

KAUNAS UNIVERSITY OF TECHNOLOGY

VIDHYALAKSHMI CHANDRASEKARAN

ENVIRONMENTAL IMPACT ASSESSMENT
OF RESIDENTIAL BUILDINGS USING LIFE
CYCLE APPROACH

Doctoral dissertation
Technological Sciences, Environmental Engineering (T 004)

Kaunas, 2023

This doctoral dissertation was prepared at Kaunas University of Technology, Institute of Environmental Engineering during the period of 2018–2022. The studies were supported by the Research Council of Lithuania.

The doctoral right has been granted to Kaunas University of Technology together with Vytautas Magnus University and Lithuanian Energy Institute.

Scientific Supervisor:

Prof. Dr. Jolanta DVARIONIENĖ (Kaunas University of Technology, Technological Sciences, Environmental Engineering, T 004).

Edited by: English language editor Dr. Armandas Rumšas (Publishing House *Technologija*), Lithuanian language editor Rozita Znamenskaitė Publishing House *Technologija*)

Dissertation Defense Board of the Technological Science Field:

Prof. Dr. Žaneta STASIŠKIENĖ (Kaunas University of Technology, Technological Sciences, Environmental Engineering, T 004) – **chairperson**;

Prof. Dr. Gintaras DENAFAS (Kaunas University of Technology, Technological Sciences, Environmental Engineering, T 004);

Dr. Darius JAKIMAVIČIUS (Lithuanian Energy Institute, Technological Sciences, Environmental Engineering, T 004);

Assoc. Prof. Dr. Francesco SCORZA (University of Basilicata, Italy, Technological Sciences, Environmental Engineering, T 004);

Prof. Dr. Lina ŠEDUIKYTĖ (Kaunas University of Technology, Technological Sciences, Construction Engineering, T 002).

The official defense of the dissertation will be held at 12.00 p.m. on 30 August 2023 at the public meeting of the Dissertation Defense Board of Technological Sciences Field in Rectorate Hall at Kaunas University of Technology.

Address: K. Donelaičio 73-402, Kaunas, LT-44249, Lithuania

Phone: (+370) 37 30 00 42; email doktorantura@ktu.lt

The doctoral dissertation was sent out on 28 July, 2023.

The doctoral dissertation is available on the internet at <http://ktu.edu>, at the libraries of Kaunas University of Technology (Donelaičio 20, Kaunas, LT-44239, Lithuania), Vytautas Magnus University (K. Donelaičio 52, Kaunas, LT-44244, Lithuania), and Lithuanian Energy Institute (Breslaujos 3, Kaunas, LT-4440, Lithuania).

KAUNO TECHNOLOGIJOS UNIVERSITETAS

VIDHYALAKSHMI CHANDRASEKARAN

GYVENAMŲJŲ PASTATŲ POVEIKIO
APLINKAI VERTINIMAS TAIKANT
GYVAVIMO CIKLO METODIKĄ

Daktaro disertacija
Technologijos mokslai, aplinkos inžinerija (T 004)

Kaunas, 2023

Disertacija rengta 2018–2022 metais Kauno technologijos universiteto Aplinkos inžinerijos institute. Mokslinius tyrimus rėmė Lietuvos mokslo taryba. Doktorantūros teisė Kauno technologijos universitetui suteikta kartu su Vytauto Didžiojo universitetu ir Lietuvos energetikos institutu.

Mokslinis vadovas:

prof. dr. Jolanta DVARIONIENĖ (Kauno technologijos universitetas, technologijos mokslai, aplinkos inžinerija, T 004).

Redagavo: anglų kalbos redaktorius dr. Armandas Rumšas (leidykla „Technologija“), lietuvių kalbos redaktorė Rozita Znamenskaitė (leidykla „Technologija“)

Technologijos mokslo krypties disertacijos gynimo taryba:

prof. dr. Žaneta STASIŠKIENĖ (Kauno technologijos universitetas, technologijos mokslai, aplinkos inžinerija, T 004) – **pirmininkas(-ė)**;

prof. dr. Gintaras DENAFAS (Kauno technologijos universitetas, technologijos mokslai, aplinkos inžinerija, T 004);

dr. Darius JAKIMAVIČIUS (Lietuvos energetikos institutas, technologijos mokslai, aplinkos inžinerija, T 004);

doc. dr. Francesco SCORZA (Bazilikatos universitetas, Italija, technologijos mokslai, aplinkos inžinerija, T 004);

prof. dr. Lina ŠEDUIKYTĖ (Kauno technologijos universitetas, technologijos mokslai, statybos inžinerija, T 002).

Disertacija bus ginama viešame Technologijos mokslo krypties disertacijos gynimo tarybos posėdyje 2023 m. rugpjūčio 30 d. 12.00 val. Kauno technologijos universiteto Rektorato salėje.

Adresas: K. Donelaičio g. 73-402, Kaunas, LT-44249, Lietuva
Tel. (+370) 37 300 042; el. paštas doktorantura@ktu.lt

Disertacija išsiųsta 2023 m. liepos 28 d.

Su disertacija galima susipažinti interneto svetainėje <http://ktu.edu> Kauno technologijos universiteto (K. Donelaičio g. 20, Kaunas, LT-44239, Lietuva), Vytauto Didžiojo universiteto (K. Donelaičio g. 52, Kaunas, LT-44244, Lietuva) ir Lietuvos energetikos instituto (Breslaujos g. 3, Kaunas, LT-44403, Lietuva) bibliotekose.

CONTENTS

LIST OF TABLES.....	6
LIST OF FIGURES.....	7
LIST OF ABBREVIATIONS.....	7
INTRODUCTION	9
1 LITERATURE REVIEW.....	12
1.1 Renovation of Existing Buildings	12
1.2 Depth of Renovation	13
1.3 Legislative Framework	14
1.4 Environmental Assessment Methodologies for Building Renovation	15
1.5 Indicators in Use	30
2 METHODOLOGY.....	32
3 COMPARATIVE ANALYSIS OF PERFORMANCE ASSESSMENT METHODS.....	37
3.1 Environmental Performance Assessment Schemes.....	38
3.2 Comparison of EPAS.....	39
3.3 Investigation of LCA Integration in EPAS	43
4 ASSESSMENT OF ENVIRONMENTAL PERFORMANCE OF RESIDENTIAL RENOVATION	47
4.1 Object	47
4.2 Life Cycle Assessment of Multi-family Building	48
4.3 Implementation of EPAS in Multi-family Buildings	55
4.4 Implementation of LCA in EPAS	62
5 DEVELOPMENT OF A CONCEPTUAL METHODOLOGY FOR ENVIRONMENTAL IMPACT ASSESSMENT OF RESIDENTIAL BUILDINGS BY USING LIFE CYCLE APPROACH.....	66
5.1 Conceptual Methodology for Multi-apartment Renovation.....	66
5.2 Proposed Indicators for the Evaluation of Multi-impact Renovation	69
5.3 Development of a List of Indicators and Questionnaire	71
5.4 Analysis and Weightage of Indicators	77
5.5 Implementation and Results of FAHP Analysis	80
5.6 Application of Methodology on Example and Results	83
CONCLUSIONS.....	99
SANTRAUKA.....	101
LITERATURE.....	123
CURRICULUM VITAE	136
ACKNOWLEDGEMENTS	138
ANNEXES	139

LIST OF TABLES

Table 1. Review of life cycle assessment on residential building renovation.....	18
Table 2. Review of environmental performance assessment in previous studies	24
Table 3. Review of integrated assessment from previous studies.....	26
Table 4. Review of multi-criteria decision-making methods on renovation.....	28
Table 5. Commonly studied indicators in the literature on renovation.....	30
Table 6. Environmental Performance Schemes globally [151]	37
Table 7. Main features of the selected EPAS.....	38
Table 8. Comparison of EPAS by using selected criteria	39
Table 9. Comparison of indicators of each scheme	41
Table 10. Points distribution for sustainable aspects based on categories	42
Table 11. Investigation of LCA incorporation in each method [38,82,154].....	45
Table 12. Summary of the quantities collected for the study.....	49
Table 13. Assessment of a multi-apartment building renovation and the values of criteria, in credits: BREEAM	56
Table 14. Assessment of a multi-apartment building renovation and the values of criteria, in credits: LEED	59
Table 15. Distribution of LCA in selected schemes	63
Table 16. Proposed critical indicators with description.....	70
Table 17. Categories added in the primary list	72
Table 18. Characteristics of expert participants.....	73
Table 19. List of key factors of residential renovation sourced from the expert survey	74
Table 20. Subtracted indicators and the justification of the choice	76
Table 21. Modified or grouped indicators and the justification of the choice	76
Table 22. Suggested indicators and the justification of the choice	76
Table 23. Finalized set of criteria for the evaluation of multi-impact renovation ...	77
Table 24. Fuzzy membership scale and linguistic variables	79
Table 25. Weighting (Wm) and ranking of themes based on expert opinion and FAHP	80
Table 26. Weighting (WS) and ranking of categories based on expert opinion and FAHP	80
Table 27. Weighting (Wl) and ranking of life cycle stages based on expert opinion and FAHP	80
Table 28. Results after assigning global weights (Wg) and ranking for individual criteria.....	81
Table 29. Description of the status and renovation measures of the case study buildings	83
Table 30. Results of comfort and well-being.....	84
Table 31. Scores for resources	86
Table 32. Results of the pollution category	90
Table 33. Scores for costs and functionality.....	92

LIST OF FIGURES

Fig. 1. Research methodology of this dissertation	32
Fig. 2. Steps involved in the FAHP process.....	34
Fig. 3. Process of Life Cycle Assessment	35
Fig. 4. Schematic flowchart used in this analysis.....	37
Fig. 5. Renovated multi-apartment building (Building A)	47
Fig. 6. System boundary of the study	49
Fig. 7. Distribution of environmental impacts.....	52
Fig. 8. Comparison of environmental impact of multi-apartment building before and after renovation.....	53
Fig. 9. Annual consumption of heat energy in multi-apartment buildings before and after renovation.....	54
Fig. 10. A conceptual methodology for multi-apartment renovation with combined performance and life cycle approach.....	67
Fig. 11. Distribution of indicators over the entire life cycle of building	69
Fig. 12. Excerpt of the prepared questionnaire	72
Fig. 13. Distribution of respondents' profile.....	73
Fig. 14. (a) Reasons for renovation; (b) Barriers of renovation	74
Fig. 15. (a) Consideration of LCA; (b) Consideration of LCA in different phases of renovation	75
Fig. 16. Word cloud generated from the survey	75
Fig. 17. Decision hierarchy for the prioritization of indicators	78
Fig. 18. Pie chart showing the relative weights of the selected indicators	82
Fig. 19. Consolidated values of the proposed indicators assigned for the case study	95

LIST OF ABBREVIATIONS

Acronym	Explanation
---------	-------------

ADP	Abiotic Depletion Potential
AHP	Analytical Hierarchical Process
AP	Acidification Potential
BPIE	Building Performance Institute Europe
BMCC	Building Materials and Construction Combination
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CED	Cumulative Energy Demand
DEA	Data Envelopment Analysis
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DR	Discount Rate
EC	Ecopoints

ECP	Entire Construction Process
EOL	End of Life
EP	Eutrophication Potential
EPC	Energy Performance Certificates
EPBD	Energy Performance of Buildings Directive
EPAS	Environmental Performance Assessment Scheme
ESUCO	European Sustainable Construction database
EU	European Union
FAHP	Fuzzy Analytical Hierarchical Process
FDP	Fossil Depletion Potential
GHG	Green House Gases
GSAS	The Global Sustainability Assessment System
GWP	Global Warming Potential
HTP	Human Toxicity Potential
HQE	High Quality Environmental standard
IEQ	Indoor Environmental Quality
IOA	Input-Output Analysis
ITACA	Istituto per l'innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCE	Life Cycle Energy
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
LCSA	Life Cycle Sustainability Assessment
MF	Multi-Family
MCA	Multi Criteria Analysis
MCDA	Multi Criteria Decision Analysis
MCDM	Multi Criteria Decision Making
NABERS	National Australian Built Environment Rating System
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Depletion Potential
RED	Renewable Energy Directive
SF	Single Family
SLCA	Social Life Cycle Assessment
SWOT	Strength, Weakness, Opportunity and Threat
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TPE	Total Primary Energy

INTRODUCTION

Research relevance, aim and objectives

The built environment is crucial to the national development and socio-cultural growth in any human society, whereas, at the same time, it is also well known for having a critical impact on the environment, such as the use of material and energy resources. Currently, about 35% of the buildings in EU are at least 50 years old, and about 75% of them account for energy inefficiency [1]. The European Union has developed ambitious goals on climate and energy with the commitment of achieving the goals in consecutive years. For this, the renovation of the already existing buildings has become an essential tool for achieving the climate goals. This implies that many buildings shall be renovated according to their potential to achieve the climate goals by 2050. This will be an opportunity to significantly improve the quality of the building stock and the living conditions of all Europeans. For instance, analysis revealed that most of the renovation strategies applied on already existing buildings are similar [2]. A significant focus is given to energy efficiency, and measures are based only on energy reduction. The building has a long-life cycle, and so do cities; therefore, what is developed and produced today will inevitably impact future generations. Hence, strategies must be developed and implemented without compromising environmental, social and economic factors [3]. In addition, the efforts toward sustainable construction are currently receiving great attention at various levels, including the process of renovation with a range of sustainability assessment methods [4]. These tools are often focused only on new buildings and their associated impacts and energy efficiency. Although the renovation process has been going on since 2008, the studies are fragmented and limited to energy analysis and/or the operation stage is only targeted, thus leaving out the analysis of the entire renovation process. Similarly, it has been argued that there is a lack of standardized practices, policies, and regulations which would specifically focus on the renovation process either with the sustainability focus, or without it [5].

Like many other nations in Europe, Lithuania is facing a need for large-scale, urgent renovation of the post-war residential stock that is past its technical, economic, and service life endpoint. There are 37,627 multi-apartment buildings in Lithuania, out of which, 4,335 apartments had been renovated prior to 2021 [6]. This indicates that only 11% of apartment buildings have been renovated thus far. Renovation of this multi-family (multi-apartment) housing is taking place slowly. It is challenging due to various reasons, such as lack of resources, (un)willingness to renovate, technical expertise, socio-cultural issues, and so on [7]. Nevertheless, renovation increases the service life of the buildings, and it is essential to evaluate the potential impacts of the renovation of residential buildings (the whole building) from a holistic perspective. In line with this, there is the necessity to develop an assessment methodology to analyze the performance of the renovation of residential buildings from the life cycle perspective.

Aim and objectives of the research

The research aims to develop a methodology for environmental impact assessment for the renovation of residential buildings by using the life cycle approach. To achieve this, the following tasks have been performed:

1. To investigate the already existing assessment methods and their indicators for building evaluation, and to identify the main gaps concerning renovation.
2. To assess the environmental impact of a renovated residential building over its entire life cycle by using LCA.
3. To determine the critical indicators for the performance assessment concerning the renovation process by comparing various assessment methods.
4. To develop and apply the methodology for the assessment of the environmental impact of renovated houses.

Research hypothesis

The research questions have been formed in a way to focus on in-depth analysis of the study on which the research objectives were created.

Hypothesis 1: Environmental performance tools are effective in evaluating the performance of residential renovation by considering the entire life cycle phase.

Hypothesis 2: Current environmental performance methods do not provide comprehensive assessment of apartment building renovations as they do not apply the life cycle approach to building assessment.

Research methods

The research process is as follows. Firstly, a systematic literature review intended to identify the problem, research gaps, and tools/methods used in line with the renovation of residential buildings, followed by an actual renovated building examination, has been carried out. Secondly, a survey questionnaire has been designed to identify factors relevant to the renovation process. With the help of multi-criteria models, key indicators have been identified, and a conceptual methodology has been proposed to address the research gap. Ultimately, the application of the resulting solution (the developed method) has been demonstrated in practical applications, and the findings have been communicated through scientific publications.

Research object

The research object is a renovated multi-apartment building in the Lithuanian context. For experimental analysis, two multi-apartment (multi-family) buildings were chosen with different energy renovation measures. The buildings were originally constructed in the early 1980s and renovated in 2015. The renovation included the replacement of windows/doors, improvement of the thermal performance of the building envelope, exhaust ventilation with a mechanical supply replacement, installation of solar heat collectors and an air exhaust heat pump.

Scientific novelty

The main scientific novelty is the development of a methodology for renovating multi-apartment residential buildings from the life cycle perspective. Moreover, the study focusses on the evaluation of the environmental impact of cases of renovated building by using life cycle analysis which is comprehensive and *not* confined to energy renovation alone. Similarly, renovated buildings are assessed with the already existing environmental schemes so that to understand the evaluation of these schemes. Analysis of not only the life cycle assessment but also environmental schemes has been conducted for renovated buildings for the first time to the best of the knowledge of the author of this thesis. The analysis of both methods brings out the implications concerning the two methods and provides understanding of the implementation of building renovation scenarios as a combined approach. Therefore, the methodology has been derived by using multi-decision criteria and the life cycle assessment jointly to evaluate the renovation of a residential building. This is the first ever attempt to assess the holistic impact of renovation.

Practical value

The developed methodology can be used for the evaluation of the renovation of residential buildings. Significantly, the developed methodology has been tested on multi-apartment buildings as a case study which could be useful to assess the renovation performance with the holistic and life cycle perspective throughout its process. The proposed method can be used as a support decision model to evaluate performance from the planning stage to the post-occupancy stage. Moreover, the proposed methodology can be used by a wide range of users, such as researchers, architects, consultants, operation and management teams, and authorities. The idea of the methodology is that it can be used on actual project work so that to evaluate the individual process stages which have been completed or still need to be analyzed.

Research approbation

The scientific results of the thesis have been published in three articles of international journals with the citation index. Two articles have been published in *WoS* with the impact factor, and one article has been published in a *Scopus* publication with the impact factor. The primary research results have been presented at four international scientific conferences.

Structure and content of the dissertation

The doctoral thesis contains the introduction, five chapters, general conclusions, a list of literature sources featuring 197 references, and a list of scientific publications. The doctoral dissertation is composed of 144 pages, 19 figures, and 33 tables. The dissertation contains some materials previously published in articles which have been reproduced with the publishers' permission.

1 LITERATURE REVIEW

Background

The building sector is the largest consumer of energy in Europe. It accounts for nearly 40% of the total consumption of energy and 36% of the greenhouse gas emissions [8]. While new buildings can be constructed with high energy performance levels, the currently existing stock is predominantly denoted by poor energy performance, and is consequently in need of renovation work. With their potential to deliver high energy and CO₂ savings, energy efficient buildings can play a pivotal role in a sustainable, low carbon future. At the same time, building renovation provides a number of societal benefits, including fuel poverty alleviation, health benefits, increased energy security, increased employment, higher rental and resale values, and air quality improvement. To date, however, the renovation rate of the already existing buildings in the EU are low (1%), and the renovation of already existing buildings still remains a challenge [9]. To boost the renovation of building stocks, a wide range of policies, schemes and instruments has been developed. These measures are designed, and are constantly being updated.

1.1 Renovation of Existing Buildings

European building stocks are quite heterogeneous in nature with the majority of the buildings by area (75 %) comprised of residential buildings. The building characteristics can be defined based on the following features: 1. Floor area per sector; 2. Residential buildings by construction; and 3. Building typology. The residential building typology also varies significantly across the countries with an average of 49 % of single and multi-family housings. The type of the housing greatly contributes to the impact of energy performance and insulation characteristics [10]. Moreover, most of the buildings had been built before thermal standards were introduced, i.e., they had been built before the 1970s; more than 40 % of the stock had been built before 1960, and 90 % of the stock had been built before the year 1990. Presumably, most of these buildings, will still be standing in the year 2050. Each year, new construction in Europe represents about 1% of the building stock, and this implies that the newer buildings offer better performance than the already existing ‘average’ ones [11]. The total building stock is growing over time, with the rate at which new buildings are erected exceeding the rate at which old buildings are getting demolished. The key point is that both demolition and construction rates are low. The method of demolition and rebuilding adds more stress on the environment and landfill which does not solve the purpose [12]. Therefore, improving the performance of the existing stock is seen as a crucial step towards achieving energy efficiency.

Lithuania is lagging behind in this transition as well. The largest segment of buildings in Lithuania was built in the second half of 20th century in which 60 % of the population resides in multi-family apartments constructed during 1961–1990, and 40 % live in one- or two-family buildings. Approximately, the heating season in Lithuania starts by October and runs until April, and 60 % of the dwelling stock is connected to district heating systems. According to the Lithuanian legislation for the

thermal energy supply and consumption, the heating season can be started when average outdoor air temperature is below +10 °C. Most of the buildings are denoted by poor performance standards as the buildings are equipped with inefficient heating systems and engineering equipment, and feature bad quality windows, roofs, seals between panels, which causes huge energy losses. Approximately, 80 % of multi-apartment buildings are in poor technical condition and have poor insulation [13,14]. Lithuania revamped the multi-apartment buildings with the aim of commitment to increase the energy efficiency in housing. The financing also covers the enhancement of the energy performance in the buildings, thermal insulation, doors and windows replacement in all apartments, insulation of basements, etc. With this program, buildings must reach at least C- class energy efficiency. This, in turn, would improve the quality of the living conditions, enhance the energy efficiency, and reduce the fossil fuel and CO₂ emissions [15]. With 37,627 multi-apartment buildings in Lithuania, only 11 % of buildings have been renovated thus far [6].

1.2 Depth of Renovation

The terms *retrofit*, *refurbishment*, *renovation*, and *reuse* of buildings are often used interchangeably [16]. *Retrofit* typically means addition of features for the improvement of performance in a particular area (e.g. energy efficiency and/or structural integrity) [17]. Retrofitting is defined as ‘providing a component or feature that was not fitted during the manufacture or during the initial construction phase’. Usually, the term is used to describe substantial physical changes at the building level, and it has been often termed as ‘refurbishment’ or ‘refit’ [18]. The physical or operational changes which reduce the amount of energy use are called the energy retrofit, which provides an opportunity to upgrade the building energy performance. These changes can be related to the building itself, the occupants’ behavior, or the upgrade of the energy-consuming equipment [19]. In this thesis, the term ‘renovation’ is used throughout the study. Generally, major focus is given to energy savings which can be achieved by fixing several key elements, such as walls, roofs, pipes, doors, windows, lighting, system controls, air conditioning, water, energy systems, boilers etc. of a building. Choosing a proper renovation measure could save the maintenance costs, and could also improve various aspects of the buildings, such as the energy measures and the comfort level [20–22]. Moreover, based on the energy savings attained through the installation process, the renovation stages are categorized from *deep* to *minor*. The EU building observatory defined different renovation measures as ‘below threshold’, ‘light’, ‘medium’, and ‘deep’ renovations based on the potential energy savings (<3 % to >60 %) to be achieved [23]. According to Liang *et al.*, renovation saves around 8% of residential stocks, and the real-time energy savings are 30–50 % lower than the predicted engineering models [24]. Dall’Ò *et al.* also studied the potential energy saving of different residential buildings and concluded that as little as the retrofitting envelope could save up to 24.8 % of energy [25].

Nevertheless, renovation measures are not limited to energy savings and incorporation of low carbon buildings, but it extends further: to the well-being, comfort, and other socio-cultural factors. According to Jagarajan *et al.* the renovation

measures offer significant environmental, economic and social benefits [26]. Richard Paradis termed sustainable renovation as “any upgrade or modification to the building, wholly or partially occupied, to improve its energy and environmental performance, to enhance the comfort and wellbeing of the occupant at an economically feasible way” [27]. A sustainable construction (renovation) is anticipated to improve the quality of life and comfort, while minimizing the burden on the environment and increasing economic sustainability [19].

1.2.1 Barriers of renovation

There is a strong focus on achieving the targets at the European level, yet the process of renovation is still lagging behind. The renovation of the already existing buildings has been encountering many challenges and barriers. Energy savings are seldom a decisive factor behind renovation, except for the simple measures with short payback periods [28]. Other challenges may include financial limitations which are perceived as long payback periods [29]. Moreover, the willingness of building owners to pay for the renovation measures, especially when there is no financial support from the government [29,30]. Research has investigated the drivers for renovation in three European countries, specifically, durability, costs, environment, and comfort [31]. Another study presented institutional and political, financial, technical and social categories as renovation barriers [28]. Lack of financial incentives and life cycle perspectives [2,30,32] is the most significant economic barrier, while the lack of a common direction amongst the main stakeholders, lack of overview, and the determination where to prioritize are the most important informational barriers. A few studies have confirmed that building owners and users often have different interests, but this also varies depending on the type of buildings [28,29,31]. Furthermore, the challenge has been encountered with many uncertainties, such as the climate change, services change, human behavior change, government policy change, etc., all of which directly affect the selection of the renovation technologies, and hence determine the success of the project (or lack thereof). As renovation is a highly interactive sub-system due to the interaction with many stakeholders, the impact becomes complex [30]. There is a great number of technologies available on the market; however, the decision-making on various renovation measures is still subjective because of many factors, such as building features, budget, objectives and targets, efficiency, etc.

