–17, https://doi.org/10.1016/j.energy.2017.06.159.
[92] Jan Emblemsvåg, 'Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks'(Hoboken, N.J: Wiley, 2003).p-169.

**Step 3: Identify and quantify the resources.**

Identifying the resources implies listing all the resources within the system boundary and according to the objectives of the model. While performing Step 3, the resources should be identified and quantified if possible. The identification only requires the name of the resource and type, such as depreciation, house rent, insurance, and so forth. Proper identification is important so that the resources can be identified during the analysis.

**Step 4: Create an activity hierarchy and network.**

every process within the system boundary is broken down into more and more detailed processes (activities), and thereby an activity hierarchy is created. The activities should be defined in enough detail to get reliable information. It is also important to relate the level of detail to the objectives of the modeling. When identifying the activities, each activity should be labeled in a special manner (see Figure 7). This method makes it easy to see where the activities belong in the activity hierarchy and it saves a lot of space.

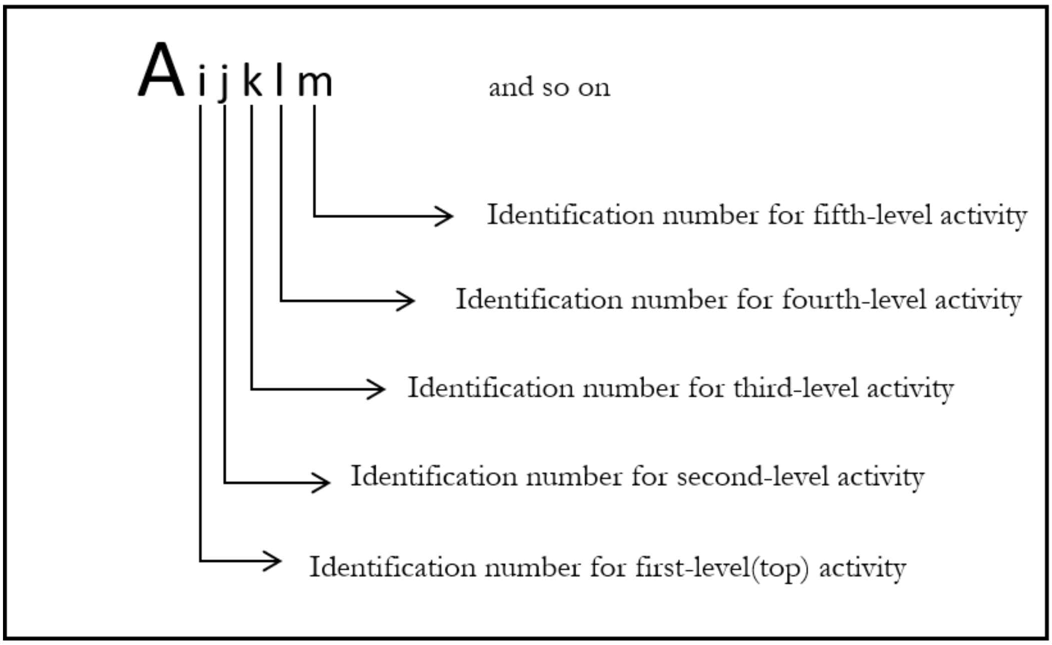


Figure 7 Activity notation

Source: author's re-elaboration from Jan Emblemsvåg, 'Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks'(Hoboken, N.J: Wiley, 2003).p-157.

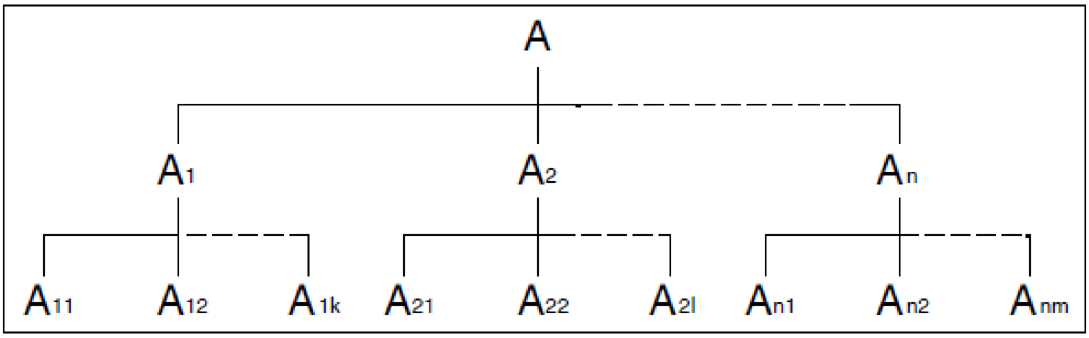


Figure 8 Generic activity hierarchy.

Source: author's re-elaboration from Jan Emblemsvåg, 'Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks'(Hoboken, N.J: Wiley, 2003).p-158.

The activity network can help identify what a decision (the diamond-shaped node) is really about. For example (Figure 8), if Product A is associated with a Yes in Decision Node A, we see immediately that Product A will incur Activity Alk and then activities $A_{21}$, $A_{22}$, $A_{2k}$, $A_{n2}$, and $A_{n3}$.

**Step 5: Identify and quantify resource drivers, activity drivers, and their intensities.**

The purpose of resource drivers is to trace how the activities consume resources, while activity drivers are to trace how the cost objects consume activities. When identifying these drivers, it is crucial that they are chosen to represent as closely as possible the actual consumption as described by cause-and-effect relationships. That is, the drivers are to represent cause-and-effect relationships between activities and resources and between cost objects and activities.

**Step 6: identify the relationships between activity drivers and design chances.**

In this step, we need to distinguish between two different design approaches. Relationships can be anything from explicit mathematical functions to action charts. Mathematical functions are very accurate but are equally difficult to establish. Hence, mathematical functions are rarely used. There is no explicit relations exist between the design parameters and activity drivers in action charts. Therefore, action charts are superb at directing attention toward any design changes in general, not just product changes.

**Step 7: Model the uncertainty**

Uncertainty exists in all situations that are unknown, unpredictable, open ended, or complex, but matters that are unknown or unpredictable are too difficult for analysis.

**Step 8: Estimate the bill of activities**

To estimate the cost of an activity, the resource driver is multiplied by its consumption intensity. This is done for all the activities and then is summed up to produce the total cost of all the activities, which is the Bill of Activities (BOA).

**Step 9: Estimate the cost of cost objects and their performance measures**

Step 9 works the same way as Step 8, the only difference is that in Step 8 resources are traced to activities, whereas in this step activity costs are traced to cost objects.

Several options are well documented and have been in use in many different business sectors since the early 1930s, here are three most commonly methods used in building sectors:

**Net Present Value (NPV).** 'Defined as the sum of money that needs to be invested today to meet all future financial requirements as they arise throughout the life of the investment. 'The system takes into account all the apparent variables acting upon a cash stream. Flannagan et al. (1989) express net present value as:'[93]

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

Where:

NPV=the net discounted value;
Ct = the estimated cost in year t;
T= the period of analysis in years;
r=the discount rate;[94]

The discount rate is a method of determining the time value of money. For example, £100 invested today at 11% per annum will be worth £111 in one year's time, or

$$\begin{aligned} T &= PV(1+r) \\ &= 100(1+0.11) \\ &= 111 \end{aligned}$$

where T is the value at one year, PV is the original investment or present value, and r is the interest or discount rate.

If we wish to know how much to invest today to meet a cost at some future year, the formula becomes:

$$PV = \frac{T}{(1+r)^n}$$

Where:

n=number of years.

**Payback Period (PBP)** in the non-discounted version (Simple PB- SPB) or in the discounted

[93] J. W. Bull and John W. Bull, 'Life Cycle Costing for Construction', 1st ed (London: Blackie Academic & Professional, 1993). Routledge, ISBN 13: 9780751400564, p-6.
[94] Flannagan, R., Norman, G., Medows, J. and Robinson, 'Life Cycle Costing, Theory and Practice', B.S.P. Professional Books, Oxford.1989

version (Discounted PB-DPB). It represents the the time taken for the return on an investment to repay the investment.

Payback period is a simple method of cost appraisal used by many in industry, particularly to evaluate energy-saving schemes. Payback period can be expressed as:

$$P = \frac{I}{R}$$

Where:

$P$=payback period (years)
$I$=capital sum invested
$R$=money returned or saved as a result of the investment

**Savings to Investment Ratio (SIR)**. It represents a cost-effective indicator of an investment of a base case. It expresses the relationship between what is saved in the operations phase (Operational Savings, Os) and additional investment costs (Ai), excluding any residual value. Formally expressed as:

$$SIR = \frac{O_S}{A_i}$$

**Internal Rate of Return (IRR)**: 'defined as the percentage earned on the amount of capital invested in each year of the life of the project after allowing for the repayment of the sum originally invested. It is a DCF technique used where investment produces a return on capital employed. In using IRR, the capital cost is balanced against income to obtain a NPV of zero. The discount rate necessary is the IRR. This can be evaluated against an expected target for return on capital employed and the project's viability can thus be assessed, primarily against the expected performance of the business.' [95]

In general, we wish to find the compound interest rate i for which the value of the series of cashflows out is equal to the value of the series of cashflows in at any point in time. The equation of value at time. The equation of value at time 0 for this general situation is

$$A_0 + A_1 \times v^{t_1} + A_2 \times v^{t_2} + \cdots + A_n \times v^{t_n} = B_0 + B_1 \times v^{t_1} + B_2 \times v^{t_2} + \cdots + B_n \times v^{t_n}$$

Where:
$A_n$=the situation in which there are payments received of amounts when time is $t_n$.
$B_n$=the disbursements (payments made out) of amounts at the same points in time.

The net amount received at time k is:

[95] J. W. Bull and John W. Bull, *Life Cycle Costing for Construction*, 1st ed (London: Blackie Academic & Professional, 1993). Routledge, ISBN 13: 9780751400564, p-10.

$$C_k = A_k - B_k$$

Suppose that a transaction has net cashflows of amounts $C_0$, $C_1$, …$C_n$, at times $t_0$, $t_1$, …$t_n$ the internal rate of return for the transaction is any rate of interest satisfying the equation:

$$\sum_{k=0}^{n} C_k \times v^{t_k} = 0$$

As long as compound interest is in effect, the equation of value can be set up at any time point t, and the values of I for which the equation holds would be the same. For instance, the equation of value set up at time $t_n$ is: [96]

$$C_0(1+i)^{t_n} + C_1(1+i)^{t_n - t_1} + \cdots + C_{n-1}(1+i)^{t_n - t_{n-1}} + C_n$$

$$= \sum_{k=0}^{n} C_k(1+i)^{t_n - t_k} = 0$$

The internal rate of return is a solution to the equation, the internal rate of return is given by r

in:

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} = 0$$

'All three methods are accounting systems developed initially for the manufacturing industry to determine the financial worth of an investment. The three methods have been developed to determine if an original investment is worthwhile. Here the investment generates a known return. In building we generally wish to know if additional money spent on the construction of a building is worth the savings that will be made by a subsequent reduction in running costs.'[97]

[96] Samuel A. Broverman, *Mathematics of Investment and Credit*, Sixth Edition, Actex Academic Series (Winsted, CT: ACTEX Publications, Inc, 2015).p278-280

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[14] European Council for an Energy Efficient Economy, 'Cost optimal building performance requirements', Sweden, 2011.

[15] United Nations Environment Programme UNEP (2011), 'Towards a Life Cycle Sustainability Assessment: Making informed choices on products.’

[16] International Organization for Standardization, ISO 14040:2006, 'Environmental Management - Life Cycle Assessment - Principles and Framework', ISO/TC 207/S05, International Organization for Standardization, Geneva, Switzerland, 2006.

[17] UNEP/ SETAC Life Cycle Initiative, “Life Cycle Approaches-The road from analysis to practice”,2005.

[18] International Organization for Standardization, ISO 15686-5:2017, 'Buildings and constructed assets - Service-life planning', Part 5: Life Cycle Costing, ISO/TC 59/CS 14, International Organization for Standardization, Geneva, Switzerland, 2017.

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Methods to Manage Future Costs and Risks'(Hoboken, N.J: Wiley, 2003).

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# Chapter 3

# Literature selection

# INTRODUCTION

The aim of this chapter of the study is to gather information on green residential building interventions using established methodologies such as Whole Life Costing (WLC), Life Cycle Costing (LCC), Life Cycle Assessment (LCA) in the Chinese and European publications. Selecting the methods used to analyze and assess life cycle costs in design solutions, in order to allow the design solution to satisfy green and sustainable criteria while controlling the overall costs.

This chapter presents scientific publications on life cycle approaches to the design, development and retrofitting of green residential, searched by inserting keywords into the database, 'sustainable residence' or 'green housing (green residential)', 'green retrofitting', 'life cycle approach', 'life cycle cost', 'life cycle cost analysis', 'life cycle analyses.

For the purposes of this study, the subject matter of the scientific publications was restricted to green residential building or green retrofitting of residential. The year of publication is considered to be from 2010 to 2022.

In view of the subject matter of this thesis, the geographical scope of the article is limited to European countries and China.

The open-source databases used in the study are Web of Science, Scopus, Google Scholar, Science Direct, Scopus. Articles were identified by searching online on these six major databases. By entering the author's name, title or using keywords, a targeted search was conducted on the topic of interest.

The open-source databases used here were designed to limit the selection to the economic assessment of sustainability in construction, and we considered the following scientific subject areas: engineering, energy, environmental science, business management and accounting, and mathematics, economics and finance. The type of publications was limited to open access articles. Finally, all articles have been individually detailed on the basis of a pre-defined layout by the authors.

The collection and selection process resulted in a list of 41 publications, 19 from China and 22 from European countries, which can be considered as example of publications in the European and Chinese scientific context.

## 3.1 Item Index: Summary table

The search for scientific publications in the open-source database is limited to English literature due to the language proficiency of the authors.

In this searching the following keywords are inserted in open-spaces:

'Sustainable residential' or 'green housing (green residential)', 'green retrofitting', 'life cycle approach', 'life cycle cost (LCC)', 'Life cycle assessment (LCA)', 'life cycle cost analysis (LCCA)', 'global cost', 'optimal cost', 'sensitivity analyses'.

After the scientific publications had been collected, two summary tables were created for cataloguing and classifying the various publications, listed main information of every publication. The form provides the following details:

- Serial number
- Title
- Year of publication
- Authors
- Publisher
- Country
- Methodology (from key words and context)

### 3.1.1 The geography of articles

The map shows the geographical location of the collected articles, marking the geographical locations of the cities analysed in the articles, which are mainly located in Europe and China.

Figure 1 Geolocation of articles from Europe(Author's elaboration)

Figure 2 Geolocation of articles from China(Author's elaboration)

Figure 3 shows the Summary table of 41 publications.

| | Title | Publication Year | Authors | Publisher | Country | Methodology |
|---|---|---|---|---|---|---|
| 1 | Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design | 2013 | Miro Ristimäki, Antti Säynäjoki, Jukka Heinonen, Seppo Junnila | ENERGY | Finland | LCC+LCA+sensitivity analysis |
| 2 | A methodology for economic efficient design of Net Zero Energy Buildings | 2012 | M. Kapsalaki, V. Leal, M. Santamouris | Energy and Buildings Volume 55, December 2012, Pages 765-778 | Portugal | LCC |
| 3 | Sustainability assessment of renovation packages for increased energy efficiency for multi-family buildings in Sweden | 2013 | Nils W.O. Brown, Tove Malmqvist, Wei Bai, Marco Molinari | Building and Environment Volume 61, March 2013, Pages 140-148 | Sweden | LCC |
| 4 | A life-cycle cost analysis of the passive house "POLITEHNICA" from Bucharest | 2014 | Adrian Badea , Tudor Baracu , Cristian Dinca , Diana Tutica , Roxana Grigore , Madalina Anastasiu | Energy and Buildings Volume 80, September 2014, Pages 542-555 | Romania | LCCA |
| 5 | Green housing: Toward a new energy efficiency paradox? | 2015 | Sergio Copiello, Pietro Bonifaci | Cities， Volume 49, December 2015, Pages 76-87 | Italy | LCC(DCF) |
| 6 | Cost optimality assessment of a single family house: Building and technical systems solutions for the nZEB target | 2015 | Becchio Cristina, Dabbene Paolo,Fabrizio Enrico | Energy and Buildings Volume 90, 1 March 2015, Pages 173-187 | Italy | optimal cost |
| 7 | Towards a More Sustainable Building Stock: Optimizing a Flemish Dwelling Using a Life Cycle Approach | 2015 | Matthias Buyle,Amaryllis Audenaert ,Johan Braet and Wim Debacker | Buildings 2015, 5(2), 424-448 | Belgium | LCA,LCC |
| 8 | A methodology to assess energy-demand savings and cost effectiveness of retrofitting in existing Swedish residential buildings | 2015 | Qian Wang, Sture Holmberg | Sustainable Cities and Society Volume 14, February 2015, Pages 254-266 | Sweden | LCCA, sensitivity analysis |
| 9 | Retrofit Scenarios and Economic Sustainability. A Case-study in the Italian Context | 2016 | E. Fregonara, V. R.M. Lo Verso, M. Lisac, G. Callegaria | Energy Procedia Volume 111, March 2017, Pages 245-255 | Italy | LCC |
| 10 | Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects | 2017 | Roberta Moschetti Helge Brattebø | Energies 2017, 10(11), 1851 | Norway | LCC,LCA,sensitivity analyses |
| 11 | Life-cycle cost analyses of heat pump concepts for Finnish new nearly zero energy residential buildings | 2017 | Satu Paiho, Sakari Pulakka, Antti Knuuti | Energy and Buildings Volume 150, 1 September 2017, Pages 396-402 | Finland | LCC |
| 12 | Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate | 2017 | Sergio Copiello, Laura Gabrielli , Pietro Bonifaci | Energy Volume 137, 15 October 2017, Pages 104-117 | Italy | LCC+ Monte Carlo simulation |

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| | Title | Publication Year | Authors | Publisher | Country | Methodology |
|---|---|---|---|---|---|---|
| 13 | Energy retrofit alternatives and cost-optimal analysis for large public housing stocks | 2018 | Luca Guardigli, Marco A. Bragadin, Francesco Della Fornace, Cecilia Mazzoli, Davide Prati | Energy and Buildings Volume 166, 1 May 2018, Pages 48-59 | Italy | LCCA+ Cost optimal analysis |
| 14 | Cost-effective passive house renovation packages for Swedish single-family houses from the 1960s and 1970s | 2018 | Tomas Ekström, Ricardo Bernardo, Åke Blomsterberg | Energy and Buildings Volume 161, 15 February 2018, Pages 89-102 | Sweden | LCC |
| 15 | Life cycle thinking toward sustainable development policy-making: The case of energy retrofits | 2019 | Olatz Pombo, Beatriz Rivela, Javier Neila | Journal of Cleaner Production Volume 206, 1 January 2019, Pages 267-281 | Spain | LCA,LCC |
| 16 | Life Cycle Cost of Building Energy Renovation Measures, Considering Future Energy Production Scenarios | 2019 | Moa Swing Gustafsson,Jonn Are Myhren,Erik DotzauerandMarcus Gustafsson | Energies 2019, 12(14), 2719 | Sweden | LCC + sensitivity analysis |
| 17 | Sustainable energy efficiency retrofits as residenial buildings move towards nearly zero energy building (NZEB) standards | 2020 | Paul Moran, John O'Connell, Jamie Goggins | Energy and Buildings Volume 211, 15 March 2020, 109816 | Ireland | LCA +LCC + cost optimal + sensitivity analysis |
| 18 | Economic performance assessment of three renovated multi-family buildings with different HVAC systems | 2020 | Alaa Khadra, Mårten Hugosson, Jan Akander, Jonn Are Myhren | Energy and Buildings Volume 224, 1 October 2020, 110275 | Sweden | LCCA,LCC |
| 19 | Sensitivity analysis as support for reliable life cycle cost evaluation applied to eleven nearly zero-energy buildings in Europe | 2021 | Roberta Pernetti , Federico Garzia, Ulrich Filippi Oberegger | Sustainable Cities and Society Volume 74, November 2021, 103139 | multiple | LCC + sensitivity analysis |
| 20 | Analysis of environmental impacts and costs of a residential building over its entire life cycle to achieve nearly zero energy and low emission objectives | 2022 | Modeste Kameni Nematchoua, Rakotomalala Minoson Sendrahasina , Charline Malmedy , Jose A. Orosa d, Elie Simo e, Sigrid Reiter b | Journal of Cleaner Production，Pages 373 | Belgium | LCA |
| 21 | Refurbish or replace? The Life Cycle Carbon Footprint and Life Cycle Cost of Refurbished and New Residential Archetype Buildings in London | 2022 | Yair Schwartz, Rokia Raslan, Dejan Mumovic | Energy Volume 248, 1 June 2022, 123585 | UK | LCA,LCC |
| 22 | Analysis and Valuation of the Energy-Efficient Residential Building with Innovative Modular Green Wall Systems | 2022 | Elena Korol, Natalia Shushunova | Sustainability 2022, 14(11), 6891 | Russia | LCA |
| 23 | Life Cycle Cost Evaluation of Green Building | 2010 | Xiaoyan Wang, Rui Zhang | PROCEEDINGS OF THE 2010 INTERNATIONAL CONFERENCE ON INFORMATION TECHNOLOGY AND SCIENTIFIC MANAGEMENT pp681-684 | China | LCC |
| 24 | Optimum insulation thickness of residential roof with respect to solar-air degree-hours in hot summer and cold winter zone of china | 2011 | Jinghua Yu, Liwei Tian, Changzhi Yang, Xinhua Xu, Jinbo Wang | Energy and Buildings Volume 43, Issue 9, September 2011, Pages 2304-2313 | China | LCC |

The chart is incomplete. Proceed to the next page

| | Title | Publication Year | Authors | Publisher | Country | Methodology |
|---|---|---|---|---|---|---|
| 25 | A methodology for estimating the life-cycle carbon efficiency of a residential building | 2013 | D.Z. Li, H.X. Chen, Eddie C.M. Hui, J.B. Zhang, Q.M. Li | Building and Environment Volume 59, January 2013, Pages 448-455 | China | LCA |
| 26 | Evaluating construction cost of green building based on life-cycle cost analysis: An empirical analysis from Nanjing, China | 2015 | Hongmei Liu | International Journal of Smart Home Vol. 9, No. 12, (2015), pp. 299-306 | China | LCC |
| 27 | The nexus among employment opportunities, life-cycle costs, and carbon emissions: a case study of sustainable building maintenance in Hong Kong | 2015 | Yat Hung Chiang, Jing Li, Lu Zhou, Francis K.W. Wong, Patrick T.I. Lam | Journal of Cleaner Production Volume 109, 16 December 2015, Pages 326-335 | China | LCC |
| 28 | A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings | 2015 | C.K. Chau, T.M. Leung, W.Y. Ng | Applied Energy Volume 143, 1 April 2015, Pages 395-413 | China | LCA |
| 29 | Carbon emission analysis of a residential building in China through life cycle assessment | 2016 | Yin Zhang, Xuejing Zheng, Huan Zhang, Gaofeng Chen & Xia Wang | Frontiers of Environmental Science & Engineering volume 10, pages150–158 (2016) | China | LCA |
| 30 | Life cycle assessment and life cycle cost of university dormitories in the southeast China: Case study of the university town of Fuzhou | 2018 | Lizhen Huang , Yongping Liu , Guri Krigsvoll , Fred Johansen | Journal of Cleaner Production,Volume 173, 1 February 2018, Pages 151-159 | China | LCC, LCA |
| 31 | Cost-benefit analysis for Energy Efficiency Retrofit of existing buildings: A case study in China | 2018 | Liu, Yuming, Liu, Tingting,Ye, Sudong,Liu,Yisheng | Journal of Cleaner Production Volume 177, 10 March 2018, Pages 493-506 | China | LCC, LCA |
| 32 | Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China | 2018 | Xining Yang, Mingming Hu, Jiangbo Wu, Bin Zhao | Journal of Cleaner Production Volume 183, 10 May 2018, Pages 729-743 | China | LCA |
| 33 | Study on the suitability of green building technology for affordable housing: A case study on Zhejiang Province, China | 2020 | Jian Ge, Yujie Zhao, Xiaoyu Luo, Minmin Lin | Journal of Cleaner Production Volume 275, 1 December 2020, 122685 | China | Incremental cost |
| 34 | Sustainable framework for buildings in cold regions of China considering life cycle cost and environmental impact as well as thermal comfort | 2020 | Ran Wang, Shilei Lu, Wei Feng, Xue Zhai, Xinhua Li | Energy Reports Volume 6, November 2020, Pages 3036-3050 | China | LCC, LCA, sensitivity analysis |
| 35 | Life Cycle Environmental Costs of Buildings | 2020 | Yuanfeng Wang ,Bo Pang,Xiangjie Zhang,Jingjing Wang | Energies,Volume 13, Issue 6 | China | LCCA, sensitivity analysis |

The chart is incomplete. Proceed to the next page

| | Title | Publication Year | Authors | Publisher | Country | Methodology |
|---|---|---|---|---|---|---|
| 35 | Life Cycle Environmental Costs of Buildings | 2020 | Yuanfeng Wang ,Bo Pang,Xiangjie Zhang,Jingjing Wang | Energies,Volume 13, Issue 6 | China | LCCA, sensitivity analysis |
| 36 | Life cycle cost and life cycle energy in zero-energy building by multi-objective optimization | 2021 | Chen She , Rui Jia , Bei-Ning Hu , Ze-Kun Zheng , Yi-Peng Xu , Dragan Rodriguez | Energy Reports Volume 7, November 2021, Pages 5612-5626 | China | LCC |
| 37 | Evaluation of the relative differences in building energy simulation results | 2022 | Dan Wang, Xiufeng Pang, Wei Wang, Chuan Wan & Gang Wang | Building Simulation volume 15, pages1977–1987 (2022) | China | LCA+ Monte Carlo simulation |
| 38 | Incremental cost-benefit quantitative assessment of green building: A case study in China | 2022 | Zhijiang Wu, Guofeng Ma | Energy and Buildings Volume 269, 15 August 2022, 112251 | China | LCC, cost-benefit, Incremental cost |
| 39 | Life cycle assessment of a residential building in China accounting for spatial and temporal variations of electricity production | 2022 | Long Pei, Patrick Schalbart, Bruno Peuportier | Journal of Building Engineering Volume 52, 15 July 2022, 104461 | China | LCA, sensitivity analysis |
| 40 | Framework on low-carbon retrofit of rural residential buildings in arid areas of northwest China: A case study of Turpan residential buildings | 2022 | Junkang Song, Wanjiang Wang, Pingan Ni, Hanjie Zheng, Zihan Zhang & Yihuan Zhou | Building Simulation volume 16, pages279–297 (2023) | China | LCC |
| 41 | BIM-based LCA as a comprehensive method for the refurbishment of existing dwellings considering environmental compatibility, energy efficiency, and profitability: A case study in China | 2022 | Dauletbek, A ; Zhou, PG | Journal of Building Engineering Volume 46, 1 April 2022, 103852 | China | LCA |

Figure 3 The summary table for 41 publications. (author's elaboration)

## 3.2 The description of article

In this section, the author provides a detailed description of each of the documents from Europe and China.

This section is mainly presented from top to bottom according to the following information:

- Author
- Publication year
- Publisher
- Keywords (by document)
- Locations
- Case study
- Methodology
- Abstract

The methodology in the articles is mainly derived from keywords and various references to life cycle methods or economic assessment methods (e.g. incremental cost and cost-benefit analysis) used in the articles.

In addition to the abstracts, some of the articles also present additional case studies of the analyses, their architectural context (e.g. floor plans and architectural photographs) and the steps of the life cycle analysis.

The buildings analysed in this section are all residential, including high-rise or university dormitory, mixed-use (commercial and residential) buildings.

## 3.2.1 the scientific publication from Europe

### No.1 Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design

**Author:** Miro Ristimäki, Antti Säynäjoki, Jukka Heinonen, Seppo Junnila
**Publication year:** 2013
**Publisher:** Energy, Volume 63, 15 December 2013, Pages 168-179
**Keywords (by document):** LCA (life cycle assessment), LCC (life cycle costing), LCM (life cycle management), Sustainable residential development, Energy-efficient design solutions, District energy systems.
**Locations**: Tampere, Finland.
**Case study:** seven multi-story residential buildings (3078 gross $m^2$ each with 28 apartments)
**Methodology:** LCC+LCA+ sensitivity analysis
**Abstract**
'The focus of the study is on the life cycle design of a district energy system for a new residential development in Finland. This study analyses LCC (life cycle costs) and carbon emissions (LCA (life cycle assessment)), i.e., the "viability" of different energy systems through a methodological life cycle framework. By combining LCC and LCA, a LCM (life cycle management) perspective is portrayed to support decision-making on a long-term basis. The comparable energy design options analysed are (1) district heating (reference design), (2) district heating with building integrated photovoltaic panels, (3) ground source heat pump, and (4) ground source heat pump with building-integrated photovoltaic panels. The results show that the design option with the highest initial investment (4) is in fact the most viable from a life cycle perspective. This study further strengthens the connection between cost savings and carbon emissions reduction in a life cycle context. Thus, by implementing LCC and LCA analysis in an early design phase, justified economic and environmental design decisions can be identified to develop more sustainable urban areas.' [1]


Figure 4, Life cycle costs (NPC) for the evaluated options (25/50/100 years).
Source: Miro Ristimäki et al., 'Combining Life Cycle Costing and Life Cycle Assessment for an Analysis of a New Residential District Energy System Design'. *Energy* 63 (15 December 2013): 168–79, p-175.

[1] Miro Ristimäki et al., 'Combining Life Cycle Costing and Life Cycle Assessment for an Analysis of a New Residential District Energy System Design', *Energy* 63 (15 December 2013): 168–79, https://doi.org/10.1016/j.energy.2013.10.030.

## No.2 A methodology for economic efficient design of Net Zero Energy Buildings

**Author:** M. Kapsalaki, V. Leal, M. Santamouris
**Publication year:** 2012
**Publisher:** Energy and Buildings, Volume 55, December 2012, Pages 765-778
**Keywords (by document):** Net Zero Energy Building, Sustainable building, Energy efficient building, Life cycle cost, Microgeneration.
**Locations**: Stockholm (cold winter), Lisbon (mild winter), Iraklion (very mild winter but warm summer).
**Case study:** a large one-floor single-family detached dwelling, with 266 $m^2$ of heated floor area and five bedrooms.
**Methodology:** LCC
**Abstract**
'This work developed a methodology and an associated calculation platform in order to identify the economic efficient design solutions for residential Net Zero Energy Building (NZEB) design considering the influence of the local climate, the endogenous energy resources and the local economic conditions. One case study of a detached house for 3 climates was analyzed with the tool developed in order to gain insights on the economic space of NZEB solutions and the influence of the climatic context. A methodology for assisting the choice of economically efficient NZEB solutions from the early design stage is now available. Its use in practice may be of great relevance as the results showed that the differences between an economically efficient and economically inefficient NZEB can be over three times both in terms of initial and life cycle cost.

The paper is laid out as follows: Section 2 identifies and discretizes the key design variables; Section 3 addresses the calculation methodologies that were used in order to characterize the energy demand and supply of the building as well as the economic indicators of each design alternative and provides a description of the computer program developed; Section 4 provides a first application example of the methodology, while conclusions are drawn in Section 5.

The analysis of the case-study was performed for three climates scenarios: Stockholm (Sweden), representing a climate with a cold winter, Lisbon (Portugal), representing a climate with a mild winter, Iraklion (Crete, Greece) representing a climate with very mild winter but warm summer.' [2]

[2] M. Kapsalaki, V. Leal, and M. Santamouris, 'A Methodology for Economic Efficient Design of Net Zero Energy Buildings', *Energy and Buildings*, Cool Roofs, Cool Pavements, Cool Cities, and Cool World, 55 (1 December 2012): 765–78, https://doi.org/10.1016/j.enbuild.2012.10.022.

**No.3 Sustainability assessment of renovation packages for increased energy efficiency for multi-family buildings in Sweden**

**Author:** Nils W.O. Brown, Tove Malmqvist, Wei Bai, Marco Molinari
**Publication year:** 2013
**Publisher:** Building and Environment, Volume 61, March 2013, Pages 140-148
**Keywords (by document):** Renovation, LCC, Energy efficiency, Indoor environment, Sustainability Environmental rating tools
**Locations**: Stockholm, Sweden.
**Case study:** a terrace of five row houses built in 1973, apartment building from 1973 and 1963
**Methodology:** LCC
**Abstract**
‘In this paper, we propose a method for assessing renovation packages drawn up with the goal of increasing energy efficiency. The method includes calculation of bought energy demand, life-cycle cost (LCC) analysis and assessment of the building according to the Swedish environmental rating tool Miljöbyggnad (MB).

The method is further explained and analysed by applying it in three case studies. In each case study a multi-family building representing a typologically significant class in the Swedish building stock is considered, and for each building a base case and two renovation packages with higher initial investment requirement and higher energy efficiency are defined. It is shown that higher efficiency packages can impact IEQ indicators both positively and negatively and that packages reducing energy demand by approx. 50% have somewhat higher LCC. Identified positive IEQ impacts point to added value for packages that may not otherwise be communicated, while negative impacts identify areas where packages need to be improved, or where MB indicators may be referred to as specifications in procurement procedures.

In each case, the packages and base cases are compared economically using LCC with a net present cost method. The period-of-analysis is chosen to be 50 years, since this is considered a reasonable lifetime for the building over which cash-flows will be of interest for decision makers now. The calculations have been carried out exclusive of the general rate of inflation, and where specific inflation rates for the costs of specific commodities have been assumed.’ [3]

[3] Nils W. O. Brown et al., ‘Sustainability Assessment of Renovation Packages for Increased Energy Efficiency for Multi-Family Buildings in Sweden’, *Building and Environment* 61 (1 March 2013): 140–48, https://doi.org/10.1016/j.buildenv.2012.11.019.

**No.4 A life-cycle cost analysis of the passive house "POLITEHNICA" from Bucharest**

**Author:** Adrian Badea , Tudor Baracu , Cristian Dinca , Diana Tutica , Roxana Grigore , Madalina Anastasiu
**Publication year:** 2014
**Publisher:** Energy and Buildings, Volume 80, September 2014, Pages 542-555
**Keywords (by document):** Life-cycle cost analysis, Passive house, Economic efficiency
**Location**: Bucharest, Romania.
**Case study:** 14 types of houses derived from the design of the passive house POLITEHNICA
**Methodology:** LCCA
**Abstract**
'The objective of this article is to create a mathematical model based on the analysis of the life-cycle cost of a passive house, including its technical design variations. In this study, we analyzed 14 types of houses derived from the design of the passive house POLITEHNICA; every house was differentiated by the type of renewable solution used (EAHX, GHP, solar collectors, PV panels) or by the insulation thickness, and it was compared with H12, a standard house with classical HVAC systems and a thermal insulation of 100 mm. The houses were compared according to criteria of economic performance throughout their life cycle. It was found that the additional investment in an energy efficient house can be recovered in 16–26 years, 9–16 years and 16–28 years if the replaced HVAC system is classical gas fuelled, electric or district distribution. A sensitivity analysis is performed which revealed the influence of the price of electricity and PV panels. The classification system made the decision-making process easier for a possible investment in a solution. This classification system showed that the first three recommended solutions for investment are the houses H14, H17 and H20.' [4]
Fig. 2 shows the total cost of the houses involving life cycles of 24 years (even before the end of the operation of PV panels), 30, 40, 50 and 60 years.

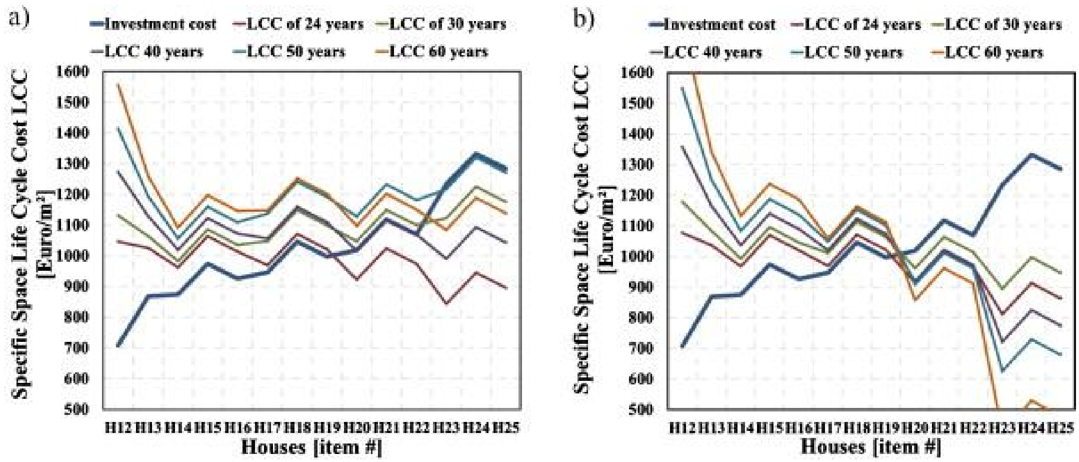



Figure 5 Specific space life-cycle cost LCC on time spans of 24, 30, 40, 50, 60 years: (a) life-cycle cost in the simplest economic conditions; (b) life-cycle cost in the best forecasted economic conditions.
Source: Adrian Badea et al., 'A Life-Cycle Cost Analysis of the Passive House "POLITEHNICA" from Bucharest', Energy and Buildings 80 (1 September 2014): 542–55, p-549.

[4] Adrian Badea et al., 'A Life-Cycle Cost Analysis of the Passive House "POLITEHNICA" from Bucharest', *Energy and Buildings* 80 (1 September 2014): 542–55, https://doi.org/10.1016/j.enbuild.2014.04.044.

## No.5 Green housing: Toward a new energy efficiency paradox?

**Author:** Sergio Copiello, Pietro Bonifaci
**Publication year:** 2015
**Publisher:** Cities, Volume 49, December 2015, Pages 76-87
**Keywords (by document):** Buildings energy efficiency, Energy efficiency paradox, Discounted Cash Flow, Energy savings
**Locations**: Bologna, Italy.
**Case study:** the refurbishment of a detached house and public housing
**Methodology:** LCC(DCF)

**Abstract**

'This study aims to assess the economic viability of improving the energy performance of residential buildings, by comparing additional costs of investment with the monetary savings achievable through reduced energy consumption.

The evaluation model relies on the methodological framework of Discounted Cash Flow analysis, from a purely financial point of view in which externalities are not considered. The assessment is applied to two case studies located in Northern Italy. For each case study, several energy improvement alternatives are investigated.

Empirical findings can be summarized as follows: at least partly, investing in buildings energy efficiency lacks economic viability; nevertheless, it can be interpreted as a hedge against a sharp rise in energy supply pricing in the coming years.

As original contribution, the achieved findings provide an empirical support to highlight a new kind of energy efficiency paradox: investing in improving the buildings energy performance should allow a reduction to both climate-altering emissions and, in an efficient market, the price of energy supplies; but a decreasing price also lowers the profitability of the self-same investment, and acts as a deterrent to further improvements.' [5]

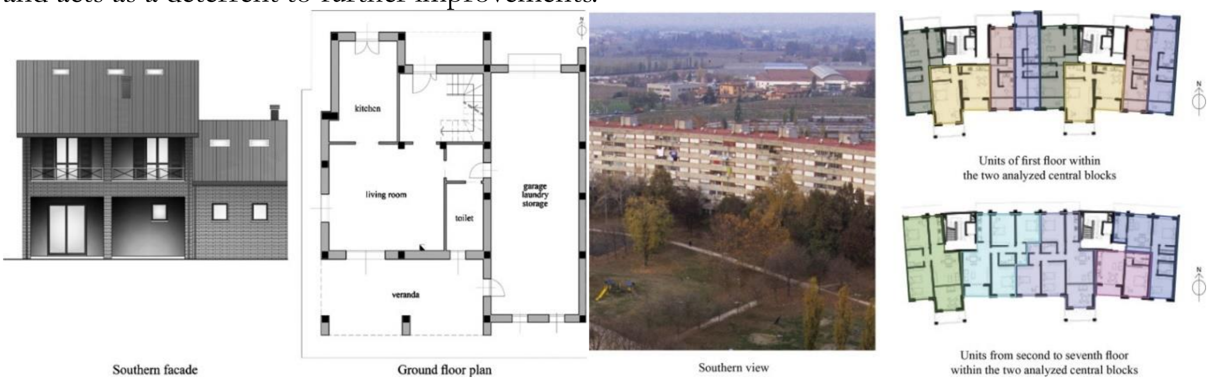



Figure 6 Front view and plan of Cases
Source: Sergio Copiello and Pietro Bonifaci, 'Green Housing: Toward a New Energy Efficiency Paradox?' Cities 49 (1 December 2015): 76–87,p-80.

[5] Sergio Copiello and Pietro Bonifaci, 'Green Housing: Toward a New Energy Efficiency Paradox?', *Cities* 49 (1 December 2015): 76–87, https://doi.org/10.1016/j.cities.2015.07.006.

## No.6 Cost optimality assessment of a single family house: Building and technical systems solutions for the nZEB target

**Author:** Becchio Cristina, Dabbene Paolo,Fabrizio Enrico
**Publication year:** 2015
**Publisher:** Energy and Buildings, Volume 90, 1 March 2015, Pages 173-187
**Keywords (by document):** EPBD recast, Nearly zero energy buildings (nZEB), Cost optimal, Dynamic simulation, Energy efficiency measures, Systems, Residential building.
**Locations**: Turin, Italy.
**Case study:** a two-storey house with a conditioned net floor area of 174 $m^2$
**Methodology:** Cost optimal
**Abstract**
'Europe has set a clear path to guide Member States into the accomplishment of the nearly zero energy buildings (nZEBs) target. To this regard, within EPBD recast directive, a cost optimality procedure has been defined. This study presents different cost optimal solutions of building and technical systems for nZEBs in Italy. In total 40 economically and technically feasible energy efficiency measures for a high performing single family house were analyzed. Special attention was devoted to the study of the building technical systems. Achieving a net zero balance required a high efficient system combined with high insulation and a large PV system, which plays a key role in the nearly and net zero building energy balance. Three net zero energy balance solutions, based on all electric systems, were presented. Net ZEB solutions allowed also the building carbon footprint to be reduced by 40% compared to the reference case study. Without proper financial subsides, net ZEB solutions are still far for being economic feasible, having a global cost 212–313 €/$m^2$ higher than cost optimal solutions. In conclusion, this paper aims to present guidelines for designing reference building envelope and technical systems solution for residential nZEB.' [6]

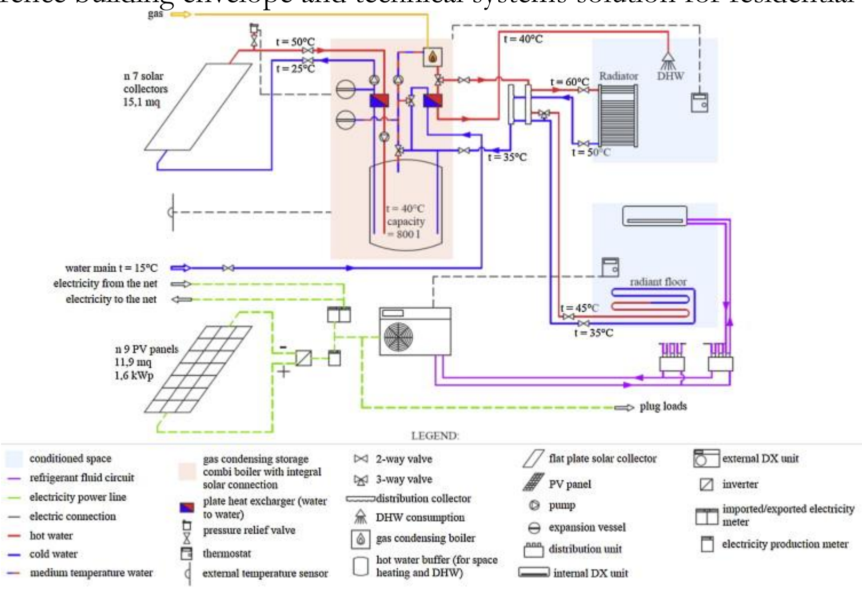



Figure 7 Layout of the building technical system 0 (BTS0).
Source: Cristina Becchio et al., 'Cost Optimality Assessment of a Single Family House: Building and Technical Systems Solutions for the NZEB Target'. Energy and Buildings 90 (1 March 2015): 173–87, p-176.

[6] Cristina Becchio et al., 'Cost Optimality Assessment of a Single Family House: Building and Technical Systems Solutions for the NZEB Target', *Energy and Buildings* 90 (1 March 2015): 173–87, https://doi.org/10.1016/j.enbuild.2014.12.050.

## No.7 Towards a More Sustainable Building Stock: Optimizing a Flemish Dwelling Using a Life Cycle Approach

**Author:** Matthias Buyle, Amaryllis Audenaert , Johan Braet and Wim Debacker
**Publication year:** 2015
**Publisher:** Buildings 2015, 5(2), 424-448.
**Keywords (by document):** life cycle assessment; life cycle energy assessment; life cycle economic performance; environmental profile; optimization
**Locations**: Flemish, Belgium.
**Case study:** housing groups composed by three connected dwellings; net floor surface is 117m$^2$.
**Methodology:** LCA+LCC
**Abstract**
‘Over the past decades, the construction sector has focused strongly on reducing operational energy consumption. Other types of environmental impact that occur during the life span of construction works, however, have to be taken into account as well. This case study focuses on developing scenarios to improve the environmental profile of new buildings in the Flemish/Belgian context. The study takes into account current energy regulation and investigates the influence of energy scenarios and building type on the environmental profile. A life cycle energy assessment (LCEA) and a life cycle impact assessment (LCIA) were carried out for all scenarios, supplemented by a screening life cycle costing (LCC). The results indicate the importance of the compactness of a building, with the best results identified for the terraced scenario. The results are due to the reduced use of materials and, to a smaller extent, a reduction in energy consumption (smaller exposed surface). The results of the energy scenarios show a discrepancy between the LCEA and LCIA. According to the LCEA, passive scenarios are always preferable, but the LCIA results suggest two ways to reach a similar environmental profile. Firstly, by providing a level of insulation based on current regulations complemented with advanced technical services, and, alternatively, by increasing the level of insulation along with standard services. The results of the LCC show a similar trend to those of the LCIA. The results therefore suggest that there are multiple ways to improve the environmental profile of new buildings. Nevertheless, the choice of impact assessment method can have a strong influence on the results.’ [7]


(a) (b)

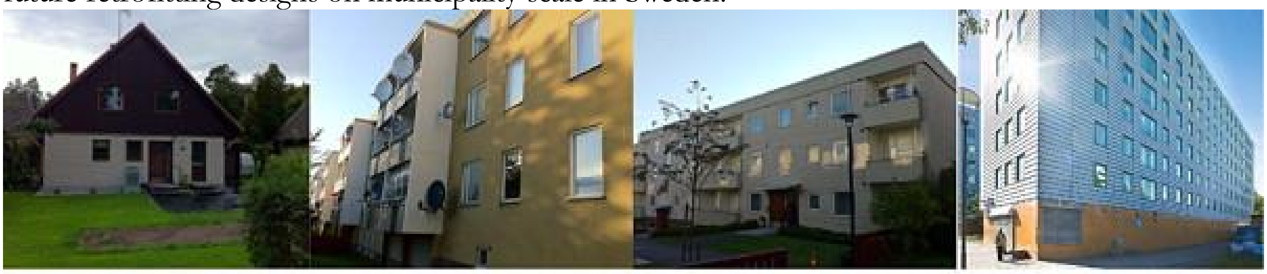
Figure 8 (a) Floor plans; (b) View of front facade.
Source: Matthias Buyle et al., ‘Towards a More Sustainable Building Stock: Optimizing a Flemish Dwelling Using a Life Cycle Approach’, Buildings 5, no. 2 (June 2015): 424–48, p-429.

[7] Matthias Buyle et al., ‘Towards a More Sustainable Building Stock: Optimizing a Flemish Dwelling Using a Life Cycle Approach’, *Buildings* 5, no. 2 (June 2015): 424–48, https://doi.org/10.3390/buildings5020424.

## No.8 A methodology to assess energy-demand savings and cost effectiveness of retrofitting in existing Swedish residential buildings

**Author:** Qian Wang, Sture Holmberg
**Publication year:** 2015
**Publisher:** Sustainable Cities and Society, Volume 14, February 2015, Pages 254-266
**Keywords (by document):** Retrofitting, Energy demand savings, Swedish residential buildings
**Locations**: Sweden
**Case study:** B1: pre-1945, detached single family house, below 3 storeys; B2: 1946–1960, multi-family houses, 3–4 storeys; B3: 1961–1975, multi-family houses, 3–4 storeys; B4: Additionally, special booming time 1965–1975 for high slab apartments (above 5 storeys)
**Methodology:** LCCA, sensitivity analysis.

**Abstract**
'Swedish residential buildings are typically retrofitted on a case-by-case basis. Large numbers of building consultants are involved in the decision-making, and stakeholders find it difficult to quantify the sustainable profits from retrofits and to make an efficient selection of the optimal alternative. The present paper presents an approach to design and assess energy-demand retrofitting scenarios. This aims to contribute to retrofitting decision-making regarding the main archetypes of existing Swedish residential buildings and to the evaluation of their long-term cost effectiveness. The approach combines energy-demand modeling and retrofit option rankings with life-cycle cost analysis (LCCA). Four types of typical Swedish residential buildings are used to demonstrate the model. Retrofits in the archetypes are defined, analyzed and ranked to indicate the long-term energy savings and economic profits. The model indicates that the energy saving potential of retrofitting is 36–54% in the archetypes. However, retrofits with the largest energy-saving potential are not always the most cost effective. The long-term profits of retrofitting are largely dominated by the building types. The finding can contribute to the standardization of future retrofitting designs on municipality scale in Sweden.' [8]



B1 B2 B3 B4

Figure 9 The appearance of the selected archetypes.
Source: Qian Wang and Sture Holmberg, 'A Methodology to Assess Energy-Demand Savings and Cost Effectiveness of Retrofitting in Existing Swedish Residential Buildings'. Sustainable Cities and Society 14 (1 February 2015): 254–66.p-257.

[8] Qian Wang and Sture Holmberg, 'A Methodology to Assess Energy-Demand Savings and Cost Effectiveness of Retrofitting in Existing Swedish Residential Buildings', *Sustainable Cities and Society* 14 (1 February 2015): 254–66, https://doi.org/10.1016/j.scs.2014.10.002.

### No.9 Retrofit Scenarios and Economic Sustainability. A Case-study in the Italian Context

**Author:** E. Fregonara, V. R.M. Lo Verso, M. Lisac, G. Callegaria
**Publication year:** 2017
**Publisher:** Energy Procedia, Volume 111, March 2017, Pages 245-255
**Keywords (by document):** Energy Retrofit, Energy Efficiency Scenarios, Economic Sustainability, Life Cycle Costing, Global Cost
**Locations**: Turin, Italy
**Case study:** a double family single house
**Methodology:** LCC
**Abstract**

'The aim of this paper is to highlight the potentialities for supporting the decision-making process and design activities, for the case of retrofit projects with alternative technological solutions to compare. A multidisciplinary approach was adopted, involving the contribution of Real Estate Market and Economic Evaluation of Project, Architectural Technology and Building Physics. A simplified application of the Life Cycle Costing methodology was used, in synergy with energy analyses, to select, among different scenarios, the most viable solution for the retrofitting project of a single house in Northern Italy.