1.3 Legislative Framework

The EU-27 countries have developed a comprehensive framework of building policies which includes building code requirements, enforcement and compliance, the use of renewable energy in buildings, nearly zero energy building, etc. The EU policies concede the significance of building renovation as a crucial element in achieving the long-term energy, economic and climate goals. As a result, the building sector is considered in all energy, climate and resource efficiency related plans take into account [8].

To boost the energy performance of buildings, the EU has devised a legislative framework which includes the *Energy Performance of Buildings*

Directive (2010/31/EU) and the *Energy Efficiency Directive* (2012/27/EU). Both directives were revised recently to promote policies which will help to achieve zero-emission and decarbonized buildings by 2050 and the building stocks will be modernized by making it more resilient and accessible. In line with the *Renovation Wave* [9], this proposal introduces EU-wide minimum energy performance standards for the worst-performing buildings while giving Member States the freedom to impose extra requirements to decarbonize the building sector. The proposed revision of the directive introduces new standards for energy performance to decarbonize the building sector. It includes changes of definitions of the energy performance standards (zero-emission, deep renovation), as well as revisions to national building renovation plans. It introduces 'Renovation passports' and facilitates the use of new performance metrics including the final energy consumed, and the life cycle carbon emissions [8,34]. The revision will also boost renewable energy integration in buildings in line with the *Renewable Energy Directive* revision (RED) [35] and includes measures to make Energy Performance Certificates (EPCs) much clearer, more reliable, with easy-to-understand information on energy performance, so that various stakeholders and public authorities could benefit.

Therefore, the directive also mandates to set cost-effective minimum energy performance standards for new buildings, existing buildings and for major renovation/replacement/retrofit of building components, such as heating and cooling systems, roofs and walls [8]. The EU countries have to commence substantial measures to tackle the energy and carbon savings potential of the existing stocks. While some of these measures are already in place, they are not always effective enough to stimulate renovation activities towards market transformation. Nonetheless, the good practices among the countries should be shared, facilitated for knowledge sharing in developing long-term strategies [36].

1.4 Environmental Assessment Methodologies for Building Renovation

The renovation of buildings has a significant potential to influence the environmental factors while, at the same time, also achieving the objectives of climate change. Several new elements and strategies have been introduced to investigate the environmental impacts of buildings. A comprehensive methodology has been established to evaluate and verify the characteristics of buildings with the use of criteria, guidelines or standards [33][37]. Two common approaches are used to investigate the building characteristics: 1. Life Cycle Assessment (LCA), and 2. Environmental Performance Assessment Schemes (EPAS). In many instances, both approaches have been combined to investigate the impacts associated with buildings [38].

1.4.1 Review of life cycle thinking in building renovation

LCA is a widely used methodology and a state-of-the-art tool which evaluates the potential environmental impacts of all input and output flows within the life cycle of a product, from its extraction of raw materials to its end-of-life [39,40]. The *International Organization of Standardization* (ISO) adopted environmental

management in 1990, with the standard series *14040* and *14044*, based exclusively on LCA methodologies. LCA comprises of the following four main components: (i) the goal and scope with the functional unit and system boundary definition; (ii) the life cycle inventory (LCI), where all the necessary data are collected; (iii) the life cycle impact assessment (LCIA) which evaluates the significant potential environmental impacts; (iv) the interpretation phase where the findings are evaluated [41,42]. LCA of buildings has been an extensively researched area because of the high environmental impacts of this sector and its integrated approach on the impact assessment and data quality [4,43–45]. The life cycle approach moves the focus from factors related to a completed building to the involvement of the entire life cycle of the building [46]. Many studies related to energy performance and the embodied energy of buildings are exclusively performed by using the LCA method with multi-faced goals [20,47–50].

Table 1 shows a detailed review of life cycle assessment related to renovated buildings which is presented in the literature. The main objective of this review is to understand the currently available studies related to LCA, renovation and residential buildings. The research under review covers studies which have analyzed various energy aspects, various scenarios with the aim to compare and propose alternative and effective energy renovation measures, while also covering the correlation between the stages of the renovation process, along with the impact analysis of alternative building construction materials. The relevant studies identifying the type of building – i.e., single family versus multi-family housing – the assessment criteria, assessment boundary and the type of assessment have been carried out. Different studies assess different criteria; however, the global warming potential, the cumulative energy demand, eutrophication, and acidification are often considered. Moreover, studies have concentrated on analyzing individual building components, such as walls, thermal insulation, the envelope, and so on, with the objective to understand the impacts and the outcome of the energy savings achieved during the renovation process [20,51–54]. The main issue with this study is on the system boundaries assessed for renovation studies. More than a half of the research excluded the transportation, construction, and the end of use modules. The studies associated these phases with a low environment burden over the entire building life cycle. Nevertheless, some relevant studies [52,54] conducted and discuss the associated impacts related to the entire building life cycle. Moreover, almost all the studies have so far focused on the operational stage of the building, i.e., the studies focused mainly on energy savings and the thermal insulation measures [17,49–52]. Although, there is a tremendous focus on this phase, other aspects, such as maintenance, water consumption, or waste, were not included in any of the studies.

Apart from the energy aspect, there are other aspects that should be taken into consideration. The overviewed studies have considered and analyzed different renovation scenarios (before and after interventions) to understand the improvement of energy savings and its impacts. Yet, a comparison of a demolished building, a renovated building, or a new construction will bring out an entirely new dimension of

the renovation studies. So far, none of the studies have focused on such an aspect, however, Kamali *et al.* studied the impacts associated with the ‘traditional’ building and the ‘modular renovated’ building [55]. Additionally, Palacios-Munoz *et al.* [53] conducted a study on comparing new and renovated buildings in Spain to understand the durability and lifespan of the renovated building with the passive house design. The assessment of such specific indicators as the lifespan provides an insight for the future studies and adds value in practice as well. However, neither the full life cycle nor the full impact categories are included in the LCA studies. On the other hand, LCA has been used into the process of the early-stage decision-making [56]. LCA has been integrated into some other schemes, such as building codes and certifications systems to compare the scenarios at the planning and design stage in order to enable informed decisions [56].

Table 1. Review of life cycle assessment on residential building renovation

Source	Country	Housing type	Study	Indicators	LC Phases	Outcome
[20]	Norway	SF	ECP	CC, PM, AP, CED	C+O+EOL	The study revealed that 20 % savings in energy were achieved when the passive envelope and the air-water heating was installed.
[52]	Lithuania	SF	ECP /BMCC	GWP, ODP	P+C+O+T	The study revealed that the operational phase of an energy-efficient house has less impact, but the use of envelope materials during the design becomes critical for sustainable structures.
[57]	Portugal	MF/SF	ECP	LCE, GHG	C+O+T	The lifecycle analysis of primary energy and GHG emissions, showed that use phase accounts 69–83 % of total energy requirement.
[51]	Canada	SF	ECP /BMCC	FDP, GWP, AP, HH, EP, REP, ODP, PCOP	P+C+O+M +EOL	The results showed that the manufacturing and operation stages had the most significant impact, and the majority of the burden is associated with walls and roofs.
[58]	Greece	MF	BMCC	NA	EOL	The conclusions of the study presented the benefits of the environmental impacts of a steel building and their positive effects in terms of environmental sustainability.
[59]	Switzerland	MF	BMCC	CED, GHG, FDP	P+T+EOL	The impact due to new materials in the renovated building is negligible, and the overall impact related to GWP is reduced.
[60]	Malayasia	SF	BMCC	GHG, ODP, HT, FDP, ET	NA	The study analyzed the environmental impact of residential buildings and concluded that PPVC is the most sustainable method.
[55]	Canada	SF	BMCC	GWP	M+C	According to the study, neither the modular nor the conventional construction methods are

						the best option for ecologically friendly construction.
[49]	Sweden	MF	ECP	GWP, AP, EP and ADP	O	The study revealed that the operational phase has the greatest environmental impact, and, during the heating season, renovation had a significant influence on the energy demand.
[61]	Sri Lanka	NA	BMCC	DR, LCC	O	The study assessed lifecycle costing of two buildings – green and conventional. The study concluded that the cost of green buildings construction is by 37 % higher than that of the conventional buildings.
[62]	Palestine	MF	ECP	Energy Demand and GHG	All	The results indicated that the energy consumption and GWP of contemporary dwellings have a greater influence on the environment than those of the traditional houses because of the use of concrete and steel.
[63]	Czech Republic	NA	BMCC	DR, CC, RC	C+O	The results concluded that there is no optimum applicable material solution as it will be unique for each building and its user.
[53]	Spain	MF	ECP	GHG, LS	C+O+EOL	The passive renovation is determined as the best choice in terms of the environmental impact and costs, but there are constraints with the lifespan.
[64]	Ireland	SF	BMCC	GWP, ODP, AP, EP, POCP, Costs	D+O	The study compared the cost-optimal approach and energy-optimal approach for building materials. The study found that energy-efficient designs based on LCA and cost differ from the cost-optimal designs based on only lifecycle energy and cost.

[65]	Kazakhstan	MF	ECP	EE, GHG	O	The findings of the study show that there is a correlation between the level of comfort and its influence on CO ₂ emissions.
[66]	Saudi Arabia	SF	ECP	CED, GWP, ODP, AP, EP, POCP	P+T+C+O+EO	The study determined that the operating phase had the highest GWP and AP of 2.61×10^6 kg CO ₂ -eq and 1.75×10^4 kg SO ₂ -eq, respectively.
[54]	Brazil	SF	BMCC	EQ, HH, Res	P	This paper determined that masonry concrete blocks have a higher environmental impact with 46 % and 69 %, mainly due to the production of the concrete during its manufacturing stage.
[67]	Spain	MF	BMCC	CED, GWP, ODP, AP, EP, POCP, SFP, NRED, RED	C+O	The results concluded that, although energy interventions can fulfill the energy-efficiency aspects, other interventions, such as the indoor comfort, the solar heat gain, or the daylight should also be considered from the design to the end of life.
[68]	Sweden	SF	WB	LS, DR, Elec. Price, WP, CC, IR, CO ₂	D+P+C+O+EO	The study explored the long-term costs of single family building during entire lifetime. Economic parameters such as discount rates, inflation rates and energy escalation rates are analyzed. The results showed that the discount rate is decreased from 7 % to 3 %, and the total costs are increased significantly by 44 % for a 100-year lifespan, in which, construction and labor costs represent a major part of the total LCC.
SF – Single Family; MF – MultiFamily; ECP – Entire Construction Process; BMCC – Building Materials and Construction Combination; EO – End of Life; GHG – Green House Gases; GWP – Global Warming Potential; CED – Cumulative Energy Demand; LCE – Life Cycle Energy; LCC – Life Cycle Costs; HH – Human Health; CC – Climate Change; EQ – Environmental Quality; Res – Resources; LS – Lifespan; DR – Discount rate; P – Plan; C – Construction; O – Operation; T – Transportation.						

1.4.2 Review of the environmental performance methods for residential building assessment

Apart from the life cycle assessment, environmental performance schemes are widely used to evaluate the performance of buildings. There is a number of individual systems globally such as BREEAM, LEED, DGNB, HQE, etc. devised to assess the environmental sustainability of a building with such extensive criteria as emissions to air, water, greenhouse emissions, waste, impact of materials, the level of daily illumination in structures, or some other specific combinations of parameters, etc. [69]. These schemes are available to access over various typologies of buildings, such as residential and non-residential buildings covering different stages of construction. The *Building Research Establishment Environmental Assessment Method* (BREEAM, UK) [70] was the first developed comprehensive performance scheme, followed by *Leadership in Energy and Environmental Design* (LEED, USA) [71], *Comprehensive Assessment System for Built Environment Efficiency* (CASBEE, Japan) [72], GreenStar (Australia) [73], *High Quality Environmental standard* (HQE, France) [74], and *Deutsche Gesellschaft für Nachhaltiges Bauen* (DGNB, Germany) [75]. Internationally, there are several assessment tools available across all regions over the world (Annex 1). These methods have been adapted to the local climate, regulations and objectives, and their functioning and weightage also varies accordingly [76]. Several assessment tools have been adapted for renovation purposes, along with the assessment tools specifically developed for renovation, such as reSBToolCZ [77]. Furthermore, these schemes are constantly being revised; thus, they are evolving according to the global objectives and markets. For example, BREEAM revised the weightage credits from its 2014 version to the version of 2018 [78].

Previous studies (Table 2) attempted a comprehensive comparison of all the currently existing assessment schemes and compared them with other international or regional methods [37,58,76,79–82]. Specific assessment methods LEED, BREEAM, and ITACA were compared in [83,84]. Moreover, several authors compared more than three systems together, e.g. Illankoon *et al.* [85] compared eight certification systems in Australia; similarly, Mattoni *et al.* and Doan *et al.* compared ca. 10 systems including the regional ones [79,82]. BREEAM, LEED, CASBEE, and DGNB are most commonly analyzed methods among the research community. On the other hand, so far, few researchers have attempted to apply these methods in actual case studies. One of such attempts is Rastogi *et al.* who compared two versions of LEED and applied energy analysis on a case study residential building in the USA. The study compared the feasibility and flexibility of both versions [86]. Some studies attempted to review the international system and sought to recommend the suitable findings to their regional version [37]. The studies have also raised a concern about the common consensus of these schemes, thereby providing various suggestions and recommendation based on the available resources.

Moreover, the studies presented in this dissertation have analyzed the categories associated to building performance tools. Most of the literature compared *energy*,

materials, *site*, and *comfort* as the four major areas of interest; also, a conclusion was made that the environmental aspect is widely acknowledged. A contemporary-built environment is created and managed by utilizing large amounts of energy and materials, thus impacting the health and well-being of the occupant [73]. Out of all the relevant studies, only one study (which focused majorly on the well-being and comfort of the occupant, i.e. Obrecht *et al.*) studied the aspects of comfort from the occupant's perspective by using the appropriate performance assessment methods [87]. Moreover, a few studies have also highlighted the wide differences in the evaluation methodology and the allocation of weightage across the categories [82,86,88]. Nevertheless, these methods follow the common approach towards evaluating the performance of buildings [76].

On the other hand, the comprehensive nature of these methods makes it challenging to integrate all of the assessment criteria, as this would be not only time consuming, but also a large amount of information would be required. Although there is a vast number of studies analyzing the comprehensiveness of these methods, the literature has not yet presented the LCA aspects and their incorporation. Moreover, our investigation found no literature and no small-extent studies related to the influence of these methods with respect to the project life phase of the building, i.e., the design, operation, construction, etc. Major focus on different categories of these methods, their links and integration between different sustainability aspects could not be found in the literature discussing this field of science.

1.4.3 Review of other assessment methods and building renovation

Multi-criteria analysis has been increasingly developed to achieve sustainability in the building sector and renovation projects. Following the environment impacts, economic assessments are commonly considered to contribute to the analysis of the renovation scenarios from the multi-criteria perspective. In 1983, Gero *et al.* were the first to propose a multi-criteria model to be used in the building design process to explore the trade-offs, such as the capital cost and the usable area [89]. Many researchers have focused on multi-criteria evaluation of renovation scenarios, decision-making, and optimization in the renovation process (Table 2). Multi-criteria decision making is used as an important technical tool for the decision support, weighting, ranking and prioritizing various aspects of renovation. The different multi-criteria techniques, such as the *Weighted Sum Method* (WSM), the *Weighted Product Method* (WPM), the *Analytical Hierarchy Process* (AHP), the *Preference Ranking Organization Method for Enrichment Evaluation* (PROMETHEE), the *Technique for Order Preference by Similarity to Ideal Solutions* (TOPSIS), the *Fuzzy Set Theory* and so on have been considered. There are several methods that have been deployed to evaluate different renovation scenarios, alternatives, costs, social opinions, and to develop a framework (**Table 3**). Tupenaite *et al.* analyzed different renovated projects by using the multi-criteria method to evaluate the energy performance of buildings [90]. Multi-criteria analysis is often used to compare and evaluate the renovation solutions and scenarios for different stakeholders.

With respect to these studies, multi-criteria evaluation is also used as the methodological approach which served for many authors to analyze the application of frameworks. Addy *et al.* used MCA to evaluate the weightage score for the energy performance criteria for residential building renovation [91]. Gervasio *et al.* and Jafari *et al.* used MCA for optimizing and benchmarking the energy performance of buildings [19,92]. Besides, the authors also included such aspects as the economic and social aspects in their studies [19,93,94]. Several researches have put forward frameworks which include sustainability by using MCA. A few researchers also exclusively focused on the social dimension of renovation in their studies and proposed a framework for social assessment [29,95–97].

As cited above, the studies related to LCA have emerged in the construction sector over the past decade. Some of the studies have integrated LCA with MCA to compare various renovation solutions during different stages of renovation. Kaklauskas *et al.* developed a multi-utility design to analyze the energy performance of various integration designs during renovation [98]. Similarly, Hu proposed an integrated framework combining LCA and MCA for comprehensive impact assessment aiming to bridge the missing indicators, such as water, waste, etc. to be included in the building renovation [99]. Liu and Qian developed a framework focusing on the environment and social impact of building renovation by using MCA [100].

LCA is also used as optimization and quantification method in the renovation process. LCA and LCC are integrated to analyze housing blocks by quantifying environmental impacts in monetary terms [2]. Cetiner and Edis proposed a methodology based on LCA/LCC to evaluate such retrofits as thermal insulation and windows that can be beneficial to select the alternatives during renovation [101]. Cellura *et al.* also studied the environmental benefits of building retrofits in the Italian context and proposed an assessment model which included the environmental effects due to the consumer behavior along with other energy-related indicators [102]. Risholt *et al.* assessed the long-term viability of two nearly-zero energy renovation options in a Norwegian detached house and developed an iterative method for evaluating sustainability, encompassing energy and technical performance after renovation, life cycle cost, and homeowner preferences [103]. Based on the findings, different researches attempted to integrate LCA and MCA in different stages of renovation. The current studies also indicate so much focus being given on the environment aspect, some studies optimize with algorithms to evaluate the costs involved in renovation [104]. Attempts related to S-LCA have not yet been organized and/or standardized, and different methods propose several indicators related to the social aspect, however, there is no common ground on this topic. The literature also shows that studies have considered region-specific case studies so that to evaluate the performance of a building; on the other hand, the indicators under consideration are not region-specific.

Table 2. Review of environmental performance assessment in previous studies

Source	Country	Building type	Study type	Tools analyzed	Study Outcomes
[37]	Slovenia	All buildings	Review and recommendation	BREEAM, LEED, DGNB, SBTool	The study was concluded with the determination of the possibility to implement the discussed methods in Slovenia and their future developments.
[83]	Portugal	Residential	Case study	LiderA, SBToolPT, CSH, LEED	The study concluded that the final class is identical in the various other tools, still it is unclear whether the tools point to the passive design as major solution to achieve efficient NZEBs.
[105]	Italy	Residential	Case study	LEED, ITACA	Both schemes were employed on selected residential buildings in Italy. The results showed no significant technical differences between the two certification methods
[106]	Spain	Residential	Qualitative analysis & Case study	SPE, BREEM, LEED, GBT tool	The study concluded that the integration of a new tool is user-friendly and capable of producing highly comparable results. Also, the results demonstrated that a better performance is required when pursuing changes.
[80]	Colombia, Qatar, Jordan	All buildings	Integration study	LEED, QSAS, SABA, BraVe	The research attempted to incorporate the (BRaVe) methodology into the already existing tools to embrace ‘cross-disciplinary’ criteria in the developing countries.
[84]	Hong Kong	All buildings	Comparative study	LEED and BEAM Plus	Comparison of two assessment systems BEAM plus and LEED regarding the aspect of materials, indoor quality, and water management. The findings concluded that the BEAM plus system was more suitable to Hong Kong because of its regional adaptability.

[79]	NA	All buildings	Statistical analysis	BREEAM, LEED, CASBEE, and Green Star	BREEAM is the only tool which could assess all the four sustainable factors, such as the indoor environment quality, energy, and materials. More focus should be given to the economic and institutional factors so that to improve the capability of these systems.
[86]	USA	Residential	Case study	LEED	The compared results revealed significant differences in LEED v3 and v4 performance points, which are employed for multi-family building energy performance evaluations. LEED v4 is advantageous in terms of the required minimum energy performance improvement, however, LEED v3 is beneficial if the percentage energy performance is greater than 34% for mid-rise multi-family structures.
[107]	Qatar	All buildings	Comparative study	LEED, BREEAM, GSAS, Estidama	The limitation of this study is the adaptability to climate change, and its importance on sustainable communities and cities.
[88]	Malaysia	All buildings	Comparative study	GBI, GreenRE	The research concluded that both tools have a similar objective and are well suited for the Malaysian built environment; however, the GreenRE score credits are much easier to attain than the GBI tools.
[82]	NA	All buildings	Review	BREEAM, CASBEE, LEED, ITACA, Greenstar	The study concluded that the certification tools are not similar in terms of six areas: site, water, energy, comfort and safety, materials and outdoor quality.
[85]	Australia	All buildings	Review	AccuRate, BERS, FirstRate, Ecospecifier, Greenstar, NABERS, NatHERS	According to the findings of this study, rating instruments in Australia lack obligatory standards, rules, and incentives.

[87]	Slovenia	All buildings	Review	BREEAM, LEED, DGNB, WELL	The study indicated that occupant health and well-being are crucial, and this is based not just on building design, but also on building management and the services supplied within the structure.
[81]	Denmark	All buildings	Comparative analysis	Active House, BREEAM, DGNB, Greenstar, HQE, LEED, LBC, Miljobyggnad, Nordic Ecolabel and WELL	The research showed a large gap in the weight allocation of various dimensions, and all the schemes majorly focused on the environmental aspects, except for DGNB, where economy is not represented good enough.
[108]	UK	All buildings	Review	BREEAM, LEED, GSAS, GRIHA	According to the study, assessment systems should follow the same standard to replicate science-based decisions, procedures are needed, and progressive standards should advance industry practises rather than simply rewarding businesses.
[109]	NA	All buildings	Review	BREEAM, CASBEE, GreenStar, ASGB, BEAM GM, GBI, GG, GRIHA, LEED	The most prominent evaluation criteria in the descending average weights across the analyzed instruments are energy efficiency, indoor environment, health and welfare, material efficiency, water efficiency, and innovation.

Table 3. Review of integrated assessment from previous studies

Source	Country	Study	LC Phases	Aspects assessed	Indicators	Particularities
[98]	Lithuania	MCDM + LCA	NM	Env, Eco, soc	LC energy	Model System
[110]	Italy	LCA + IOA	Plan	Env	CO ₂	Case study
[111]	Turkey	LCA +L CC	NM	Env, Eco	EC, CI	Case study

[29]	Sweden	LCA, SLCA	O	Env, Eco, soc	Social interaction, Identity & Experience, safety, security & openness, Health & Green environments	Methodology
[104]	Spain	Algorithm, LCA	NM	Env, Eco, soc	Eco Indicator 99	Decision-making optimal method
[2]	Spain	MCM	O	Env	Energy and GHG	Case study and framework
[90]	Lithuania	MCM	O	Env	Energy efficiency, GHG emission, working condition	Assessment
[91]	Ghana	MCDM	D, O	Env	Energy efficiency	Framework
[19]	USA	MCM, LCC	PD, D	Env, Eco	TC, CO ₂	Optimization framework
[92]	Europe	MCM	D	Env	GWP and TPE	Framework Benchmarking
[60]	Malaysia	LCA, LCC, SLCA	D	Env, Eco, soc	GWP, FDP, AP, EP, HTP, LCC, SLCA	Assessment
[100]	Singapore	MDCA, LCA	P, C,O, EOL	Env, Soc	Worker, occupant, local community	Theoretical framework
[99]	USA	MDCA, LCA	D	Env	GWP, AP, EP, HT, Smog, ODP, water, waste	Framework
[95]	Denmark	MCDM	PD, D	Soc	Health, functionality, communication, identity, education	Framework
[112]	Spain	MCDM, LCA	O	Env, Soc	Social, security, comfort, aesthetics, identity	Model
[94]	Switzerland	Statistical, LCA, LCC	O	Env, Eco	GWP, NPV	Assessment
[96]	Italy	SWOT	D	Soc	Social interaction, participation, flexibility,	Framework

					architectural identity, security	
[113]	Australia	LCSA	D, O	Env, Eco, Soc	Service life, CO ₂ , EP, AP, CED, IEQ	Application result
[97]	Tehran	MCDM	O	Soc	Anti-social behavior, security, social cohesion	Application result
[93]	Portugal	LCA-DEA	D	Env, Eco	CC, AP, EP, ADP, net present value	Decision support methodology
[114]	Serbia	MCM	O	Env	LS, CO ₂	Application result
[115]	Spain	MCDM	O	Env	Total energy demand, cost, acoustics, payback period	Framework
MCDM – Multi Criteria Decision Making; LCC – Life Cycle Costing; LCA – Life Cycle Assessment; SLCA – Social Life Cycle Assessment; LCSA – Life Cycle Sustainability Assessment; IOA – Input-Output Analysis; SWOT analysis – Strength, Weakness, Opportunity, and Threat; DEA – Data Envelopment Analysis; T – Transportation; PD – Pre-Design; D – Design; C – Construction; O – operation; EOL – End of Life ; EC – Ecopoints; CI – Cost Ratio; HTP – Human Toxicity Potential; GWP – Global Warming Potential; EP – Eutrophication Potential; AP – Acidification Potential; NM – not mentioned.						