The energy evaluation was conducted with the following aims: i) to calculate the thermal transmittance U and the periodic thermal transmittance YIE of the envelope (walls and roof); ii) to calculate the energy consumption for heating and DHW, and then the primary annual energy Ep of the various scenarios, as well as the Energy Performances Class EPC (according to Law 90/2013); iii) to quantify the effect of the renewable energy systems on the energy consumption, also calculating the annual energy cost; iv) to verify to what extent the different scenarios were able to comply with the limit values set by the Italian technical-regulatory framework.' [9]

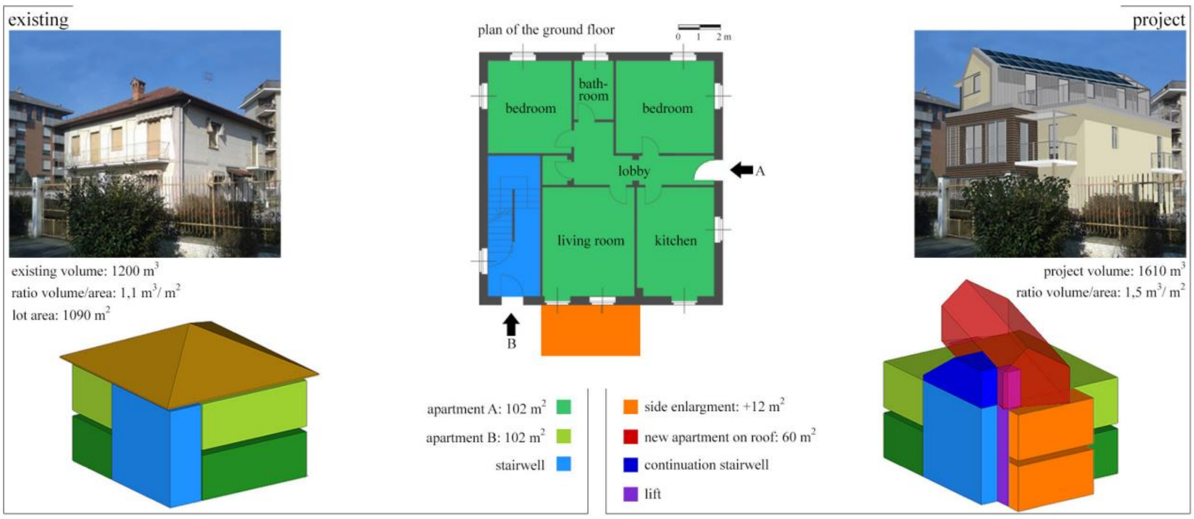



Figure 10 The residential building used as case-study: existing and project schemes (the second floor having the same layout of ground floor). Source: Elena Fregonara et al., 'Retrofit Scenarios and Economic Sustainability. A Case-Study in the Italian Context'. Energy Procedia, 8th International Conference on Sustainability in Energy and Buildings, SEB-16, 11-13 September 2016, Turin, Italy, 111 (1 March 2017): 245–55,p-249.

[9] Elena Fregonara et al., 'Retrofit Scenarios and Economic Sustainability. A Case-Study in the Italian Context', *Energy Procedia*, 8th International Conference on Sustainability in Energy and Buildings, SEB-16, 11-13 September 2016, Turin, Italy, 111 (1 March 2017): 245–55, https://doi.org/10.1016/j.egypro.2017.03.026.

## No.10 Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects

**Author:** Roberta Moschetti, Helge Brattebø
**Publication year:** 2017
**Publisher:** Energies 2017, 10(11), 1851; https://doi.org/10.3390/en10111851
**Keywords (by document):** buildings; energy renovation; dynamic energy simulation; life cycle assessment (LCA); life cycle costing (LCC); sensitivity analyses.
**Locations**: Oslo, Norway
**Case study:** a single-family house
**Methodology:** LCC+LCA+ sensitivity analyses
**Abstract**
'Buildings currently play a fundamental role for the achievement of the sustainable development goals as they are responsible for several environmental, social, and economic impacts. Energy renovation projects of existing buildings can support the reduction of environmental impacts by leading, at the same time, to economic and social advantages. In this paper, the life cycle assessment and life cycle costing methodologies were used in a combined performance assessment applied to a case study, i.e., the energy renovation project of a single-family house in Norway. Several scenarios based on alternative energy efficiency measures were analyzed, and life cycle environmental and economic indicators were computed, i.e., global warming potential (GWP), cumulative energy demand (CED), and net present cost (NPC). The results demonstrated the close to negative linear regression between the environmental and economic indicators computed. However, the values of CED and GWP for the best scenarios in environmental terms were respectively 50% and 32% lower than the values of the worst scenarios, while their NPC was around 6% higher than the lowest values. The findings can be helpful in the decision-making context towards a meaningful combination of environmental and economic assessments in building energy renovation projects for selecting the most sustainable scenario.' [10]


Figure 11 Floor plans and perspective of the single-family house analyzed.
Source: Roberta Moschetti and Helge Brattebø, 'Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects'. Energies 10, no. 11 (November 2017): 1851, p-4.

[10] Roberta Moschetti and Helge Brattebø, 'Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects', *Energies* 10, no. 11 (November 2017): 1851, https://doi.org/10.3390/en10111851.

## No.11 Life-cycle cost analyses of heat pump concepts for Finnish new nearly zero energy residential buildings

**Author:** Satu Paiho, Sakari Pulakka, Antti Knuuti
**Publication year:** 2017
**Publisher:** Energy and Buildings, Volume 150, 1 September 2017, Pages 396-402
**Keywords (by document):** Heat pump, Nearly zero-energy building (nZEB), Life-cycle costs, Residential building, Finland, Case study
**Locations**: Finland
**Case study:** single-family house and apartment building
**Methodology:** LCC
**Abstract**
'During the recent years in Finland, there has been a clear trend that ground source heat pumps are the most widely used main heating source in new detached houses. In addition, other heat pumps have been installed as a supporting heat source and/or to provide cooling. Similar trend cannot be seen in new apartment buildings but heat pumps could be utilized more widely also there.

Going towards nearly zero-energy buildings (nZEBs) is a new opportunity for heat pumps. The nZEB concepts often combine passive structural solutions and renewable energy production. This paper analyses life-cycle costs (LCCs) of different heat pump based nZEB concepts for a Finnish new detached house and a new apartment building. The concepts included different heat pumps without and with solar systems. For the apartment building, district heating based concepts were also included as a reference.

For both building types, the LCCs were the smallest with the ground source heat pumps (GSHPs) followed by the air-to-water heat pumps. For almost all concepts, the LCCs were bigger for the solar included concepts. The economic order of the solutions did not change when the results were sensitized but the GSHPs were proven to be the most economic alternatives.' [11]

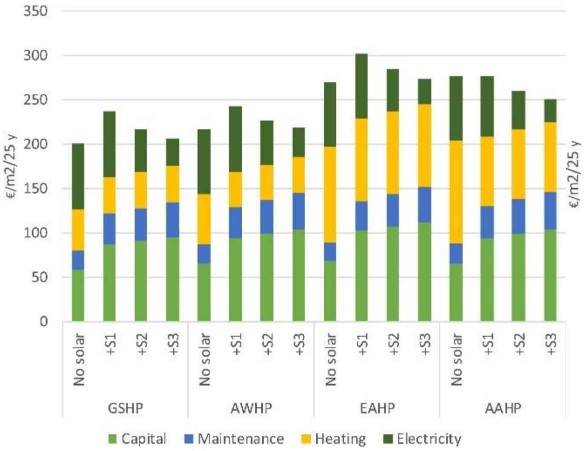


Figure 12 The LCCs of the new detached house

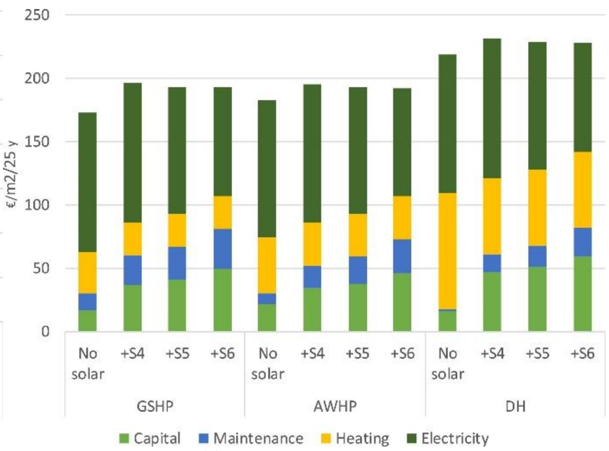


Figure 13 The LCCs of the new apartment building

Source: Satu Paiho, Sakari Pulakka, and Antti Knuuti, 'Life-Cycle Cost Analyses of Heat Pump Concepts for Finnish New Nearly Zero Energy Residential Buildings'. Energy and Buildings 150 (1 September 2017): 396–402. P399-400.

[11] Satu Paiho, Sakari Pulakka, and Antti Knuuti, 'Life-Cycle Cost Analyses of Heat Pump Concepts for Finnish New Nearly Zero Energy Residential Buildings', *Energy and Buildings* 150 (1 September 2017): 396–402, https://doi.org/10.1016/j.enbuild.2017.06.034.

## No.12 Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate

**Author:** Sergio Copiello, Laura Gabrielli , Pietro Bonifaci
**Publication year:** 2017
**Publisher:** Energy, Volume 137, 15 October 2017, Pages 104-117
**Keywords (by document):** Residential buildings, Energy efficiency, Uncertainty, Life-cycle cost, Monte Carlo simulation, Discount rate
**Locations:** Bologna, Italy
**Case study:** a single residential block composed of thirty flats
**Methodology:** LCC+ Monte Carlo simulation
**Abstract**
'A growing literature has focused on the economic viability of energy retrofit in buildings. As regards the valuation tools, the Life-Cycle Cost (LCC) method has established itself among the leading approaches. The results are usually affected by a core of influential, uncertain parameters: energy supply cost and energy price changes. Monte Carlo (MC) simulation may be integrated with LCC analysis to deal with that uncertainty. In this study, we apply an LCC and MC-based analytical model to a case study. Several retrofit scenarios are defined to improve the poor energy performance of a public housing building. The less investment-intensive alternative enable to achieve a 27% energy saving in comparison to the building as is, while the more investment-intensive alternative allows reducing consumptions by about two-thirds. We find that the scenarios characterized by lower upfront costs are more likely to show lower LCCs, regardless of the energy price. The novelty of this study lies in the fact that we show the prominence of the discount rate, which is a remarkable source of additional uncertainty. We find that the discount rate affects the results four times as much as the energy price; therefore, its estimation is critical to the soundness of thermo-economic evaluations.' [12]

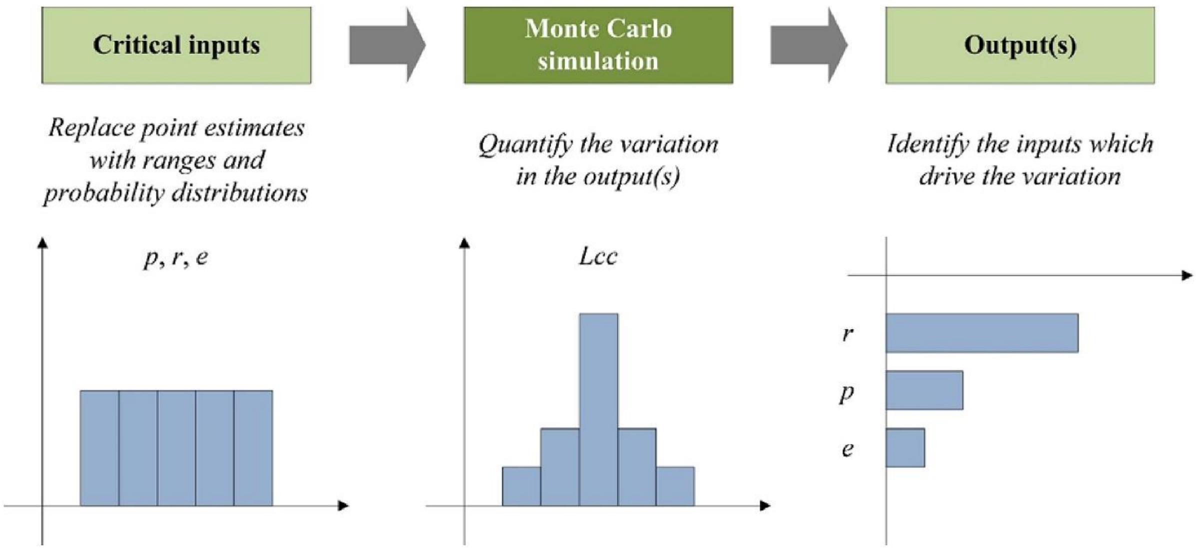



Figure 14 Monte Carlo Simulation model diagram
Source: Sergio Copiello, Laura Gabrielli, and Pietro Bonifaci, 'Evaluation of Energy Retrofit in Buildings under Conditions of Uncertainty: The Prominence of the Discount Rate'. Energy 137 (15 October 2017): 104–17.p-110.

[12] Sergio Copiello, Laura Gabrielli, and Pietro Bonifaci, 'Evaluation of Energy Retrofit in Buildings under Conditions of Uncertainty: The Prominence of the Discount Rate', *Energy* 137 (15 October 2017): 104–17, https://doi.org/10.1016/j.energy.2017.06.159.

## No.13 Energy retrofit alternatives and cost-optimal analysis for large public housing stocks

**Author:** Luca Guardigli, Marco A. Bragadin, Francesco Della Fornace, Cecilia Mazzoli, Davide Prati
**Publication year:** 2018
**Publisher:** Energy and Buildings, Volume 166, 1 May 2018, Pages 48-59
**Keywords (by document):** Cost optimal analysis, Economic sustainability, Housing stock, Energy retrofit, Payback period, Global cost, Net present value, Energy performance index, Decision support system, Design alternatives
**Locations:** Bologna, Italy
**Case study:** multi-function services Centers
**Methodology:** LCCA+ Cost optimal analysis
**Abstract**
'The study of cost-effective solutions for the energy retrofitting of existing buildings is of capital importance for building asset owners, since high up-front investments are required and long payback times are encountered in building renovation projects. The aim of the work is to propose a decision support system (DSS) for the assessment of different renovation strategies through the measure of their economic sustainability in relation to the achieved energy efficiency. The cost optimal analysis of energy retrofit alternatives is performed in the case of a large housing stock owned by a semi-public real estate company, with the goal of meeting nearly zero energy building standards. Energy performances as well as related energy and construction costs are analysed for different retrofit options, adopting Italian laws and regulations. The proposed DSS evaluates the economic sustainability of various design alternatives with the net present value (NPV) and the global cost (GC), as suggested by the EPBD recast EU directive. These indicators are finally compared with the building energy performance index (EP), providing the most efficient design alternatives for each building typology and the most advantageous renovation project among the considered ones.'[13]

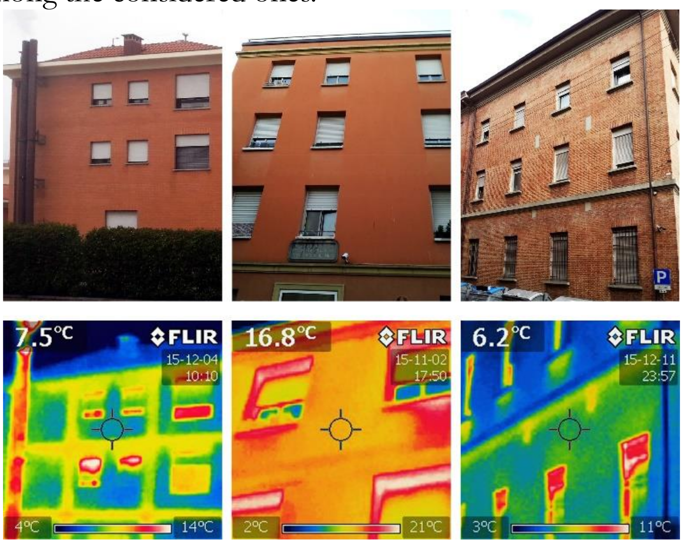



Figure 15 a) Building No. 1 "Lercaro" Service Centre; b) Building No.2 "San Nicolò di Mira" Service Centre; c) Building No.3 "Albertoni" Service Centre.
Source: Luca Guardigli et al., 'Energy Retrofit Alternatives and Cost-Optimal Analysis for Large Public Housing Stocks', Energy and Buildings 166 (1 May 2018): 48–59,p-52.

[13] Luca Guardigli et al., 'Energy Retrofit Alternatives and Cost-Optimal Analysis for Large Public Housing Stocks', *Energy and Buildings* 166 (1 May 2018): 48–59, https://doi.org/10.1016/j.enbuild.2018.02.003.

## No.14 Cost-effective passive house renovation packages for Swedish single-family houses from the 1960s and 1970s

**Author:** Tomas Ekström, Ricardo Bernardo, Åke Blomsterberg
**Publication year:** 2018
**Publisher:** Energy and Buildings, Volume 161, 15 February 2018, Pages 89-102
**Keywords (by document):** Cost-effective, Energy efficiency measures, Passive house, Renovation packages, Single-family houses, Renewable energy production
**Locations:** Sweden
**Case study:** single-storey house with a cellar, 1½-storey house
**Methodology:** LCCA
**Abstract**
'This paper evaluates the cost-effectiveness of renovating single-family houses to Passive House level, as compared to maintaining the existing buildings or renovating to building regulation level. The assessment involved life cycle cost analyses, and concerns the Swedish single-family housing stock constructed between 1961 and 1980, which accounts for about a third of Sweden's two million single-family houses. These houses, now in need of major renovation, are represented in this study by two reference buildings. The results show that Passive House renovations can be cost-effective, but this largely depends on the type of heat generation used in the houses. The most cost-effective individual renovation measure was installing an exhaust air heat pump, and the least cost-effective was installing new windows. In houses using direct electric heating, the Passive House renovation package was the most cost-effective alternative.' [14]


Figure 16 Visualisation of the two reference houses with basic data about location, year of construction and heated floor area

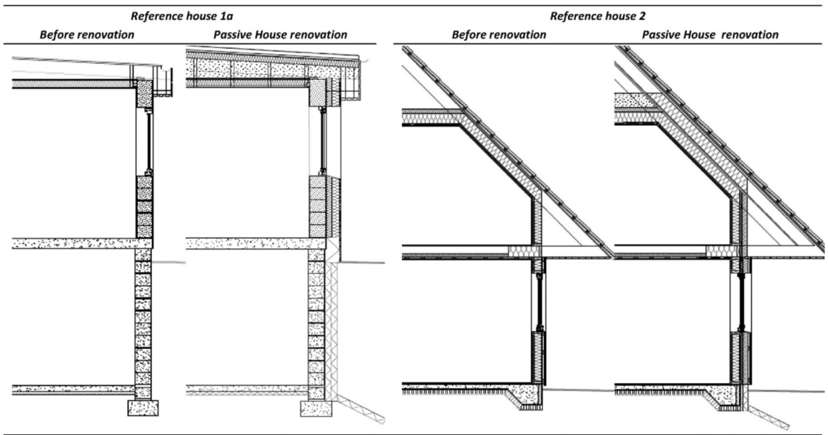



Figure 17 Section drawings of the reference houses before and after renovation showing the Passive House level renovation and energy efficiency measures.
Source: Tomas Ekström, Ricardo Bernardo, and Åke Blomsterberg, 'Cost-Effective Passive House Renovation Packages for Swedish Single-Family Houses from the 1960s and 1970s'. Energy and Buildings 161 (15 February 2018): 89–102,p-92.

[14] Tomas Ekström, Ricardo Bernardo, and Åke Blomsterberg, 'Cost-Effective Passive House Renovation Packages for Swedish Single-Family Houses from the 1960s and 1970s', *Energy and Buildings* 161 (15 February 2018): 89–102, https://doi.org/10.1016/j.enbuild.2017.12.018.

## No.15 Life cycle thinking toward sustainable development policy-making: The case of energy retrofits

**Author:** Olatz Pombo, Beatriz Rivela, Javier Neila
**Publication year:** 2019
**Publisher:** Journal of Cleaner Production Volume 206, 1 January 2019, Pages 267-281
**Keywords (by document):** Life cycle thinking, Public policy, Energy, Housing renovation, Retrofit
**Locations:** Spain
**Case study:** a ten-story building, containing 120 dwellings of 2 and 3 bedrooms, with a net floor area of 49 and 64 $m^2$
**Methodology:** LCA+LCC

**Abstract**

‘Viable implementation of building energy-efficiency policies is inevitable to mitigate climate change, above all as buildings account for around 40% of the world's energy consumption. Although some 75% of all buildings in Europe are energy-inefficient, only 0.4–1.2% of the whole stock is renovated each year. The greatest challenge for the coming decades is to increase the rate, quality and effectiveness of building renovation. The overall goal of the present article is to illustrate the key role to be played by Life Cycle Thinking in sustainable development policies and its implementation in the design of optimal retrofit solutions. The main housing renovation policies implemented in Spain were submitted to analysis using the focus of Life Cycle Approaches. Representative case studies were selected based on the analysis of 3245 real renovation solutions funded by policy programmes in the period between 2010 and 2014. Current solutions were assessed and compared to other retrofit scenarios that a priori might seem more desirable when striving for energy-efficient buildings. Multi-criteria assessment results reveal that the current renovation strategies applied in Madrid and Seville are, by no means optimal solutions, while only a small additional cost could produce significant performance improvement in Bilbao. The Passivhaus standard that offers the greatest reduction of energy consumption in all three cities would appear, however, not to be the solution of choice for any of them. These findings demonstrate the need to integrate Life Cycle thinking into the building process to identify the most sustainable energy pathways.’ [15]

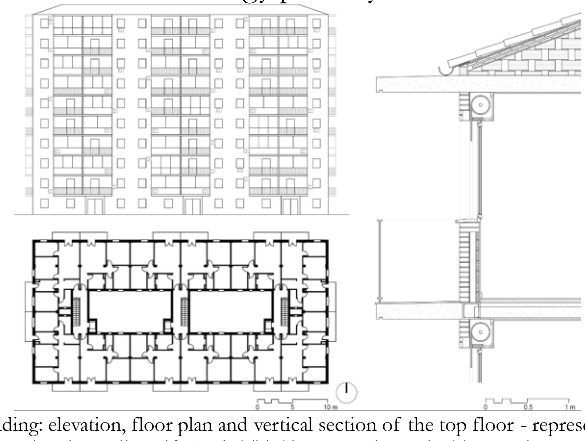


Figure 18 Layout of the existing building: elevation, floor plan and vertical section of the top floor - representative typology of Spanish housing. Source: Olatz Pombo, Beatriz Rivela, and Javier Neila, ‘Life Cycle Thinking toward Sustainable Development Policy-Making: The Case of Energy Retrofits’. Journal of Cleaner Production 206 (1 January 2019): 267–81. p-271.

[15] Olatz Pombo, Beatriz Rivela, and Javier Neila, ‘Life Cycle Thinking toward Sustainable Development Policy-Making: The Case of Energy Retrofits’, *Journal of Cleaner Production* 206 (1 January 2019): 267–81, https://doi.org/10.1016/j.jclepro.2018.09.173.

## No.16 Life Cycle Cost of Building Energy Renovation Measures, Considering Future Energy Production Scenarios

**Author:** Moa Swing Gustafsson, Jonn Are Myhren, Erik Dotzauerand, Marcus Gustafsson
**Publication year:** 2019
**Publisher:** Energies 2019, 12(14), 2719
**Keywords (by document):** life cycle cost; energy system; district heating; energy renovation measures; heat pump; mechanical ventilation with heat recovery; combined heat and power; wind power
**Locations:** Sweden
**Case study:** typical Swedish multi-family building, with a heated floor area of 4700 $m^2$ and 60 apartments
**Methodology:** LCC + sensitivity analysis

**Abstract**

'A common way of calculating the life cycle cost (LCC) of building renovation measures is to approach it from the building side, where the energy system is considered by calculating the savings in the form of less bought energy. In this study a wider perspective is introduced. The LCC for three different energy renovation measures, mechanical ventilation with heat recovery and two different heat pump systems, are compared to a reference case, a building connected to the district heating system. The energy system supplying the building is assumed to be 100% renewable, where eight different future scenarios are considered. The LCC is calculated as the total cost for the renovation measures and the energy systems. All renovation measures result in a lower district heating demand, at the expense of an increased electricity demand. All renovation measures also result in an increased LCC, compared to the reference building. When aiming for a transformation towards a 100% renewable system in the future, this study shows the importance of having a system perspective, and also taking possible future production scenarios into consideration when evaluating building renovation measures that are carried out today, but will last for several years, in which the energy production system, hopefully, will change.' [16]

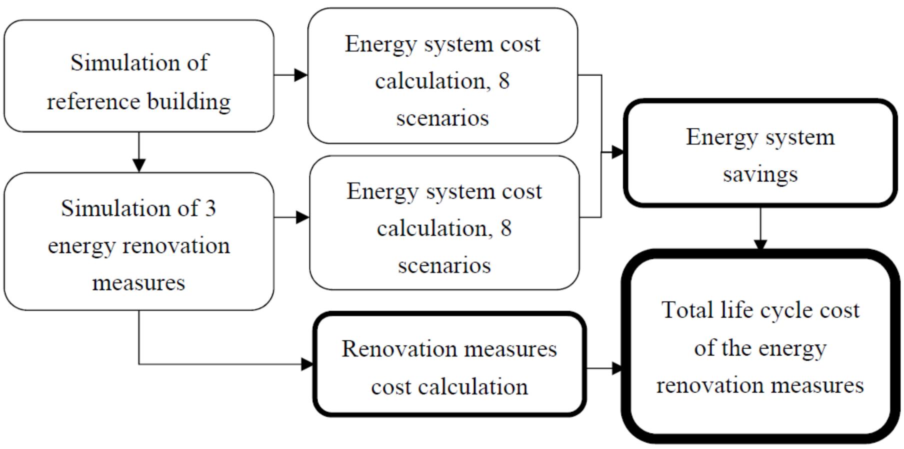



Figure 19 Flowchart describing the methodology
Source: Moa Swing Gustafsson et al., 'Life Cycle Cost of Building Energy Renovation Measures, Considering Future Energy Production Scenarios'. Energies 12, no. 14 (January 2019): 2719, p-3.

[16] Moa Swing Gustafsson et al., 'Life Cycle Cost of Building Energy Renovation Measures, Considering Future Energy Production Scenarios', *Energies* 12, no. 14 (January 2019): 2719, https://doi.org/10.3390/en12142719.

## No.17 Sustainable energy efficiency retrofits as residenial buildings move towards nearly zero energy building (NZEB) standards

**Author:** Paul Moran, John O'Connell, Jamie Goggins
**Publication year:** 2020
**Publisher:** Energy and Buildings, Volume 211, 15 March 2020, 109816
**Keywords (by document):** Energy retrofit, Residential buildings, Nearly zero energy building, Life cycle analysis, Cost-optimal
**Locations:** Ireland
**Case study:** gas-heated semi-detached and end-terraced houses built in Ireland between 1991 and 2000
**Methodology:** LCA +LCC + cost optimal + sensitivity analysis
**Abstract**
'1.9 million housing units in Ireland are required to be retrofitted for the existing Irish national housing stock to be considered nearly zero energy building (nZEB). This paper assesses optimum retrofit packages aimed at improving the building material thermal efficiencies and energy demand of gas-heated semi-detached and end-terraced houses in Ireland. The cost-optimal methodology framework for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements is used to determine the optimum retrofit packages from both a householder perspective and a societal perspective. The results of the cost-optimal approach are compared to the results from a weighted framework approach which incorporates life cycle environmental and cost indicators from both a householder perspective and a societal perspective.

The results found that the ranking of energy efficiency retrofit designs based on multiple life cycle environmental and cost indicators differ compared to cost optimum designs based on only life cycle energy and cost indicators. The cost-optimal approach was found to be effective for identifying retrofit packages that are among the best packages even without accounting for multiple environmental indicators. However, once multiple indicators were considered, the hierarchy of the optimal retrofit packages changed. In the Irish context, the environmental impact of the Irish electricity grid was found to play a significant role in the hierarchy of the retrofit packages examined.

While the cost-optimal method should not be relied on solely for identifying the optimum retrofit package solution, it could be employed as part of the multistage assessment methodology for narrowing down design solution sample sizes. Using the remaining array of retrofit packages solutions, the optimum retrofit package could be identified using multiple indicators.' [17]

[17] Paul Moran, John O'Connell, and Jamie Goggins, 'Sustainable Energy Efficiency Retrofits as Residenial Buildings Move towards Nearly Zero Energy Building (NZEB) Standards', *Energy and Buildings* 211 (15 March 2020): 109816, https://doi.org/10.1016/j.enbuild.2020.109816.

## No.18 Economic performance assessment of three renovated multi-family buildings with different HVAC systems

**Author:** Alaa Khadra, Mårten Hugosson, Jan Akander, Jonn Are Myhren
**Publication year:** 2020
**Publisher:** Energy and Buildings, Volume 224, 1 October 2020, 110275
**Keywords (by document):** Building renovation, Life cycle cost, Life cycle cost analysis, Discount rate, Energy price escalation, HVAC systems
**Locations:** Borlänge, Sweden
**Case study:** three buildings have 36 apartments each and a heated floor area (Atemp) of 3879 $m^2$
**Methodology:** LCC+LCCA

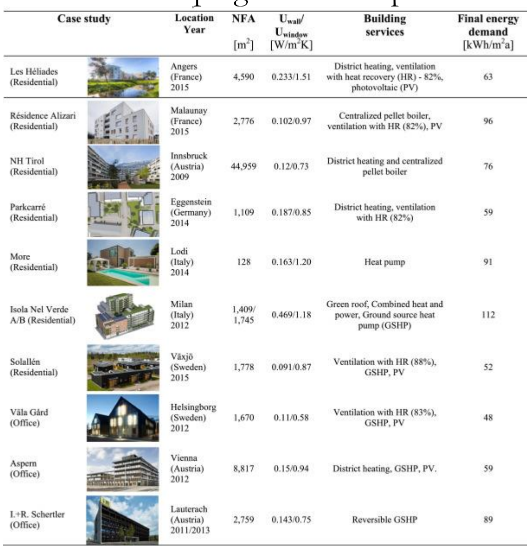
**Abstract**

'The EU has adopted several policies to improve energy efficiency. One of these policies aims to achieve energy efficient renovations in at least 3% annually of buildings in EU. The aim of this study was to provide an accurate economic comparison between three similar multi-family buildings that have undergone the same energy efficiency measures, with essential differences regarding the installed ventilation systems. The selected ventilation systems were: 1) balanced mechanical ventilation with heat recovery; 2) exhaust ventilation with air pressure control; and 3) exhaust ventilation with an exhaust air heat pump. In the latter two cases, radiators pre-heat supply air. Life cycle cost analysis were conducted using real investment and operational costs for the three buildings. Sensitivity analysis was also made for different discount rates and energy price escalation patterns. It was found that the building with exhaust ventilation has the lowest life cycle cost. At 2% inflation rate, 3% real discount rate and 1% real energy price escalation, the building with exhaust air heat pump and the building with mechanical ventilation with heat recovery has 13% and 29% higher life cycle cost than the building with exhaust ventilation, respectively. The sensitivity analysis further showed that a lower discount rate gives higher future costs and gives more profitability of systems with heat recovery with lower future costs. Energy price assumptions have a crucial impact on the results and change the profitability of studied renovation packages.' [18]

[18] Alaa Khadra et al., 'Economic Performance Assessment of Three Renovated Multi-Family Buildings with Different HVAC Systems', *Energy and Buildings* 224 (1 October 2020): 110275, https://doi.org/10.1016/j.enbuild.2020.110275.

## No.19 Sensitivity analysis as support for reliable life cycle cost evaluation applied to eleven nearly zero-energy buildings in Europe

**Author:** Roberta Pernetti , Federico Garzia, Ulrich Filippi Oberegger
**Publication year:** 2021
**Publisher:** Sustainable Cities and Society, Volume 74, November 2021, 103139
**Keywords (by document):** nearly zero-energy buildings, life cycle cost, sensitivity analysis
**Locations:** multiple countries in Europe
**Case study:** eleven nearly zero-energy buildings with different uses
**Methodology:** LCC+ sensitivity analysis
**Abstract**
'Life cycle cost analysis represents a strategic tool for supporting the decision-making process while designing a new building or a renovation towards a nearly zero-energy target. Nevertheless, one of the main obstacles undermining the wide application of life cycle cost analysis deals with the effort in collecting the whole set of inputs and boundary conditions and the associated reliability of the results. To address the issue, this work compares the application of different sensitivity analysis methodologies on eleven nearly zero-energy buildings with different uses and in several European contexts, highlighting the strengths and weaknesses. Moreover, it introduces and assesses an approach for applying sensitivity analysis in life cycle cost evaluations to find an effective balance between the effort for calculation, data collection and the reliability of life cycle cost. A main result is the demonstration of a sensitivity analysis procedure to identify and evaluate parameters and boundary conditions with the largest impact on the life cycle cost of the analysed buildings, namely, the interest rate, construction and equipment maintenance costs, structural element costs, and electricity prices. These parameters lead to variations in LCC of up to 37%, with an average of 26% around the median. By focusing a more detailed analysis on these parameters, we could assess the potential life cycle cost range due to input uncertainties with a high degree of confidence while keeping efforts for practitioners reasonable.'[19]



| Case study | Location Year | NFA [m²] | $U_{wall}$/ $U_{window}$ [W/m²K] | Building services | Final energy demand [kWh/m²a] |
|---|---|---|---|---|---|
| Les Héliades (Residential) | Angers (France) 2015 | 4,590 | 0.233/1.51 | District heating, ventilation with heat recovery (HR) - 82%, photovoltaic (PV) | 63 |
| Résidence Alizari (Residential) | Malaunay (France) 2015 | 2,776 | 0.102/0.97 | Centralized pellet boiler, ventilation with HR (82%), PV | 96 |
| NH Tirol (Residential) | Innsbruck (Austria) 2009 | 44,959 | 0.12/0.73 | District heating and centralized pellet boiler | 76 |
| Parkcarré (Residential) | Eggenstein (Germany) 2014 | 1,109 | 0.187/0.85 | District heating, ventilation with HR (82%) | 59 |
| More (Residential) | Lodi (Italy) 2014 | 128 | 0.163/1.20 | Heat pump | 91 |
| Isola Nel Verde A/B (Residential) | Milan (Italy) 2012 | 1,409/ 1,745 | 0.469/1.18 | Green roof, Combined heat and power, Ground source heat pump (GSHP) | 112 |
| Solallén (Residential) | Växjö (Sweden) 2015 | 1,778 | 0.091/0.87 | Ventilation with HR (88%), GSHP, PV | 52 |
| Väla Gård (Office) | Helsingborg (Sweden) 2012 | 1,670 | 0.11/0.58 | Ventilation with HR (83%), GSHP, PV | 48 |
| Aspern (Office) | Vienna (Austria) 2012 | 8,817 | 0.15/0.94 | District heating, GSHP, PV. | 59 |
| I.+R. Schertler (Office) | Lauterach (Austria) 2011/2013 | 2,759 | 0.143/0.75 | Reversible GSHP | 89 |

Figure 20 Main features of the case studies.
Source: Roberta Pernetti, Federico Garzia, and Ulrich Filippi Oberegger, 'Sensitivity Analysis as Support for Reliable Life Cycle Cost Evaluation Applied to Eleven Nearly Zero-Energy Buildings in Europe'. Sustainable Cities and Society 74 (1 November 2021): 103139, p-5.

[19] Roberta Pernetti, Federico Garzia, and Ulrich Filippi Oberegger, 'Sensitivity Analysis as Support for Reliable Life Cycle Cost Evaluation Applied to Eleven Nearly Zero-Energy Buildings in Europe', *Sustainable Cities and Society* 74 (1 November 2021): 103139, https://doi.org/10.1016/j.scs.2021.103139.

## No.20 Analysis of environmental impacts and costs of a residential building over its entire life cycle to achieve nearly zero energy and low emission objectives

**Author:** Modeste Kameni Nematchoua, Rakotomalala Minoson Sendrahasina
**Publication year:** 2022
**Publisher:** Journal of Cleaner Production, Pages 373
**Keywords (by document):** Environmental impacts, Costs, Residential building, Near-zero energy, LCA
**Locations:** Sart-Tilman, Belgium
**Case study:** a three-story apartment building
**Methodology:** LCA
**Abstract**

‘Nowadays, European Union (EU) requests that all its members encourage Net-zero energy and emission in the buildings by 2050. There are multiple studies within the EU related to this field, but few of them are associated with environmental cost assessment and reduction. What can be the new strategies allowing to reduce ecological impact costs at the scale of the building? In response to this question, this research has been carried out, with, the main objective, to evaluate, analyse, and propose some scenarios allowing to design of residential buildings with nearly zero energy, low emission, and low cost throughout the world. The strategies detailed in this research can be applied and adapted in all the regions of the world. A life cycle assessment (LCA) of a typical building is carried out using the Pleiades software database comprising a Dynamic Thermal Simulation calculation engine (STD) making it possible to simulate the thermal in order to describe the energy behaviours of a building and its equipment. Four life cycle phases (construction, use, renovation, and end of life) of buildings have been assessed. The results showed that the use of a dual-service air-to-water heat pump enables a considerable reduction in greenhouse gas (GHG) emissions and, on average, the indicators decrease by around 9%. It was concluded that the use of heat pumps makes it possible to reduce the cost of 9 environmental impacts between 8.7% and 13.1% compared to the initial cost, over a period of 80 yr.’ [20]

Figure 21 Global view of the Sart-Tilman eco-district (a) and study residence (c)
Source: Modeste Kameni Nematchoua et al., ‘Analysis of Environmental Impacts and Costs of a Residential Building over Its Entire Life Cycle to Achieve Nearly Zero Energy and Low Emission Objectives’, Journal of Cleaner Production 373 (1 November 2022): 133834,p-3.

[20] Modeste Kameni Nematchoua et al., ‘Analysis of Environmental Impacts and Costs of a Residential Building over Its Entire Life Cycle to Achieve Nearly Zero Energy and Low Emission Objectives’, *Journal of Cleaner Production* 373 (1 November 2022): 133834, https://doi.org/10.1016/j.jclepro.2022.133834.

## No.21 Refurbish or replace? The Life Cycle Carbon Footprint and Life Cycle Cost of Refurbished and New Residential Archetype Buildings in London

**Author:** Yair Schwartz, Rokia Raslan, Dejan Mumovic
**Publication year:** 2022
**Publisher:** Energy, Volume 248, 1 June 2022, 123585
**Keywords (by document):** Life cycle analysis, Refurbishment, Replacement, Embodied carbon, Whole life carbon, Life cycle carbon footprint, Life cycle cost, Environmental impact
**Locations:** London, UK
**Case study:** mid-terrace-house and a bungalow in London
**Methodology:** LCA+LCC
**Abstract**
'The environmental performance of existing buildings can have a major role in achieving significant reductions in CO2 emissions: In the UK, around 75% 2050's housing stock has already been built. While building performance improvement efforts mostly focus on operational performance, buildings environmental impact is the result of processes that occur throughout their life cycle.

To achieve significant emission reductions in an economically viable way, this study uses Life Cycle Performance approaches to carry a cross-comparison between the refurbishment and replacement of two housing archetypes in London: mid-terrace-house and a bungalow. Specifically, the study integrates Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) protocols (EN 15978:2011 and BS ISO 15686–5), thermal simulations (EnergyPlus), building generative design framework (PLOOTO - Parametric Lay-Out Organisation generator) and mathematical optimization algorithms (NSGA-II).

Results show that the optimal refurbishment archetypes generally performed better than replacements (Refurbishments LCCF ranges between 1,100 and 1,500 kgCO2e/m2 and LCC 440-680 £/m2, compared to that of the replacements scenarios, ranging 1,220-1,850 kgCO2e/m2 and 550-890 £/m2). The study also highlights benefit of incentivizing re-use to achieve quicker emissions reductions. The study lastly discusses a range of embodied and operational performance issues.' [21]

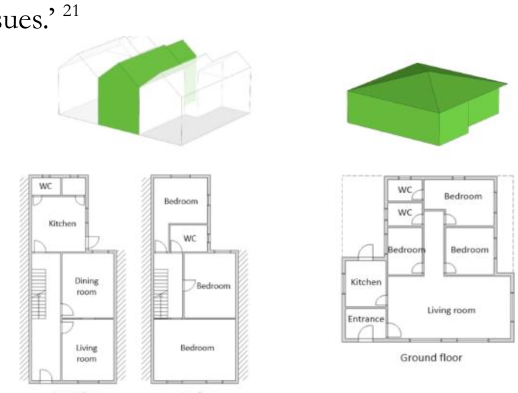



Figure 22 The existing-buildings case studies. Mid-terrace house (left) and the Bungalow house (right)
Source: Yair Schwartz, Rokia Raslan, and Dejan Mumovic, 'Refurbish or Replace? The Life Cycle Carbon Footprint and Life Cycle Cost of Refurbished and New Residential Archetype Buildings in London'. Energy 248 (1 June 2022): 123585, p-8.

[21] Yair Schwartz, Rokia Raslan, and Dejan Mumovic, 'Refurbish or Replace? The Life Cycle Carbon Footprint and Life Cycle Cost of Refurbished and New Residential Archetype Buildings in London', *Energy* 248 (1 June 2022): 123585, https://doi.org/10.1016/j.energy.2022.123585.

## No.22 Analysis and Valuation of the Energy-Efficient Residential Building with Innovative Modular Green Wall Systems

**Author:** Elena Korol, Natalia Shushunova
**Publication year:** 2022
**Publisher:** Sustainability 2022, 14(11), 6891
**Keywords (by document):** green wall system; green construction assessment; green building materials; energy-efficient residential building; green building technologies; Life Cycle Assessment
**Locations:** Russia
**Case study:** green wall system on the residential buildings
**Methodology:** LCA
**Abstract**
'The installation of green wall systems on the residential buildings is a complex technological process, the parameters of which vary depending on design solutions, methods of performing work, instrumental and technical support, professional skills of the work performers and many other factors. The authors used the life cycle approach for the assessment of the energy-efficient residential building with integrated greening systems. The aim of the study was to evaluate an energy-efficient residential building with an innovative modular green wall system and to compare it with existing technological solutions. We show that the life cycle approach provides the choice of a decision that is also optimal in conditions of risk, which indicates the effective use of the green wall system. The results of the work are presented by the development of technology with modular green systems, which will expand the practice of technological design, experimental construction and the renovation of buildings, to improve the quality of the urban environment by implementing rational construction and technological solutions and appropriate work methods. This study will be helpful for researchers in green construction to develop their future research studies and for various residential green building owners.' [22]

[22] Elena Korol and Natalia Shushunova, 'Analysis and Valuation of the Energy-Efficient Residential Building with Innovative Modular Green Wall Systems', *Sustainability* 14, no. 11 (January 2022): 6891, https://doi.org/10.3390/su14116891.

## 3.2.2 the scientific publication from China

### No.23 Life Cycle Cost Evaluation of Green Building

**Author:** Xiaoyan Wang, Rui Zhang
**Publication year:** 2010
**Publisher:** Proceedings of the 2010 international conference on information technology and scientific management, Vols 1-2, p681-684.
**Keywords (by document):** green building, life-cycle cost, costs, effective, economical efficiency
**Locations:** Pingdingshan, China
**Case study:** mix(residential and commercial)
**Methodology:** LCC
**Abstract**
'The article according to the green building's significance of social and economic development and the analysis of its promotion's constraints, proposed the life-cycle cost method to evaluate green buildings. Based on green buildings' life-cycle cost evaluation methods and requirements, use a case to analyse and confirm the feasibility of green building and the huge economic benefits to society. In addition, give a number of recommendations for strengthening policies and regulations and guiding the development of green building in China, in order to improve the economic efficiency as well as environmental benefits of the construction and improve the urban living environment by developing the city green building hardly.

In 2007, the new campus of Pingdingshan Institute of Technology will build a green comprehensive building with 8 floors, construction area of 12,000 square meters, estimated cost of 15 million yuan, and designed service life of 30 years. The building uses a fully intelligent lighting system, new insulation panels are laid on the exterior walls, renewable energy accounts for 20% of the building's energy consumption, and at least 110 cubic meters of water is recycled every day. Through the life cycle cost calculation, the author concluded that the annual economic benefit generated by the building through water saving, node, energy saving and land saving is 854,900 RMB, and the net benefit is 264 million RMB. Therefore, this green building scheme is completely feasible.' [23]

[23] Xiaoyan Wang and Rui Zhang, 'Life Cycle Cost Evaluation of Green Building', in *Proceedings of the 2010 International Conference on Information Technology and Scientific Management, Vols 1-2*, ed. C. Q. Ye (Irvin: Sci Res Publ, Inc-Srp, 2010), 681–84, https://www.webofscience.com/wos/woscc/full-record/WOS:000289700300185(overlay:export/exp).

## No.24 Optimum insulation thickness of residential roof with respect to solar-air degree-hours in hot summer and cold winter zone of China

**Author:** Jinghua Yu, Liwei Tian, Changzhi Yang, Xinhua Xu, Jinbo Wang
**Publication year:** 2011
**Publisher:** Energy and Buildings, Volume 43, Issue 9, September 2011, Pages 2304-2313
**Keywords (by document):** Optimum thickness, Payback period, Life cycle cost, Life cycle savings, Solar-air degree-hours
**Locations:** Shanghai, Changsha, Shaoguan, and Chengdu, China
**Case study:** residential
**Methodology:** LCC
**Abstract**
'Thermal protection of building envelope is one of the most effective ways for building energy conservation. In this study, the determination of optimum insulation thickness for residential roof with different surface colors is studied based on life cycle cost analysis and solar-air degree-hours in four typical cities of hot summer and cold winter zone of China. Four insulation materials including expanded polystyrene, extruded polystyrene, foamed polyurethane and foamed polyvinyl chloride are analyzed. The solar-air degree-hours are calculated considering night time operation and 24-h operation of the cooling and heating equipments. Life cycle total costs (LCT), life cycle savings (LCS) and payback period resulting from the use of optimum insulation thickness are calculated. Depending on different cities, insulation materials and roof surface colors, optimum insulation thicknesses of a typical roof vary from 0.065 to 0.187 m and payback periods vary from 0.9 to 2.3 years for 24-h operation of cooling and heating equipments; optimum insulation thicknesses are between 0.051 and 0.149 m and the payback periods are between 1.1 and 2.8 years for night time operation. At last, the effects of present worth factor, thermal resistance and climate on the optimum thicknesses are studied which is very useful for practical use to estimate the optimum thickness of insulation material.' [24]

[24] Jinghua Yu et al., 'Optimum Insulation Thickness of Residential Roof with Respect to Solar-Air Degree-Hours in Hot Summer and Cold Winter Zone of China', *Energy and Buildings* 43, no. 9 (1 September 2011): 2304–13, https://doi.org/10.1016/j.enbuild.2011.05.012.

## No.25 A methodology for estimating the life-cycle carbon efficiency of a residential building

**Author:** D.Z. Li, H.X. Chen, Eddie C.M. Hui, J.B. Zhang, Q.M. Li
**Publication year:** 2013
**Publisher:** Building and Environment, Volume 59, January 2013, Pages 448-455
**Keywords (by document):** Carbon efficiency, Carbon emission, Carbon dioxide, Residential building, Residential property value, Life-cycle assessment, emission
**Locations:** Jiangsu, China
**Case study:** residential
**Methodology:** LCA
**Abstract**
'Residential buildings account for a large share of global carbon emission, while they play important roles in economic growth and social development at the same time. Therefore, the appropriate evolution routes of residential buildings need balancing their carbon emission and value creation, which is realized in this paper by creating a new concept of life-cycle carbon efficiency and its relative methodology. First, the life-cycle carbon efficiency of a residential building is defined as the ratio of its life-cycle value to carbon emission, and the life-cycle of a residential building is divided into five stages, including construction materials preparation, building construction, building operation, building demolition, and construction & demolition wastes disposal. Second, the life-cycle carbon emission of a residential building is estimated through calculating the carbon emission at each stage based on its consumed energy and resources. Third, the product of the service life span of a residential building (in year), its building area (m(2)) and its storey height (m) is recommended to represent its life-cycle value, since this product is a physical measure and more useful to develop action plans to improve its performance. In the end, the proposed methodology is exemplified in estimating the life-cycle carbon efficiency of a five-storey brick-concrete residential building in Nanjing city (China) at its design phase. Possible measures to enhance the estimated carbon efficiency are further put forward, such as prolonging the service life span, enhancing 3R (reduce, reuse and recycle) principles of cement and rolled steel, saving electricity and natural gas at the stage of building operation.' [25]

[25] D. Z. Li et al., 'A Methodology for Estimating the Life-Cycle Carbon Efficiency of a Residential Building', *BUILDING AND ENVIRONMENT* 59 (January 2013): 448–55, https://doi.org/10.1016/j.buildenv.2012.09.012.

## No.26 Evaluating Construction Cost of Green Building Based on Lifecycle Cost Analysis: An empirical analysis from Nanjing, China

**Author:** Hongmei Liu
**Publication year:** 2015
**Publisher:** International Journal of Smart Home, Vol. 9, No. 12, (2015), pp. 299-306
**Keywords (by document):** Construction cost; green building; life cycle model; architectural design
**Locations:** Nanjing, China
**Case study:** residential
**Methodology:** LCC

**Abstract**

'With the economic development, energy consumption is increasingly serious, land resources becoming scarcer and scarcer. Green building can effectively solve the problem of resource shortage; however, the development of green buildings in China is very slow because of its higher cost, compared with conventional buildings.. In this paper, we analyze the construction cost of green building based on life-cycle cost method, and try to find out the key factors that affect the cost. Through the empirical analysis, the results prove that there are six main factors that influence the cost of green building, such as green building technology, policy support, project positioning, construction technology, building materials prices and local conditions. On this basis, we put forward relevant policy suggestions.

This article firstly analyze existing estimation methods and whole life cycle cost estimation to do further research, so as to put forward the whole life cycle cost estimation model as well as carry out empirical estimation. The first step is Cost estimation based on fuzzy recognition theory. In the second step future cost is calculated according to operation cost, maintenance cost and value to the division formula. From these two steps the author built up the research and calculation model for evaluating construction cost of green building and the index of calculating.' [26]

[26] Liu, Hongmei. "Evaluating construction cost of green building based on life-cycle cost analysis: An empirical analysis from Nanjing, China." International Journal of Smart Home 9, no. 12 (2015): 299-306.