Table 4. Review of multi-criteria decision-making methods on renovation

Source	Country	MCDM Method	Objective	Application	Performance Method
[116]	Malaysia	DELPHI-FAHP	Ranking	Environmental efficiency	CASBEE
[90]	Lithuania	SAW, TOPSIS COPRAS	Ranking	Environmental efficiency	None
[117]	India	AHP	Ranking	Environmental efficiency	SBTool
[118]	Turkey	Fuzzy sets	Decision making	Energy performance	BREEAM, LEED
[115]	Germany	Pairwise comparison TOPSIS	Decision making	Alternative design	None
[91]	Ghana	DELPHI-AHP	Weighting	Energy efficiency	None
[119]	France	ELECTRE III	Decision making	Renovation scenarios	None
[120]	Canada	TOPSIS	Decision making	Quantification of alternatives	None

[121]	Oman	AHP	Weighting	Performance assessment	BREEAM, LEED, PBRs, QSAS
[122]	Lithuania	SAW, COPRAS	Evaluation	Evaluation of sustainability	None
[123]	Egypt	AHP	Decision making	Sustainable performance	LEED, SBTool, BREEAM, CASBEE
[124]	China	AHP	Weighting	Performance assessment	LEED, BREEAM, CASBEE, GB50378
[125]	USA	COPRAS	Decision making	Housing affordability	None

1.5 Indicators in Use

Evaluation and monitoring of performance require a certain set of parameters which are both qualitative and quantitative in nature. An indicator can quantify and simplify information in a manner which makes it understandable for the decision makers and stakeholders [99]. Several assessment tools set their indicators according to the nature of the study and the context which is needed. The list of indicators related to the building activity is comprehensive as it holds a wide spectrum of typology, characteristics, and associated impacts. Often, these comprehensive sets of indicators are categorized based on their impact category and the theme, such as the environment, social, economic, or cultural themes. With a large number of assessment methods throughout the world, there is a wide scope of indicators that are consolidated from the literature studies (Table 5).

Table 5. Commonly studied indicators in the literature on renovation

Indicators	Aspects			Category	References
	Env	Soc	Eco		
Energy performance	×	-	-	Energy	[99,121,126–129]
Greenhouse emissions	×	-	-		[99,126,130–136]
Primary energy	×	-	-		[126,130,135]
Human health	×	×	-	Health/wellbeing	[99,131,134,137–139]
Accessibility	-	-	×	Functionality	[99,127,140]
Thermal comfort	×	×	-	Indoor quality	[126,136,138,140]
Parking	-	-	-	Functionality	[140,141]
Ventilation	×	-	-	Energy	[127,134,136,139,140,142]
Waste management	×	-	-	Waste	[126,134,138,140,142]
Indoor quality	×	×	-	Indoor quality	[121,127,137,140,143]
Materials recycle	×	-	×	Energy	[134,141,143]
Air pollution	×	-	-	Pollution	[121,132,134]
Water consumption	×	-	×	Resources	[99,126,132,134,139]
Acoustic comfort	×	-	-	Indoor quality	[121,134,142]
Visual comfort	×	-	-	Indoor quality	[130,138,139,143]
Maintenance cost	-	-	×	Costs	[126,128,131,138]
Building maintenance	-	-	-	Management	[134,140–142]
User satisfaction	-	-	-	Management	[133,137,141,143]
Building materials	×	-	-	Energy	[126,139,140,142]
Heritage value	-	×	-	Culture	[127,141]
Safety	-	×	-	Functionality	[132,138,140–142]
Durability	-	×	-	Functionality	[126,130]
Life cycle costs	-	-	×	Costs	[131,136,137,139]
Potential savings	-	-	×	Costs	[128,131,137,141]
Investment costs	-	-	×	Costs	[131,133,134,136,137,139]
Payback period	-	-	×	Costs	[128,131,137]

From **Table 5**, it is possible to observe several indicators for the performance evaluation of a building that have been studied before. Studies have also grouped the specific indicators according to their impact category for better understanding and easier evaluation. It is understandable that the ‘energy-related’ indicator is often analyzed more, and indicators of costs are followed by since costs represent an important factor in the renovation actions and comfort and health aspects. The least studied aspects from the table are the historical value and durability of the building during/after the renovation process.

Chapter Conclusion

The main objective of this section is to analyze the already existing literature on renovation and residential buildings. During the recent decades, multiple assessment tools for renovation have emerged in the academic and construction industries. These tools/methods are applied at different stages of renovation projects, while most approaches focus on the performance estimation of renovation scenarios both quantitatively and qualitatively. It is evident from the literature studies covering different aspects of building evaluation, such as the life cycle assessment, energy performance and sustainability. Despite a large number of studies related to the renovation process, studies related to renovation and residential buildings are lopsided and fragmented. From the earlier studies, it can be inferred that two major approaches are established to evaluate the environmental impact of buildings: 1. Life cycle assessment; 2. Environmental performance assessment schemes; and 3. A combination of these assessment methods along with multi-criteria decision-making.

The building performance schemes are used widely to address energy performance, thus leaving out the impact of the whole building throughout its renovation process. This means that, despite this fact, LCA is used in these schemes, and the emphasis on renovation largely focuses on the energy component only. A few studies have considered the renovation process holistically and comprehensively so that to evaluate the performance; meanwhile, studies related to residential typologies, such as multi-apartment buildings, are rare. Therefore, various existing methods and tools were reviewed from the renovation and life cycle perspectives. The review revealed that the existing methods can be used as a support tool or a combination methodology to evaluate the impact of renovation at multiple levels. Against this backdrop, the environmental performance schemes and life cycle assessment tools are used as the main tool to develop a methodology for environmental impact assessment for the residential renovation. Therefore, the primary goal of this thesis is to develop a methodology for environmental impact assessment for the renovation of residential buildings using the life cycle approach. Furthermore, the renovated multi-apartment building was taken as a research object along with other techniques to achieve the primary objectives of this thesis which are presented in Chapter 2.

2 METHODOLOGY

The selection of a right research methodology are reflection of the principles and procedures of logical research thoughts which depends on the precise identification of the research finding's scope and depth [144]. The aim and objectives of the dissertation are formulated based on the problem identified during the review of literature. The previous studies helped to achieve the aim of this dissertation, that is, a combined methodology and the relevant indicators were developed for which a case scenario was applied. The following flowchart (**Fig. 1.**) represents the main stages of this doctoral dissertation and the involved steps to achieve the objective of this research.

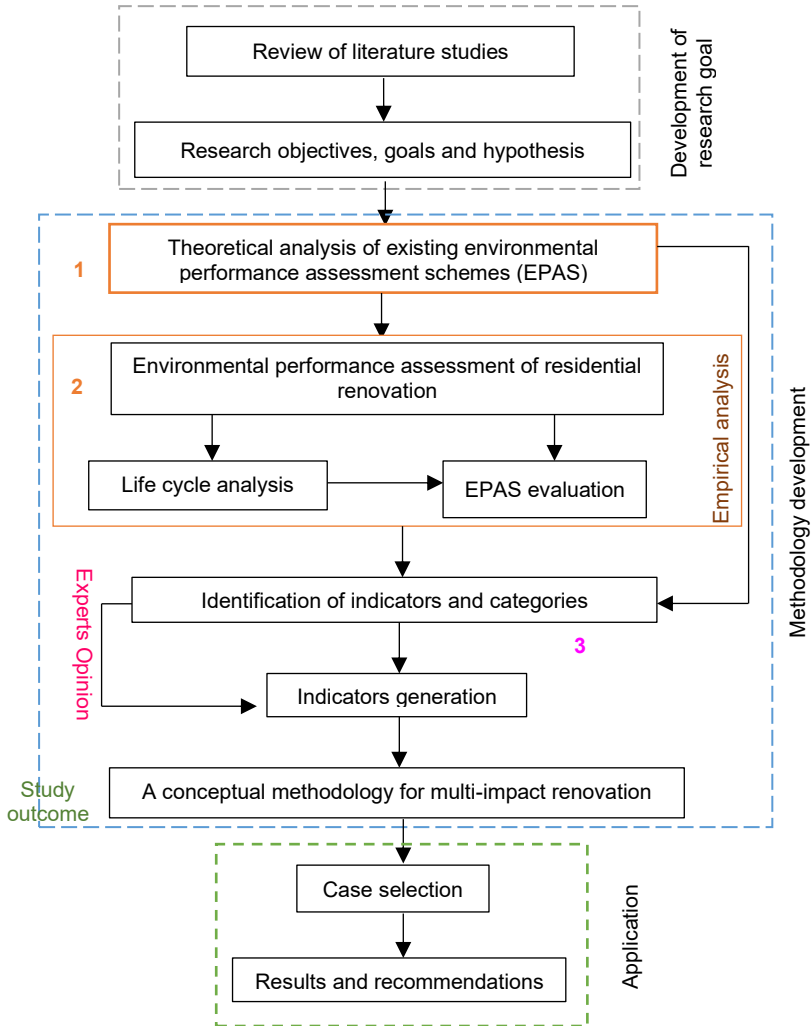


Fig. 1. Research methodology of this dissertation

As a part of the research, the following methods, concepts and tools were used to achieve the goal of this research. The materials used for this research are presented as follows:

a. Review and/or content analysis of literature and comparison

For this study, the comparison of the relevant literature was imparted as a primary step to formulate the research problem. The content analysis was implemented by using specific/relevant technical manuals, official documents and websites as a part of the desk research. This analysis is both qualitative and quantitative as it is used to consolidate the base from which further investigation can take place. At the development stage, the combination of these approaches was employed as the primary principle.

b. Survey research

In this research, the survey technique was used to validate the identified indicators so that to evaluate the results of the proposed methodology with the help of a questionnaire to receive opinions from experts. A questionnaire is an effective tool in conducting survey research [116]. The set of questions was formulated with relation to the renovation process, factors, barriers, life cycle process and indicators. The results of the questionnaire were interpreted by using FAHP process by weight prioritization. The standardized design of the questionnaires was expected to result in superior data collecting efficiency and elimination of misunderstanding.

c. Multi-criteria decision making

MCDM is a collection of methods for combining multiple evaluation criteria to select, rank, sort, or describe a set of options. The primary goal is to offer decision makers with tools that will allow them to progress in problem solving (i.e. the selection of multiple indicators) [90]. As mentioned in the literature, there are several methods will enable a decision-maker to weigh the performance indicators with a simple empirical study. There are specific steps which need to be considered while following the decision-making methods. 1. The criteria in use shall be chosen in coherence with the decision and represented through the same scale that can be measured and validated; 2. The subjects available for evaluation shall be compared and shall be feasible to decide for (if selected); 3. The researcher shall be aware of the MCA method and its type to be used in the study; 4. The aggregation method shall be suitable to achieve a product, an average, and a function.

This study employs the *Fuzzy Analytical Hierarchy Process* (FAHP) model to determine the importance of the performance indicators by weighting them with a structured technique. The principle of FAHP involves a few steps starting with the structure of the problem which is presented in the hierarchy. Next, triangular fuzzy numbers are used to build pairwise matrices with fuzzy judgments, as shown in **Fig. 2**. Based on the aggregation, fuzzy weights are calculated, and then defuzzification of weights is done [145]. A detailed content, scale and formulae are discussed in the following chapters (see Chapter 5).

FAHP enables methodical approaches to qualitative, imprecise information, or even ill-structured decision challenges. Despite the ease with which AHP can handle both quantitative and qualitative data, there is often a bias in judgements. Fuzziness and vagueness may be present in these decisions which contribute to imprecise decisions [146]. Furthermore, multilateral data collection is far more practical than the alternatives. In the pair-wise comparison, the approach provides more pragmatic results and it derives significances from both consistent and inconsistent processes of comparison [147].

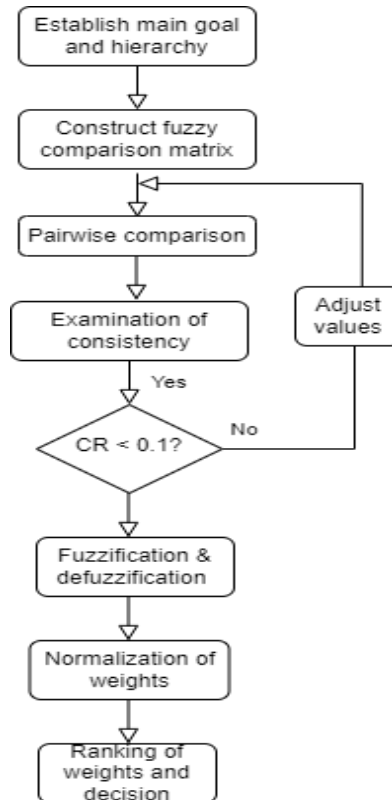


Fig. 2. Steps involved in the FAHP process

d. Life cycle analysis

A leading tool which has the potential to fully evaluate all sources and different means of impact/emissions is the *Life Cycle Assessment (LCA)*. LCA is often used as in-deep analysis instrument on different scenarios and variables that can affect the decision to renovate or search for alternatives [148]. LCA is deployed in this study to analyze and quantify the impacts associated with the building renovation. For this

analysis, a case scenario was selected to study the performance of the renovated building to understand their entire impact over different phases.

LCA is an approach for quantifying the potential environmental impacts of a product, process, or activity over its entire life cycle. The LCA-based environmental impact research was carried out in accordance with the procedure, and suggestions are included in the European standards series ISO 14040 and ISO 14044 [41,42]. According to the standards, the LCA evaluation is carried out in the following steps [149] (**Fig. 3**).

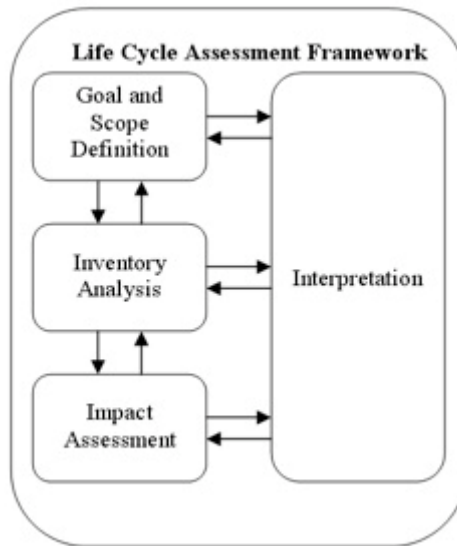


Fig. 3. Process of Life Cycle Assessment

1. The goal and the scope of the study define the purpose of the intended application and set a boundary for the assessment.
2. The *Life Cycle Inventory* (LCI) is used to collect data to accomplish the intended goal of the study. Accounting various input-output data related to the analysis/service, which helps carry out impact assessment.
3. The *Life Cycle Impact Assessment* (LCIA) contains the category definition, classification, characterization, and weighing as the main elements. Depending on the goal and the scope of the study, the above elements are used as each of them represents a different set of procedures
4. The life cycle interpretation is anticipated to assess the results in determining the inferences that can be made based on the inventory results that are consistent with the purpose of the study.

By adopting the LCA methodology, there is no need to focus on a single element, i.e., on waste, or on a certain emission category. The LCA methodology

provides an opportunity to include different environmental impact categories so that to analyze the entire life stage of the building [150].

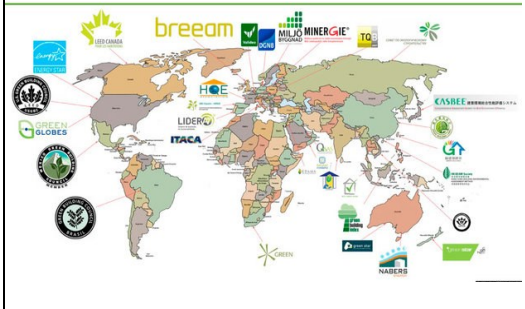
e. Case studies

In this research, the case study was employed to evaluate a few aspects of the existing methods and the new proposed methodology. For this, a multi-apartment residential building was taken to assess the impact of the renovation process. Moreover, a comprehensive study was conducted with the quantitative assessment for life cycle impacts. The case studies will help to understand the situation in great depth, the output can thus be validated, and the results are expected to contribute to the further modification of the methodology for future studies.

3 COMPARATIVE ANALYSIS OF PERFORMANCE ASSESSMENT METHODS

This chapter analyzes how the different drivers may contribute to the further development of a conceptual framework for the renovation process. For this analysis, *Environmental Performance Assessment Schemes* (EPAS)/certification have been chosen for further study to explore the differences between the schemes. Based on the studies of the previously developed literature, the following schemes were selected to analyze further (see **Table 6**). The selected schemes are most popular and most widely used across the world to certify various types of buildings. These schemes were considered based on the number of projects (more than 3000) and their availability across regions. There are around 600 schemes available worldwide, out of which, four schemes have been selected for further research [151].

Table 6. Environmental Performance Schemes globally [151]

	Schemes	Countries	Projects	Maturity
	BREEAM	93	31 113	31
	DGNB	20	8 700	12
	HQE	26	380 000	29
	LEED	10	80 000	21

The following steps are used to compare and analyze the assessment schemes based on various criteria (**Fig. 4**). The first part explores the differences between the criteria and their relation with renovation and residential buildings.

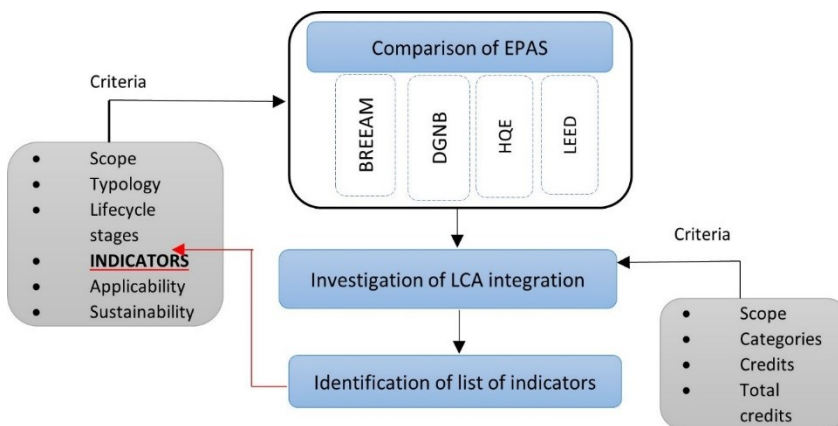


Fig. 4. Schematic flowchart used in this analysis

3.1 Environmental Performance Assessment Schemes

BREEAM

The *British Building Research Establishment Environmental Assessment Method* was the first multi-criterion scheme designed in 1990 to evaluate the performance of buildings which includes evaluation indicators across a broad range. The scheme has been adopted across various countries as the international version in 2008. The scheme offers a wide range of categories and distinguishes different construction stages and building typologies [70].

DGNB

This scheme was first established by the *German Sustainable Building Council* (*Deutsche Gesellschaft für Nachhaltiges Bauen*) in 2007 with the aim to evaluate environmentally friendly and resource efficient buildings. The scheme is based on the European standards and norms. The scheme also distinguishes between different typologies of buildings and is considered as more flexible and more easily adaptable than BREEAM and LEED. The scheme covers the key aspects related to the three pillars of sustainability by giving equal importance to each of them [75].

HQE

The *High Quality Environmental Standard* (Haute Qualité Environnementale) was first designed for non-residential buildings in France to evaluate their performance based on sustainability. Currently, this scheme is also applicable for residential, commercial, and other types of buildings. This scheme covers four themes, namely, energy, environment, comfort, and health [152].

LEED

The *Leadership in Energy and Environmental Design* is the second most widely adopted certification which was designed by the *US Green Building Council* in 1998. The system is used for construction and green building certifications which are spread across a number of countries worldwide. It is in current use. It distinguishes over ten different building typologies for various construction stages [71,153].

Table 7. Main features of the selected EPAS

Scheme	Categories	Weighting System	Rating Levels
BREEAM (1990), UK	Energy, waste, water, pollution, materials, transport ecology, management, health & wellbeing, innovation	Applied to each level	Unclassified, Pass, Good, Very good, Excellent, Outstanding
DGNB (2007), Germany	Ecological, economic, technical, process, socio-cultural & functional, quality	Applied to each level	Bronze, Silver, Gold, Platinum

HQE (1994), France	Eco construction, eco management, comfort, health	Not available	Pass, Good, Very good, Excellent, Exceptional
LEED (1998), USA	Energy, materials & resources, water efficiency, indoor quality, innovative design, sustainable sites, regional priority	All credits are equally weighted	Certified, Silver, Gold, Platinum

All these schemes are market-focused voluntary assessment methods to be used by a third-party auditor who will evaluate the achievement of each project. HQE certification has the strongest presence in Europe, and it focuses on the overall quality by balancing the energy performance, health, and well-being, while BREEAM and LEED allocate considerable coverage to the environmental and energy aspects of a building. **Table 7** shows the main features of all the selected assessment methods. These assessments are performed on a variety of different types of buildings, including educational institutions, business and residential structures, commercial kitchens, and communities. To ensure a thorough assessment, each assessment is assigned its own module and rating scores covering various aspects.

3.2 Comparison of EPAS

This section compares the assessment that has been made based on the criteria that have been embraced by the most widely used performance tools worldwide. The assessments are investigated based on: 1) scope; 2) building typology; 3) life cycle stages; 4) accessibility; 5) indicators/criteria; and 6) sustainability. The following table provides a detailed comparison of each selected method to understand their differences in environmental performance assessments. **Table 8** shows a detailed analysis of the scope of the selected methods to determine their performance.

Table 8. Comparison of EPAS by using selected criteria

Criteria	BREEAM	DGNB	HQE	LEED
Scope				
New	✓	✓	✓	✓
Existing	✓	✓	✓	✓
Refurbishment	✓	✓	✓	✓
Typology				
Residential	✱	✓	✓	✱
Offices	✓	✓	✓	✓
Urban Planning	✓	✕	✓	✓
Commercial	✓	✓	✓	✓
Institutions	✓	✓	✓	✓
Healthcare	✓	✕	✕	✓
Industrial	✓	✓	✓	✕
Life cycle Stages				
Predesign	✕	✕	✓	✕
Design	✓	✓	✓	✓

Manufacture	×	✓	×	×
Construction	✓	✓	✓	✓
Operation***	✓	✓	✓	✓
Demolition & Disposal	×	✓	×	×
Accessibility				
Academicians	✓	✓	×	✓
Authorities	✓	×	×	✓
Building consultants	✓	✓	✓	✓
Building owners/partners	×	×	✓	✓
Occupants	✓	×	×	×
Manufacturers	✓	✓	✓	×
*** includes renovation; ★ Multifamily residential; ✓ included in the criteria; × not included in the criteria				

1. *Scope and Typology of Building*: Each assessment method is unique in its application to various types of buildings, including industrial, commercial, educational, residential, and it focuses on the building's management in relation to the local and global environment. Additionally, BREEAM, DGNB, HQE, and LEED include specialized schemes for a variety of solutions, such as new or refurbished buildings.
2. *Life cycle Phases*: BREEAM, DGNB, HQE cover four stages of a building's life cycle (design, construction, operation, and maintenance). Except for DGNB, no other instrument evaluates a building's demolition and deconstruction phases. Additionally, all methods, except for HQE, exclude the predesign stage.
3. *Accessibility*: The usage and availability of systems for a different audience makes the system robust and identifies the level of social inclusiveness. On the other hand, systems, such as BREEAM, DGNB and LEED, have been developed based on an academic framework. Therefore, their accessibility ranges from experts to building owners and users. However, all the assessment methods suggest having an exclusive expert from their respective systems to audit the performance of a building.
4. *Indicators*: Based on the analysis, all major evaluation systems have focused on the following criteria: energy use, materials, project management, pollution, waste management, and water. Similarly, other indicators, such as the indoor quality, visual comfort, economic and cultural and social identity, have been given the highest priority in terms of sustainability (see **Table 9**). The above listed categories often refer to the same items or different items in the same or different categories. Sometimes they do not assess the same attributes. For example, in LEED, transport is not assessed as a separate criterion, whereas it is included under the site selection category. Similarly, DGNB does not assess transport, indoor quality, and ecology as separate categories. These are summed up under ecological quality. Correspondingly, the olfactory comfort is considered in HQE separately, whereas the other systems are included in the general category of air quality. The quality of a building is investigated by using different parameters and indicators to study the impact associated with a building.