## No.27 The nexus among employment opportunities, life-cycle costs, and carbon emissions: a case study of sustainable building maintenance in Hong Kong

**Author:** Yat Hung Chiang, Jing Li, Lu Zhou, Francis K.W. Wong, Patrick T.I. Lam
**Publication year:** 2015
**Publisher:** Journal of Cleaner Production, Volume 109, 16 December 2015, Pages 326-335
**Keywords (by document):** Building maintenance, Life-cycle cost, Carbon emission, Labor, Optimization
**Locations:** Hong Kong, China
**Case study:** a typical residential flat development in South Bay Road, Hong Kong Island
**Methodology:** LCC
**Abstract**
'Hong Kong's construction industry is currently facing problems involving a rapidly aging workforce and labor shortage. With Hong Kong as the case study, this paper illustrates how existing residential buildings can be repaired and maintained using alternative materials, in order to minimize life-cycle labor inputs, costs, or carbon emissions. With different combinations of repair and maintenance materials, two of the three objectives can be achieved at any one time, when labor inputs, costs, and carbon emissions are set as separate constraints. With our methodology, we are able to identify materials that would cost the least, emit minimum carbon levels, and require the right levels of labor resources in relation to residential building maintenance. These can support the adoption of green technologies that suit the socio-economic and physical environment of Hong Kong.

Authors describes the quantitative methods and the carbon database, including the data envelopment analysis (DEA), the LCC analysis, and the inventory of carbon and energy (ICE) database, for carbon emission coefficient (CEC). The scope of our empirical work is focused on the repair and maintenance of a typical residential building in Hong Kong. In addition to the maintenance technologies adopted in the case building, alternative technologies will also be compiled for our comparative analysis. Different methods have different implications on the combinations of resources, and consequently, on LCC, construction employment, and carbon emissions.' [27]

[27] Yat Hung Chiang et al., 'The Nexus among Employment Opportunities, Life-Cycle Costs, and Carbon Emissions: A Case Study of Sustainable Building Maintenance in Hong Kong', *Journal of Cleaner Production*, Special Issue: Toward a Regenerative Sustainability Paradigm for the Built Environment: from vision to reality, 109 (16 December 2015): 326–35, https://doi.org/10.1016/j.jclepro.2014.07.069.

## No.28 A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings

**Author:** C.K. Chau, T.M. Leung, W.Y. Ng
**Publication year:** 2015
**Publisher:** Applied Energy, Volume 143, 1 April 2015, Pages 395-413
**Keywords (by document):** Life Cycle Assessment, Buildings, Decision making
**Locations:** Hong Kong, China
**Case study:** residential
**Methodology:** LCA
**Abstract**
'This paper provides a review on three streams of life cycle studies that have been frequently applied to evaluate the environmental impacts of building construction with a major focus on whether they can be used for decision making. The three streams are Life Cycle Assessment (LCA), Life Cycle Energy Assessment (LCEA) and Life Cycle Carbon Emissions Assessment (LCCO2A). They were compared against their evaluation objectives, methodologies, and findings. Although they share similar objectives in evaluating the environmental impacts over the life cycle of building construction, they show some differences in the major focuses of evaluation and methodologies employed. Generally, it has been revealed that quite consistent results can be derived from the three streams with regard to the relative contribution of different phases of life cycle. However, discrepancies occur among the findings obtained from the three streams when different compositions of fuel mixes are used in power generation, or when the overall impacts are not contributed mostly by greenhouse gases emissions. The use of different functional units in different studies also makes it difficult to compare results with benchmarks or results from previous studies. Besides, there are drawbacks in boundary scoping, methodology framework, data inventory and practices which impair their usefulness as a decision making support tool for sustainable building designs.' [28]

[28] C. K. Chau, T. M. Leung, and W. Y. Ng, 'A Review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on Buildings', *Applied Energy* 143 (1 April 2015): 395–413, https://doi.org/10.1016/j.apenergy.2015.01.023.

**No.29 Carbon emission analysis of a residential building in China through life cycle assessment**

**Author:** Yin Zhang, Xuejing Zheng, Huan Zhang, Gaofeng Chen & Xia Wang
**Publication year:** 2016
**Publisher:** Frontiers of Environmental Science & Engineering volume 10, pages150–158 (2016)
**Keywords (by document):** carbon emission; factor influence analysis; life cycle assessment
**Locations:** Tianjin, China
**Case study:** residential
**Methodology:** LCA
'In this paper, a quantitative life cycle model for carbon emission accounting was developed based on the life cycle assessment (LCA) theory. A residential building in Sino-Singapore Tianjin Eco-city (Tianjin, China) was selected as a sample, which had been constructed according to the concept of green environmental protection and sustainable development. In the scenario of this research, material production, construction, use and maintenance, and demolition phases were assessed by building carbon emission models. Results show that use and maintenance phase and material production phase are the most significant contributors to the life cycle carbon emissions of a building. We also analyzed some factor influences in LCA, including the thickness of the insulating layer and the length of building service life. The analysis suggest that thicker insulating layer does not necessarily produce less carbon emissions in the light of LCA, and if service life of a building increases, its carbon emissions during the whole life cycle will rise as well but its unit carbon emission will decrease inversely. Some advices on controlling carbon emissions from buildings are also provided.' [29]

[29] Yin Zhang et al., 'Carbon Emission Analysis of a Residential Building in China through Life Cycle Assessment', *Frontiers of Environmental Science & Engineering* 10, no. 1 (1 February 2016): 150–58, https://doi.org/10.1007/s11783-014-0684-7.

## No.30 Life cycle assessment and life cycle cost of university dormitories in the southeast China: Case study of the university town of Fuzhou

**Author:** Lizhen Huang , Yongping Liu , Guri Krigsvoll , Fred Johansen
**Publication year:** 2018
**Publisher:** Journal of Cleaner Production, Volume 173, 1 February 2018, Pages 151-159
**Keywords (by document):** Life cycle assessment, Life cycle cost, $CO_2$, University dormitories, China
**Locations:** Fujian, China
**Case study:** university dormitories
**Methodology:** LCC, LCA

**Abstract**

The aim of this paper is to assess university dormitories in terms of life cycle environmental impact and cost, as part of the university campuses sustainable development in southeast China. This life cycle assessment follows the ISO 14040/44 methodology, considering the construction, operation, maintenance and demolition stages. The reference unit of this study is defined as 'one useful square meter university dormitories with 50 years life time'. This study estimates the life cycle inventory by: 1) tenders information of university dormitories built in the university town of Fuzhou during 2007–2011, 2) water and energy bills of those building over past 5 years, 3) damage and maintenance report of dormitories in Fuzhou University and Fujian University of traditional Chinese medicine during 2004–2014. The Eco-invent database provides the background data to the analysis.

The results indicate that 1) the use stage, including operation and maintenance is the dominate part of the life cycle environmental impacts and cost of university dormitories. 2) The consumption of electricity constitutes the main elements causing the environmental impacts over the life cycle of university dormitories. The technology for more energy efficient building is more important than other factors. 3) The window, concrete, steel, and cement have the largest contribution to the embodied environmental impacts but with the relatively small contribution to the life cycle cost. Therefore, two main improving opportunities for reducing the environmental impacts of Chinese university dormitories development are identified: 1) improving building with deep renovation for current dormitories and implementing low energy buildings standards for new built dormitories the buildings energy efficiency and 2) increasing the use of low environmental impacts building material by implementing the carbon tax on main building material and introducing timbers as structure material. Moreover, policies to promote the more renewable energy supply and the implementation of carbon capture and storage technology constitute another import issue. [30]

[30] Lizhen Huang et al., 'Life Cycle Assessment and Life Cycle Cost of University Dormitories in the Southeast China: Case Study of the University Town of Fuzhou', *Journal of Cleaner Production*, Sustainable urban transformations towards smarter, healthier cities: theories, agendas and pathways, 173 (1 February 2018): 151–59, https://doi.org/10.1016/j.jclepro.2017.06.021.

## No.31 Cost-benefit analysis for Energy Efficiency Retrofit of existing buildings: A case study in China

**Author:** Liu Yuming, Liu Tingting, Ye Sudong, Liu Yisheng
**Publication year:** 2018
**Publisher:** Journal of Cleaner Production, Volume 177, 10 March 2018, Pages 493-506
**Keywords (by document):** Life cycle assessment, Life cycle cost, $CO_2$, University dormitories, China
**Locations:** Beijing, China
**Case study:** residential
**Methodology:** LCC, LCA

**Abstract**

‘Energy Efficiency Retrofit (EER) of existing buildings is a key program for improving building energy efficiency in northern regions of China. This paper presents a methodological framework to conduct an economic cost-benefit analysis for EER projects, based on the calculation of costs and benefits over life cycle. By conducting a case study of a retrofit project located in Huixin Western Street Residential Area, Beijing, China, this research empirically examines its economic sustainability. The research found that in China, retrofit of existing buildings generally lack of attractiveness to investors from an economic perspective. The retrofit of heat source and outdoor heating pipe networks is cost effective, whilst buildings envelopes retrofit is not economically beneficial. For building envelopes retrofit, if replacing windows using appropriate material, retrofit of external windows represents higher cost effectiveness than that of external walls. By applying sensitivity analysis, the research further discussed the effects of relevant factors on the economic viability of retrofit projects, and found that energy price is the most sensitive factor, followed by initial costs and energy conservation rate. The selection of retrofit materials also greatly influences the economic outcomes. This research offers directions for policy makers and managers to develop incentive mechanisms and management interventions to promote the implementation of the retrofit program.’ [31]

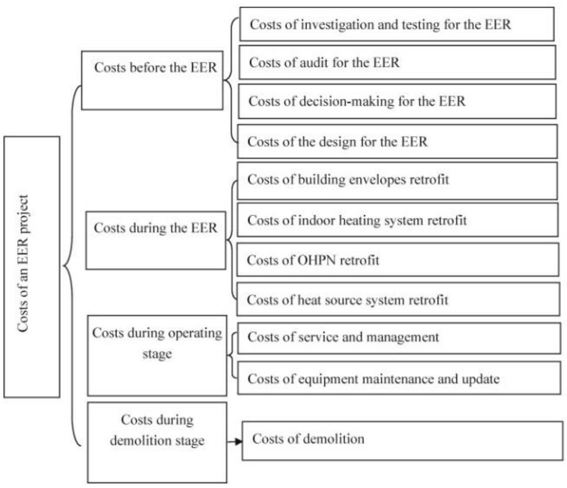



Figure 23 The retrofit picture of Building                Figure 24 Benefits of an EER project.
Source: Yuming Liu et al., ‘Cost-Benefit Analysis for Energy Efficiency Retrofit of Existing Buildings: A Case Study in China’, Journal of Cleaner Production 177 (10 March 2018): 493–506, p-498.

[31] Yuming Liu et al., ‘Cost-Benefit Analysis for Energy Efficiency Retrofit of Existing Buildings: A Case Study in China’, *Journal of Cleaner Production* 177 (10 March 2018): 493–506, https://doi.org/10.1016/j.jclepro.2017.12.225.

## No.32 Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China

**Author:** Xining Yang, Mingming Hu, Jiangbo Wu, Bin Zhao
**Publication year:** 2018
**Publisher:** Journal of Cleaner Production, Volume 183, 10 May 2018, Pages 729-743
**Keywords (by document):** Residential building, Energy efficiency retrofit, Comprehensive benefit, Multi cases, Comparative analysis
**Locations:** Chonggqing, Beijing,
**Case study:** residential
**Methodology:** LCA

'Building Information Modeling (BIM) is regarded as a potential vehicle to tremendously improve the information flow throughout the life cycle of a building. The integration of BIM and Life Cycle Assessment (LCA) has potential to reduce the time for life cycle inventory, and at the same time, substantially improve the representativeness of the LCA results for the specific building design. The latter merit is not trivial. For instance, due to time limit, most building LCA studies estimate the building materials and fuels consumed in construction phase quite roughly, which excludes the choices on a wide range of construction techniques, materials, specialties and machines, no need to mention the energy consumption in operation phase, which is usually estimated in an even bolder manner. The roughness of the LCA practice undermines its credibility and hinders its application as a decision supporting tool for low carbon design. Currently, China's Architecture, Engineering and Construction (AEC) sector is undergoing a smart transformation, steered by the increased use of BIM. This paper presents a BIM-enabled LCA method and illustrates how the method can be used to facilitate the low carbon design under the circumstance of the smart AEC transition in China. A case study on carbon footprint accounting for a residential building is conducted. In this study, various software tools and data sources are combined to enhance the data flow and interoperability between BIM models and LCA models. BIM tools are used to create the BIM model, calculate the inputs (materials, construction machines, energies, water and so on) of on-site construction process and simulate the energy consumption of building operation. The eBalance, a China's local LCA software tool is applied to build the LCA model. The Chinese Life Cycle Database is used as the main data source (72.73%) to calculate the carbon footprint of the given building while the Ecoinvent database and European Life Cycle Database act as supplementary. The results show that the carbon footprint of the building is 2993 kg CO2eq/m2. The operation phase contributes to 69% of the total greenhouse gas (GHG) emission, while the building material production contributes to 24%. Concrete is the most used building material, which accounts for 82% of mass but contributes to only 44% of the material related GHG emission. Although steel and aluminum account for only 2.6% and 1.4% of mass, they contribute to 28% and 17% GHG emission, respectively. Through BIM-enable LCA modeling, the potential life cycle environmental performance of the buildings can be assessed in detail. This makes the LCA not only more accessible but also more credible for the AEC professionals to use it as a guide for the low carbon design of buildings.' [32]

[32] Xining Yang et al., 'Building-Information-Modeling Enabled Life Cycle Assessment, a Case Study on Carbon Footprint Accounting for a Residential Building in China', *Journal of Cleaner Production* 183 (10 May 2018): 729–43, https://doi.org/10.1016/j.jclepro.2018.02.070.

## No.33 Study on the suitability of green building technology for affordable housing: A case study on Zhejiang Province, China

**Author:** Jian Ge, Yujie Zhao, Xiaoyu Luo, Minmin Lin
**Publication year:** 2020
**Publisher:** Journal of Cleaner Production, Volume 275, 1 December 2020, 122685
**Keywords (by document):** Green building technology, Affordable housing, Maturity, Incremental cost, Environmental load, Environmental quality
**Locations:** Zhejiang, Beijing,
**Case study:** residential
**Methodology:** Incremental cost

**Abstract**

'With the further promotion of green buildings in China, the adoption of green building technology (GBT) to improve building performance is a new requirement. Meanwhile, government-financed affordable housing to address the housing problems of a large number of low-income residents and migrant workers is in high demand. The specific service attributes of affordable housing determine its typical characteristics of low construction costs, its compact nature and short construction period, which distinguish it from commodity housing. However, the current research on the suitability of GBT mainly focused on individual technologies, or lack the capability to evaluate a given GBT system from a comprehensive performance aspect. According to the requirements of green affordable housing, this study established a multi-objective suitability evaluation model with maturity, economy and environmental load and quality as evaluation indexes. Based on 43 cases of green-certified residential communities in China's Zhejiang province, this study screened 37 common GBTs and evaluated them using the aforenamed model. As a result, a list of suitable GBTs was obtained, among which 11 technologies were identified as the optimal GBTs for affordable housing, capable of improving the performance of buildings without unduly increasing their economic burden and construction difficulty. The results of this study provide clear guidance for affordable housing and GBT selection during the design and construction processes.' [33]

[33] Jian Ge et al., 'Study on the Suitability of Green Building Technology for Affordable Housing: A Case Study on Zhejiang Province, China', *Journal of Cleaner Production* 275 (1 December 2020): 122685, https://doi.org/10.1016/j.jclepro.2020.122685.

## No.34 Sustainable framework for buildings in cold regions of China considering life cycle cost and environmental impact as well as thermal comfort

**Author:** Ran Wang, Shilei Lu, Wei Feng, Xue Zhai, Xinhua Li
**Publication year:** 2020
**Publisher:** Energy Reports, Volume 6, November 2020, Pages 3036-3050
**Keywords (by document):** Life Cycle Assessment, Life cycle cost, Greenhouse gas emissions, Thermal comfort, Sustainable building
**Locations:** Beijing, China
**Case study:** slab-type apartment
**Methodology:** LCC, LCA, sensitivity analysis
**Abstract**
'In recent decades, environmental problems have enforced designers to estimate the level of environmental emission of building design and reduce their environmental impact. On the premise of ensuring indoor comfort, the cost-effectiveness of solutions for reducing the building's greenhouse gas has become a critical issue. Based on the Life Cycle Assessment (LCA), this paper establishes a building performance trade-off framework for indoor thermal comfort, economics, and environmental implication. This framework consists of four parts: the establishment of the optimization model; sensitivity analysis; obtain of Pareto frontier solutions, and decision-making analysis. Optimization variables involve envelope type and some envelope physical parameters. The "design variables-building performances" database is obtained by using building simulation software combined with the Latin hypercube sampling algorithm. Sensitivity analysis is used to extract the key factors affecting building performance. The designer can prioritize these key factors and it can reduce the uncertainty of building performance. A multi-objective optimization method coupling Gradient Boosted Decision Tree (GBDT) and non-dominated sorting genetic (NSGA-II) algorithm is proposed to seek the trade-off between three performances (obtain Pareto frontier solutions). The Pareto solution provides a more comprehensive reference for the preferences of different stakeholders, and the set of alternative solutions is further shrunk. Finally, take a specific residential building in China's cold climate zone as a showcase of the trade-off framework. According to the obtained Pareto frontier solution, the solution set is shrunk to a certain range, and the distribution ranges of Life Cycle Costs, the greenhouse gas emissions, and the annual thermal discomfort hour ratio are 122.3–137.1 USD/m2, 15.6–44.8 kg CO2/m2, and 19.1–25.2%, respectively. The trade-off framework adopts the order of objective Pareto optimal and then subjective preference selection, narrowing the scope of alternatives for designers and saving time-cost of decision-making.' [34]

[34] Ran Wang et al., 'Sustainable Framework for Buildings in Cold Regions of China Considering Life Cycle Cost and Environmental Impact as Well as Thermal Comfort', *Energy Reports* 6 (1 November 2020): 3036–50, https://doi.org/10.1016/j.egyr.2020.10.023.

## No.35 Life Cycle Environmental Costs of Buildings

**Author:** Yuanfeng Wang ,Bo Pang,Xiangjie Zhang,Jingjing Wang
**Publication year:** 2020
**Publisher:** Energies, Volume 13, Issue 6
**Keywords (by document):** building; environmental costs; green GDP, China; uncertainty analysis; sensitivity analysis
**Locations:** Beijing, Xiamen, China
**Case study:** slab-type apartment
**Methodology:** LCCA, sensitivity analysis


**Abstract**

'Energy consumption and pollutant emissions from buildings have caused serious impacts on the environment. Currently, research on building environmental costs is quite insufficient. Based on life cycle inventory of building materials, fossil fuel and electricity power, a calculating model for environmental costs during different stages is presented. A single-objective optimization model is generated by converting environmental impact into environmental cost, with the same unit with direct cost. Two residential buildings, one located in Beijing and another in Xiamen, China, are taken as the case studies and analyzed to test the proposed model. Moreover, data uncertainty and sensitivity analysis of key parameters, including the discount rate and the unit virtual abatement costs of pollutants, are also conducted. The analysis results show that the environmental cost accounts for about 16% of direct cost. The environmental degradation cost accounts for about 70% of the total environmental cost. According to the probabilistic uncertainty analysis results, the coefficient of variation of material production stage is the largest. The sensitivity analysis results indicate that the unit virtual abatement cost of CO2 has the largest influence on the final environmental cost.' [35]

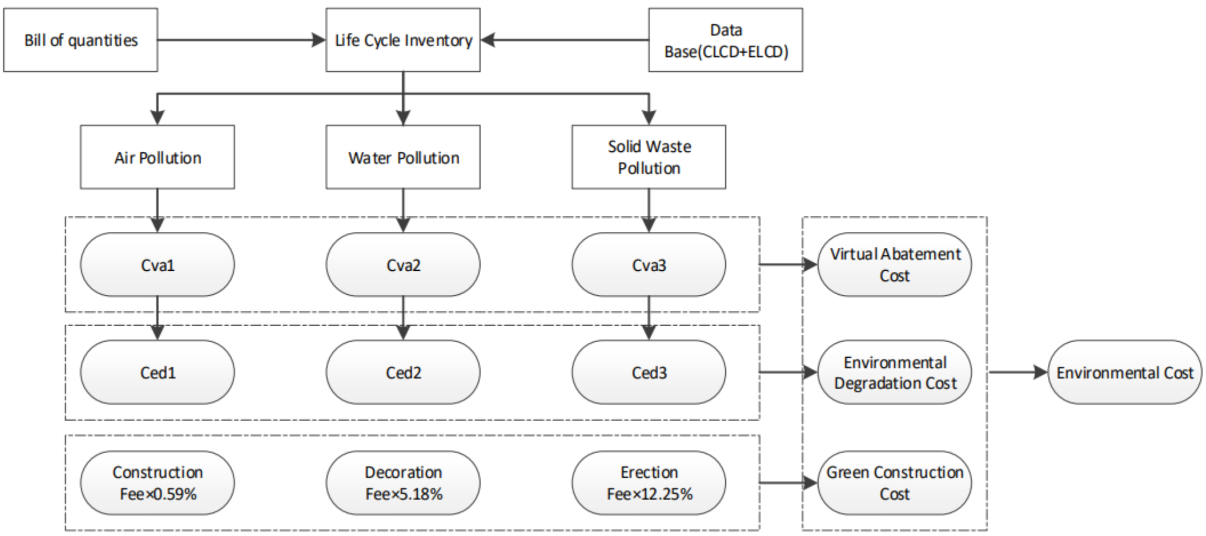




Figure 25 The flowchart of the model
Source: Yuanfeng Wang et al., 'Life Cycle Environmental Costs of Buildings', Energies 13, no. 6 (January 2020): 1353, p-3.

[35] Yuanfeng Wang et al., 'Life Cycle Environmental Costs of Buildings', *Energies* 13, no. 6 (January 2020): 1353, https://doi.org/10.3390/en13061353.

## No.36 Life cycle cost and life cycle energy in zero-energy building by multi-objective optimization

**Author:** Chen She, Rui Jia, Bei-Ning Hu, Ze-Kun Zheng, Yi-Peng Xu, Dragan Rodriguez
**Publication year:** 2021
**Publisher:** Energy Reports, Volume 7, November 2021, Pages 5612-5626
**Keywords (by document):** Multiple-objective optimization, Archimedes optimization algorithm, Zero-energy building, Solar photovoltaic system, Energy-efficiency measures, Life cycle energy, Life cycle cost
**Locations:** Shanghai, China
**Case study:** nearly zero-energy residence
**Methodology:** LCC

**Abstract**

'The energy consumption in buildings is increasing, then, a new global multiple-objective optimization method for zero-energy buildings with the comprehensive assessment method is used in this study. The applied optimization design methods for renewable energy systems are the multiple-objective optimization by Enhanced Archimedes Optimization Algorithm (EAOA) on the original design for energy costs and energy optimal models. The Hybrid Gray Multiple-Level Comprehensive Assessment Method (HGMLCAM) is utilized to the optimal model including the solar energy use efficacy, energy conservation, economic and social factors. By the selected decision based on the global optimal model, the best solution is presented. For designing the practical building, the defined solution can be useful for the architects and decision-makers. Consequently, a multiple-objective design for a building located in Shanghai, in China, is studied. Based on the results, it can be concluded that the presented method is efficient to make decisions.' [36]

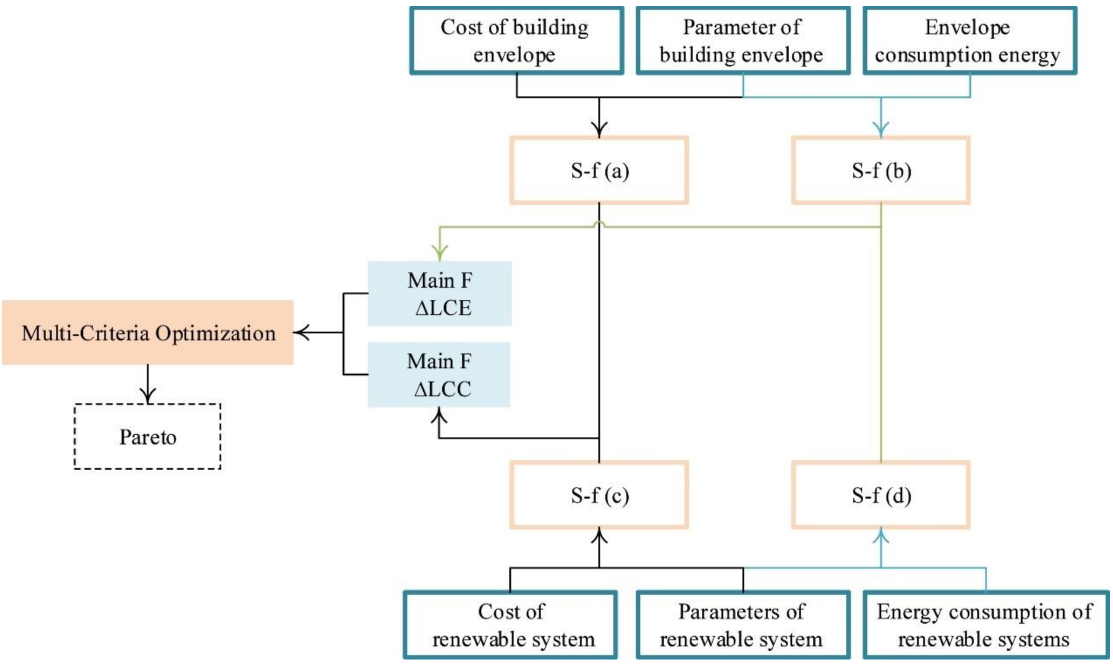



Figure 26 The zero-energy building optimization model. (F: function, S-f: sub-function).
Source: Chen She et al., 'Life Cycle Cost and Life Cycle Energy in Zero-Energy Building by Multi-Objective Optimization', Energy Reports 7 (1 November 2021): 5612–26, p-5619.

[36] Chen She et al., 'Life Cycle Cost and Life Cycle Energy in Zero-Energy Building by Multi-Objective Optimization', *Energy Reports* 7 (1 November 2021): 5612–26, https://doi.org/10.1016/j.egyr.2021.08.198.

### No.37 Evaluation of the relative differences in building energy simulation results

**Author:** Dan Wang, Xiufeng Pang, Wei Wang, Chuan Wan & Gang Wang
**Publication year:** 2022
**Publisher:** Building Simulation volume 15, pages1977–1987 (2022)
**Keywords (by document):** simulated relative differences; building energy simulation; Monte Carlo simulation; Energy Plus
**Locations:** China
**Case study:** Existing residence
**Methodology:** LCA, Monte Carlo simulation
**Abstract**
‘Building energy modeling, also known as building energy simulation, has developed rapidly in recent years and plays a crucial role in building life-cycle analysis. It can be employed in the design phase to predict the energy consumption of different design schemes and evaluate various control and retrofitting measures at the operation stage. In such simulations, it is commonly understood and accepted that the simulated relative differences are more reliable than the predictions of absolute energy results. However, whether this common understanding is true is yet to be thoroughly investigated. In this study, we investigate the simulated relative differences and the extent to which they are affected by the degree of model input deviation. Simulation and Monte Carlo approaches are adopted for the analysis. The results indicate that the simulated relative differences are not as reliable as expected, and the outputs strongly depend on the degree of the model input deviation. When the degree of deviation is less than 15% or the model inputs are within reasonable ranges, the simulated relative differences match the baseline obtained using Monte Carlo simulations. Moreover, the model’s error indicators meet the requirements of the ASHRAE Guideline 14–2014 when the degree of input deviation is below 15%.’ [37]

[37] Dan Wang et al., ‘Evaluation of the Relative Differences in Building Energy Simulation Results’, *Building Simulation* 15, no. 11 (1 November 2022): 1977–87, https://doi.org/10.1007/s12273-022-0903-2.

## No.38 Incremental cost-benefit quantitative assessment of green building: A case study in China

**Author:** Zhijiang Wu, Guofeng Ma
**Publication year:** 2022
**Publisher:** Energy and Buildings, Volume 269, 15 August 2022, 112251
**Keywords (by document):** Green building, Incremental costs, Incremental benefits, Data Envelopment Analysis (DEA)
**Locations:** China
**Case study:** 6 green buildings (residentials and office buildings)
**Methodology:** LCC, cost-benefit, Incremental cost
**Abstract**
'As a resource-saving and environment-friendly building form, the green building aims to provide occupants with an ecological and humanistic living space. To promote the popularity of green buildings in the construction industry, effective incremental cost-benefit evaluation is an essential prerequisite. However, miscellaneous elements and fuzzy evaluation criteria often make challenges for accurate evaluation. Further, the fluctuation of incremental cost-benefit elements in the whole life cycle of green buildings also limits the applicability of static evaluation methods. To address these limitations, this study proposes to identify the elements of incremental costs and incremental benefits on the premise of extracting the phase characteristics. Simultaneously, we also introduced the concept of production efficiency (PE) in the manufacturing industry and developed the BCC model through data envelopment analysis (DEA) to quantitatively evaluate the PE of green building. Finally, six green buildings in China are taken as cases to implement the quantitative evaluation of PE. The results show that the divergence of PE mainly comes from the personalized configuration of various elements. Moreover, the PE is floating due to the influence of "input–output" balance adjustment in the whole life cycle. This study is a dynamic prediction of green building efficiency and provides suggestions for practitioners to reconstruct the allocation of project resources.' [38]

[38] Zhijiang Wu and Guofeng Ma, 'Incremental Cost-Benefit Quantitative Assessment of Green Building: A Case Study in China', *Energy and Buildings* 269 (15 August 2022): 112251, https://doi.org/10.1016/j.enbuild.2022.112251.

## No.39 Life cycle assessment of a residential building in China accounting for spatial and temporal variations of electricity production

**Author:** Long Pei, Patrick Schalbart, Bruno Peuportier
**Publication year:** 2022
**Publisher:** Journal of Building Engineering, Volume 52, 15 July 2022, 104461
**Keywords (by document):** Life cycle assessment, Electricity production mix, Future scenarios, Environmental impacts, Residential buildings
**Locations:** 5 Chinese cities in different climate zone
**Case study:** high-rise residential building consisting of 34 floors
**Methodology:** LCA, sensitivity analysis
**Abstract**
'Life cycle assessment (LCA) is widely used to reduce a building's environmental impacts in the design phase. Buildings consume a lot of electricity, and heat pumps are often proposed as a way to reduce greenhouse gases emissions. The electricity production mix is therefore an important aspect in building's LCA. Many studies use a static national average mix, ignoring its variations in space and time. This might be questioned in a large country undergoing energy transition such as China. A comprehensive study on this topic for China is lacking, therefore this article aims at filling this gap by investigating how the variations of the energy mix at spatial (five regions in five climate zones) and temporal (four future energy mix scenarios) scales influence the LCA results. A model is proposed to evaluate local future energy mixes. The life cycle inventory (LCI) database was contextualised considering different local energy mixes. Environmental impacts calculated using the local energy mixes and the national average energy mix were compared in the static approach and the dynamic approach (future scenarios are considered) for a residential building. The results indicated that using a national average mix instead of a local mix in the static approach brought non-negligible differences for most provinces, e.g. the overestimation of global warming potential (GWP) reached 500% in Yunnan. Similarly, differences between the static and dynamic approaches are large for most environmental impact indicators, e.g. the difference in GWP could reach around 900% in Guangdong. The differences highly depend on the prospective future scenarios and showed regional features. This paper highlights the importance of the choice of energy mix in buildings' LCA in China regarding both spatial and temporal scales, which is beneficial for more reasonable decisions.' [39]

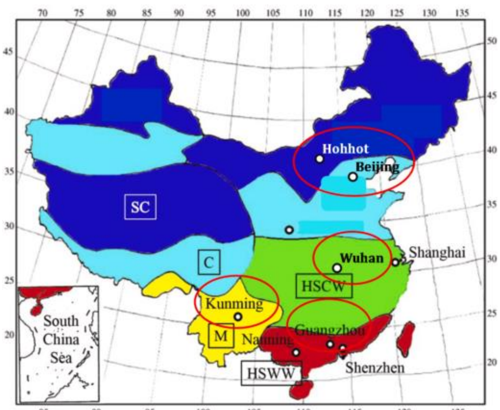



Figure 27 Five climate zones and representative cities in China
Source: Long Pei, Patrick Schalbart, and Bruno Peuportier, 'Life Cycle Assessment of a Residential Building in China Accounting for Spatial and Temporal Variations of Electricity Production', Journal of Building Engineering 52 (15 July 2022): 104461, p-2.

[39] Long Pei, Patrick Schalbart, and Bruno Peuportier, 'Life Cycle Assessment of a Residential Building in China Accounting for Spatial and Temporal Variations of Electricity Production', *Journal of Building Engineering* 52 (15 July 2022): 104461, https://doi.org/10.1016/j.jobe.2022.104461.

No.40 **Framework on low-carbon retrofit of rural residential buildings in arid areas of northwest China: A case study of Turpan residential buildings**

**Author:** Junkang Song, Wanjiang Wang, Pingan Ni, Hanjie Zheng, Zihan Zhang & Yihuan Zhou
**Publication year:** 2022
**Publisher:** Building Simulation volume 16, pages279–297 (2023)
**Keywords (by document):** life cycle assessment, arid regions, deep neural networks, entropy-based TOPSIS method, multi-criteria optimization
**Locations:** Xinjiang, China
**Case study:** rural residential building
**Methodology:** LCC

'At present, buildings in arid and hot regions are facing severe challenges of indoor comfort improvement and carbon emission reduction, especially in rural areas. Multi-objective optimization could be an effective tool for tackling the aforementioned challenges. Therefore, this paper proposes a life-cycle optimization framework considering thermal comfort, which is beneficial to promoting residents' motivation for low-carbon retrofit in arid climate regions. First, in response to the above problems, three objective functions are specified in the framework, which are global warming potential (GWP), life cycle cost (LCC), and thermal discomfort hours (TDH). To improve the optimization efficiency, this research uses Deep Neural Networks (DNN) combined with NSGA-II to construct a high-precision prediction model (meta-model for optimization) based on the energy consumption simulation database formed by the orthogonal multi-dimensional design parameters. The accuracy index of the modified model is $R2 > 0.99$, cv(RMSE) $\leq 1\%$, and NMBE $\leq 0.2\%$, which gets rid of the dilemma of low prediction accuracy of traditional machine learning models. In the scheme comparison and selection stage, the TOPSIS based on two empowerment methods is applied to meet different design tendencies, where the entropy-based method can avoid the interference of subjective preference and significantly improve the objectivity and scientific nature of decision analysis. Additionally, sensitivity analysis is conducted on the variables, which supports guidance for practitioners to carry out the low-carbon design. Finally, the multi-objective optimization analysis for a farmhouse in Turpan is taken as a case study to evaluate the performance of the framework. The results show that the framework could significantly improve the building performance, with 60.8%, 52.5%, and 14.2% reduction in GWP, LCC, and TDH, respectively.' [40]


(a) Elevation of the Model1 (b) Elevation of the Model2 (c) Building plan

Figure 28 Reference building overview
Source: Junkang Song et al., 'Framework on Low-Carbon Retrofit of Rural Residential Buildings in Arid Areas of Northwest China: A Case Study of Turpan Residential Buildings', Building Simulation 16, no. 2 (1 February 2023): 279–97, p-289.

[40] Junkang Song et al., 'Framework on Low-Carbon Retrofit of Rural Residential Buildings in Arid Areas of Northwest China: A Case Study of Turpan Residential Buildings', *Building Simulation* 16, no. 2 (1 February 2023): 279–97, https://doi.org/10.1007/s12273-022-0941-9.

## No.41 BIM-based LCA as a comprehensive method for the refurbishment of existing dwellings considering environmental compatibility, energy efficiency, and profitability: A case study in China

**Author:** Dauletbek, A ; Zhou, PG
**Publication year:** 2022
**Publisher:** Journal of Building Engineering, Volume 46, 1 April 2022, 103852
**Keywords (by document):** Passive house, Building information modeling, Life cycle assessment, Energy efficiency
**Locations:** Jiangsu, China
**Case study:** university dormitories
**Methodology:** LCA

**Abstract**

'In the light of special attention of world governments to a viable and sustainable decarbonization way of the existing building stock, this article considered the feasibility of using a method of Building Information Modeling (BIM)-enabled Life Cycle Assessment (LCA) for the refurbishment in terms of environmental compatibility, energy efficiency, and profitability. An existing residential building in Nanjing was chosen as a case study. The paper investigated the environmental, energy, and economic efficiency of the case building hypothetically refurbished to the Passive House (PH) and "low energy building" (LEB) technologies. The analysis was made based on real construction and energy consumption data, monitored over three years. Also, a comparison of the environmental, energy-efficient, and economic feasibility of two hypothetical models refurbished to the PH and LEB technologies is considered. The results show that BIM-enabled LCA is a powerful tool for refurbishing existing residential buildings due to a comprehensive assessment of environmental compatibility, energy efficiency, and profitability. According to the results, special attention should be paid to reducing cooling loads, using materials with a high recycling rate and low cost, reducing the thickness of the insulation layer, using polyvinyl chloride (PVC) windows with movable sunshades, and setting horizontal and vertical greenery systems.' [41]

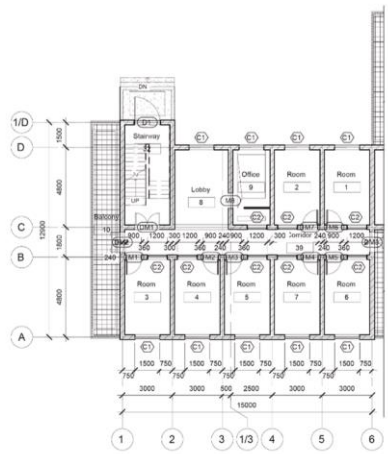


Figure 29 BIM-model of Scenario 0 Figure 30 Typical floor plan of the dormitory

Source: Assima Dauletbek and Peiguo Zhou, 'BIM-Based LCA as a Comprehensive Method for the Refurbishment of Existing Dwellings Considering Environmental Compatibility, Energy Efficiency, and Profitability: A Case Study in China', Journal of Building Engineering 46 (1 April 2022): 103852, p-5.

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[32]Xining Yang et al., 'Building-Information-Modeling Enabled Life Cycle Assessment, a Case Study on Carbon Footprint Accounting for a Residential Building in China', *Journal of Cleaner Production* 183 (10 May 2018): 729–43, https://doi.org/10.1016/j.jclepro.2018.02.070.

[33] Jian Ge et al., 'Study on the Suitability of Green Building Technology for Affordable Housing: A Case Study on Zhejiang Province, China', *Journal of Cleaner Production* 275 (1 December 2020): 122685, https://doi.org/10.1016/j.jclepro.2020.122685.

[34]Ran Wang et al., 'Sustainable Framework for Buildings in Cold Regions of China Considering Life Cycle Cost and Environmental Impact as Well as Thermal Comfort', *Energy Reports* 6 (1 November 2020): 3036–50, https://doi.org/10.1016/j.egyr.2020.10.023.

[35]Yuanfeng Wang et al., 'Life Cycle Environmental Costs of Buildings', *Energies* 13, no. 6 (January 2020): 1353, https://doi.org/10.3390/en13061353.

[36]Chen She et al., 'Life Cycle Cost and Life Cycle Energy in Zero-Energy Building by Multi-Objective Optimization', *Energy Reports* 7 (1 November 2021): 5612–26, https://doi.org/10.1016/j.egyr.2021.08.198.

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# Chapter 4

# Conclusion remarks

# INTRODUCTION

The fourth and final chapter of the study delves into the analysis of literature, drawing upon the collected and archived materials in the third chapter. By employing the life cycle method discussed in the second chapter, the study proceeds to undertake the design and transformation of environmentally-friendly housing. These approaches prove valuable in assessing economic sustainability, allowing researchers to examine the overall expenses associated with a new construction and retrofitting project, as well as to evaluate design choices based on their cost-effectiveness and environmental impact throughout the housing's life cycle.

In this chapter, the author will further classify and analyse the literature in Chapter 3, as follows:

- Methodology
- Year of publication
- Publication type
- Case study method

In the end, the author uses VOSviewer software for bibliometric analysis. 'VOSviewer is a software tool for constructing and visualizing bibliometric networks. The software was chosen because of the desire to verify the bibliometric map of the search conducted by reading the results.'[1] This analytical technique aims to understand the interrelationships between citations in selected publications and can provide an indication of the technical status of existing or emerging research topics.

In order to build a bibliometric network by using VOSviewer software, we can provide bibliographic database files (which can be downloaded from Web of science, Scopus) and reference management files (i.e., RIS, EndNote, endnote, And Refworks files as program input)

[1] 'VOSviewer - Visualizing Scientific Landscapes', VOSviewer, accessed 17 June 2023, https://www.VOSviewer.com//.

## 4.1 Analysis of the selected literature by different approaches

When we select articles, we mainly select keywords in every publication which related to life cycle approaches, then we will define which approaches do these publications used. We divide the articles into several main groups:

1. LCC
2. LCA
3. LCA+LCC
4. LCCA
5. Others(Added other cost approaches mentioned in these publications)

Figure 1 shows the classification of publications (according to different life cycle approaches).

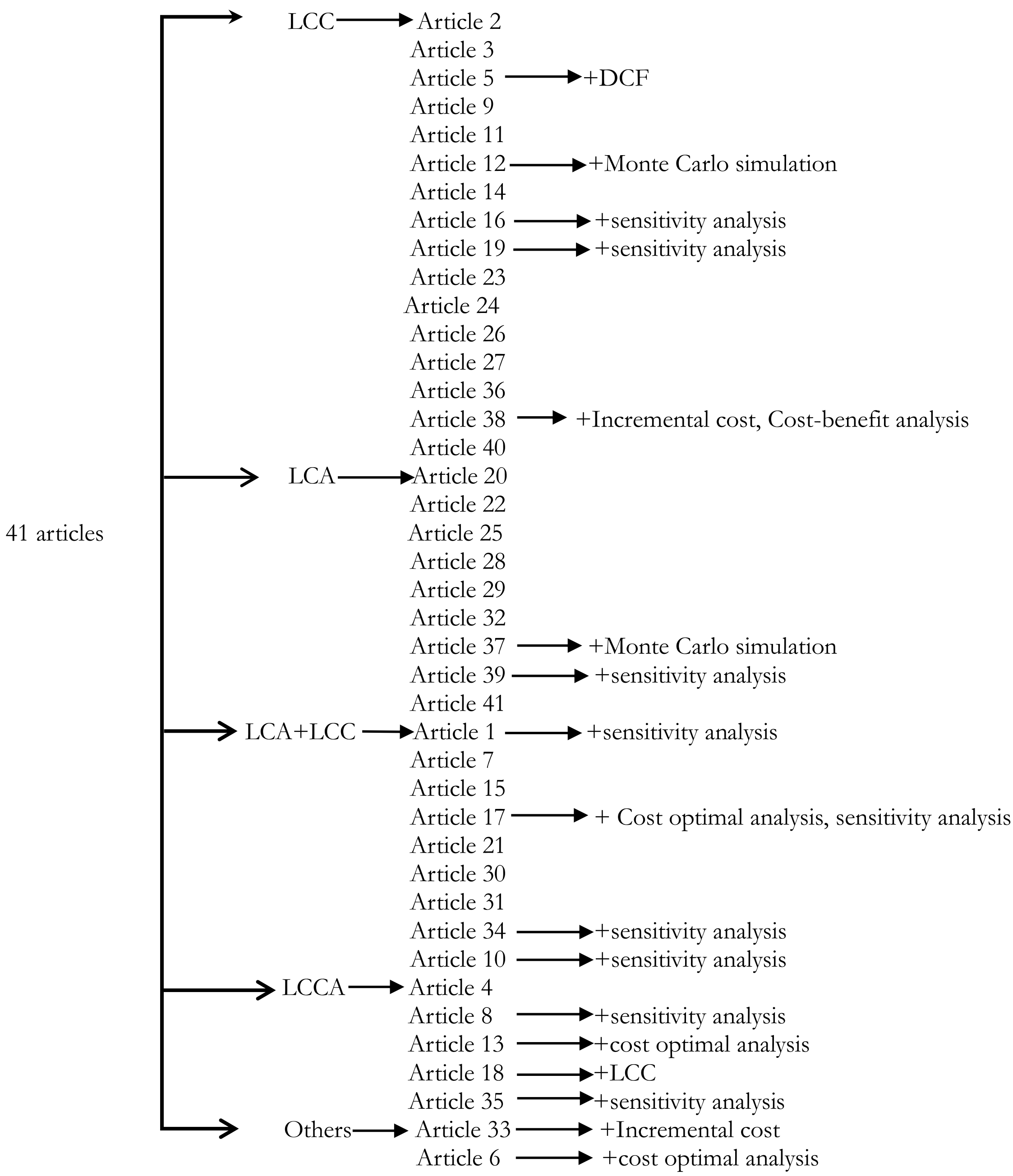


Figure 1 Approaches Overview: Approaches used in the 41 articles analyzed (elaborated by the author)

Figure 2 and 3 visualize the classification results of Figure 1 in two pie charts, this allows us to clearly see the use of various life cycle approaches and costing approaches.

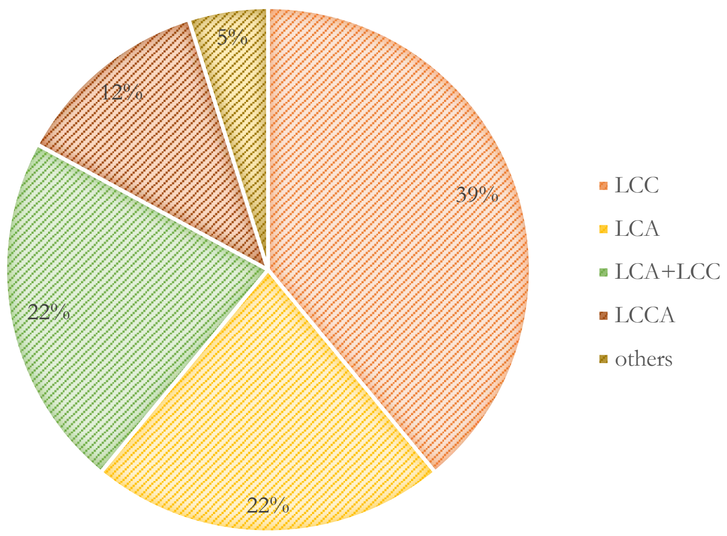


Figure 2 Statistics on the percentage of life cycle analysis approaches applied in 41 articles (elaborated by the author)

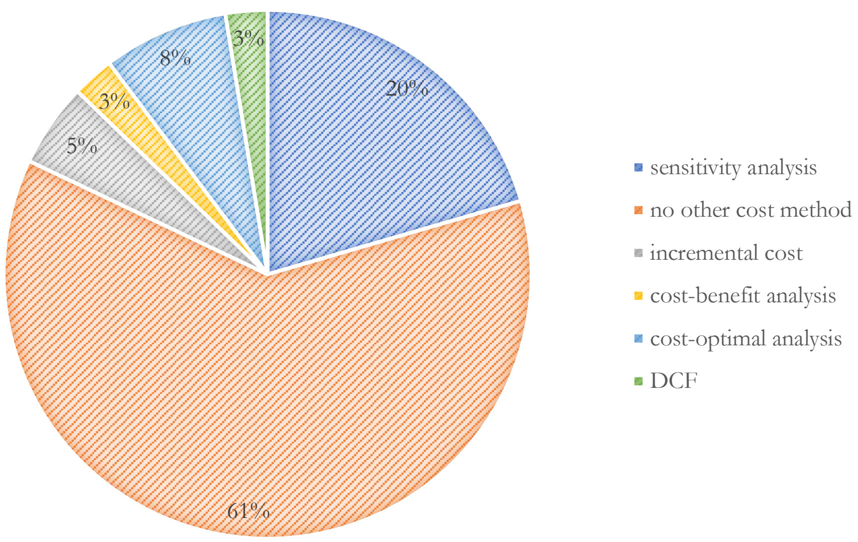


Figure 3 Percentage statistics of other cost analysis approaches applied in 41 articles (elaborated by the author)

As previously mentioned, a total of 41 articles were gathered during the research period. Among these, 22 originated from Europe, while 19 were sourced from China.

The methodology employed in these articles adhered to the terminology outlined in their respective abstracts and keywords. Articles that incorporated Life Cycle Cost Analysis (LCCA) were tallied and presented separately from those involving Life Cycle Cost (LCC) and Life Cycle Assessment (LCA).

Figure 2 illustrates the utilization of life cycle and cost analysis approaches across all the articles. Based on the data, we computed the prevalence of each life cycle method within the 41 articles and depicted it in a pie chart. In residential applications, the LCC method emerged as the most prevalent at 61%, followed by articles employing the LCA approach at 44%. Notably, 22% of the articles employed a combined LCC+LCA approach.

Furthermore, the majority of articles did not incorporate alternative cost analysis methodologies, comprising 61%. Additionally, 20% of the articles featured sensitivity analysis, while 11% employed cost-optimal analysis and cost-benefit analysis.

## 4.2 Analysis of the selected literature by year of publication

In this section we will look at the distribution of these publications over the period 2010-2022, with the year indicated as the year in which they were published. The chart below mainly shows the year of publication of 41 articles, and their related methods used to study their time trends. Articles from China are labeled "PRC"

2010 → Article 23 (PRC) → LCC
2011 → Article 24 (PRC) → LCC
2012 → Article 2 → LCC
2013 → Article 25 (PRC) → LCA
→ Article 1 → LCA + LCC + sensitivity analysis
→ Article 3 → LCC
2014 → Article 4 → LCCA
2015 → Article 28 (PRC) → LCA
Article 26 (PRC) → LCC
Article 27 (PRC) → LCC
Article 5 → LCC
Article 6 → cost optimal analysis
Article 7 → LCA + LCC
Article 8 → LCCA + sensitivity analysis
2016 → Article 29 (PRC) → LCA
Article 9 → LCC
2017 → Article 10 → LCA + LCC + sensitivity analysis
Article 11 → LCC
Article 12 → LCC
2018 → Article 32 (PRC) → LCA
Article 30 (PRC) → LCA + LCC
Article 31 (PRC) → LCA + LCC
Article 13 → LCCA + cost optimal analysis
Article 14 → LCC
2019 → Article 15 → LCA + LCC
Article 16 → LCC + sensitivity analysis
2020 → Article 33 (PRC) → Incremental cost
Article 34 (PRC) → LCA + LCC + sensitivity analysis
Article 35 (PRC) → LCCA + sensitivity analysis
Article 17 → LCA +LCC + cost optimal + sensitivity analysis
Article 18 → LCCA +LCC
2021 → Article 36 (PRC) → LCC
Article 37 (PRC) → LCC
Article 19 → LCC + sensitivity analysis
2022 → Article 37 (PRC) → LCA + Monte Carlo simulation
Article 38 (PRC) → LCC + cost benefit + Incremental cost
Article 39 (PRC) → LCA + sensitivity analysis
Article 40 (PRC) → LCC
Article 41 (PRC) → LCA
Article 20 → LCA
Article 21 → LCA + LCC
Article 22 → LCA

Figure 4 Year statistics: 41 articles were classified according to year (elaborated by the authors)

Figure 5 shows the line statistics chart of the publication years of 41 articles, and figure 6 shows the line charts of the number of articles from China and Europe in different years.