Table 9. Comparison of indicators of each scheme

Indicators	BREEAM	DGNB	HQE	LEED
Energy				
Energy performance [en]	✓	✓	+	✓
Greenhouse emissions [en]	✓	×	+	✓
Transportation				
Public transport accessibility [sc]	✓	✓	×	☑
Alternative transportation [sc]	✓	×	×	×
Green vehicles [en,sc]	✓	✓	×	☑
Pollution				
Construction waste management [en]	✓	×	×	✓
Noise pollution [en]	✓	×	×	✓
Light pollution [en]	✓	×	×	✓
Air pollution [en]	✓	×	×	✓
Impacts of refrigerants [en]	✓	×	×	☑
Waste [en]	×	×	✓	×
Water efficiency				
Water consumption [en]	×	×	+	✓
Water quality [en]	✓	×	+	✓
Potable water demand [en]	×	✓	+	×
Wastewater [en]	×	✓	+	×
Indoor comfort and quality				
Indoor air quality [en]	×	✓	×	✓
Thermal comfort [sc]	✓	✓	✓	✓
Acoustic performance [sc]	×	✓	✓	✓
Visual comfort [sc]	✓	×	✓	✓
Olfactory comfort [sc]	×	×	✓	×
User comfort & satisfaction [sc]	×	✓	×	×
Smoke control [sc]	×	×	×	✓
Humidity control [sc]	×	×	×	✓
Resources and materials				
Material efficiency [en]	✓	×	×	×
Responsible procurement [ec, en]	✓	✓	☑	×
Fundamental material safety [en]	×	×	☑	✓
Land-use & ecology [en]	✓	✓	✓	×
Ecological value [en]	×	×	×	×
Local environment impact [en]	×	✓	✓	×
Site assessment development [en]	✓	×	✓	×
Health and well-being				
Hazards [sc]	✓	✓	✓	×
Quality of outdoor spaces [sc]	×	×	✓	✓
Safety and security [sc]	×	☑	×	✓

Toxic material reduction [en]	✓	✓	×	✓
Quality of indoor spaces[sc]	×	×	×	×
Management				
Project brief and design [sc]	✓	✓	×	×
Commissioning and handover [sc]	✓	✓	×	✓
Responsible construction practices [en]	✓	×	×	×
Environmental management [sc]	×	×	×	×
Building information [sc]	×	×	×	×
Cleaning & maintenance [sc]	×	×	✓	×
Innovation [sc]	✓	×	×	✓
Functional and technical aspects				
Adaptability [en, ec]	✓	✓	×	×
Durability and resilience [ec, en]	✓	×	×	×
Flexibility [ec, en]	✓	✓	×	×
Design & quality of construction [en]	×	✓	×	×
Life cycle impacts [en]	✓	✓	×	✓
Life cycle costs [ec]	✓	×	×	×
Commercial viability [ec]	×	×	×	✓
Deconstruction [en]	×	✓	×	×
✓ Included; ✓✓ Included as a separate category; ✓ Considered under another category; + included together with other indicators; × Not included; en – Environment; ec – Economy; sc – Social				

5. *Sustainability*: With so many options available, and to keep up with the global updates, many methods have been devised to include aspects of sustainability. Therefore, the purpose of this criterion is to analyze selected EPAS with relevance to the definition of sustainability. It is noticeable that each EPAS system allocates weightage for categories and sub-categories. It is also possible to understand that all EPAS methods follow different evaluation patterns and a different placement of indicators under categories.

Table 10. Points distribution for sustainable aspects based on categories

	BREEAM (pts)	DGNB (pts)	HQE (targets)	LEED (pts)
Environment	Energy ~22.5 Waste ~6.5 Water ~6.5 Pollution ~9 Materials ~6 Ecology ~15	Ecological ~40	Eco construction ~4	Energy~38 Resources ~10 Water Efficiency ~12 Sustainable Sites ~7
	Total ~78 %	Total ~40 %	Total ~25 %	Total ~62 %
Social	Health ~6 Innovation ~10 Management ~6.5	Socio-cultural & functional ~30	Comfort ~4 Health ~4	IEQ ~16 Innovation ~6 Transportation ~15

				Regional Priority ~4
	Total ~ 20%	Total ~ 30%	Total ~ 50%	Total ~38 %
Economy	Management ~2	Economic ~30	Eco management ~4	Total 0 %
	Total ~2 %	Total ~30 %	Total ~25 %	

BREEAM, DGNB, and LEED are compared directly based on their individual categories and the percentage of allocation. However, HQE could not be compared because of their allocation in the system. HQE does not assign a weighting factor to each category because this framework assigns equal weight to each category throughout the assessment. This gives a picture of how each indicator spreads across the groups and their weightage assigned. Therefore, all the indicators were analyzed to group them under three aspects, specifically, environment, society, and economy, based on the credit points from the system (**Table 10**). The grouping of categories under sustainable aspects is completely based on the author's personal understanding and subjective perspective [37,60].

Environment is the primary aspect on which all methods focus. More than 75 % of indicators are adopted based on the environmental aspects. On average, 60 % of all methods focus on the environment factor. The highest significance is given to energy efficiency, water utilization, and materials under the environment category. The social category shows a highest distribution of 50 %; this implies that the social aspect has been receiving a lot of attention in the recent times. The functional aspects, such as aestheticism, indoor quality, and thermal quality, visual comfort and occupant well-being, are indicators which receive significant scores. BREEAM modestly contributes to the aspect of economy with an average of 3 % approximately. On the other hand, DGNB assigns equal weightage to all the three pillars of sustainability. However, the indicators under the categories provide more insight and bring to attention that few indicators to be looked beyond the social aspects. For example, it would be accurate to group the areas of procedural, management and innovation under sustainability. From the analysis, it is evident that not all the currently available methods give equal priority to all the three aspects of sustainable pillars; nor are these categories classified under any sustainable pillars. Therefore, mostly, the credit points are based on the stakeholders and different local contexts. This brings us to the point of discussing the global consensus or the common language for these indicators [37,79]. Hence, it is perfectly clear how these methods may ensure that sustainability is achieved.

3.3 Investigation of LCA Integration in EPAS

Firstly, it should be noted that the LCA method and indicators are integrated within the performance assessment methods. The purpose of this section is to understand the LCA protocols which have been incorporated in EPAS. The information relevant to the LCA components was collected through various means, such as technical manuals, websites, and research papers. Table 9 defines the comparison between the selected systems and their LCA incorporation within each

method. It is analyzed over the following criteria: scope, LCA credits, relevant LCA indicators, so that to show their level of utility and importance.

3.3.1 Implementation of LCA

- a. BREEAM: The credits are awarded in Mat 01 for life cycle impacts. This requires *Environmental Product Declaration* (EPD) data to calculate greenhouse gas emissions. Similarly, *Materials for hard landscaping and boundary protection* Mat 02 provide direct assessment by using the BRE tool [154,155]. To encourage the minimum operational energy demand, Ene 01 *Reduction of energy use and carbon emissions* score is assessed based on CO₂ emissions. The criteria are evaluated in two ways: 1. Energy performance with authorized building energy calculation software; 2. Energy efficient design features. However, BREEAM, as an assessment method of the entire building, does not endorse specific products as *BREEAM compliant*. Compliance with the applicable criteria and performance of the selected products shall be demonstrated for evaluation purposes [70,108,156].
- b. DGNB: The system assigns equal weightage to the following categories: ecological, economic, sociocultural, and functional quality. The tool integrates LCA and LCC along with the building process. The scores of the individual criteria are applied as a fixed weighting factor, and a performance score is calculated for each criterion relative to a reference building. LCA was analyzed for the raw materials, construction, operation, and end-of-life stages. The data is acquired from the *European Sustainable Construction* database (ESUCO), or project-specific data. The points are given to those entities which conform with the reference values, and additional points are given for carbon neutrality in design and construction as per *Agenda 2030* [37,75].
- c. HQE: Certification is based on four themes: construction, comfort, health, and environmental management. The environmental performance of a building can be assessed by focusing on primary nonrenewable energy sources and the emission control. The assessment relies on data based on EPDs [74,153].
- d. LEED: LCA is incorporated at the materials and resources level and is calculated for six environmental impacts, such as GHGs, depletion of stratospheric ozone, eutrophication, acidification of water and land, and formation of tropospheric ozone indicators. A minimum of 10 % is assigned for the reduction of impacts, and additional five points are awarded for new buildings that reduce their ‘life cycle’ impacts during its design and construction phase. The weightage was calculated based on LCA-TRACI [71,153,156].

3.3.2 Comparison of integration of LCA in EPAS

The relationship with LCA in all methods provides insight into the level of integration of indicators within the system. In DGNB, the evaluation system covers the whole building and all phases, while, in BREEAM and LEED, it is only applied

at the materials level. In the case of BREEAM, the crediting of indicators (Materials and Energy) is not entirely transparent at each phase of the process. The LEED method gives more points for energy efficiency in the operational stage, where a high score is awarded for embodied energy. As mentioned above, the credits for building emission reduction for the cases of both new and renovated buildings are based on baseline building requirements. The building reference should be self-declared as a baseline design that must be comparable to the function, size, orientation, and so on to establish a reference. Regarding the distinction between BREEAM and LEED, in terms of calculation, LEED provides a direct score based on evaluation, and credits are awarded based on the fulfilment of the category [37,108,156].

Table 11. Investigation of LCA incorporation in each method [38,82,154]

	Scope		Categories	Indicators	Total weightage
BREEAM	Material level	Whole building level	Energy, Materials	Ene 01 Energy Efficiency Mat 01 Life Cycle Impacts Mat 02 Hard Landscaping and Boundary Protection Mat 03 Responsible Construction Products Wst 05 Adaptation to Climate Change Man 02 Life Cycle Costing	5.9%
DGNB	Material level	Whole building level	Global, Local Environment, Resource, Waste	Env 1.1 Life Cycle Impact Assessment Env 2.1 LCA – Primary Energy	13.5%
HQE	Material level		Materials	2.2 Environmental Quality of the Materials, Products, and Equipment used 4.1 Thermal Design	9%
LEED	Material level	Whole Building level	Materials, Resources	MRc1 Building Life Cycle Impact Reduction MRc2 Environmental Product Declarations and Product Optimization MRc3 Sourcing of Raw Materials	2.7%

DGNB and HQE methods rely mostly on EPDs of building products to award credits to the LCA component. HQE awards credits, but it is not necessarily based on the evaluation of the LCA results, and it does not clearly implement LCA, nor does it

specify the technical criteria. In comparison to the other approaches, DGNB is the most comprehensive in terms of life cycle impacts as it considers the energy demand of the building throughout its life, including the construction and renovation stages, as well as the operational stage. DGNB is the most comprehensive in terms of providing credits based on LCA. On the other hand, the DGNB's reference values establish a limit as they are self-proclaimed based on previously conducted and certified studies. Therefore, this does not showcase the full spectrum of the construction industry to validate the certification and to create a benchmark [157,158]. This is considered to be a major limitation in the DGNB system. In terms of the indicator point calculation, each EPAS method uses a different LCA tool or its own internal calculation tools. In the case of BREEAM, the tools for calculations are internally developed (e.g., the Mat01 Calculator, which is even not available as an open resource). Similarly, the software such as IMPACT, e-tool, Oneclick LCA that is used for life cycle impact assessment must be recognized by BREEAM. DGNB and HQE assess the impact based on the project specific data or from regional specifications. LEED uses LCA software that are recognized data based on ISO 14044, for example, Athena Impact Estimator, GaBi, and SimaPro [154,159].

Chapter Conclusion

Some methods have included LCA indicators and EPD requirements within their credits. However, the methods adopt different approaches and weights relevant to the outputs. However, the real question is how far these indicators compute the actual impacts and demonstrate the absolute reduction in implications. This lack of clarity leads to confusion for practitioners [159,160]. Moreover, these credits are relatively lower in weightage than the energy-related credits, and most of them are qualitative by nature. The analysis helps to understand the gaps associated with the major schemes and their credit allotment. Moreover, the indicators used for evaluation have been analyzed to understand their distribution over different stages of renovation. Similarities in indicators and categories help to see that all significant schemes have 'important indicators' are almost the same. These indicators are different only in terms of their credits or weightage assigned to them.

Furthermore, selecting and matching widely used indicators that would suit this study was possible. A consolidated list of indicators from literature studies and technical manuals is put forth for the further research. A comprehensive list of performance indicators is presented in the Appendix (see Annex 2). The evaluation of renovation impacts is not limited to qualitative assessment as many aspects of renovation also have precise values. Therefore, quantitative analysis of renovation is also required. For this purpose, the next chapter shall evaluate the building performance by using two currently available performance methods: LCA and EPAS because the selection of the appropriate indicators is an important task to formulate the methodology. Therefore, both methods are considered for further evaluation to gain a wider perspective

4 ASSESSMENT OF ENVIRONMENTAL PERFORMANCE OF RESIDENTIAL RENOVATION

4.1 Object

The researched multi-apartment residential buildings are situated in Kaunas Municipality (54°N). The two apartment buildings with 54 apartments each were renovated and are identical in terms of appearance and the building space. The buildings were built in the early 1980s and were renovated in 2015. These buildings were constructed by using reinforced concrete panels which form the walls, the plinth, and the roof. Their total useful floor area is 3,469.24 m². In order to refer to the two objects clearly, these two apartments will be termed *Building A* and *Building B*. Both buildings were renovated with little distinction. Buildings A and B were modernized in a complex way by insulating walls and roofs, and replacing the wooden or old plastic windows with new plastic windows. Additionally, Building B was equipped with hot water, solar collectors, and heat pump installations.



Fig. 5. Renovated multi-apartment building (Building A)

The specification of renovation in multi-apartment buildings (Buildings A and B) are as follows: The exterior walls of reinforced concrete were covered with 180mm-thick polystyrene foam panels *EPS70*. These panels are covered with decorative gypsum plaster. In addition, the ground part of the plinth is covered with polystyrene facade foam for thermal insulation (*EPS100*). The thermal insulation system is covered with reinforced structural synthetic plaster. The bituminous coating of the roof was replaced with new insulation materials with 40 mm mineral wool and 170 mm polystyrene foam. All the windows and balcony doors were replaced with new plastic windows with lower heat permeability.

Additional equipment in Building B: Additionally, hot water preparation, vacuum solar renovation, and air-water heat pumps were installed. Solar collectors installed on roof with 6 bar as maximum working pressure. The heat from the solar

collector is taken to the solar module which heats up the return heat from the heat station. The hydromodule ensures the circulation of a solar coolant. The solar heat exchanger is hydraulically connected to the inside of the heat pump system and to the pipeline to the heat substation. The heat pump features the listed power of 6.82 kW. The heat pump consists of external and internal units. The external unit consists of a compressor, a heat exchanger (evaporator), and a fan. The internal unit contains a heat exchanger (capacitor).

According to the *Lithuanian Energy Standards*, the selected building was certified as *Class E* of energy certification before the renovation process. After renovation, the building was upgraded to *Class C* since all the renovated apartment buildings are required to reach a minimum of *Class C* [161]. The classification of energy performance ranges from class G to A++, which corresponds to poor energy performance versus higher energy performance (i.e. equals to nearly zero energy building). A comparison of the total energy consumption and the energy consumption for heating was obtained during the certification process [162].

4.2 Life Cycle Assessment of Multi-family Building

Life cycle thinking has been applied in the construction industry over two decades to evaluate the environmental impacts of products and processes. The review of literature has shown that LCA has been used as a comparative tool to evaluate different environmental impacts of a product, process, or activity over the entire life span [163]. Moreover, studies also conclude that the majority of research focused primarily on the operational energy of the buildings [39,95,162–164]. Since the number of studies and methods has increased, it emphasizes the evaluation of the environmental impact of the buildings by using the life cycle thinking. LCA is a versatile tool that has been applied for various types of assessment, such as embodied impacts, emissions, the usage of natural resources of a product or service for their entire life cycle. It quantifies the impact of a product or the services associated with it. Therefore, only a handful of studies show the importance of considering and evaluating the complete life cycle impact assessment of buildings.

Goal, scope, and system boundary

Both Buildings A and B were refurbished by upkeeping the operation of ventilation and heating system, insulating the walls and roofs, as well as replacing old windows. The study aims to evaluate the environmental impacts of the renovated multi-apartment buildings by identifying and analyzing potential environmental impacts before and after the renovation process. Based on the characteristics of the study, the function unit is taken as the entire building with a service life of 40 years.

The system boundaries are the product life cycle stages and components reviewed during the cycle assessment. Some other characteristics, such as water consumption, indoor air quality, acoustics, and the economic value, are not considered in this study for the functional unit. The study boundary was based on Vilches *et al.* The author studied the possibility of the refurbishment process itself with various

system boundaries by considering standard building assessment modules for *Life Cycle Assessment* according to Standard EN15804:2012 [4]. Technically, it seems that no materials were discarded from the building during the renovation period except for the doors and window frames. However, for this study, the replaced end of stage materials is not included. Figure 6 shows the system boundary of the study, and they are as follows:

- the main building materials utilized in the construction and renovation of the apartment building;
- processes and energy consumption required to manufacture building materials [data from the *Ecoinvent* database];
- thermal energy use for the heating of the building premises and hot water preparation across the life cycle of the building, (i.e., the average 40 years heat energy consumption).

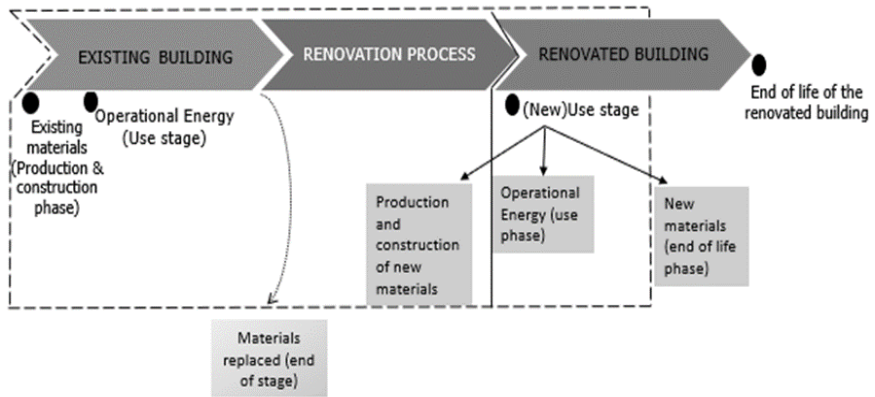


Fig. 6. System boundary of the study

The collected data was fed into *SimaPro 8.0* software to design the material flow. The software uses *Ecoinvent 3.0* as a source database for the *Life Cycle Inventory* (LCI) for calculations [167]. Usually, the datasets are adopted based on the *Environmental Product Declarations* (EPD). In this particular case, there was no availability of EPD, and thus generic data was adopted from the *Ecoinvent* database. **Table 12** shows the building materials data compiled on the grounds of the information from the construction company.

Table 12. Summary of the quantities collected for the study

Content	Quantity	Units
Rough estimation of building materials – before renovation		
Concrete	1098.16	metric ton
Window frame (wooden)	112	m ²
Bitumen adhesive compound	1114.35	kg
Glass (density 2580 kg/m ³)	4	m ²
Reinforcing steel	2196.65	metric ton

Clay bricks	13000	kg
Stone wool	10261	kg
Paint	3572	kg
Cement cast plaster flooring	4970	kg
Polystyrene foam	13179.25	kg
Rough estimation of new materials – added during renovation		
Window frame (PVC)	112	m ²
Gypsum plasterboard	32007.47	kg
Thermal plaster (outdoor)	20058.3	kg
Glass fiber reinforced plastic, polyester resin	38528	kg
Heat distribution equipment	1	p
Solar collectors	495	m ²
Heavy fuel oil	38528	kg
Paint	1572	kg
Transportation of materials to a construction site via road (by truck or carrier)	20	km
Energy for construction	113.189	MJ
Water	109820	kg
Machine operation	5	hr
Use stage – before renovation		
Electricity consumption	960.48	MWh
Water consumption	1750	m ³
Natural gas consumption (cooking)	19.9	kWh/m ²
Heat energy consumption for SH & HW preparation	590	MWh
Use stage – after renovation		
Electricity consumption	314	MWh
Water consumption monthly	1750	m ³
Natural gas consumption (cooking)	19.9	kWh/m ²
Heat energy consumption for SH & HW preparation	352.47	MWh
Heat energy consumption for SH & HW preparation (without solar panels)	444.42	MWh
Discarded materials (End of life)		
Polystyrene	100	kg
Rockwool	100	kg
Windows (wooden)	7.8	ton
Doors	2	metric ton
Glasses	2.6	metric ton
Steel and other (non) metals	80	metric ton
Other debris	0.5	metric ton
Transportation output of the building = 30 km to a disposal site after 50 years of lifespan		
Disposal scenario: Landfill = 20 %, Disposal = 20 %, Reuse = 60 %; 80 % of the building materials will be recycled, and the remainder will be incinerated		

Furthermore, the *Life Cycle Impact Assessment* (LCIA) aims to connect the different LCI result to the various parameters of environmental impact based on their process flow, or by the intervention of the product or by the service defined. . Each of the impacts is classified into different categories and category indicators. This indicator helps to connect and interpret the result corresponding to the impact categories. The impact factors, such as the climate change, human health, acidification, eutrophication etc., are commonly assessed as per the defined goal. The CML methodology was used to evaluate the impact assessment of the identified buildings. The CML 2000 method employs midpoint indicators to assist quantify (i.e., reduce) the numerous results of the life cycle inventory to a few key indicators [168]. The following impact factors, such as the climate change, human health, acidification, eutrophication, and photochemical oxidation, were determined (of all the above listed factors) to have the greatest impact on the environment.

Life cycle assessment results and discussion

With the help of software *SimaPro 8.0*, three life cycle scenarios have been modelled:

- a non-renovated multi-apartment building;
- a renovated multi-apartment (Building A);
- a modernized multi-apartment building equipped with renewable energy sources – a solar collector and a heat pump (Building B).

The impact of buildings on the environment has been assessed by calculating the quantities of the main building materials and the cost of thermal energy in the course of the operation of an apartment (estimated life cycle of the building is 40 years).

Use of materials

Materials play an important role in determining the environmental impact of the buildings. As a matter of fact, materials already embody impacts since the purchase of materials. However, during the process of renovation, a significant number of environmental impacts could be made due to the inclusion of retrofitting measures. **Fig. 7** (presented below) shows the distribution of different materials used during the construction of a building – before and after renovation. The indicator has been chosen corresponding to the selected potential impacts, viz. Global warming (GWP100a), Human health, Photochemical oxidation, Acidification, Eutrophication. Based on the normalization, among the other building materials used, the reinforced concrete was weighed high and it contributes 40 % in the eutrophication and photochemical oxidation category.

The main materials, such as cement concrete, reinforced concrete, mortar for plastering, which were used in the building remain the same as these materials were not replaced during the process of renovation. As per the study, by replacing general cement materials with recycled materials such as fly ash or burnt furnace slag, it is possible to reduce the embodied energy of the building. Although the renovation process minimizes the total environmental impact, installation of energy-saving

devices, such as solar collectors and a heat distribution system in the building, contributes a considerable impact on the land and water level.

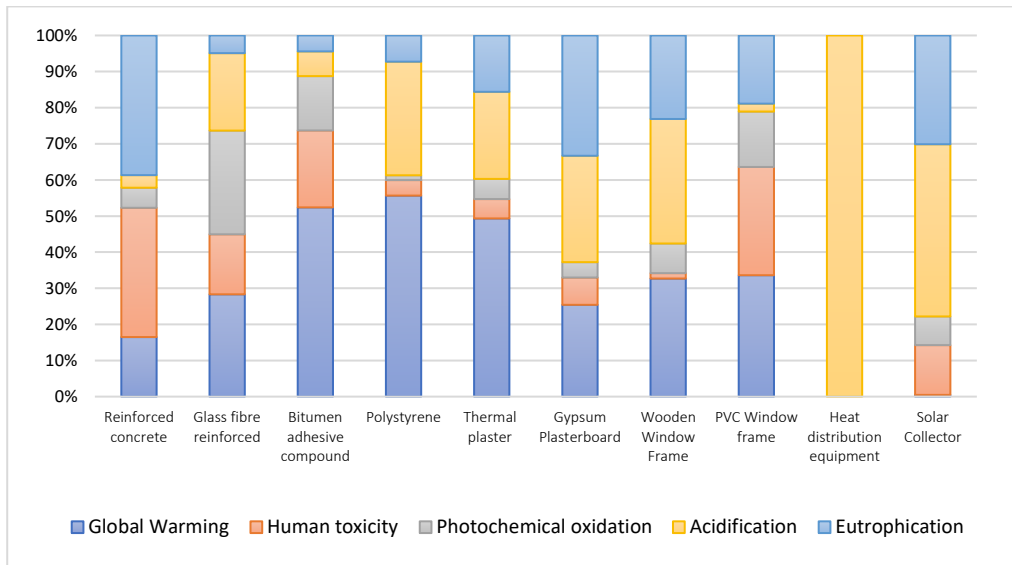


Fig. 7. Distribution of environmental impacts

Overall environmental impact assessment of a multi-apartment building

The overall environmental impact on various aspects was calculated by using the CML method in which the most significant midpoint categories in the building sector were evaluated. The indicator was chosen corresponding to the selected potential impacts, viz. Global warming (GWP100a), Human health, Photochemical oxidation, Acidification, and Eutrophication. The total environmental impact is represented in **Fig. 7**. Analysis of Figure 14 suggests that the residential construction, renovation, and operation processes have the greatest environmental impact in the climate change category. The impact of an old building in this category is:

- about 1.14 times greater than that of a regularly modernized building (i.e., insulation of the building's facade walls, the ground part of the plinth, the roof and the windows);
- about 2 times higher than the environmental impact of a modernized home where renewable energy sources are used.

The comparison of different renovation scenarios (**Fig. 8**) reveals a significant impact in the climate change category. The impact of a house in the climate change category can be reduced by 12 % after the regular modernization of the building. Renovating a residential house and installing solar cells and a heat pump (Building B) can reduce the negative impact on the climate change by up to 48 %. These differences are due to the energy efficiency and the reduced thermal energy consumption, thus resulting in reduced greenhouse gas emissions from fossil fuels.

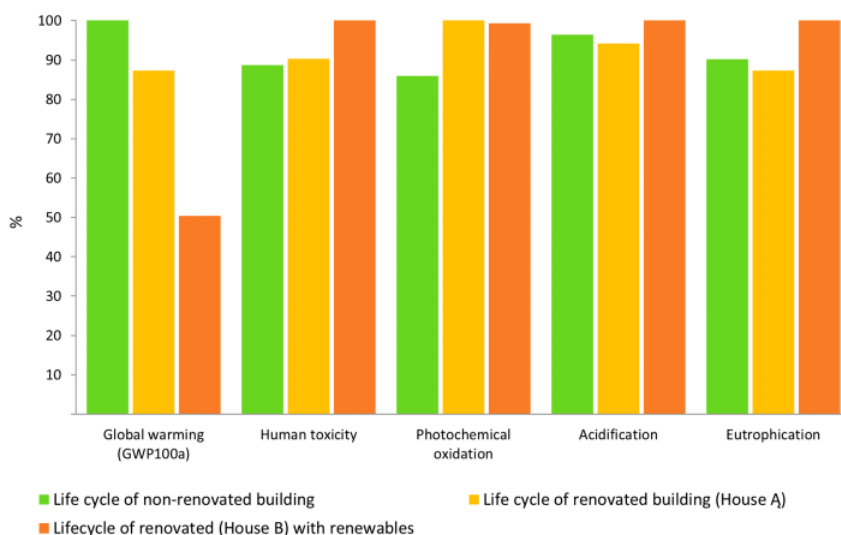


Fig. 8. Comparison of environmental impact of multi-apartment building before and after renovation

Other assessed exposure categories – the effects on human health, acidification and eutrophication – have a greater negative impact on the environment when the building is renovated with renewable energy measures rather than in the case of conventional renovation. It is of interest to note that the installation of solar collectors and heat pumps contributes to the negative impact on human health which can increase by up to 9 %, in the acidification category by up to 5 %, and regarding eutrophication by up to 10 %. This could be due to the production of solar energy and the heat pump systems, as seen in **Fig. 8**. The amount of energy used for the heating purposes was significantly higher in the non-renovated building due to burning fossil fuels. Likewise, the renovated building without any renewable measures (Building A) has a greater impact on the climate change (due to the generation of thermal energy used during the heating season), as well as the impact on other parameters, such as human health, eutrophication, acidification, and photochemical oxidation. The renovated building with renewable measures (Building B) shows a considerable increase regarding such categories as human health, eutrophication, and acidification in comparison to the overall impact on the climate change compared to a non-modernized building.

Heating energy consumption

The apartment building is heated for seven months a year –from October to April. The useful floor area of the building is 3469.24 m². During the building's life cycle, most of the energy (about 80–90 %) is used for heating the building. When analyzing the data on the energy used for space heating and hot water preparation, the changes in the thermal energy consumption before and after renovation of apartment buildings are assessed. There are two types of estimation of the heat needed to heat the building's premises:

- absolute for calculating the heat cost of heating the entire area of a dwelling house per year;
- relative for calculating the heat cost required to heat 1 m² of the building space per year and per month.

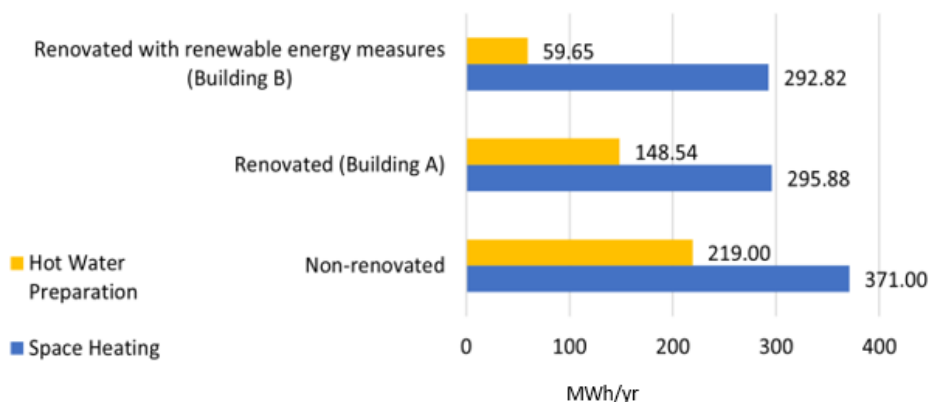


Fig. 9. Annual consumption of heat energy in multi-apartment buildings before and after renovation

The following **Fig. 9** represents the annual heat energy consumption of the building before and after renovation. By comparing the energy consumption of the non-renovated and the renovated buildings, renovated buildings save about 20 % of the annual heating energy used for the space heating of the building. Moreover, Building A and Building B reduce the annual heat energy use for preparing hot water by 32 % and 72 %, respectively.

Operating Costs

When calculating the difference in heat costs economically for non-renovated and renovated buildings (Buildings A and B), the investment needed to carry out the modernization work was not considered. Additionally, the electricity costs required to maintain the heat pump functions were not included in the calculations.

- The price of heat energy in Kaunas city is 0.038 EUR/kWh;
- The cost of the thermal energy used for space heating and hot water preparation in a non-renovated residential building is EUR 22,420 per year;
- Modernization of the residential building reduces the cost of thermal energy to EUR 16,888. With the additional installation of solar panels and heat pumps, the annual cost of thermal energy is EUR 13,394 per year.

Nonetheless, depending on the type of renovation, heating and hot water costs can be reduced:

- by 24 % in the case of normal building refurbishments.
- by 40 % when residential buildings are equipped with solar collectors and heat pumps.

According to the study, depending on the type of renovation measures could reduce the impact on the climate change from 12 % and 48 %. It is also clear from the schemes evaluated that the greatest impact was due to the supply of thermal energy in non-renovated buildings, yet this number is reduced by installing renewable energy measures. Moreover, in a renovated apartment building, the potential savings in the thermal energy used for space heating and domestic hot water preparation are 25 % and 40 % after conventional renovation (Building A) and renovation with renewable measures (Building B), respectively.

However, it seems that the installation of renewable measures, such as solar cells and heat pumps, likely has a massive impact on the human health and the environment due to the nature of its production and the non-renewable energy used for manufacturing of the equipment. Besides, selecting an appropriate construction material during the renovation could reduce the environmental burden. Additionally, based on the literature analysis carried out, it has been found that the application of the life-cycle approach in the construction sector also poses such problems as:

- lack of data collection and standardization of building surveys;
- difficult/inaccurate comparison of building surveys due to different system boundaries;
- lack of data, which leads to inaccurate results.

4.3 Implementation of EPAS in Multi-family Buildings

Energy performance assessment is a key instrument in measuring, evaluating and implementing sustainable renovation. Renovated buildings are often certified based on their energy performance which is known as the *Energy Performance Certificate* (EPC). As studied in detail in the previous Chapter 3, there are several schemes around the world such as BREEAM, LEED, DGNB, or HQE. Moreover, many regional systems have also been developed based on the local regulations and market(s). Many of these systems are suited to the region where they were developed, while some were adapted to be used internationally: LEED – in North America, BREEAM – in the UK, etc. what concerns Lithuania, the *Lithuanian Building Sustainability Assessment System* (LBSAS) is based on the BREEAM and LEED frameworks and adopted to the local standards. This system was designed according to international sustainability standards to be applied in the local Lithuanian market in a more suitable and less expensive way (up to ten times cheaper compared to the costs of BREEAM or EPAS LEED certification). Nevertheless, BREEAM and LEED are the most commonly used systems in Lithuania so far [169]. With respect to evaluating residential renovation, Lithuania has its own energy performance certificates, thus, both BREEAM and LEED are often used to certify business and commercial units. For this analysis, a renovated multi-family house (Section 5.1) was taken to be examined further so that to understand the implications of various schemes. For further study, both BREEAM and LEED were taken to be analyzed further. As mentioned above, both BREEAM and LEED are widely adopted in Lithuania and both systems have exclusive modules focusing on residential buildings and renovation.

4.3.1 BREEAM results

BREEAM has developed assessment systems for the design stage and the post occupancy stage. For this evaluation, domestic refurbishment was taken into consideration. The renovated building was evaluated based on the information collected from the construction company. **Table 13** shows the detailed assessment of all categories associated with renovation. The BREEAM certification rating benchmarks are as follows: OUTSTANDING ($\geq 85\%$), EXCELLENT ($\geq 70\%$), VERY GOOD ($\geq 55\%$), GOOD ($\geq 45\%$), PASS ($\geq 30\%$) and UNCLASSIFIED ($< 30\%$).

Table 13. Assessment of a multi-apartment building renovation and the values of criteria, in credits: BREEAM

Categories	Weightage (%)	Available Credits	A	B
Management	12	11	6	6
Home users		3	1	1
Responsible construction practices		2	1	1
Construction site impacts		1	0	0
Security		2	1	1
Protection and enhancement of ecological features		1	1	1
Project management		4	2	2
Health & well-being	17	12	4.5	4.5
		2	1	1
		4	1	1
Volatile organic compounds		1	0.5	0.5
Inclusive design		2	0	0
Ventilation		2	1	1
Safety		1	1	1
Energy	43	29	7.5	12
Improvement in energy efficiency rating		6	0.5	0.5
Energy efficiency rating post refurbishment		4	0.5	0.5
Primary energy demand		7	0.5	2
Renewable technologies		2	0	2
Energy labelled white goods		2	1	1
Drying space		1	1	1
Lighting		2	2	1
Display energy devices		2	0	2
Cycle storage		2	1	1
Home office		1	1	1
Water	11	4	2.5	2.5
Internal water use		3	0.5	0.5
External water use		1	1	1
Water metering		1	1	1
Materials	8	45	19	19

Environmental impact of materials		25	10	10
Responsible sourcing of materials		12	4	4
Insulation		8	5	5
Waste	5	5	2	2
Household waste		2	1	1
Refurbishment site waste management		3	1	1
Pollution	6	8	3	3
Nitrogen oxide emissions		3	1	1
Surface water runoff		3	1	1
Flooding		2	1	1
Innovation	10	10	4	5
Total credits		110	48.5	54
Rating			Good	V Good

Management: Good management of the building renovation project, its implementation and operation are very important. It affects the longevity of the building and the environment. In this method, the control group is evaluated according to at least 6 criteria. The evaluated multi-apartment renovation project partially meets the requirements of four out of six criteria: 2 credits are awarded for commissioning and project management, 2 credits are allocated to the impact of the construction site on the environment as it is planned to control and achieve the set goals by reducing the negative impact on the environment, 1 credit is awarded to the building's user instructions and safety features with doors and lockpad systems.

Health and well-being: This category is described by 6 criteria. The building renovation meets all the criteria. One possible credit is allocated to the natural lighting and the internal lighting as well as the control systems; 1 point is allotted to the sound insulation of the background noise from HVAC and the partition between two rooms with a wall. The assumption that the building is free from VOC during construction and after it scores half a credit. Ventilation is given 1 credit along with safety.

Energy: The energy criteria are given the highest priority when evaluating a renovation project. The depletion of natural resources and factors affecting the climate change depends on the energy consumption. The group of energy is assessed according to the improvement in the energy efficiency rating after occupancy, the building to be assessed was improved from class D to class C and B according to the Lithuanian energy performance standards by achieving the minimum performance after renovation. Renewable energy scored 2 credits to building B because of the installation of solar cells and the achieved energy saving of up to 48 %. All the electrical appliances were installed according to the EU energy class certificates by achieving a further 1 credit. The drying space for multi-family buildings is not adequate; however, the buildings are equipped with balconies which are sufficient for drying works thus achieving one credit. Both buildings have a storage area in their basements to store bicycles. One credit is given for energy metering and display devices in rooms.

Water: When evaluating the criteria for water, 2.5 credits are achieved for the following: 1. Half a credit point is scored for internal water use assuming 20 % of water reduction due to the installation of energy efficient appliances and water sensitive mechanisms. 2. One point is assigned for installing water meters for cold and hot water. 3. One credit is given to external water assuming the use of watering plants and other subsystem coverage.

Materials: The materials used for building renovation must have as little negative impact on the environment as possible. Therefore, it is important not only to ensure their quality, but also to consider the energy consumed during their production. Raw materials must be procured responsibly and locally whenever possible. The material category is assigned high weightage, thus encouraging the use of responsible construction products. Environment impact assessment can be assessed by a method prescribed in the scheme by calculating the impact categories associated with materials. Therefore, 10 credits are given based on the calculation. Insulation is given 5 credits due to the installation of thermal insulation on roofs and walls along with other measures.

Waste: As the amount of waste increases, its negative impact on the environment becomes stronger, so it is important to evaluate this group of criteria when evaluating building renovation. The category has two aspects: one credit is given to the household waste, and one credit is given to C&W management by assuming that discarded structures are re-used within the existing building.

Pollution: Environmental pollution is assessed by three criteria: one credit is given for surface water run-off as the buildings are equipped with water management for surface water. One credit is assigned for the mitigation of flooding as the management of surface and storm water management helps to reduce flooding. One credit is provided for NO_x emissions.

Innovation: Building B achieved an innovation credit of up to 5 points because of the installation of a solar system and heat pumps during renovation. Moreover, the project is legally deemed to be an integrative project commenced as per the program of the Government of Lithuania, thus achieving 4 credits. Overall, Building B is better in terms of the achievement of performance after renovation because of its energy saving measures and the primary energy demand criteria.

Overall, the BREEAM score for the renovated Buildings A and B are 48.5 and 54, which is equivalent to *very good* and *good* in terms of performance. Both selected buildings underwent renovation (minor and major) thus upgrading their energy performance and additionally installing a renewable energy source, which has led to the achievement of a good performance score for Building B. However, the total score difference between the two buildings is marginal, and there is not much difference in the other categories apart from the energy and renewables installation.

4.3.2 LEED results

LEED, as well as BREEAM, has schemes for different buildings, but, for this study, *LEED v4.1* (BD+C) was used only. The categories assessed by LEED are described in **Table 14**. LEED system points are awarded for each criterion, and the scoring points are summarized. The total final score is then calculated. The LEED ratings are: Certified (40–49 points), Silver (50–59 points), Gold (60–79 points), Platinum (80 points and above) [16]. As mentioned before, the multi-apartment building defined above in Section 5.1 is used as the object.

Table 14. Assessment of a multi-apartment building renovation and the values of criteria, in credits: LEED

Categories	Credits	Weightage (%)	Achieved	
			A	B
Location and Transportation	16	14.54	6	6
LEED for Neighborhood Development Location	1		2	2
Sensitive Land Protection	1		1	1
High Priority Site and Equitable Development	2		1	1
Surrounding Density and Diverse Uses	5		1	1
Access to Quality Transit	5		1	1
Bicycle Facilities	1		1	1
Reduced Parking Footprint	1		0	0
Electric Vehicles	0		0	0
Sustainable Sites	10	9.091	6	6
Construction Activity Pollution Prevention	PR		✓*	✓
Site Assessment	1		1	1
Protect or Restore Habitat	2		1	1
Open Space	1		1	1
Rainwater Management	3		1	1
Heat Island Reduction	2		1	1
Light Pollution Reduction	1		1	1
Water Efficiency	11	10	5	5
Building-Level Water Metering	PR		✓	✓
Outdoor Water Use Reduction	2		1	1
Indoor Water Use Reduction	6		3	3
Optimize Process Water Use	1		0	0
Water Metering	1		1	1
Energy and Atmosphere	33	30	9	15
Fundamental Commissioning and Verification	PR		✓	✓
Minimum Energy Performance	PR		✓	✓

Building-Level Energy Metering	PR		✓	✓
Fundamental Refrigerant Management	PR		✓	✓
Enhanced Commissioning	6		4	4
Optimize Energy Performance	18		4	7
Advanced Energy Metering	1		1	1
Grid Harmonization	2		0	0
Renewable Energy	5		0	3
Enhanced Refrigerant Management	1		0	0
Materials and Resources	13	11.82	6	7
Storage and Collection of Recyclables	PR		✓	✓
Building Life Cycle Impact Reduction	5		3	3
Environmental Product Declarations	2		1	1
Sourcing of Raw Materials	2		1	1
Materials Ingredients	2		0	0
Construction and Demolition Waste Management	2		1	1
Indoor Environmental Quality	16	14.54	8	8
Minimum Indoor Air Quality Performance	PR		✓	✓
Environmental Tobacco Smoke Control	PR		✓	✓
Enhanced Indoor Air Quality Strategies	2		1	1
Low-Emitting Materials	3		0	0
Construction Indoor Air Quality Management Plan	1		1	1
Indoor Air Quality Assessment	2		1	1
Thermal Comfort	1		1	1
Interior Lighting	2		1	1
Daylight	3		1	1
Quality Views	1		1	1
Acoustic Performance	1		1	1
Innovation	6	5.45	1	2
Regional Priority	4	3.63	1	1
Total Points Achieved	110	100	43	50
Ratings	-		Certified	Silver
*Prerequisite				

Location and Transportation (LT): When the selected building was originally constructed, it was built on already developed land. Thus, we can assume that the lot in which the house is standing is actually *not* sensitive land. The building is located close to the city center and is well-connected to the public transportation, such as buses, electric scooters and bicycles. The road infrastructure is provided with bicycling and walking paths with an average distance of 1 to 1.5 kms from the entity. Moreover, the bicycle network connects to various parts of the city and center for both

recreational and transportation purposes. However, parking is a challenging situation for both the investigated building, and off-road parking is essentially not available for the multi-family buildings. Parking on the roads is allowed with a fee, whereas the parking of electric vehicles is free of charge on on-street parking. However, there are no facilities to charge EV in the vicinity. Therefore, the location of the buildings under discussion qualifies for 6 credits in the LT category.

Sustainable Site (SS): The buildings A and B under discussion were built with the compliance of urban and town planning norms, thus ensuring that the construction activities were done in a way to reduce harm on the local environment. The building was provided with green and open spaces to have a garden space so that to ensure the diversity of local vegetation. The rainwater system is connected to stormwater to avoid flooding, yet a rainwater harvesting system is not available. Still, this need is addressed through stormwater management. The existing buildings are surrounded with plenty of green spaces, and these garden spaces help in cooling down the temperatures. However, the building is equipped to insulate heat as most buildings are built for the long spells of cold days. The placement of street lights is available. It has been set up according to the municipality norms. Therefore, the location satisfies the criteria for at least 6 points for sustainable sites.

Water Efficiency (WE): The reduction of water usage both indoor and outdoor is a mandatory requisite for the building. The building is equipped with a water meter for cold and hot water use. Water reduction is calculated based on the 20 % reduction of water per building. This is achieved through installing low water flow faucets in kitchens, bathrooms, along with other subsystem watering assuming the buildings are denoted by energy efficiency (A+ labels) on washing machines, and dishwashers. A baseline reduction up to 25 % is assumed for both cases. The buildings are qualified for 5 credits each for water efficiency.

Energy and Atmosphere (EA): The building was renovated and commissioned after verification based on a construction company in accordance with a program approved by the Government of the Republic of Lithuania. Minimum energy performance and building energy metering are a prerequisite. The building fulfils energy performance upgraded from D and lower classes to class C and class B up to energy savings of 15 % and 45 %, correspondingly. The energy meters are aggregated in terms of electricity, hot water preparation, and heating at the building level. Upon considering the commissioning of HCFC, eliminating the ozone depleting refrigerants, therefore, it is assumed that the building has achieved the prerequisite. Moreover, the energy performance is optimized in Building B with the installation of hot water preparation through solar panels. Moreover, Building B has also achieved renewable energy usage of up to 40 %; the lighting systems are managed with efficient natural light and an efficient monitoring system. Therefore, Building B has achieved higher credits in this category than Building A. A total credit of 9 and 15 has been achieved on energy and atmosphere corresponding to Buildings A and B.

Materials and Resources (MR): The buildings A and B under assessment are adequately provided with storage and collection of recyclables. Different grades of recyclable items are collected, and most of the multi-family buildings are equipped with collection containers with a scheduled hauler. The building's life cycle impact was assessed with *Simapro* software as suggested in the scheme. GHG emissions are one of the main factors along with six other impact categories which were assessed for both buildings. The materials associated with new construction were provided with EPD; however, EPDs were not available for all building products. Raw materials were sourced locally or from other parts of Europe, some parts of building structures were reused during the renovation process. As some parts of the discarded building structures are used for the current construction as recycling process, the parts that are not suitable for recycling, e.g., CDW, are handled accordingly by the constructor as per the relevant norms. Therefore, this category fulfills the requirement for a partial credit of 6 and 7 for Buildings A and B.

Indoor Environmental Quality (IEQ): The minimum indoor air quality is a prerequisite for the scheme by assuming that the renovation of a building also improves the indoor quality and thus the comfort for the user. Both buildings thus satisfy the minimum requirements. Moreover, the building has developed enhanced air quality strategies with natural and mechanical ventilation on condition of no smoking indoors. The buildings are equipped with smoke detectors and alarms. However, it is quite common that most apartment buildings have no designed area for smoking; however, since March 2020, smoking in balconies has been prohibited. Moreover, windows have been replaced for the thermal comfort along with insulated roofs and walls. Interior lighting is also equipped with the European standard energy lamps and lighting controls (at least 75 % of the total connected lighting load uses light sources that have a rated life (or L70 for LED sources) of at least 24,000 hours). Assuming that paints and varnishes are free from VOCs and formaldehyde, this adds to the indoor quality. The buildings are assessed for the micro climate and air quality according to the national standards. A user survey has also been performed to analyze the comfort and user satisfaction regarding the indoor quality. Quality views are provided by (1) flora, fauna, or sky; (2) movement. For occupied places, HVAC noise is insulated from the background noise, and, as for a residential building, regarding the minimum requirement of wall barrier compartments between two rooms so that to avoid noise. With this, both buildings have achieved credits of 8 each in terms of indoor quality monitoring.

Overall, the building performance has been calculated in points, thus contributing 43 points and 50 points, correspondingly, for Buildings A and B under the LEED scheme. This implies that Building B has been certified as 'silver' according to the scheme which translates into a better performance level.

4.4 Implementation of LCA in EPAS

This section aims to compare the LCA aspects available in all the selected schemes and their contributions. Furthermore, for the credit estimation, a reference

building is used to award credits and weightage so that to understand the scope of LCA in detail.

BREEAM: *Refurbishment and Domestic Building Manual* (2015) was selected for this study. Two categories – energy and materials – show the LCA reflection and credit distribution. The criterion *Environmental Impact of Materials* Mat 01 is directly accessed by using the BRE Manual [38], and the corresponding weightage has a maximum allocation. Moreover, Table 15 shows the distribution of specific life cycle stages as per EN15804 Standard [70].

LEED: For this study, LEED residential multi-family homes (version 2020) scheme was used [71]. The optimization of energy performance, building life cycle impact the reduction, and the sourcing of environmentally preferable products reflect the LCA indicators.

Table 15. Distribution of LCA in selected schemes

	BREEAM	LEED
Investigated Module	Refurbishment of Domestic Buildings	Residential Multi-family Homes
Minimum requirement	Good	Gold
LCA criteria and credits	Ene 02 (4) Ene 03 (7) Mat 01 (25)	EA (18) MRc1 (5)
LCA credits available	36	23
Original building score	0 (Ene 02) 0 (Ene 03) 2 (Mat 01)	0 (EA) 0 (MRc1)
Renovated building Score (House B)	2 (Ene 02) 1 (Ene 03) 9.5 (Mat 01)	14 (EA) 3 (MRc1)

What concerns LCA results, both original and renovated buildings consider the environmental impact in the Lithuanian context. The original building (used as a reference building) compares the weightings of BREEAM and LEED to allocate the scores according to the LCA credits within the schemes (Table 15) between the original and the renovated building (House B). House B is taken as a renovated building because the building's major/deep renovation has been done (including renewable sources). The original building (non-renovated) has been chosen as a baseline to differentiate between the two scenarios.

Discussion

Based on the previous section, both renovated buildings are allotted credits so that to understand the difference between the two schemes. To understand the LCA incorporation in each scheme, a score was derived from the main schemes, and LCA related indicators were given points based on the reference modules from both BREEAM and LEED.

The BREEAM scheme indicates the difference between the two buildings having an overall score of 11.5 % as a final score related to the LCA criteria. The BREEAM scheme provides almost 12.5 credits out of 36 available LCA points, out of which, the material categories were given the highest score based on the life cycle assessment and provision of retaining/reusing old building materials. However, the assessment process of the scheme is not transparent as it requires the *Mat01* calculator (which is not an open source) to estimate the absolute credit values for providing the proper credits [70,154]. Moreover, the BRE Green Guide examines only the material impacts of each building's materials, but it does not cover the operational phase. In BREEAM, the significant allocation of LCA is based on materials in their product stage; therefore, it does not focus on all phases of the building. Moreover, it also points out the requirement of developing strong reference-building values for the Lithuanian context.