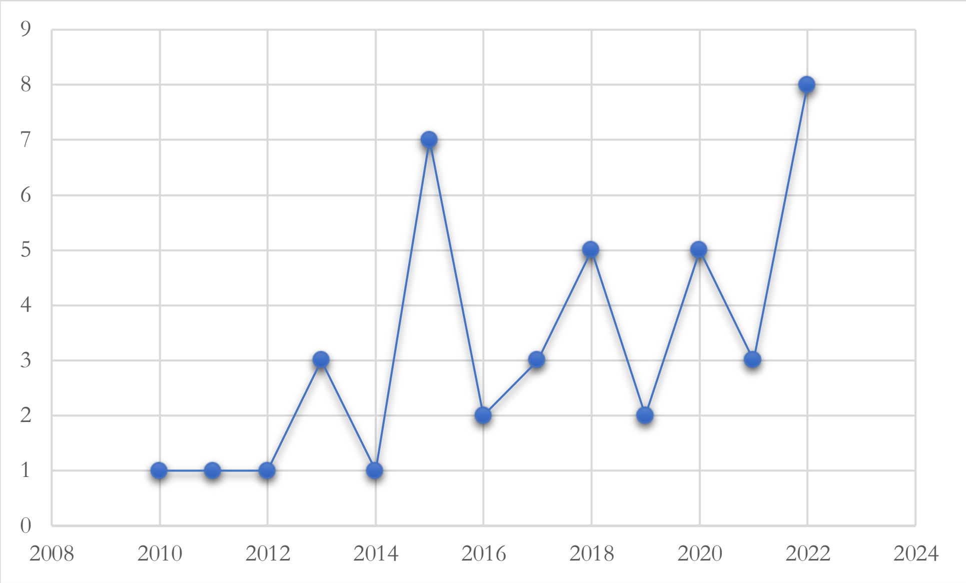


Figure 5 Line statistics chart: 41 articles were classified according to year (elaborated by the authors)

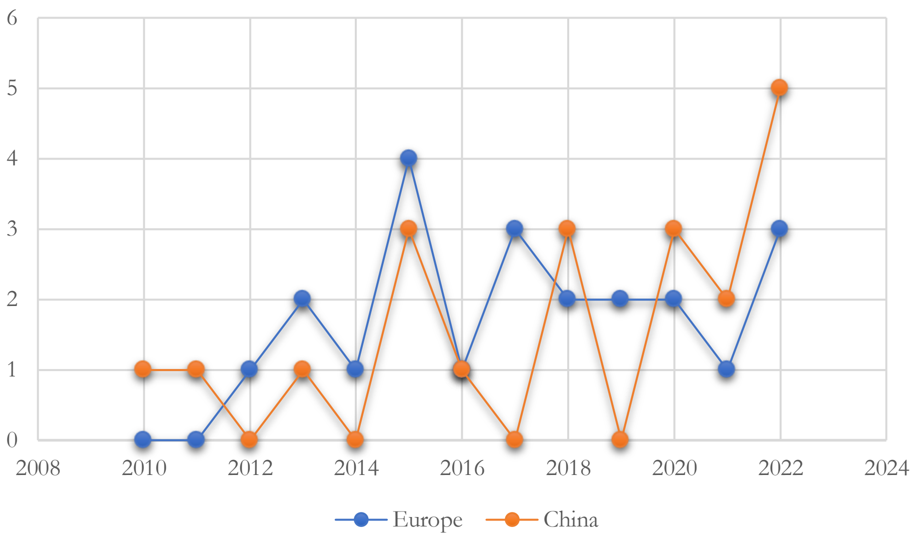


Figure 6 line charts of the number of articles from China and Europe in different years.

Figure 5 depicts a steady, incremental rise in the volume of literature pertaining to life cycle analysis within the context of green residential buildings, spanning the years from 2010 to 2022. Notably, since 2014, a conspicuous surge in this domain has been witnessed both in Europe and China. Subsequently, the ebb and flow of pertinent literature in these regions have mirrored each other. Derived from these findings, we can infer that scholars from China and Europe have bestowed equal attention on the realm of economic sustainability assessment within the sphere of green housing.

Remarkably, the trajectory of research endeavors is progressively converging towards the nexus of "life cycle method + other cost method." Among these approaches, the most prominently employed techniques encompass sensitivity analysis, cost-optimal analysis, and cost-benefit evaluation.

Furthermore, the escalation in scholarly output dedicated to the amalgamation of life cycle tools and risk analysis since 2015 signals an escalating concern among researchers in both China and Europe regarding the intricacies of economic evaluation within the ambit of green residential developments. Specifically, 'Sensitivity analysis provides the impact of various assumptions on the overall project in a quantitative manner.'[2]

[2] Elena Fregonara and Sara Pattono, 'A Sustainability Indicator for Building Projects in Presence of Risk/Uncertainty over Time: A Research Experience', *Aestimum*, 8 March 2019, 173-205 Pages, https://doi.org/10.13128/AESTIMUM-24928.

## 4.3 Analysis of the selected literature by publication type

In this section, we analyze the publication types of the 41 selected articles by dividing the literature into 4 categories:

- Case studies
- Methodological
- Energy simulated
- Accomplished (or not)

| NO. | Methodology | Country | Case study | Methodological | Energy simulated | Accomplished(or not) | Year of publication |
|---|---|---|---|---|---|---|---|
| 1 | LCC + LCA + sensitivity analysis | Finland | X | | X | | 2013 |
| 2 | LCC | Portugal | X | | X | | 2012 |
| 3 | LCC | Sweden | X | | X | | 2013 |
| 4 | LCCA | Romania | X | | X | | 2014 |
| 5 | LCC(DCF) | Italy | X | | X | X | 2015 |
| 6 | optimal cost | Italy | X | | X | | 2015 |
| 7 | LCA, LCC | Belgium | X | | X | | 2015 |
| 8 | LCCA, sensitivity analysis | Sweden | X | X | X | | 2015 |
| 9 | LCC | Italy | X | | X | | 2016 |
| 10 | LCC, LCA, sensitivity analyses | Norway | X | | X | | 2017 |
| 11 | LCC | Finland | X | | X | | 2017 |
| 12 | LCC+ Monte Carlo simulation | Italy | X | | X | X | 2017 |
| 13 | LCCA+ Cost optimal analysis | Italy | X | | X | | 2018 |
| 14 | LCC | Sweden | X | | X | | 2018 |
| 15 | LCA, LCC | Spain | X | | X | X | 2019 |
| 16 | LCC + sensitivity analysis | Sweden | X | | X | | 2019 |
| 17 | LCA +LCC + cost optimal + sensitivity analysis | Ireland | X | | X | | 2020 |
| 18 | LCCA, LCC | Sweden | X | | | | 2020 |
| 19 | LCC + sensitivity analysis | multiple | X | | | X | 2021 |
| 20 | LCA | Belgium | X | | X | X | 2022 |

The chart is incomplete. Proceed to the next page

| NO. | Methodology | Country | Case study | Methodological | Energy simulated | Accomplished(or not) | Year of publication |
|---|---|---|---|---|---|---|---|
| 21 | LCA, LCC | UK | x | | | | 2022 |
| 22 | LCA | Russia | | x | | | 2022 |
| 23 | LCC | China | x | x | | | 2010 |
| 24 | LCC | China | x | | x | | 2013 |
| 25 | LCA | China | x | | | x | 2013 |
| 26 | LCC | China | x | | | x | 2015 |
| 27 | LCC | China | x | x | | | 2015 |
| 28 | LCA | China | x | x | | x | 2016 |
| 29 | LCA | China | x | x | | x | 2017 |
| 30 | LCC, LCA | China | x | | | x | 2018 |
| 31 | LCC, LCA | China | x | | | x | 2018 |
| 32 | LCA | China | x | | | | 2019 |
| 33 | Incremental cost | China | x | x | | x | 2020 |
| 34 | LCC, LCA, sensitivity analysis | China | x | | x | | 2020 |
| 35 | LCCA, sensitivity analysis | China | x | | | x | 2020 |
| 36 | LCC | China | x | x | | x | 2020 |
| 37 | LCA + Monte carlo simulation | China | x | | x | x | 2021 |
| 38 | LCC, cost-benefit, Incremental cost | China | x | | | x | 2022 |
| 39 | LCA, sensitivity analysis | China | x | | x | | 2022 |
| 40 | LCC | China | x | | x | | 2022 |
| 41 | LCA | China | x | | x | x | 2022 |

Figure 7 The table shows the methodology by publication type, country, and year of publication for the 41 articles applicable to the analysis, with reference to years 2010-2022(author's elaboration).

Figure 7 delineates the array of research methodologies embraced within the documented publications, with an organized arrangement that begins with European works and subsequently transitions to those originating from China, facilitating a seamless reading experience.

The analysis conducted unveils a predominant reliance on case study approaches across the majority of publications. Particularly, within the European landscape, a notable proportion of works are fortified by energy simulations and economic analyses. Energy simulations predominantly leverage an assortment of energy software, occasionally supplemented by methodologies such as sensitivity analysis and cost-optimal analysis.

In contrast, the Chinese publications, primarily grounded in case studies, are characterized by a distinct focus. Among these, merely six incorporate energy simulation components. Predominantly, the research focuses on buildings that have already undergone renovation or construction, probing into the economic implications stemming from their behavioral transformations. However, a discernible shift post-2022 witnesses a gradual upsurge in publications featuring energy simulations applied to residential structures.

While European publications frequently explore a multifaceted approach encompassing multiple methodologies, the Chinese counterparts stand out for their pronounced engagement with research methodologies. This heightened emphasis might be attributed to the burgeoning nature of green residential building endeavors in China. Additionally, a considerable proportion of these publications employ European theories as a foundational framework, tailoring life cycle assessment theories to align with local nuances and distinct characteristics.

## 4.4 Analysis of the selected literature by case study method

As the final analysis, this section studies the case analysis methods of the article, and makes a separate summary of the case analysis methods of 41 articles.

Figure 8 shows the number, title, and methodology of 41 articles, as well as the case analysis method, as well as the year.

| | Title | Country | Methodology | Case study method | Year of publication |
|---|---|---|---|---|---|
| 1 | Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design | Finland | LCC + LCA+ sensitivity analysis | Comparison of multiple retrofitting options | 2013 |
| 2 | A methodology for economic efficient design of Net Zero Energy Buildings | Portugal | LCC | Comparison of multiple climatic conditions | 2012 |
| 3 | Sustainability assessment of renovation packages for increased energy efficiency for multi-family buildings in Sweden | Sweden | LCC | Comparison of multiple building cases | 2013 |
| 4 | A life-cycle cost analysis of the passive house "POLITEHNICA" from Bucharest | Romania | LCCA | Comparison of multiple retrofitting options | 2014 |
| 5 | Green housing: Toward a new energy efficiency paradox? | Italy | LCC(DCF) | Comparison of multiple building cases | 2015 |
| 6 | Cost optimality assessment of a single family house: Building and technical systems solutions for the nZEB target | Italy | optimal cost | Comparison of multiple energy retrofitting options | 2015 |
| 7 | Towards a More Sustainable Building Stock: Optimizing a Flemish Dwelling Using a Life Cycle Approach | Belgium | LCA,LCC | Comparison of multiple energy retrofitting options and building cases | 2015 |
| 8 | A methodology to assess energy-demand savings and cost effectiveness of retrofitting in existing Swedish residential buildings | Sweden | LCCA, sensitivity analysis | Comparison of multiple retrofitting options | 2015 |
| 9 | Retrofit Scenarios and Economic Sustainability. A Case-study in the Italian Context | Italy | LCC | Comparison of multiple retrofitting options | 2016 |
| 10 | Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects | Norway | LCC, LCA, sensitivity analyses | Comparison of multiple energy retrofitting options | 2017 |
| 11 | Life-cycle cost analyses of heat pump concepts for Finnish new nearly zero energy residential buildings | Finland | LCC | Comparison of multiple energy retrofitting options and building cases | 2017 |
| 12 | Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate | Italy | LCC+ Monte Carlo simulation | Comparison of multiple energy retrofitting options and comparison of multiple macroeconomic parameters | 2017 |
| 13 | Energy retrofit alternatives and cost-optimal analysis for large public housing stocks | Italy | LCCA+ Cost optimal analysis | Comparison of multiple energy retrofitting options and building retrofitting options | 2018 |
| 14 | Cost-effective passive house renovation packages for Swedish single-family houses from the 1960s and 1970s | Sweden | LCC | Comparison of multiple energy retrofitting options and building options, building retrofitting options | 2018 |
| 15 | Life cycle thinking toward sustainable development policy-making: The case of energy retrofits | Spain | LCA, LCC | Comparison of multiple climatic conditions and building cases | 2019 |

The chart is incomplete. Proceed to the next page

| | Title | Country | Methodology | Case study method | Year of publication |
|---|---|---|---|---|---|
| 16 | Life Cycle Cost of Building Energy Renovation Measures, Considering Future Energy Production Scenarios | Sweden | LCC + sensitivity analysis | Comparison of multiple energy retrofitting options and building retrofitting options | 2019 |
| 17 | Sustainable energy efficiency retrofits as residential buildings move towards nearly zero energy building (NZEB) standards | Ireland | LCA +LCC + cost optimal + sensitivity analysis | Evaluate the best building renovation options | 2020 |
| 18 | Economic performance assessment of three renovated multi-family buildings with different HVAC systems | Sweden | LCCA, LCC | HVAC comparison of multiple building cases | 2020 |
| 19 | Sensitivity analysis as support for reliable life cycle cost evaluation applied to eleven nearly zero-energy buildings in Europe | multiple | LCC + sensitivity analysis | Comparison of sensitivity analysis from multiple building cases | 2021 |
| 20 | Analysis of environmental impacts and costs of a residential building over its entire life cycle to achieve nearly zero energy and low emission objectives | Belgium | LCA | Economic assessment of the four life cycle stages of the building | 2022 |
| 21 | Refurbish or replace? The Life Cycle Carbon Footprint and Life Cycle Cost of Refurbished and New Residential Archetype Buildings in London | UK | LCA, LCC | Cost comparison of renovation and replacement of buildings | 2022 |
| 22 | Analysis and Valuation of the Energy-Efficient Residential Building with Innovative Modular Green Wall Systems | Russia | LCA | Evaluation and analysis of residential green wall system | 2022 |
| 23 | Life Cycle Cost Evaluation of Green Building | China | LCC | Summarized the economic evaluation methods of residential | 2010 |
| 24 | Optimum insulation thickness of residential roof with respect to solar-air degree-hours in hot summer and cold winter zone of china | China | LCC | Economic evaluation of residential from the view of life cycle | 2011 |
| 25 | A methodology for estimating the life-cycle carbon efficiency of a residential building | China | LCA | life cycle analysis for residential | 2013 |
| 26 | Evaluating construction cost of green building based on life-cycle cost analysis: An empirical analysis from Nanjing, China | China | LCC | Economic evaluation of retrofitting on residential from the view of life cycle | 2015 |
| 27 | The nexus among employment opportunities, life-cycle costs, and carbon emissions: a case study of sustainable building maintenance in Hong Kong | China | LCC | Economic evaluation of retrofitting on residential from the view of life cycle | 2015 |
| 28 | A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings | China | LCA | Economic evaluation of green residential buildingfrom the view of life cycle | 2015 |
| 29 | Carbon emission analysis of a residential building in China through life cycle assessment | China | LCA | Economic evaluation of retrofitting on residential from the view of life cycle | 2016 |
| 30 | Life cycle assessment and life cycle cost of university dormitories in the southeast China: Case study of the university town of Fuzhou | China | LCC,LCA | Economic evaluation of green residential buildingfrom the view of life cycle | 2018 |
| 31 | Cost-benefit analysis for Energy Efficiency Retrofit of existing buildings: A case study in China | China | LCC, LCA | Economic evaluation of retrofitting on residential from the view of life cycle | 2018 |

The chart is incomplete. Proceed to the next page

| | Title | Country | Methodology | Case study method | Year of publication |
|---|---|---|---|---|---|
| 32 | Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China | China | LCA | Comparison of multiple building cases, Economic evaluation of green residential buildingfrom the view of life cycle | 2018 |
| 33 | Study on the suitability of green building technology for affordable housing: A case study on Zhejiang Province, China | China | Incremental cost | Comparison of multiple building cases, Economic evaluation of green residential buildingfrom the view of life cycle | 2020 |
| 34 | Sustainable framework for buildings in cold regions of China considering life cycle cost and environmental impact as well as thermal comfort | China | LCC, LCA, sensitivity analysis | Economic evaluation of different design decisions | 2020 |
| 35 | Life Cycle Environmental Costs of Buildings | China | LCCA, sensitivity analysis | Comparison of multiple building cases, Economic evaluation of green residential buildingfrom the view of life cycle | 2020 |
| 36 | Life cycle cost and life cycle energy in zero-energy building by multi-objective optimization | China | LCC | Economic evaluation of retrofitting on residential from the view of life cycle | 2021 |
| 37 | Evaluation of the relative differences in building energy simulation results | China | LCA+ Monte Carlo simulation | Optimal design model, Economic evaluation of different design decisions | 2022 |
| 38 | Incremental cost-benefit quantitative assessment of green building: A case study in China | China | LCC, cost-benefit, Incremental cost | Comparison of multiple building cases, Economic evaluation of green residential buildingfrom the view of life cycle | 2022 |
| 39 | Life cycle assessment of a residential building in China accounting for spatial and temporal variations of electricity production | China | LCA, sensitivity analysis | The same building is placed in multiple climate zones to simulate the energy structure | 2022 |
| 40 | Framework on low-carbon retrofit of rural residential buildings in arid areas of northwest China: A case study of Turpan residential buildings | China | LCC | Research how to retrofit a home to improve building performance | 2022 |
| 41 | BIM-based LCA as a comprehensive method for the refurbishment of existing dwellings considering environmental compatibility, energy efficiency, and profitability: A case study in China | China | LCA | Study the economic feasibility of BIM-based LCA renovations of existing buildings | 2022 |

Figure 8 The table shows the case study method of 41 publications, countries, methodologies and year (from 2010-2022), author's elaboration.

As depicted in Figure 8, a predominant trend among European literature is the utilization of research methodologies centered on comparative analyses of multiple building cases and energy transformation simulations, underpinning the formulation of article conclusions. Notable instances include investigations into the influence of alterations in macroeconomic parameters on research outcomes through Monte Carlo simulation (No.12). Moreover, in No.19, diverse sensitivity analyses are employed to discern parameters and boundary conditions wielding significant influence over the computation of life cycle costs.

In contrast, the majority of Chinese publications exhibit a concentrated focus on a single residential type, individual buildings, or an economic evaluation of green residential renovations. Commencing from 2019, there has been a discernible upsurge in the incorporation of various building cases and methods for simulating and contrasting energy transformations. Noteworthy examples, such as No.34 and No.37, evaluate divergent design decisions through a life cycle lens, culminating in the identification of optimal design approaches. No.39 undertook a life cycle assessment of energy structures within the same building across diverse climatic zones in China, culminating in the derivation of more judicious decisions aimed at mitigating the built environment's impact during the design phase.

## 4.5 Bibliometric Analysis

In this section we analyze the scientific literature by using data collected by bibliometrics, a field of scientometrics.

Diverging from the conventional practice observed in many bibliometric mapping software, VOSviewer places distinct emphasis on the visual depiction of bibliometric maps. 'VOSviewer can be employed to view any two-dimensional distance-based map, regardless of the mapping technique that has been used to construct the map. Distance-based maps are maps in which the distance between two items reflects the strength of the relation between the items. A smaller distance generally indicates a stronger relation.'[3]

This section describes the steps taken to implement a bibliometric network in the field of economic evaluation of green homes or energy retrofitting/green retrofitting of residential.

Saving the 41 publications that have been searched in web of science, and choose to export the record content of "full record and cited references", "tab delimited files" file format, and save it in the computer.

By VOSviewer, we can choose to make a map analysis of the literature:

1. Co-authorship analysis
   In these networks, researchers, institutions, or countries can be linked to each other by the number of publications they are co-authors of.

2. Co-occurrence analysis
   Analyze the number of files they appear together.

3. Citation
   Analyzes the number of times files reference each other

4. Bibliographic coupling
   Analyzes the number of references for files sharing.

5. Co-citation
   Analyze the number of times files are co-referenced.

Steps for using VOSviewer:

Step 1: Create a map based on bibliographic data.
Step 2: Read data from reference manager files.
Step 3: choose files from Web of science
Step 4: Choose types and analysis and counting method.

Figure 9 shows steps on VOSviewer.

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[3] Nees Jan van Eck and Ludo Waltman, 'Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping', *Scientometrics* 84, no. 2 (1 August 2010): 523–38, https://doi.org/10.1007/s11192-009-0146-3.

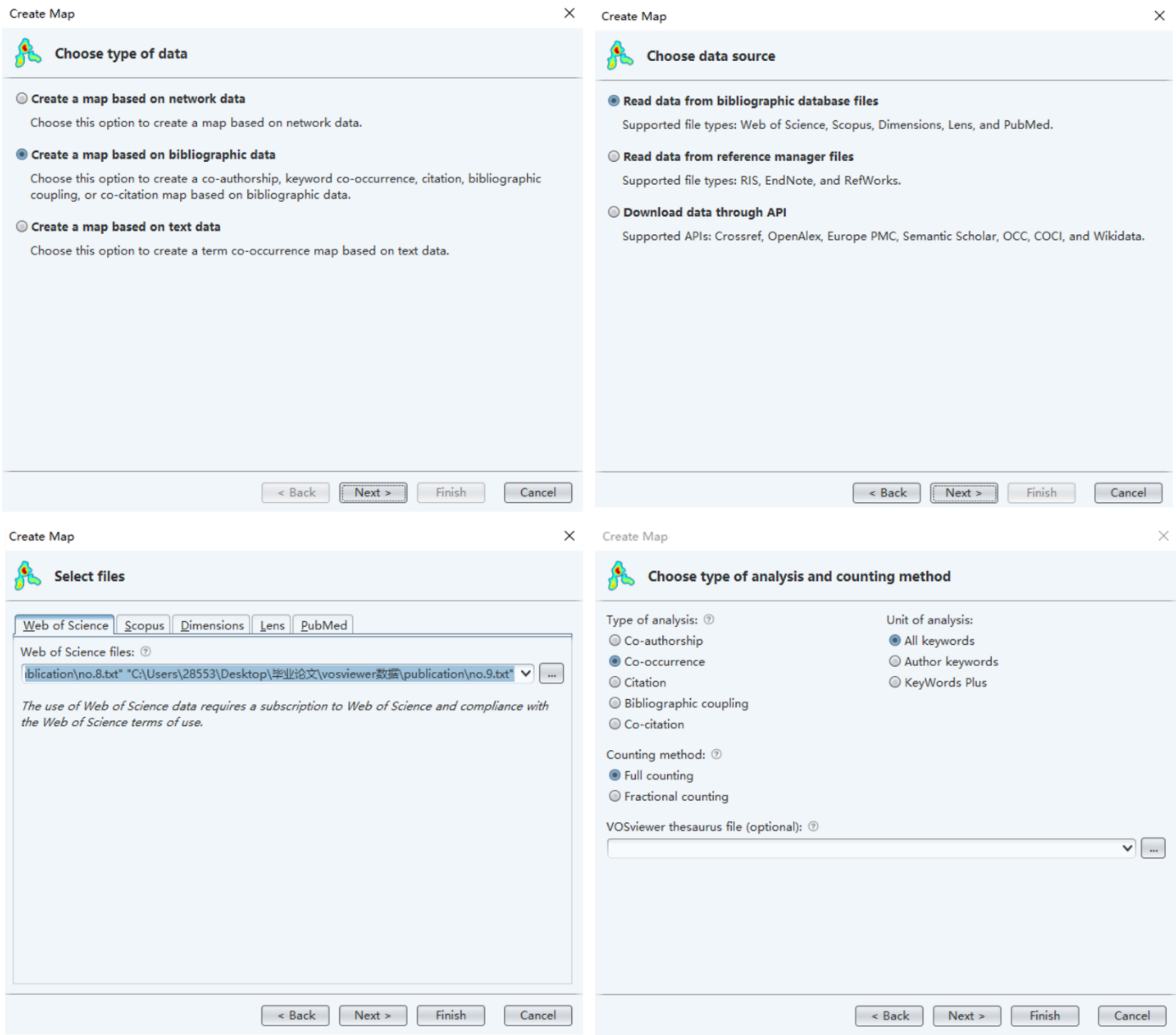


Figure 9 How to use VOSviewer to import and analyse data, from VOSviewer software.

Then we can choose what we want to analyze, such as co-authors, keywords, and citations.

## 4.5.1 Application in VOSviewer for 41 publications

Through the search of Web of Science, 41 articles from 12 years (2010-2022) are obtained, and the preliminary bibliometric analysis is conducted through VOSviewer to obtain the drawings.

The first step is co-occurrence analysis, select all keywords in the units of analysis, select the keywords that appear more than once, and draw a map with 15 groups, each named by a keyword.

VOSviewer employs a web-based visualization process that involves the identification and extraction of terms from the titles and abstracts of individual publications. Each term is represented by a vividly colored circle accompanied by a corresponding label. The circle's size is directly proportional to the frequency of the term's occurrence within the publication—larger circles denoting higher occurrence frequencies. The spacing between terms provides a rudimentary indication of their degree of interrelation. In map selection, correlations are established through co-occurrence rates. A heightened co-occurrence rate between words signifies a stronger association, implying a more frequent appearance of the two words together within publications.