The LEED scheme provides a high proportional score on the energy aspects covering optimization and primary energy reduction. Moreover, LEED gives a high score on the operational phase of the building and provides five credits on the environmental impact of building materials. The effect of building materials is assessed based on the life cycle assessment (the performance in any 3 LCA indicators) or/and retaining or efficient reusing the existing structure and building materials. The renovated building (House B) scores 14 credits for optimizing energy and three credits for reducing the burden in two LCA impact categories.

The BREEAM and LEED schemes also evaluate the life cycle indicators; however, they separate between the product stage of the materials and the operational phase. BREEAM offers an exclusive method for the renovation standards for all buildings undergoing light or major renovation. When using EPDs, BREEAM's material impact evaluation uses different methodologies, and it depends heavily on the Green Guide compliance [170]. This implies that the awarding of LCA credits is based on building products rather than the LCA results. Moreover, BREEAM and LEED do not make a requisite for the criteria related to LCA, apart from the energy efficiency as a minimum standard or prerequisite. In LEED, materials and/or products are critically reviewed based on EPDs and are graded based on the product life cycle [171].

By applying both methods (LCA and EPAS), it is possible to consider that both are used for analyzing the building performance at various levels. LCA is largely applied to understand the quantitative process of the renovation process here. This helped in rating the performance of the building by implementing EPAS (BREEAM and LEED). This implies that LCA will be an ideal tool to evaluate the entire impact of building renovation from the scientific point of view, which helps to know the 'actual' impact of the building throughout all the stages of the renovation process, whereas, in EPAS, the application of these methods is related to 'after operations', and very limited indicators access the pre-design or construction stages. Therefore, based on the results, it is not possible to opine whichever method is ideal for

evaluating the renovation process, as both of them have different purposes and have been used in different contexts and perspectives. The integration of these two would be really beneficial in real time case studies for better implementation and analysis.

Chapter Conclusions

In a nutshell, the environmental performance of renovated multi-apartment buildings has been assessed. For this analysis, both life cycle assessment and environmental performance schemes (BREEAM and LEED) have been selected for further studies. The results from the LCA study have revealed that thermal energy from the non-renovated building (the original one) exerts the most significant impact. However, it was reduced by installing renewable energy as a renovation measure. After renovation, there were potential savings in terms of the thermal energy used for hot water preparation and space heating, 25 % and 40 % after the conventional renovation (Building A) and the major renovation (Building B), respectively. On the other hand, on the material level, solar cells had the highest impact on human health and the environment; this could be caused by the nature of their production and non-renewable energy used for its manufacturing. Besides, selecting the appropriately suitable construction material(s) could reduce the environmental burden and environmental toxicity.

Regarding the environmental performance scheme, BREEAM and LEED performance scores have been calculated for both Buildings A and B. In terms of BREEAM, Building A achieved 48.5 %, whereas Building B reached 50 %, which is 'good' and 'very good'. Similarly, the overall score of LEED for Building A is 43 points, while Building B scores 50 points, which converts into 'bronze' and 'silver'. This implies that Building B is better in terms of performance compared to Building A. Both schemes awarded Building B with good performance because of the renovation measures. However, the total score difference between the two buildings is marginal, with little difference in the score regarding the categories other than energy and renewables installation. Furthermore, the provision of LCA in both schemes is about 11.5 % of the final score for BREEAM and 15.4 % in LEED. BREEAM and LEED do not make a requisite for the criteria related to LCA, apart from energy efficiency as the minimum standard or prerequisite.

5 DEVELOPMENT OF A CONCEPTUAL METHODOLOGY FOR ENVIRONMENTAL IMPACT ASSESSMENT OF RESIDENTIAL BUILDINGS BY USING LIFE CYCLE APPROACH

5.1 Conceptual Methodology for Multi-apartment Renovation

The renovation process is equivalent to re-developing a new construction as it requires various building materials and components and is enabled and facilitated by using various building service equipment. It is far more challenging to carry out a renovation process, especially when an older building is concerned, as it entails a more significant risk of both financial and environmental aspects [129]. Therefore, the renovation process should be carried out comprehensively, by considering all factors throughout the stages of renovation. A conceptual methodology for renovating a multi-apartment building has been proposed; it considers expert opinions, an extensive literature review, and real-life cases. Overall, the renovation process can be divided into four phases: pre-design, design, construction, and operation.

While setting up the desk work, it was discovered that the operational phase of the building is given high importance due to energy renovation, and thus construction and other phases are neglected in the course of implementing renovation projects. Renovating an already existing building accounts for new impacts along with the ‘accumulated’ impacts of the old building, and, in several cases, the accumulated impacts of older buildings are not considered in practice. Typically, the addition of new construction materials along with the renovation scenarios are often analyzed for the environmental impact, thus calculating the effect of new materials; however, the entire process cycle of transportation, on-site results, ‘accumulated impacts’ of the already existing building and the potential recovery of the materials in present use, etc. is commonly left out completely [158]. The purpose of developing this methodology is to represent an integrated method for multi-apartment building renovation and decision-making support for the renovation process. This methodology puts forth a sequence of steps during the renovation process and proposes indicators for pre-/post-renovation by considering the environmental, economic, and social factors. Therefore, it is possible to capture the entire life cycle of a building during its renovation process, thereby aligning it with the premise of sustainability.

The methodology created during the research activity can be used to describe the critical areas and actions so that to achieve comprehensive building renovation. The collected data relating to the key factors and indicators gives fundamental and broad understanding of the renovation project, and, in the larger picture, it reveals whether the building has the potential to be renovated. Although 26 indicators were proposed, considering the unique characteristics of buildings, the methodology is flexible to add or delete the (un)suitable indicators based on the specific objectives. For this, a complete data collection effort is required, including reviews, site visits, desktop studies, surveys, and interaction with the key stakeholders. Consequently, it can be used to do a baseline appraisal, investigate potential gaps, and analyze and

observe the various measures so that to determine their specific relevance which varies from case to case, and to assess the performance.

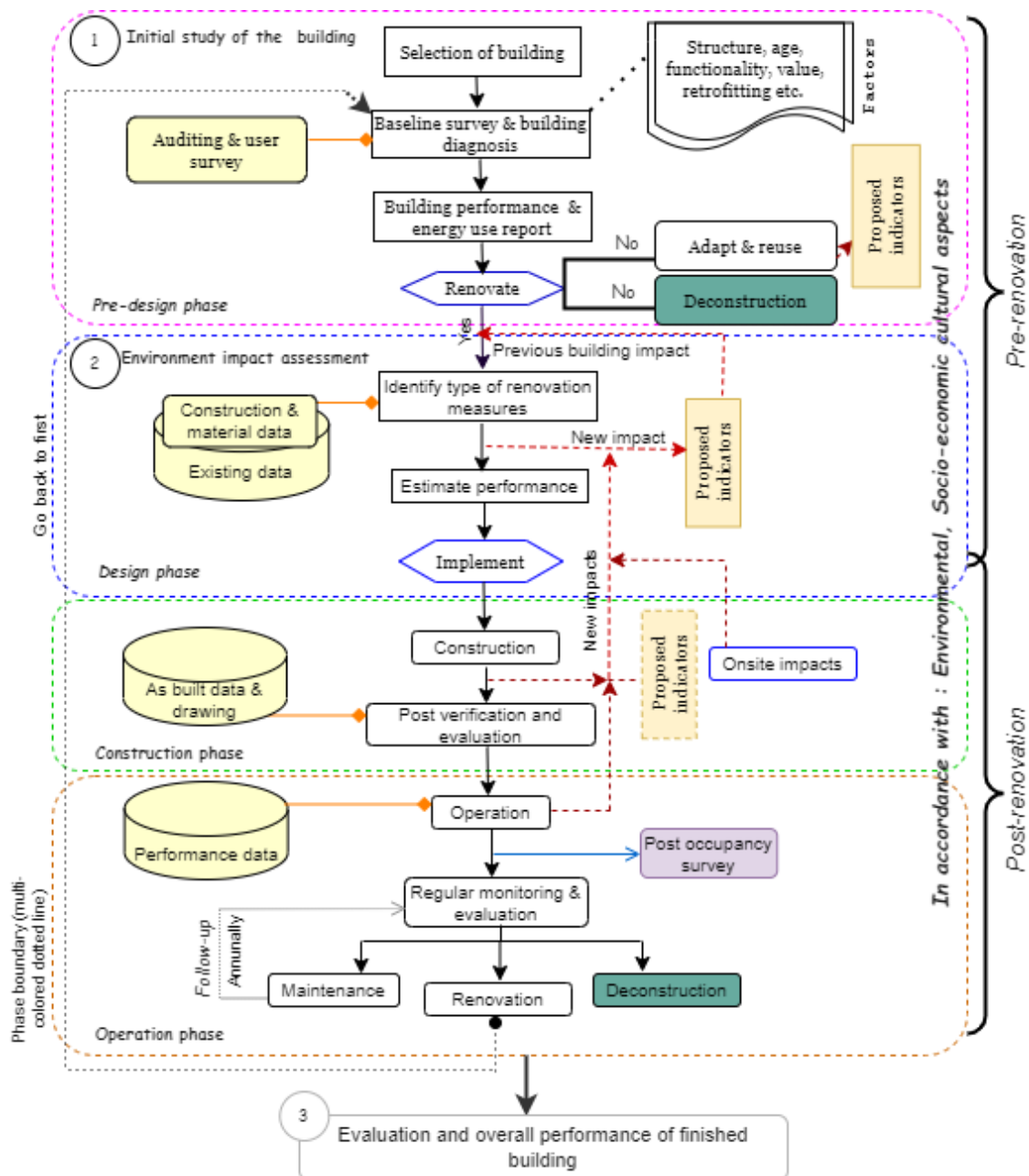


Fig. 10. A conceptual methodology for multi-apartment renovation with combined performance and life cycle approach

In the first phase, the initial study of the building comprises due diligence, baseline, and user survey. Pre-diagnostics of the building is conducted with intensive data gathering and performance assessment. Auditing can be used to analyze the energy data, understand the energy use, and to identify the areas with the energy waste, indoor climate, and other maintenance requirements with the objective to propose renovation measures. Appropriate measures and alternatives of renovation were presented during the design stage. Based on the results, the options are based on relevant energy-related and non-energy-related factors. During the third phase is construction, the selected measure(s) will be implemented on-site at the optimal level. During the occupancy stage, renovation reports are generated to validate the implementation, and a post-occupancy survey is also carried out to understand the occupants' feedback. The entire renovation process was evaluated for its associated impacts from its design to the operation stage.

Steps involved in the proposed conceptual methodology: The methodology consists of two stages, specifically, (a) the pre-renovation stage; and (b) the post-renovation stage.

(a) Pre-renovation stage:

Initial study of the building

- Identification of priorities with the determination of a need for renovation;
- Analysis of the physical characteristics and micro/macro level criteria by using the available methods;
- Determination of the relative importance of criteria and goal(s) based on actual analysis;
- Implementation of life cycle-based evaluation to assess the current burden and to give the best outcome on intervention;
- Based on the analysis suggestion on the kind of intervention required – major renovation or deconstruction is suggested;
- If a building is deemed to require renovation, identification of the depth of renovation and alternative materials is made.

Environment Impact assessment

- Estimation of the energy and the entire building performance of the selected extent is considered;
- Renovation with the help of the available databases and the life-cycle approach is implemented;
- Estimation of the whole building performance with the help of criteria-based assessment is made.

(b) Post-renovation stage:

On-site impacts

- Construction
 - Implementation of construction with the selected renovation intervention;
 - Plan to manage and reuse the deconstruct materials within the building construction;
 - Post-construction verification and evaluation of renovation measures;
 - Analysis of criteria-based performance of construction by using the life cycle approach;
 - Accumulation of the collected data along with the existing physical data of the building;
 - Building is ready for occupancy after the renovation.

Post-occupancy

- Operation
 - Detailed renovation report along with terms for continuous monitoring of performance and user comfort is drafted;
 - Post-occupancy criteria-based evaluation, user survey and life cycle evaluation of performance is implemented;
 - Regular monitoring and evaluation for maintenance and building use is performed.

5.2 Proposed Indicators for the Evaluation of Multi-impact Renovation

The newly proposed indicators are defined over four categories, and, in total, 26 main criteria were addressed throughout the application of the research methodology. These indicators have been considered as effective based on the perspectives given by experts and studies analyzed with respect to the renovation process (see **Table 16**). While the final results show minimal overall differences in terms of categories, as discussed in the section covering data analysis, the indicator weights also show moderate differences within most categories. The fact that the respondents assigned relative importance differences to the indicators could be related to their professional experience, current practices of each respondent, and the local requirements. The distribution of the indicators over the entire life cycle phase of the building is shown below (**Fig. 11**).

	Health and wellbeing				Resources									Pollution							Costs and functionality					
	CW1	CW2	CW3	CW4	R1	R2	R3	R4	R5	R6	R7	R8	R9	P1	P2	P3	P4	P5	P6	P7	CF1	CF2	CF3	CF4	CF5	CF6
Plan																										
Construction																										
Operation																										
End of Life																										

Fig. 11. Distribution of indicators over the entire life cycle of building

Table 16. Proposed critical indicators with description

Category	Critical Indicators	Description
Comfort and well-being (CW)	Indoor living conditions (CW1)	Quality, user comfort and satisfaction with renovation
	Thermal comfort (CW2)	Room temperature control quality
	Resilience and adaptation (CW3)	Actual/expected climate change adaptation
	Acoustic performance (CW4)	Efficient noise control
Resources (R)	Local material sourcing (R1)	Increased use of locally available materials
	Loss of biodiversity (R2)	Damage to local environment
	Cumulative energy demand (R3)	Use of non-renewable primary energy resources as raw materials
	Energy performance (R4)	Improvement of energy performance measures
	Cumulative water use (R5)	Indicator of the relative amount of water used
	Toxic material reduction (R6)	Non-toxic and hazard-free material
	Reuse of existing structures (R7)	Efficient reuse of discarded components to existing structures
	Recycling potential (R8)	Potential to recycle materials with less burden on the environment
	Ease of dismantling (R9)	Provision for deconstruction/dismantling and recycling of components
Pollution (P)	Greenhouse gas emission (P1)	CO ₂ emissions measured in sq. m per year
	Acidification (P2)	Emission to air measured in sq. m per year
	Eutrophication (P3)	Emission to water measured in sq. m per year
	Ozone depletion (P4)	Emissions to air in kg
	Photochemical ozone formation (P5)	Emissions to air of the individual substances in kg
	Human toxicity (P6)	Impact on humans of toxic substances emitted to the environment
	Waste disposal (P7)	Disposal of waste per year
Costs and Functionality (CF)	Transportation and mobility (CF1)	Easy access to alternative transportation
	Social and cultural inclusion (CF2)	Improvement of personal security and cultural respect
	Quality outdoor (CF3)	Quality surroundings
	Durability (CF4)	Durable structure and materials of the building
	Life cycle costs (CF5)	Economic performance of the building
	Potential savings (CF6)	Potential energy savings

Multi-criteria decision-making tools are often useful in developing a methodological framework for various scenarios, ranging from the selection of alternatives, and development of renovation measures, to the future potential use. Therefore, MCDA is suitable for prioritizing indicators so that to evaluate the multi-level impact associated with the renovation process [144]. Moreover, the usage of expert opinion is considered effective, although the implication in this analysis is the inevitable fuzziness and/or vagueness. However, expert opinions are supported based on their scientific views/reviews and/or comments; it provides a systematic overview and/or analysis during each stage [116]. Therefore, MCDA provides a comprehensive way to address various interactions regarding each element, while at the same time allowing it to be integrated with a wide range of environmental, social, etc. concerns. The MCDA method is used further, and the following steps are performed to select the critical indicators related to the renovation process.

5.3 Development of a List of Indicators and Questionnaire

The initial set of indicators included all indicators from the environment, social and economic categories identified from EPAS technical manuals and literature studies. This approach is similar to the one used by other authors, e.g. [127,172,173] in the development of the building sustainability methods for specific contexts. The following literature survey and analysis are considered to feature a preliminary set of indicators for renovation.

- Three most commonly used building performance assessments, at the international level, to assess the performance of residential buildings, namely: *BREEAM Refurbishment and Fit-Out* [70], *DGNB Existing Buildings and Renovation* [75], and *LEED V4 Homes* [71] are analyzed comprehensively for their indicators and life cycle components in their schemes.
- A list of indicator results from the comprehensive analysis of previous literature studies on the life cycle and certification assessment is considered.

5.3.1 Questionnaire design

Regarding the survey, a comprehensive list of questions combining both open and closed questions was derived. The questionnaire consisted of four sections: Section A comprised of personal information; Section B comprised of general questions related to the renovation of residential buildings, barriers, and definition; Section C consisted of comprehensive indicators related to building renovation and life cycle phases; Section D consisted of some open-ended questions related to post-occupancy, evaluation duration, etc. A 10-point scale ranging from 1 (equally important) to 10 (extremely important) was used to obtain the responses from experts, and a sample of the questionnaire was sent to experts, as shown below.

Please assess the importance of LCA "the most suitable phase to incorporate LCA indicators"? *

	Very important	Important	Equally important	Moderately important	Extremely important
Pre-design	☐	☐	☐	☐	☐
Design and development	☐	☐	☐	☐	☐
Construction	☐	☐	☐	☐	☐
Operation	☐	☐	☐	☐	☐
Refurbishment and demolition	☐	☐	☐	☐	☐

Fig. 12. Excerpt of the prepared questionnaire

The questionnaire was tested with a few experts initially so that to understand that the content is comprehensible and relevant to the objective of the survey. The experts from various backgrounds working on building, renovation and environment coming from various locations were selected to participate in the survey. The experts were given instructions and details about the survey, and the questionnaire was sent out online via email. The questionnaire was sent to a total of 25 persons for the first round, and nine participants received it for the second round. As a result, the questions and answers allowed coming up with the relevant indicators, and some indicators that were considered not relevant were subtracted; suggestions were added or formed as a group from the initial set of indicators. The primary list of indicators is categorized under eleven categories are shown in **Table 17**.

Table 17. Categories added in the primary list

Energy	Resources
Transport	Management
Waste	Technical aspects
Water efficiency	Financial aspects
Indoor quality	Commercial viability
Health & well-being	

Interpretation and analysis of survey results

As mentioned above, the respondents were contacted via email, the questionnaire was sent to a total of 25 persons, and, out of those, 21 responses were received, and the distribution of the respondents and their demographic characteristics are shown in **Table 18**. Hence, in this study, the response rate is 84%, and their employment background is shown in **Fig. 13**. Similarly, the second round of the survey was sent only to nine respondents willing to take part further with a comprehensive list of indicators for prioritization.

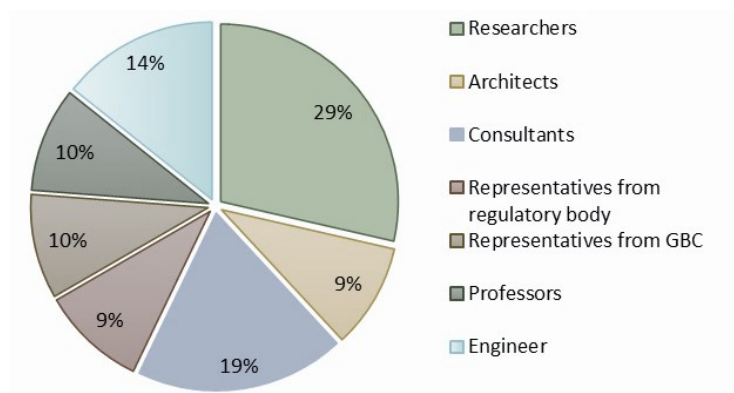


Fig. 13. Distribution of respondents' profile

Table 18. Characteristics of expert participants

Experts	Occupation/Profile	Gender	Country	Years of Experience
Expert 1	Professor	F	Lithuania	between 10–19 years
Expert 2	Researcher	F	Lithuania	between 1–4 years
Expert 3	Researcher	F	Lithuania	between 1–4 years
Expert 4	Sustainability consultant	F	Germany	between 1–4 years
Expert 5	Project engineer	M	Germany	between 5–9 years
Expert 6	Regulatory body	M	Poland	More than 20 years
Expert 7	Sustainability consultant	M	Germany	More than 20 years
Expert 8	Green building council	M	Lithuania	More than 20 years
Expert 9	Researcher	M	Lithuania	between 10–19 years
Expert 10	Regulatory body	F	Italy	between 10–19 years
Expert 11	Green building council	F	Italy	between 10–19 years
Expert 12	Researcher	M	Italy	between 5–9 years
Expert 13	Project engineer	M	Netherlands	between 1–4 years
Expert 14	Project engineer	M	Poland	between 5–9 years
Expert 15	Researcher	M	Spain	between 5–9 years
Expert 16	Architect	M	Spain	between 1–4 years
Expert 17	Researcher	M	Germany	between 1–4 years
Expert 18	Professor	F	Estonia	between 1–4 years
Expert 19	Architect	F	Spain	between 5–9 years
Expert 20	Sustainability consultant	F	Spain	between 5–9 years
Expert 20	Sustainability consultant	F	Estonia	between 5–9 years
Expert 21	EPD specialist	F	Estonia	between 1–4 years
Grey shades – the expert participated in the second round				

Main drivers of renovation

a) Key factors of residential renovation

A list of key factors was generated from the survey questionnaires based on the expert opinions, as shown in **Table 19**.

Table 19. List of key factors of residential renovation sourced from the expert survey

Building typology	Materials impact	Monitoring
Structure	Type of renovation	Cultural value
Age	Quality	Inclusivity
Reuse	Durability	Comfort
Efficiency	Performance	Value for money
Waste	Renewables	Savings
Investments	Maintenance	Functionality
Building impact	Lifespan	Design

- Based on the survey results, energy savings, durability, and comfort are the main reasons for renovation.
- The result of the survey shows that 10 out of 21 respondents consider that lack of both financial and technical expertise is the main contribution for the slow renovation process.

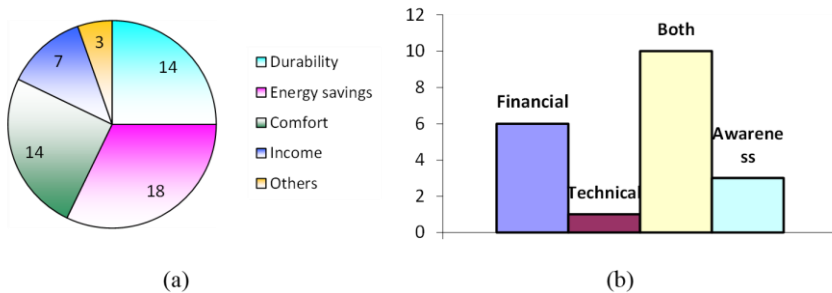


Fig. 14. (a) Reasons for renovation; (b) Barriers of renovation

5.3.2 Life cycle thinking

The buildings have been evaluated according to their components and were optimized separately. The interlinkages between each stage – the design, construction, use, maintenance, demolition, and the collective effect of these components are hardly ever considered, nor is their upstream and/or downstream impact explored, either. In order to achieve this, it is essential to see beyond the current system which is explicitly disjointed from energy savings, or planting greenery. There is a need for life cycle thinking as the primary approach towards sustainability in the building, renovation and construction sector.

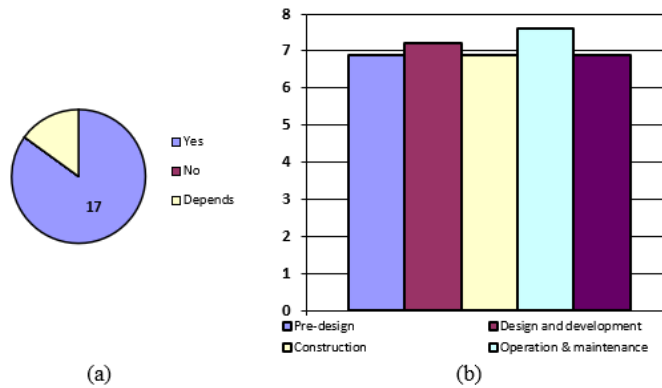


Fig. 15. (a) Consideration of LCA; (b) Consideration of LCA in different phases of renovation

1. The importance of the life cycle thinking in renovation was explored in the survey. 17 out of 21 respondents insisted on implementing the life cycle approach in the renovation process. Four respondents mentioned it in the sense that it ‘depends’ on the project size.
2. The respondents were also asked to indicate at which stage the LCA approach should be implemented. **Fig. 15(b)** shows the different stages of building renovation and the points given to each phase. As per the survey, the respondents suggest preliminary implementation of LCA in operation and design.

Moreover, the survey had open questions related to the renovation process, and additional indicators were suggested regarding the definition of renovation in their view. Based on the answers given by the respondents, a word cloud (**Fig. 16**) was generated to form a key word related to renovation.