Figure 10 shows a visualization of the co-occurrence network for keywords used by authors in 41 articles.

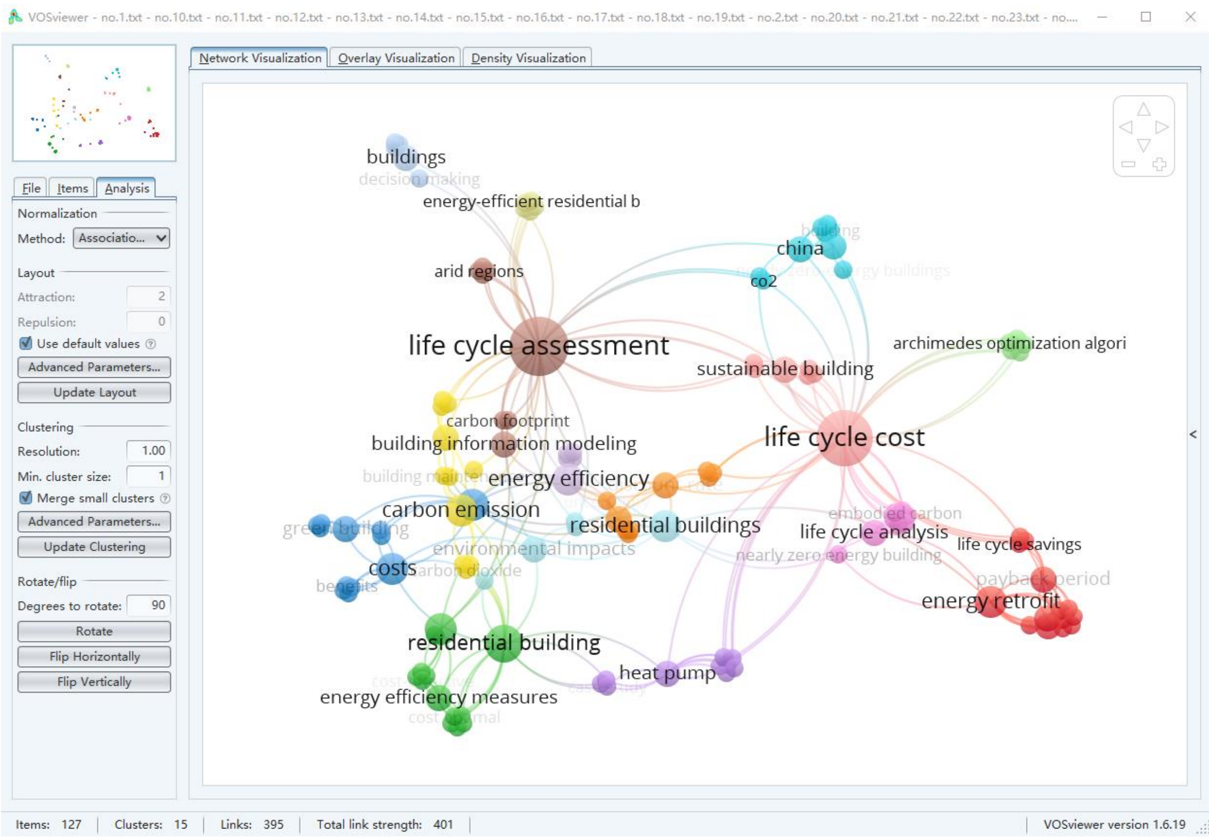


Figure 10 Visualization of a co-occurrence network based on the keywords used by the authors from the 41 articles analysed, years of reference-2010-2022. Processing by VOSviewer software.

There are 15 clusters in this map, each cluster has several items. Every cluster is named by the most important item.

15 items are listed below:

Cluster 1: economic sustainability (red), 14 items.
Cluster 2: energy efficiency measures (green), 13 items.
Cluster 3: costs (blue), 12 items.
Cluster 4: carbon emission (yellow), 11 items.
Cluster 5: heat pump (purple), 10 items.
Cluster 6: China (Cyan), 9 items.
Cluster 7: Monte Carlo simulation (Orange), 9 items.
Cluster 8: life cycle assessment (light brown), 8 items.
Cluster 9: life cycle analysis (pink), 8 items.
Cluster 10: life cycle cost (light red), 7 items.
Cluster 11: Archimedes optimization algorithm (light green), 6 items.
Cluster 12: buildings (light blue), 5 items.
Cluster 13: energy-efficient residential building (chartreuse), 5 items.
Cluster 14: energy efficiency (light purple), 5 items.
Cluster 15: residential buildings (light blue), 5 items.

As can be seen from figure 10, cluster 10 "life cycle cost" is closely related to economics such as discount rate, sensitivity analysis and payback period. cluster 8 'life cycle assessment' is closely related to ecology such as carbon footprint, low carbon design and carbon emission. Sustainable building establishes a link between the two terms. In cluster 15 residential building, more emphasis is placed on energy retrofitting, energy efficiency and life cycle assessment, as well as cost estimation. The sustainability assessment of green housing is closely related to energy efficiency and energy transformation, and the content of carbon footprint and near-zero carbon is also the focus of scholars in recent years.

Figure 11 shows the connection of cluster 'life cycle cost' and cluster 'life cycle assessment'

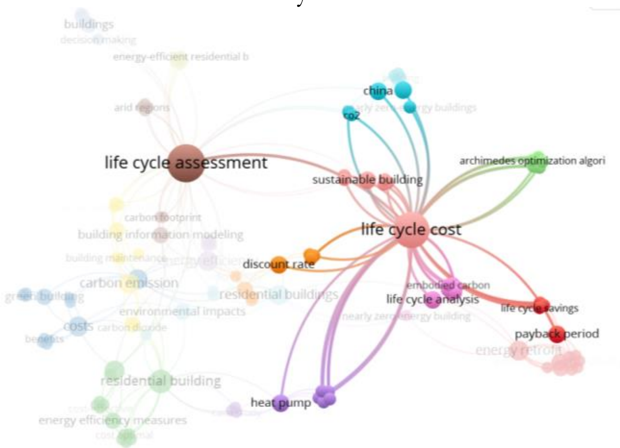


Figure 11 Visualisation of a co-occurrence network based on the keywords used by the authors from the 41 articles analysed, when point to cluster 'life cycle cost'. Processing by VOSviewer software.

Illustrated in Figure 12 is the superimposed visualization of author-assigned keywords spanning 41 publications. This map offers insights into the mean years during which author keywords were employed across these works. Notably, the lower right corner delineates the temporal scope within which these author keywords were utilized, encompassing the timeline from 2014 to 2022.

Evident from the figure, the period spanning 2014 to 2022 demonstrates a discernible evolution in the thematic focus of the publications' keywords. The trajectory shifts from emphasizing economic and environmental assessment towards themes centered on energy efficiency, carbon footprint, and green technologies. These transitions signify pivotal drivers fostering the technological advancement of both green residential construction and residential retrofitting endeavors.

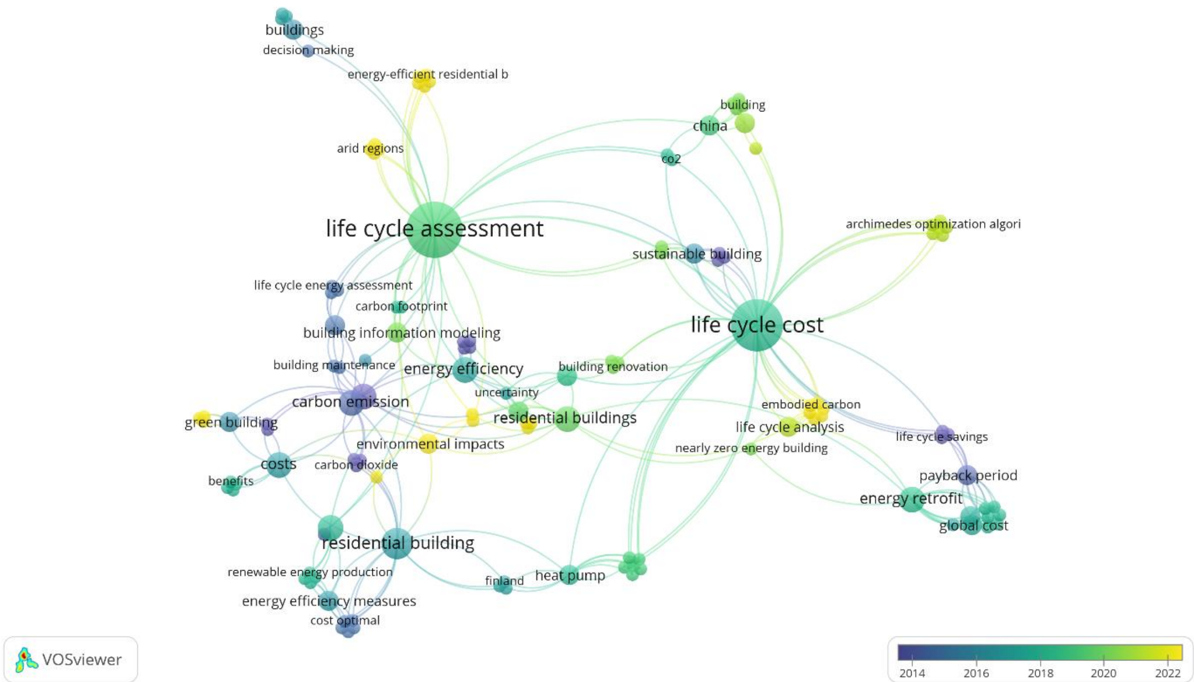


Figure 12 Visualisation of a co-occurrence network based on the author keywords from the 41 articles analysed, focus on the average years of keywords. Processing by VOSviewer software

## 4.5.2 Application in VOSviewer for 515 publications in 2010-2022

For a more comprehensive analysis, the author conducted a further publication search on the Web of Science using keywords ('life cycle cost', 'residential building') to come up with open access publications published between 2010 and 2022, Open access publications were selected and 515 publications were obtained.

515 results from Web of Science Core Collection for:

**Life-cycle-cost** (All Fields) and **residential building** (All Fields)
Publication years: 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014 or 2013 or 2012 or 2011 or 2010

Figure 13 produces a bibliographic network of relevant publication country associations by selecting the "Country" option for bibliographic citation analysis, and in overlay visualization it is also possible to determine when countries have started scientific research on sustainability assessment and energy efficiency in residential. The association of countries is determined by the number of references they share.

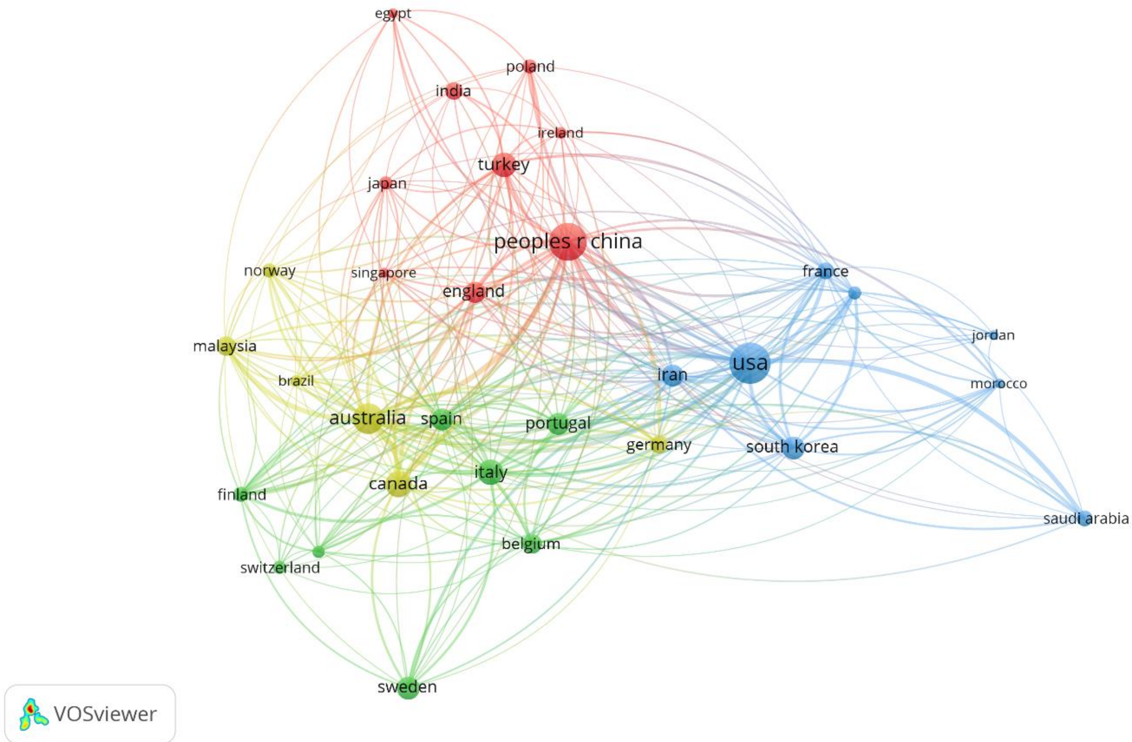


Figure 13 Visualizations of a bibliographic citation network based on the country of publication, overlay visualization map mode, from 515 articles analysed, reference year 2010-2022. Processing by VOSviewer software

Figure 14 shows the number of countries ranked by number (2010-2022).

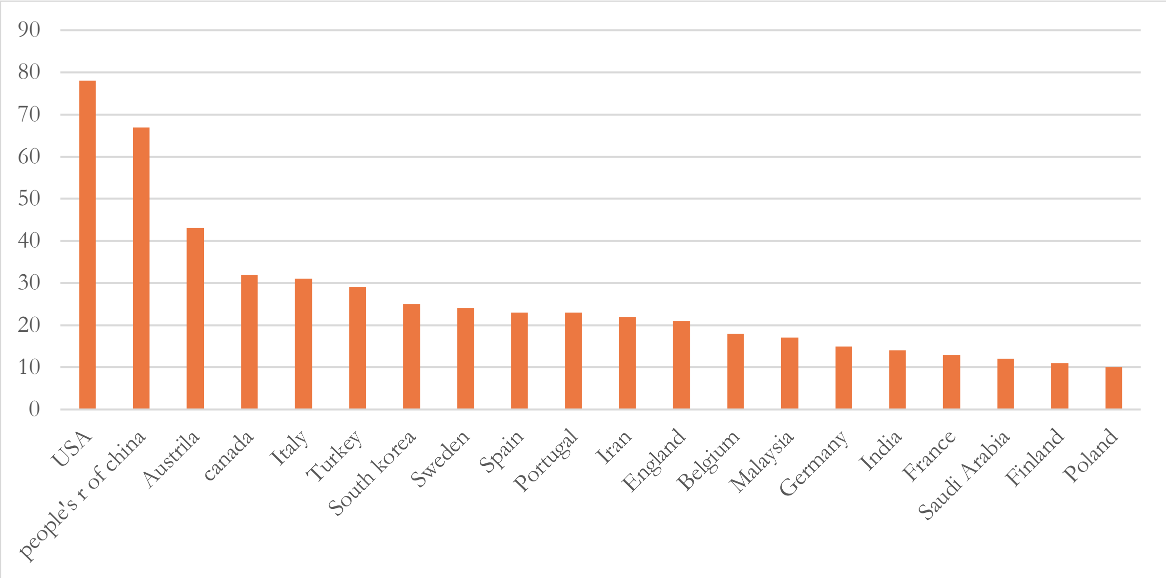


Figure 14 Number of publications from Web of Science in each country worldwide, ranked by number of documents (by author)

As can be seen from the two charts, the United States, China and Australia are among the three countries with the largest number of publications, Italy is the country with the largest number of publications among European countries, and the other countries with the largest number of publications are also distributed in Asia and Europe. However, the number of publications in the United States and China is very much ahead of other countries.

The findings postulate the potential existence of correlations between literature production and various factors, including a nation's size, population density, the vibrancy of its real estate and construction industries, and the level of technological advancement.

Figure 15 shows the change in the number of publications per year from 2010 to 2022

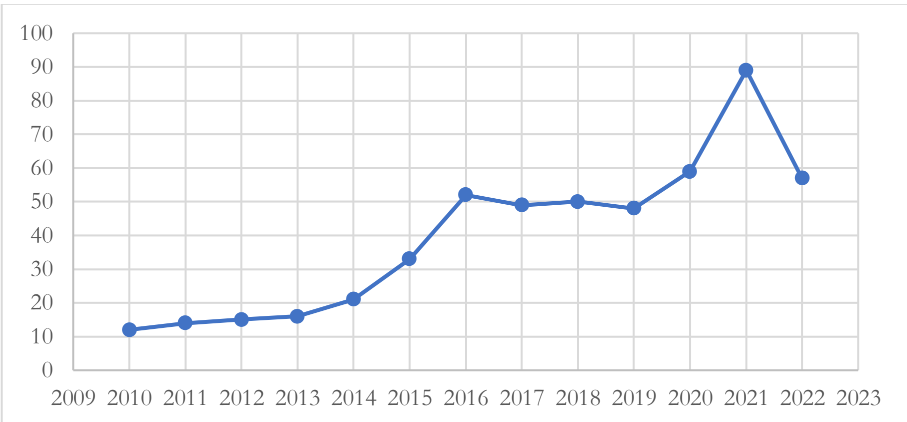


Figure 15 Number of publications from all countries in each year (2010-2022) , ranked by year (by author)

As can be seen from the figure above, the number of publications about 'LCC' and 'residential building' each year from 2010 to 2021 is gradually increasing, with a rapid increase in the number from 2014 to 2016 and 2021, but a decrease in the number in 2022. This could be determined by the fact that not all the research products of the 2022 are already indexed in the bibliometric data based.

Figure 16 shows the changes in the number of LCC and residential building publications in Europe from 2010 to 2022.

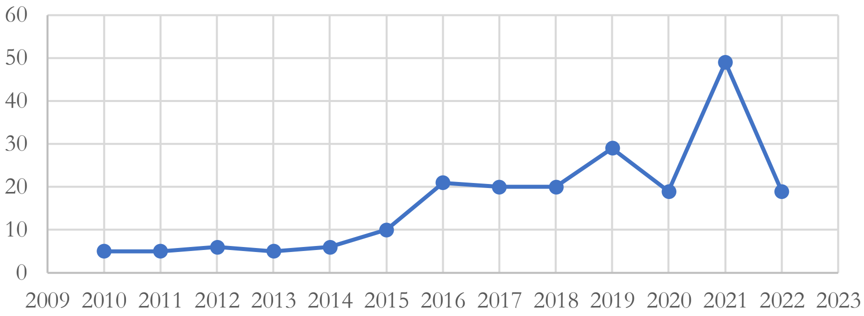


Figure 16 Number of publications from European countries in each year (2010-2022) , ranked by year (by author)

Figure 16 portrays a gradual augmentation in the count of publications within the European region, spanning the period from 2010 to 2019. However, an abrupt spike in publication numbers surfaced in 2021, potentially attributed to the European Commission's unveiling of the Renovation Wave strategy in 2020—a comprehensive initiative aimed at enhancing the energy performance of pre-existing buildings. It is noteworthy that the majority of residential structures across Europe are characterized by suboptimal HVAC systems and insulation measures. Consequently, an escalating number of scholars are immersing themselves in research related to building energy efficiency and renovation methodologies.

Turning attention to Figure 17, it reveals the visualized co-occurrence network derived from collaborative efforts among author keywords within 515 articles. The illustration underscores the prominence of "Life cycle assessment" and "life cycle cost" as the most frequently invoked terms. Trailing closely is "energy efficiency," signifying that, within the realm of residential building literature, the discourse on energy efficiency continues to occupy a central position, manifesting as a focal point in research endeavors pertaining to Life Cycle Cost (LCC) analysis of residential buildings.

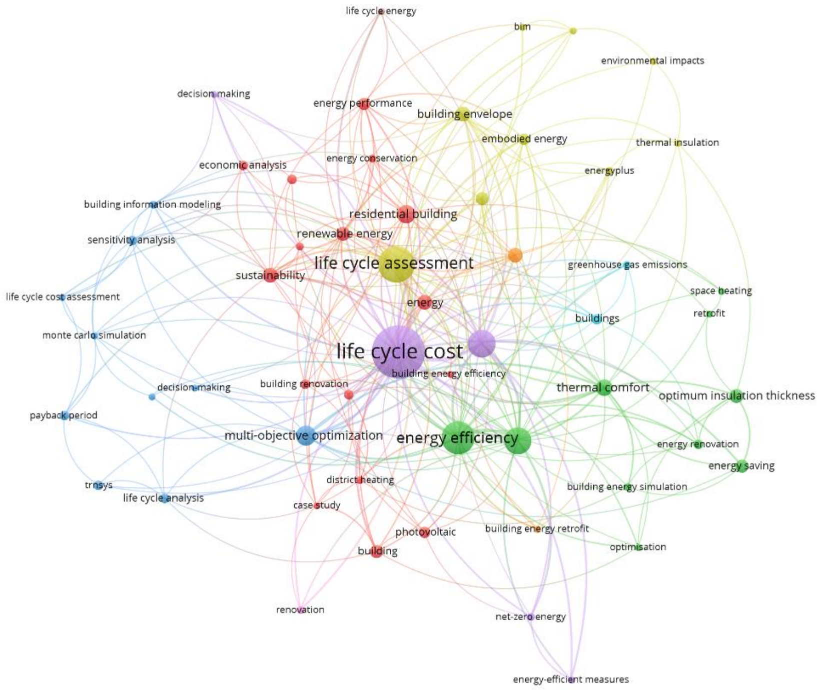


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Figure 17 Visualisation of a co-occurrence network based on the author keywords from the 515 articles analysed, from 515 articles analysed, reference year 2010-2022. Processing by VOSviewer software

In combination with figure 17, we can see that the economic and environmental assessment methods of life cycle thinking have a great impact on the construction of green residential buildings and the assessment of residential renovation. From the keywords, it can be determined that the routes of joint economic and environmental sustainability evaluation research are as follows:

1. Energy analysis evaluation is used in conjunction with LCC and LCA analysis.
2. Joint use of building energy transformation schemes with LCC analysis and LCA analysis.
3. 'Combined application of LCC analysis and risk analysis to manage uncertainty in the economic evaluation of construction projects.'[4] Such as sensitivity analysis, cost-benefit and cost optimal.

This analysis posits that life-cycle economic assessment applied to the green retrofitting of residences not only serves to recalibrate retrofitting strategies and dwelling design but also augments the cost-effectiveness of dwellings. This is accomplished by facilitating the precise determination of economic and environmental costs at every stage of the life cycle. Moreover, this approach plays a pivotal role in appraising the program feasibility of building interventions.

[4] Elena Fregonara and Sara Pattono, 'A Sustainability Indicator for Building Projects in Presence of Risk/Uncertainty over Time: A Research Experience', *Aestimum*, 8 March 2019, 173-205 Pages, https://doi.org/10.13128/AESTIMUM-24928. P-182.

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[1] 'VOSviewer - Visualizing Scientific Landscapes', VOSviewer, accessed 17 June 2023, https://www.VOSviewer.com//.

[2]Elena Fregonara and Sara Pattono, 'A Sustainability Indicator for Building Projects in Presence of Risk/Uncertainty over Time: A Research Experience', *Aestimum*, 8 March 2019, 173-205 Pages, https://doi.org/10.13128/AESTIMUM-24928.

[3]Nees Jan van Eck and Ludo Waltman, 'Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping', *Scientometrics* 84, no. 2 (1 August 2010): 523–38, https://doi.org/10.1007/s11192-009-0146-3.

[4]Marta Vitale, 'la valutazione della sostenibilità degli interventi di riqualificazione energetica degli edifici storici in ottica life cycle', tesi di Laurea Magistrale, Politecnico di Torino, A.A.2021-2022.

# Conclusion

The main objective of this study is to explore the scientific research of the life cycle approach in the field of economic assessment by reviewing the relevant literature on green retrofitting of residential and economic assessment methods for green residential building. We selected articles from the literature on the use of LCC, LCA methods or both in Europe and China, totaling 41 articles. A comprehensive analysis of the literature focuses on the benefits of residential retrofitting and overall assessment on economic aspects. Our study aims to identify the most frequently used assessment methods and strategies under this topic, as well as to understand the current trends to the application of the LCC approach in the green residential building sector in Europe and China.

Research assumes that life-cycle economic assessment for green retrofitting of dwellings is not only effective in reorienting retrofitting and dwelling design, but also increases the cost-effectiveness of dwellings by helping to determine the actual economic and environmental costs at each life-cycle stage, and determining the programme viability of building interventions. Furtherly, another sample with more publications is proposed, even only with the purpose to explore the use of a research tool for literature analysis, i.e. the VOSviewer software.

Analyzing more publications through programs such as VOSviewer allows for a deeper analysis of keywords and the timing of publications. It can be seen that research on green homes cannot be analyzed without research on energy retrofit as well as energy efficiency. Most of the European publications focus on actual or virtual case studies, where the feasibility is calculated using a life cycle approach or a cost approach through different variables of energy retrofit and environment; most of the Chinese publications focus on actual case studies, and on the basis of the European research methodology an overall life cycle assessment and life cycle costing for the green residential building itself is also added. The United States and China have the largest number of publications and the largest number of studies on life cycle costing of residential buildings, ahead of any other country. On the European continent, Italy is the country with the highest number of publications in life cycle cost assessment studies of green residential building and residential building retrofits. Of course, these last conclusions should be validated by means of a punctual analysis of the sampled articles.

As residential markets around the world gradually move from an incremental market to a stock market, the issue of developing green residential, improving their energy performance and reducing their various consumption over the life cycle will become increasingly important. Therefore, this thesis can support future researchers to explore the practice of green residential building and green retrofit technologies in depth, in relation to cost effectiveness.