Fig. 16. Word cloud generated from the survey

A list of indicators was consolidated from literature studies after manual analysis. The list of indicators was finalized based on the opinions of experts. From the preliminary list of indicators, various categories and sub-categories were deleted, added or grouped based on their relevance to the appropriate categories. The following list was established as a set of criteria to evaluate the multi-impact renovation of residential buildings. During the analysis, multi-criteria decision-making was performed which is explained in the following Section 5.2.

Table 20. Subtracted indicators and the justification of the choice

Subtracted Indicators	Justification
Safety from flooding	Not considered necessary while surveying; most of the buildings already have stormwater management
Provision of home office	Major renovation does not change the main functions of the house design; a dedicated space for a home office is not a priority
Free smoking area	Designated 100 % smoke-free area instead of nominating some kind of ‘no-smoking’ area; this indicator is grouped as sub-criterion under indoor living conditions
Accessibility to workplace	Specific transportation to the workplace is not considered as the indicator that can be part of a major criterion

Table 21. Modified or grouped indicators and the justification of the choice

Initial Indicator	Modified or grouped indicator	Justification
Free smoking area	Indoor living conditions	Not all existing buildings can be altered with design during renovation, ‘no smoking area’ is a sub-criterion under indoor living conditions
Safety and security	Social and cultural inclusion	The safety and security aspects are included in the part of social and cultural inclusiveness
Accessibility to workplace/ bicycling	Transportation and mobility	The initial indicator is included under transportation and mobility as an overall indicator representing all modes of transport

Table 22. Suggested indicators and the justification of the choice

Initial Indicator	Justification
Reuse of existing structures	Efficient reuse of an existing structure within the renovation process/or rerouting the structures for potential recycling. Experts suggested this indicator
Local material sourcing	Procurement of local materials during construction added as per expert suggestion
Recycling potential	Recycling potential of the materials added, and the existing structures are supplemented as per suggestions
Ease of dismantling	Deconstruction/easy dismantling of components to promote recycling and circularity – added as expert suggestion

Table 23. Finalized set of criteria for the evaluation of multi-impact renovation

Key Indicators		Indicators derivation: Literature/Survey
1	Indoor living conditions	Survey, [113,139,174]
2	Thermal comfort	[133,135,139,174–176]
3	Resilience and adaptation	Survey, [113,139,174]
4	Acoustic performance	[139,176]
5	Local material sourcing	Survey, [113]
6	Loss of biodiversity	[113,133]
7	Cumulative energy demand	[113]
8	Energy performance	[70,135,174,176,177]
9	Cumulative water use	Survey, [99,135,139]
10	Toxic material reduction	[70,135,174,175,178]
11	Reuse of existing structures	Survey, [175,178]
12	Recycling potential	Survey, [113,175]
13	Ease of dismantling	Survey, [133,175,177]
14	Greenhouse gas emission	[99,113,133,135,136,139,177–179]
15	Acidification	[75,99,113,133,139,178]
16	Eutrophication	[75,113,178,180]
17	Ozone depletion	[75,99,113]
18	Photochemical ozone formation	[99,113]
19	Human toxicity	[113,174]
20	Waste disposal	Survey, [113,174]
21	Transportation and mobility	[70,71,141,174]
22	Social and cultural inclusion	Survey, [29,75,133,139,141,174,179]
23	Quality outdoor	[29,70,71,174]
24	Durability	Survey, [29,136], [75], [179]
25	Life cycle costs	Survey, [29,136], [75], [179]
26	Potential savings	Survey, [133,179]

5.4 Analysis and Weightage of Indicators

5.4.1 Fuzzy theory set

The following definition of the fuzzy set theory was implemented for this analysis:

Definition 1: The FAHP method applied is the *Triangular Fuzzy Number* (TFN) or the fuzzy triangle number for the fuzzification process from a crisp comparison matrix. TFN is a special class of fuzzy numbers whose function is defined in three real numbers, i.e. (l , m , and u), where l is the lowest possible value, m is the value of the possibility of the middle/peak value, and u is the highest possible value respectively, as shown in [144].

$$\mu_N(x) = f(x) = \begin{cases} \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Definition 2: let two TFNs, a and $\sim b$ be defined as $a = (a^l, a^m, a^u)$ and $b = (b^l, b^m, b^u)$. The distance between a and b is expressed as follows:

$$D(a, b) = \sqrt{\frac{1}{3}[(a^l - b^l)^2 + (a^m - b^m)^2 + (a^u - b^u)^2]} \quad (2)$$

5.4.2 Fuzzy AHP

It is a quantitative technique, and it involves the multi experts to arrive a decision. To integrate the vagueness of human reasoning, when AHP is integrated with the fuzzy set theory, it is called Fuzzy-AHP. With fuzzy AHP, more accurate and adequate decision making can be achieved in the problems involving uncertainty. Basically, the steps in the FAHP method are almost identical to the AHP method in *Multi Criteria Decision Making* (MCDM) by Saaty used for decision applications with a judgment scale of 1–9. To determine the relative preferences for two elements in the fuzzy AHP-matrix, the *Triangle Fuzzy Scale* was used [144]. The general steps of fuzzy AHP and their application in this study are presented as follows:

Step 1: Problem definition and construction of the hierarchical structure (**Fig. 17**).

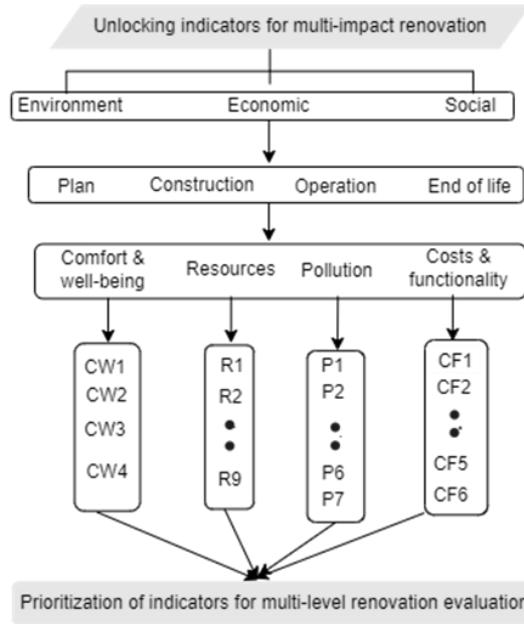


Fig. 17. Decision hierarchy for the prioritization of indicators

Step 2: Define the Linguistic variables as shown in **Table 24** to show the relative importance of one indicator to other for each pair of factors in the same hierarchy.

Table 24. Fuzzy membership scale and linguistic variables

Level of importance	Linguistic variables	Triangular numbers	Reciprocal of TFN
1	Equally important	(1, 1, 2)	(1/3, 1/2, 1)
3	Moderately important	(1, 2, 3)	(1/4, 1/3, 1/2)
5	Important	(2, 3, 4)	(1/5, 1/4, 1/3)
7	Very important	(3, 4, 5)	(1/5, 1/4, 1/3)
9	Extremely important	(4, 5, 6)	(1/6, 1/5, 1/4)
2, 4, 6, 8	Values between two adjacent matrices		

Step 3: Construct a pairwise comparison matrix based on the expert opinion. Eq. (3) shows a fuzzy pairwise comparison matrix [181].

$$X = \begin{bmatrix} x_{11} & x_{12} \cdots & x_{1n} \\ 1/x_{12} & x_{22} \cdots & x_{2n} \\ \vdots & \ddots & \vdots \\ 1/x_{1n} & 1/x_{2n} \cdots & x_{nn} \end{bmatrix} \quad (3)$$

Step 4: Create fuzzy pairwise comparison matrices for individual experts based on their judgements about the main categories and subcategories of indicators as well as indicators within a subcategory.

Step 5: Examine the consistency of the matrix with the consistency ratio (CR). It is evaluated by using a pairwise matrix; for matrix $A = (a_{ij})_{n \times n}$, we calculate the consistency index using the following formulae (Eq. 4) [144,182]

$$CI = \frac{\lambda_{\max}}{n-1}; CR = \frac{CI}{RI} \quad (4)$$

where $\lambda_{\max}$ represents the maximal eigenvalue of matrices A , and RI is a known random index. If $CR < 0.10$; then it means that the consistency of the matrix is acceptable, otherwise, judgements should be removed for undesirably high estimations, and comparison should be repeated in pairs until the degree of consistency has been achieved.

Step 6: Fuzzification and Defuzzification process: calculate the fuzzy synthetic extent value which is represented as (S_i) with respect to the i th criterion is given by relation [183].

$$\tilde{S}_i = \sum_{j=1}^n \bar{a}_{ij} \otimes M^{-1} = \sum_{j=1}^n (l_{ij}, m_{ij}, u_{ij}) \otimes M^{-1}, i = 1, n \quad (5)$$

$$M = \sum_{i=1}^n \sum_{j=1}^n \bar{a}_{ij} = \sum_{i=1}^n \sum_{j=1}^n (l_{ij}, m_{ij}, u_{ij}) \quad (6)$$

The obtained TFNs are ranked based on their total integral method according to negative, optimistic attitudes towards risk. By using TFN, $\tilde{S}_i = (l_i, m_i, u_i)$, the total integral value (w_i) is calculated as a part of defuzzification as shown in Eq. 7 [183].

$$w_i = I_T^\lambda(\bar{S}_i) = \frac{1}{2}(\lambda u_i + m_i + (1 - \lambda)l_i), i = 1, n, \lambda \in [0, 1] \quad (7)$$

Step 7: Normalization of the weight vector $w = (w_1, w_2, w_3, \dots, w_n)^T$ to obtain the vector for each criterion, as related by [183].

$$w_i^* = w_i(\sum_{i=1}^n w_i)^{-1} \quad (8)$$

Step 8: The ranking and prioritization of the selected criteria can be established by multiplying the respective weights of criteria and sub-criteria. By sorting the weights, we get the ranks [183].

5.5 Implementation and Results of FAHP Analysis

Before the application of FAHP analysis, the survey response was collected from the experts. In the preliminary round, a set of indicators was subtracted, added, or grouped, as per the suggestions of the experts. In the second round, 9 experts agreed to rate the indicators to prioritize the further use of the consistency ratio of $CR < 0.1$. As described in the above Section (5.4.1), Fuzzy AHP analysis was performed following the steps to achieve the decision making of indicators. The global (W_g) and local weights (w_m, w_s, w_l) of the indicators along with their ranking are presented in the following tables.

Table 25. Weighting (w_m) and ranking of themes based on expert opinion and FAHP

Theme	Weight (w_m)	Rank
Environment (En)	0.531	1
Economy (Ec)	0.170	3
Social (Sc)	0.299	2
w_m – local weight for the theme		

As observed from **Table 25**, the local weight (w_m) indicates the significance of the indicators in this category. The main theme environment has the highest weight of 0.5331 followed by the social and economic themes.

Table 26. Weighting (w_s) and ranking of categories based on expert opinion and FAHP

Category	Weight (w_s)	Rank
Resources (R)	0.239	3
Comfort & well-being (CW)	0.246	2
Pollution (P)	0.298	1
Costs & Functionality (CF)	0.217	4
w_s – local weight for category		

Table 27. Weighting (w_l) and ranking of life cycle stages based on expert opinion and FAHP

Life cycle stage	Weight (w_l)	Rank
Design	0.297	2
Construction	0.103	3
Operation	0.564	1

End of life	0.036	4
w_l - local weight for the life cycle stage		

Similarly, **Table 26** and **Table 27** also indicate the local weights on the category and life cycle stages (w_s and w_l). It can be observed from **Table 26** that the Pollution category scored the highest weight of 0.298. It was followed by comfort, resources, and costs and functionality. The results also show that there is very little difference between the weightage values given by the experts. **Table 27** shows that the operational stage is given the highest priority with the weightage, and it is followed by the design phase of the building renovation.

Table 28. Results after assigning global weights (w_g) and ranking for individual criteria

Category	Key Indicators	Local weights	Global weights (w_g)	Ranking
Comfort and well-being (0.246)	Indoor living conditions (CW1)	0.64	0.15744	5
	Thermal comfort (CW2)	0.71	0.17466	3
	Resilience and adaptation (CW3)	0.5	0.123	9
	Acoustic performance (CW4)	0.3	0.0738	16
Resources (0.239)	Local material sourcing (R1)	0.3	0.0717	17
	Loss of biodiversity (R2)	0.23	0.05497	20
	Cumulative energy demand (R3)	0.3	0.0717	17
	Energy performance (R4)	0.71	0.16969	4
	Cumulative water use (R5)	0.16	0.03824	24
	Toxic material reduction (R6)	0.14	0.03346	25
	Reuse of existing structures (R7)	0.45	0.10755	10
	Recycling potential (R8)	0.14	0.03346	25
	Ease of dismantling (R9)	0.41	0.09799	11
Pollution (0.298)	Greenhouse gas emission (P1)	0.75	0.2235	1
	Acidification (P2)	0.42	0.12516	6
	Eutrophication (P3)	0.42	0.12516	6
	Ozone depletion (P4)	0.32	0.09536	12
	Photochemical ozone formation (P5)	0.32	0.09536	12
	Human toxicity (P6)	0.59	0.17582	2
	Waste disposal (P7)	0.42	0.12516	6
Costs and Functionality (0.217)	Transportation and mobility (CF1)	0.23	0.04991	21
	Social and cultural inclusion (CF2)	0.21	0.04557	23
	Quality outdoor (CF3)	0.22	0.04774	22
	Durability (CF4)	0.41	0.08897	14
	Life cycle costs (CF5)	0.3	0.0651	19
	Potential savings (CF6)	0.4	0.0868	15

Each category was measured by using several performance indicators, and their corresponding results were obtained by employing the direct ranking method using the local and global weights. The final list of indicators (the total is 10) was normalized for the practical assessment based on their local weights. Similar scaling

methods had already been used in the literature [116,121,183]. Variation within each criterion and weight is unavoidable. **Fig. 18** shows that some of the indicators were also weighted equally, and a few of them only had slight differences in values. The global consequences are used to conclude the threshold and the mandatory requirements for the performance methodology. The results show the ranking of each indicator and the grouping of indicators.

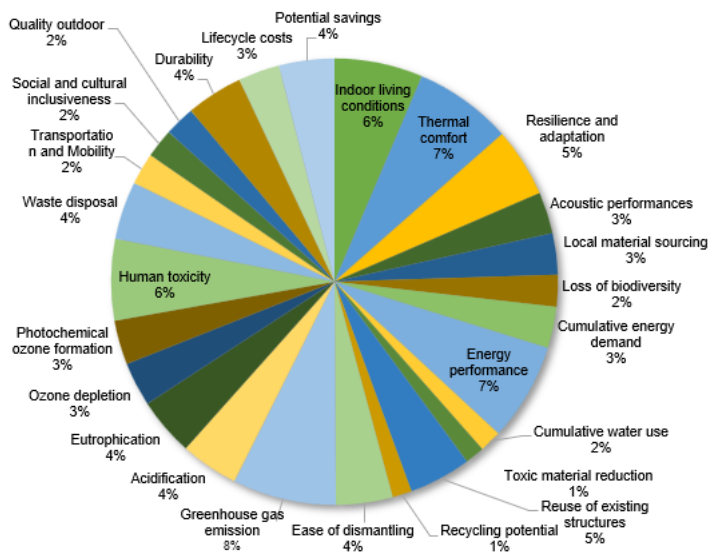


Fig. 18. Pie chart showing the relative weights of the selected indicators

Critical indicators of comfort and well-being: According to the responses, the comfort and well-being category has four indicators: thermal comfort and indoor living condition are rated the highest and are ranked 3 and 5, respectively. This category weighs about 23 % comparing to the other categories.

Critical indicators of resources: The resources category contains nine indicators, which is the highest number of indicators within the class (**Table 28**). Energy performance is the highest weighted (76 %) indicator within the category. Following this, the reuse of the already existing structure and the ease of dismantling are weighted the highest within the category.

Critical indicators of pollution category: According to the response, the pollution category comprises about 29 % of the weightage, including seven indicators; greenhouse gas emission is the highest scoring, and it is ranked the first during the prioritization. It is followed by human toxicity which is given the second preference and is ranked number two as the dominant weightage. The remaining indicators follow

this order of importance: waste disposal, acidification, eutrophication, ozone depletion, and photochemical oxidation.

Critical indicators of costs and functionality: This category consists of six indicators, with durability and potential savings being weighted the highest in terms of the response and analysis. This category comprises about 21 % of all the types. Outdoor quality and social inclusion are the least weighted of all the indicators after the recycling potential.

System scores and weights

No consensus exists on the best evaluation approach for building assessment because the individual evaluation systems are based on their local context and characteristics with separate scoring systems [85,121]. Both qualitative and quantitative approach is required to achieve a holistic and sustainable perspective. The final results and the assigned points are adopted from the benchmark methods/regional data, such as BREEAM, LEED and DGNB, along with the Lithuanian Energy Performance strategies on the qualitative basis. The assigned points depend on the importance of each criterion with the assessed categories and indicators. The global weights of indicators are used to conclude upon the threshold and the mandatory requirements for performance. They use a single number approach based on aggregating points in various effect categories. This approach can cover a wide range of indicators related to the building performance and is adopted in this research [116,121,182]. Accordingly, the levels used in this study, namely, *low*, *medium*, and *high*, depend on the achieved total scores of the building. Zhang and Lei adopted the scale and the FAHP method to develop a performance score [116]. Based on the study, the author adopted the same scoring system to calculate the performance scores by converting the conditional values to a scale of 100 corresponding to the low, medium, and high segments. The condition values converted to a scale of 100 corresponding to *Low* means up to 33 %, *Medium* up to 66.67 %, and *High* up to 100 %.

5.6 Application of Methodology on Example and Results

The buildings represent residential multi-story apartment types Lithuania and Denmark, 9-storey buildings with 54 apartments and 48 apartments were renovated in 2015 and 1991 [195] (**Table 29**). In general, the selected apartment buildings were in need for renovation due to poor energy performance.

Table 29. Description of the status and renovation measures of the case study buildings

Description	Building A (Scenario 1)	Building B (Scenario 2)
Year built:	1983	1949
Layout:	2 buildings, 9 floors	2 buildings, 7 floors
Area:	3469.24 m ²	5630 m ²
No. of apartments	54	48
Renovation year:	2015	1991
Structure:	Prefabricated concrete panels, concrete, and steel reinforcement	Brick walls, concrete slab and wooden roof

Heating: Ventilation:	District heating, radiators Natural ventilation	District heating Natural with kitchen exhaust
Renovation measures:	Insulation of exterior and interiors Replacement of windows with low heat permeability Heat pump installation Solar cells	Insulation of exterior and interiors Heat pump

Critical indicators of comfort and well-being

Indoor living conditions (CW1):

Relevance: Indoor living conditions are both a quantitative and a qualitative parameter. The indoor living conditions can be determined by various factors by delivering assessment before and after the occupancy stage.

- Air quality monitoring according to the national IAQ Standard;
- No VOC/formaldehyde to be used;
- Use of toxic-free materials as per the circular materials standard;
- Smoke free/compartmentalized smoking area.

Explanation: Buildings A and B were awarded points based on the air quality achieved according to the national standard, and there is a designated smoking area there. It can be reasonably assumed that the paints, adhesives, and sealants are free from any VOC content or formaldehyde.

Table 30. Results of comfort and well-being

Critical Indicators	Available points	A	B	References
CW1	7	3	3	ISO 21929, WELL
CW2	7	2	4	BREEAM, ISO 21929, Implementation of EPBD in Lithuania
CW3	3	1	2	ISO 21929
CW4	4	1	1	BREEAM
Total	21	7	10	

Thermal comfort (CW2):

Relevance: As a part of renovation, it is necessary to ascertain and improve the performance of the elements so that to reduce the amount of the heat loss from dwellings. Moreover, the walls, roofs, and floor are designed to keep the occupants warm inside. The insulation of materials generally corresponds to the U-value and R-value for thermal transmittance. The lower is the U-value, the less heat is being allowed to pass through. Therefore, it is necessary to use the materials with low U-values to achieve high thermal performance. The threshold values for walls, roofs and floors have been determined to achieve the minimum performance as per the EU regulations. If the minimum threshold value of above mentioned components is achieved, 2 points will be given.

Explanation: Both building meet the minimum criteria for thermal performance on the roof, walls, windows, and floors. They both are given a minimum of 2 points for achieving this criterion. Building B offers a better performance, and it achieves class B and also scores high energy performance values.

Resilience and adaptation (CW3):

Relevance: The resilience of an existing building to environmental change will partly depend on the original design characteristics, but there may also be opportunities to improve:

- internal layouts;
- ventilation pathways;
- the performance of the building fabric, and
- HVAC systems;
- Nature-based solutions (green infrastructure) could be introduced on/around the building.

Explanation: Both buildings are given the minimum score for this indicator; however, the actual or futuristic impacts are not predicted for these buildings. The minimum score is given to both buildings owing to the prerequisite condition, as it is not possible to give zero points.

Acoustic performance (CW4):

Relevance: The effective acoustic performance is an important factor for evaluating the well-being and comfort of the user. Refurbishing a dwelling is a good opportunity to inspect and improve the sound insulation of the separating walls, floors and ceilings of the dwelling so that to ensure that the impact of noise is reduced. Buildings should be designed for an effective acoustic design: HVAC background noise, Sound Transmission, and/or Reverberation time. Insulating the minimum background noise from HVAC and the partition of rooms with separating walls is the minimum requirement which is given one point.

Explanation: Both Buildings A and B are given one point each for achieving the minimum requirements during the renovation process.

Critical indicators of resources

Local materials sourcing (R1):

Relevance: Materials sourcing plays a vital role during the renovation process. Throughout the life stage of a building, the added materials will have an impact on the environment. Different materials can be sourced from different locations during the renovation process. This indicator is evaluated by using 'km' as the reference unit. The building's material is categorized based on the distance between the source and the building.

- Within 100 km from the building site (the project site);
- Within the country precincts of about 300 kms;

- Within 1000 kms from the project site.

A distance of 100 km for sourcing materials from the building site has been considered as the threshold value for this parameter. In the Lithuanian context, at least 4 % materials sourced locally within the country perimeter is given 3 points, the materials that are sourced are sourced within 100 km from the project is given 2 points, and the materials sourced at least from 800 km away or within the EU zone is given 1 point.

Explanation: Both buildings are given 1 point each by assuming that the construction materials are sourced from within the EU zone.

Table 31. Scores for resources

Critical Indicators	Available points	A	B	References
R1	3	1	2	Janjua, Sarker and Biswas (2020)
R2	3	1	1	JRC technical report (2012)
R3	3	1	2	JRC technical report (2012)
R4	6	3	4	LEED v4.1, BREEAM, Republic of Lithuania
R5	3	1	1	LEED v4.1
R6	3	2	2	BREEAM, CRADLE to CRADLE product standard
R7	3	1	1	BREEAM
R8	3	1	1	Janjua, Sarker and Biswas (2020)
R9	3	1	1,5	Janjua, Sarker and Biswas (2020)
Total	30	12	14	

Loss of biodiversity (R2):

Relevance: Each project should ideally have a positive impact on the surrounding ecosystems and biodiversity, and ensure that it does not have any negative impact over the course of the life cycle.

- Avoidance of the loss of biodiversity: The building design causes minimal loss of biodiversity through the embodiment and use phase ecosystem impacts;
- Stimulation of the local biodiversity: The building design strengthens the local biodiversity, especially for rare species.

Explanation: Based on the two factors, both buildings were given points as there is the minimum loss of biodiversity during the construction phase, and the product which is selected and used has only a minimal impact on the local biodiversity. As both buildings are old, only newly added materials could be selected based on the following aspects, the existing ones are not replaced, and it was made sure that there was less damage inflicted on the local species during the construction process as well.

Cumulative energy demand (R3):

Relevance: The *Cumulative Energy Demand* (CED) of a product represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials. This indicator can be applied for both renewable and non-renewable sources. The indicator is assessed by using the life cycle assessment.

Explanation: Based on the literature, the cumulative energy demand can be achieved in terms of up to 50 % energy reduction [184] for the type of renovation measure, in which case, Building B has achieved up to 40 % energy reduction. This will be given extra score for achieving a better performance. The minimum value of 1 point is given to either house for achieving this criterion as a requirement.

Energy performance (R4):

Relevance: The energy performance of building has vital importance in the process of renovation. The highest energy performance can be achieved by implementing various renovation measures in combination. A+ and A+++ ratings are considered to be the highest energy performance ratings with almost zero or nearly zero energy building. The energy performance is achieved through implementing the following measures:

- Reduction in GHG;
- Reduction in annual fossil fuel consumption;
- Efficient insulation;
- Efficient lighting controls;
- Efficient ventilation controls;
- Efficient hot water systems;
- Electricity control.

If all the points addressed above have been achieved, the indicator will be given the full points (six) with highest energy performance of A+++.

Explanation: Buildings A and B have had their energy performance levels considerably improved from 226kWh/m²/yr average energy consumption with a significant 40 % improvement in the energy savings with 122 kWh/m²/yr and 112 kWh/m²/yr, correspondingly.

Cumulative water use reduction (R5):

Relevance: The cumulative water reduction is considered based on the indoor and outdoor water use in the building [71]. Water reduction is calculated based on the percentage reduction of water (m³/yr/building) or (m³/yr/person).

- Water reduction can be achieved by fixing the fixtures and fittings so that to avoid further leaks. Water efficient taps, showers, baths, and toilets need to be installed;
- Energy efficient and water sense labelled appliances such as washing machines and dish washers need to be used;

- Efficient outdoor water – a design for low water consumption irrigation systems and integrated water systems for drinking and hot water, HVAC are required;
- Installing water meters is necessary.

By implementing the above listed measures, aggregated 20 % water reduction levels are considered as the baseline. The annual domestic water consumption per capita in Lithuania is 50.9 m³ [185]. Points for reducing the water use by 25–30 % is given 0.5 points, whereas above 30 % is given 1.5 points.

The water consumption of other activities apart from the operational stage is not considered here for points. The water consumption during maintenance, repairs and construction and replacement activities is considered in the construction phase as ‘on site’ impacts.

Explanation: The buildings were assigned one point each assuming that the water meter is fixed, and the fixtures and fittings were sealed during the renovation process. This could reduce the water use by 20 %; hence, both buildings are given 1 point.

Toxic materials reduction (R6):

Relevance: When choosing materials for renovation, it is important to ensure and procure materials responsibly by assessing and certifying these products. This is achieved by declaring the material ingredient reporting through the manufacturer reporting and the health product declaration of the material. No materials should be used of those inscribed into the *Banned list of Cradle to Cradle*; if used, they should not be above the threshold (as per the cradle and cradle product certified v3.1) [186,187], and the post occupancy survey and quality assessment of the indoor quality suggest that there are no emissions from VOC. If the materials in use *do* comply with the product standard during the renovation, they will be given 2 points. More than 5 materials procured from different manufacturers will be given 1 point, and, if no VOC emissions are recorded when assessing the indoor quality, 1 point will be given.

Explanation: Buildings A and B were given each 1 point assuming that at least 4 materials were sourced as toxic free materials, and the absence of VOC emissions during the post occupancy stage was given 1 point.

Reuse of existing structures (R7):

Relevance: The aim of this indicator is to improve or maximize the reuse of the elements to achieve the circularity of materials and their recycling. The reuse of the already existing structures during the renovation process, along with the reuse of the already existing structure of up to 50 %, was given 3 points, whereas less than 10% is given 0.5 points, and the use in between 10 and 25 % is given 1 credit, while the reuse of an already existing structure at a level of 25 to 45 % is given 2 points.

Explanation: For this assessment, during the building renovation, no parts of the building were discarded in the sense that no construction was discarded to landfill;

however, if assuming that it was achieved at a level of up to 10 %, each building was given 1 point.

Recycling potential (R8):

Relevance: The C&D waste recovery in Lithuania was about 74 % of the materials recovery according to the Eurostat database. Different materials have different recycling potentials ranging from 0 to 100 % [113]. However, there is no tangible evidence showing how the waste was actually treated. A literature study showed a recycling potential of C&D waste between 55 and 75 % [188]. The threshold value for the recycling potential of C&D waste is greater than 75 %/m²/yr as it is achievable by using the standard demolishing techniques.

Explanation: The two buildings was given 1 point each as the construction company provided data that the materials were discarded, and that the discarded materials were sent for proper management of waste. Considering this, 1 point was given to each building as the waste was handled accordingly.

Ease of dismantling (R9):

Relevance: The design of a building could facilitate the ease of disassembly, dismantling or deconstruction of parts and materials in the future. We consider to what extent and which parts of these buildings are possible to recover and dismantle, or reuse, or recycle. These reports are based on the data of the designers. They were made during the design stage.

- Elements and their parts are independent and easily separable;
- Connections are mechanical and reversible;
- Connections are easily accessible and sequentially reversible;
- The number and complexity of the disassembly is low.

The points are given based on achieving these above-mentioned aspects. Achieving all the aspects will score 3 points.

Explanation: The buildings were given 1 and 1.5 points each for the ease of dismantling. Building B was given 1.5 points as the building due to the installation of an energy generation system employing renewables and a heat pump considering that these items are independent and easily separable, and thus they can be easily reversible. Also, other systems, such as windows and door insulation materials which were added later, are partially recoverable. As it was impossible to determine the exact products used for this construction, it was assumed that these materials are partially recoverable.

Critical indicators of pollution

Greenhouse gas emission (P1):

Relevance: This is the indicator of the potential global warming due to emissions of greenhouse gases to air. The indicator is assessed through life cycle assessment, and the results are expressed in terms of kgCO₂ eq.

Explanation: The results show different life cycle stages of the multi-apartment building on both pre-/ post- renovation. The renovation phase contributes 25 % of CO₂ emission for Building B, which is considered as the best case due to the renovation measures. Based on the results, points were allotted to both Buildings A and B.

Acidification (P2):

Relevance: This indicator measures the potential impact on the acidification of land and water resources. The emissions to land or water can result from the manufacturing of building products, as well as the construction, use and the subsequent deconstruction (i.e., disassembly, demolition) of the building. The indicator is assessed with the help of the life cycle assessment of the building and by expressing the result in terms of SO₂ equivalent.

Explanation: The two buildings were assessed for the acidification potential by using the LCA program software which delivered the results that Buildings A and B offer a significant AP value, where Building B showed a 9 % higher score than Building A.

Eutrophication (P3):

Relevance: This indicator measures the potential impact on the eutrophication of water bodies. The emissions to water can result from the production of building products as well as the construction, use and subsequent deconstruction (i.e. disassembly, demolition) of the building. The indicator is assessed with the help of the life cycle assessment of the building and by expressing the result in terms of the PO₄ equivalent.

Explanation: The buildings are assessed for eutrophication both at the pre-operation and operation stages, which showed a significant variation in both stages with about 17 % and 83 % distribution for Building B. This shows a higher impact than that of Building A; therefore, Building B is given fewer points than Building A (Table 32).

Table 32. Results of the pollution category

Critical Indicators	Available points	A	B	References
P1	7	3	4	JRC Technical Report, LCA, Janjua, Sarker and Biswas (2020)
P2	4	3	2	JRC Technical Report, LCA, Janjua, Sarker and Biswas (2020)
P3	4	3	2	JRC Technical Report, LCA
P4	4	2	1	JRC Technical Report, LCA
P5	4	2	1	JRC Technical Report, LCA
P6	5	3	3	JRC Technical Report, BREEAM
P7	4	2	2	JRC Technical Report, LEED
Total	32	18	15	

Ozone depletion (P4):

Relevance: The emissions to air can result from the production of building products, as well as the construction, use and subsequent deconstruction (i.e. disassembly, demolition) of the building. This indicator is a building-specific indicator. The indicated areas of protection are the health and well-being; as well as the impact on the ecosystem. The indicator value is assessed with the help of the life cycle assessment of the building and by expressing the result in terms of kg NO_x eq.

Explanation: The buildings are assessed for ozone depletion both pre-operation and during the operation stage, which showed a significant variation in both stages with about 27 % and 72 % distribution for Building B. This shows a higher impact than that of Building A; therefore, Building B is given fewer points than Building A.

Photochemical ozone formation (P5):

Relevance: The indicator value is assessed with the help of the life cycle assessment of the building and by expressing the result in terms of the emissions to air of the individual substances in kg.

Explanation: The buildings are assessed for ozone depletion both pre-operation and during the operation stage. This showed a significant variation in both stages with about 27 % and 72 % distribution for Building B. This shows a higher impact than that of Building A; therefore, Building B is given fewer points than Building A.

Human toxicity (P6):

Relevance: The human toxicity potential (HTP), a calculated index which reflects the potential harm of a unit of a chemical released into the environment is based on both the inherent toxicity of a compound and its potential dose. The toxicity indicator is calculated by using the life cycle assessment.

Explanation: The LCA result g shows a high level HTP for Building B. This indicates that it has impact on humans due to the materials in use or because of some other construction practices. Building B is given fewer points for this study.

Waste disposal (P7):

Relevance: This indicator measures the production of the total volume of non-hazardous and hazardous wastes which have a potential impact on the generation of waste for disposal. The estimated total waste amounts, for each stage and type of waste, produced during the entire life cycle with special consideration needed with regard to the:

- use/users of the building;
- possibility for segregation and recycling of wastes;
- possibility to compost the organic waste.

Explanation: There will be no changes in the occupants' behavior and consumption. The waste generated per person is about 472 kg per year; however, after

renovation, the building has gained the necessary storage facilities and possibilities to facilitate the segregation and recycling of waste.

Critical indicators of costs and functionality

Transportation and Mobility (CF1):

Relevance: Transportation and mobility is an important factor for buildings in general. This indicator is a qualitative parameter. The availability of various modes and connections for users of the buildings are assessed based on the following aspects: Achieving each of these bullet points will score 3 points in total.

- Access to transportation services, such as public transport, carpooling or sharing, biking rental;
- Availability of parking spaces (off-road) and bike storage;
- Access to s charging to portal in case of e-vehicles (cars and bikes).

Explanation: Both Buildings A and B are given 1 point each for the access to public transportation as the location offers an easy access to different parts of the city with different modes of transportation. However, there are no specific off-road parking/specific parking spaces available for the vehicles, and no bike storage. On the other hand, in the case of Denmark, there is usually a designated bike storage space for the residents.

Table 33. Scores for costs and functionality

Critical Indicators	Available points	A	B	References
CF1	3	1	1,5	DGNB manual
CF2	2	1	1	ISO 21929
CF3	2	2	2	ISO 21929, LEED v4.1
CF4	2	1	1	Mesa et al (2020)
CF5	4	1	1	Petrović et al (2021)
CF6	4	2	3	Janjua, Sarker and Biswas (2020), Republic of Lithuania
Total	17	8	8	

Social and cultural Inclusion (CF2):

Relevance: The social and cultural inclusion is a qualitative indicator. This is measured based on the aesthetic quality. The following aspects were considered:

- integration and harmony of the building with the neighborhood;
- consideration during the planning and design phases of the requirements of the aesthetic quality for different stakeholders;
- inclusion of the stakeholders from the planning to the occupancy stage for decision-making;
- personal safety is also included regarding the integration with the surroundings.

In this case, regarding a specific building, being in accordance with the local building characteristics and urban planning regulations is deemed sufficient. The

architectural quality of an already existing building is preserved in case of a historic building.

Explanation: For this assessment, the buildings were given 1 point each as the already existing building complies with the regulations, and the aesthetic appearance of the buildings was improved in accordance with the perception of the society.

Quality outdoor (CF3):

Relevance: To give the occupants of the building as much connection to the natural outdoor environment through open space, green space and quality views as possible. The proximity and access to green and open spaces is measured in distance or time (km or min). The open or green space could be a park, gardens, or open spaces accessible to the general public.

- The accessibility to open areas i.e., recreation/sports infrastructure, a park, a garden, or some other public space;
- Quality views including: (1) the flora, the fauna, or the sky; (2) movement at least 25 feet from the exterior of the glazing (window).

The access to and/or the proximity to the nearest green space is assessed in km or in the time spent travelling to the location. For this, a minimum of two kilometers is used as threshold by walking, or 15 minutes by public transportation. The above-mentioned categories will score 1 point each for fulfilling this indicator.

Explanation: Both Buildings are given credit points of 2 points each as they satisfy both parameters. Both buildings offer a clear view of the nearby flora or fauna or the movements; the location of the buildings offers access to green spaces located nearby.

Durability (CF4):

Relevance: Materials can be recovered only if they remain intact during their use and dismantling. The materials in use should withstand the typical wear and tear; therefore, it is important to choose the right materials during the initial stage [189]. The durability of the material can be analyzed based on the mechanical durability, chemical durability, and environmental performance – energy consumption and the carbon footprint. Durability is listed in the material's passport and EPDs.

Explanation: The buildings were given points based on the previously carried out LCA study. The materials chosen for the study were concrete, steel, PV cells, and polystyrene insulation where the materials were assessed in terms of the extraction from use phase. The materials showed a significant impact on the energy consumption and CO₂ emission. Based on the assessment, one point was given to each building as the exact materials used in the construction are not known. The assessment assumed and analyzed the values based on the European database.

Life cycle costs (CF5):

Relevance: The implementation of LCC analysis can help to estimate the relative costs of the renovation process. The calculation of the total costs is important in the renovation process, and this can be achieved by calculating the total costs throughout the life cycle of the building from its cradle to the grave. The LCC steps include all stages starting with the design, construction costs, operational costs, and the end-of-life costs. The implementation of the life cycle costing analysis provides Buildings A and B with 3 points each.

Explanation: The full assessment of the building costs for Buildings A and B will be given 1 point. The operating costs of the buildings were calculated; however, the investment costs, materials and labor are not extensively known. Based on the literature studies, 23 % of the costs is related with labor, materials and installation. Out of these, half of the value is dedicated for the labor cost [68]. From the LCA study, it is understandable that the implemented renovation offers potential savings, and the investments into the building equal to approx. 10 % and 9 % in the Danish scenario [190].

Potential savings (CF6):

Relevance: Building materials could potentially reduce the maintenance and energy costs during their active life space of the building by 19 % [113]. The energy savings from renovation consist of the reduction in thermal and electrical energy consumption and CO₂ emissions; energy source reduction was achieved by employing renewable energy sources. This indicator is evaluated in Eur/sq. m/year (Eur/m²/yr). Based on the literature, in Lithuania, a maximum of 65 % potential savings is possible with the most energy-saving measures with performance classes A+ and A++ [190].

Explanation: Building A achieved 24 % of the potential savings, and Building B achieved 40 % savings after implementing the renovation measures. Therefore, Building A was given 2 points, and Building B was given 3 points based on the maximum achieved value.

Results and discussion

Results of the case study: According to the obtained results, the proposed methodology evaluates the impact of the building. In this case, a renovated building was considered, and the inputs are incorporated into the LCA software to understand the impact of the building under different categories. From the previous results conducted by the author, the LCA study revealed that the impact on the energy supply is the greatest in non-renovated buildings, and the energy losses have been reduced by 49 % and 54 % by installing the renovation measures (replacement of windows, insulation of roofs, walls and piping, ventilation, solar cells) for Buildings A and B. By using the proposed methodology, an aggregated primary score of the proposed criteria and the comparison of the two buildings yielded 45 % and 47 % performance scores, which translates to the medium level of performance.

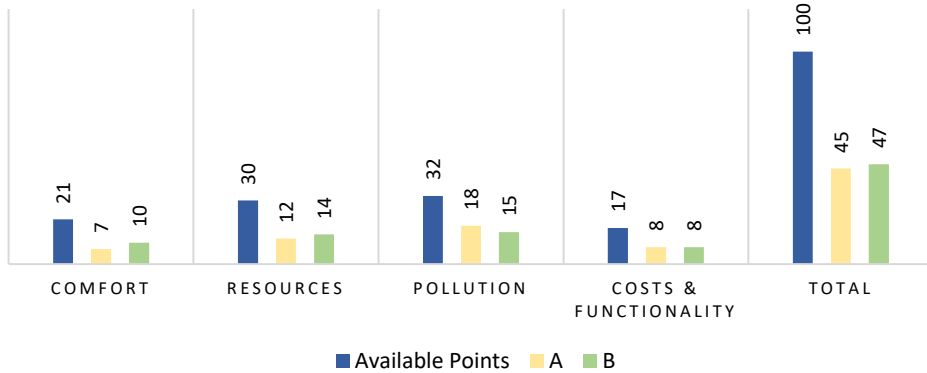


Fig. 19. Consolidated values of the proposed indicators assigned for the case study

However, in this case, the selected buildings underwent different levels of the renovation process except for renewable energy. In the Danish scenario, the renovation was carried for external walls. Heating and electricity supply were connected to DH as the building was a very old one. The replacement of hot water pipelines and the ventilation system was the main part of the renovation process. Therefore, there is not much difference in the weightage given in each case. The proposed methodology results are insignificant as the results are not prominently different regarding many of the assessed criteria. The example object chosen for this study underwent renovation of partial and major changes. Yet, the selected case study is denoted by a different geographical location within a similar climatic zone. The results are based on the comprehensive LCA, and the proposed methodology shows that there is an improvement in the performance of the renovated building based on the implemented measures. The method was applied to specific conditions according to the selected case. This could be because of the nature of the object selected for the study; except for the energy reduction, no significant changes can be observed. Indeed, Building B shows a 47 % performance score.

With the proposed methodology, it is far more appropriate to analyze a different case scenario which would present the entire construction and all the building materials in use. Thus, it is possible to analyze the impact of various currently available and new materials during the process of renovation. These results will help to deduce the suitability and conscious decision making for various stakeholders. This methodology should be implemented on various buildings and throughout the entire renovation process to verify its complete results. This methodology can be applied to the whole building as well as to individual stages of renovation.

Comparison with a similar methodology found in the previous studies: Rating tools integrate the LCA approach in the performance assessment methods to a certain extent (this is not obligatory); however, the implementation of LCA in certification is

still unclear [191]. In this methodology, an integrated approach by combining both the performance tools and the life cycle approach allows obtaining comprehensive evaluation of multi-apartment renovation. This will help to quantify environmental impacts directly and focus more on the life cycle approach so that to optimize the solutions. The compilation of the life cycle inventory of the buildings represented in each particular case study was required for the calculation of the indicator values. The quantities of the materials for the case study buildings were calculated to create a life cycle inventory of the materials, energy, and costs. A few indicators did not necessitate the use of LCA because they dealt with stage-specific issues (i.e., these indicators are related to a specific stage, such as the recycling potential; the quality of *outdoors*; social and cultural inclusiveness are all dependent on the durability of the building's components).

This section provides a comparison of the proposed methodology with the other methodologies found in the literature by applying a similar approach, although in countries with different climates. Kamari *et al.* [195] developed a holistic multi-methodology approach towards sustainable renovation to deal with the complexity of renovation projects and to improve the group decision-making and design process. The presented framework was developed by mixing methods from *Soft System Methodologies* and *MCDM*. Wallenten and Mjornell [196] presented an open accessible framework to ensure sustainable renovation covering the sustainability aspects, such as the environmental, economic, social, technical and cultural-historic aspects. The framework considered that various actors and/or stakeholders participate during the renovation process in order to improve the decision-making process and to achieve the practical targets of sustainability during all stages of renovation. In [197], a new method was proposed for renovation. It targeted the design phase of specific projects. This methodology is based on linking the economic and energy efficiency parameters in order to calculate all the associated renovation actions. A similar study was found in the literature which used the investment, payback and savings of different buildings in Spain. Its results focused only on a renovation related to the building envelope [198]. A theoretical framework was presented for sustainable housing renovation in Sweden. This framework adopts the system-level perspective and an innovative approach as the way forward so that to address the complexity of the renovation process. What regards the system perspective, the framework involves the goals, the process, and the participation and interaction of the stakeholders and the institutional regulations and rules. This framework also emphasizes innovation as a process of housing renovation intended to achieve sustainability in the renovation process [199].

Highlights of the proposed methodology: The proposed methodology focuses on the renovation process itself, and the self-evaluation yields a numerical value which represents to what extent the actors considered and implemented different aspects of the renovation process. The methodology was partially demonstrated in the selected renovated projects as a case study. The methodology follows the traditional stages from the previous studies, embracing the overview, activities description, input

of all the existing materials, and the condition of the building so that to analyze the current impact of the building depending on the condition that the existing impact is evaluated for the renovation/deconstruction process. From the initial stage, it is possible to design the renovation requirements for the already existing building. This could be achieved by linking to the external tools and software as a support. The results regarding the current impact of a building, the onsite impact and the futuristic impacts can be evaluated by using the life cycle approach with the help of analysis of various components incorporated in the building. With this, it is possible to understand the impact of the entire building over the entire phase of the building existence (the pre-design and the operation stages). This will bring a holistic approach and look into more sustainable aspects and the circularity of materials right from the beginning of the renovation process [192]. A previous study suggested a process for sustainable integrated management for the renovation of buildings and put forward the SIREn framework which would help to develop deep knowledge about the entire status of the building for different actors involved so that it would be possible to have a long-term strategy for well-planned maintenance without any emergency actions [3].

Target audience: The proposed methodology can be used by different stakeholders, such as researchers, architects, consultants, operation and management teams, and authorities. Based on the type of the project and the inclusion of different stakeholders, the methodology can be adopted for any particular building. The idea of the methodology is that it can be used on any actual project work so that to evaluate the individual process stages to be completed or to be analyzed.

Outputs from the Survey: The survey also revealed that there is an inherent requirement for the follow-up after the renovation process. The proposed methodology also suggests a continuous follow-up annually during the use phase, as per the opinion of experts [176]. The continuous follow-up could be highly useful to achieve the objectives as monitoring provides an opportunity to formulate the adequate maintenance or attention in the early stage, which could make it easier to plan and select the further measures as part of the renovation process, if required [193]. Moreover, the survey also revealed that, on many occasions, user satisfaction surveys rarely include questions about the indoor environmental quality. This was supported by a study revealing that none of the construction organizations performed any kind of a special survey among the tenants before a renovation project [194]. The methodology also strongly recommends a user survey before renovation and after the renovation of the building. The addition of such questions could be an effective way to garner resident opinions and identify the areas for improvement [31,194].

Limitations: The selected building was already renovated; therefore, the data before the renovation was unavailable. Some data was extracted from the previous literature, and additional assumptions were made. Building-specific information, such as the geographic location, the building type, its size, age, occupancy schedule, operation and maintenance, energy sources, utility rate structure, building fabric, and

the services system – all of these aspects influence the effectiveness of renovation. As a result, the access to each dataset is nearly impossible in practice; additionally, the data used in this study is EU-relevant in the generalized sense without being attributable to any particular country; not all data was used in the regional context. Especially, when it comes to older buildings, the availability of the data related to the previous building phase (non-renovated) is almost null, except the data which is based on user data. In many cases, it makes the evaluation far from accurate. The weightage and scoring system are based on the previous study which can be optimized with the MCDA methods such that distribution of scores can be standard for future application. Moreover, by comparing to other assessments, the suggested method offers the advantage of combining the LCA approach and MCDA, which allows for different assessment scores based on the varying preferences of the stakeholders [99].

Chapter Conclusion

Building renovation is a complex process which necessitates thorough examination of the environmental, energy, water, and human health implications. The single current criterion (energy-centric) approach is insufficient, and an integrated evaluation requires a multi-criteria approach [99]. The benefits of renovation are hardly captured from the sustainability perspective. In this regard, the proposed methodology shall guide decision-makers, thereby allowing them to capture all the data of the building and the associated impacts systematically, thus allowing for regional optimization and database building. In line with the ‘renovation passport’ [9], this methodology could be a support tool to establish a concept in the scope of multi-apartment buildings [176]. Moreover, these available details will benefit the policymakers and decision-makers in any further projects so that they could better understand and identify the issues, solutions, and data associated with the renovation of multi-apartment buildings [143].

CONCLUSIONS

1. The investigation has identified the main gaps concerning the evaluation of the renovation of residential buildings. With the help of the literature, a comprehensive list of indicators and the methods that are used to evaluate the renovation of residential buildings is analyzed and consolidated. The environmental performance schemes and life cycle assessment methods are the most widely used methods. They were selected to evaluate the performance of a renovated building. Moreover, a multi-criterion assessment method was selected to prioritize the indicators for the evaluation through a new methodology. Therefore, the literature study helped to formulate a research methodology and indicators to carry out the environmental impact assessment for the renovation of buildings.
2. The selected methods – the life cycle assessment and the environmental performance schemes – have been applied to a renovated multi-apartment building in order to understand the actual impacts and the credit allocation between the two methods. (a) The LCA results revealed that Building A and Building B achieved energy savings of about 12 % and 48 % based on the renovation type. After renovation, the potential thermal savings in the thermal energy used for space heating and hot water preparation are 25 % and 40 % after the conventional renovation and the renovation with renewable energy measures. (b) When assessing the EPAS, a comparison of LEED and BREEAM suggests that both systems showed good performance on Building B contributing 50 points on LEED and 54 points on BREEAM, which is equivalent to ‘very good’ and ‘good’ performance. Furthermore, the provision of LCA in both schemes is about 11.5 % of the final score for BREEAM and 15.4 % in LEED.
3. An assessment methodology for the renovation of residential buildings with the LCA approach was developed. The assessment methodology was developed based on integrating the life cycle assessment approach and the environmental performance schemes in order to evaluate the performance of renovation from the initial stage of the process. The methodology can be applied on the actual already existing project in order to understand the current burden on the environment, future impact, and the onsite impact over the entire phase of the building (including the pre-design and the operation stages) depending on the selected indicators. It is thus possible to bring a holistic approach and look into more sustainability and circularity aspects right from the beginning of the renovation process.
4. The developed methodology was applied to the selected building, and the results were obtained for four categories and 26 indicators in total. According to the obtained results, the proposed methodology, an aggregated primary score of the proposed criteria and the comparison of the two buildings showed 45 % and 47 % performance scores, which translates to the low and medium performance levels. The developed methodology aggregates about 10 % of the indicators relevant to the life cycle parameters spread over all the life cycle phases, compared to BREEAM and LEED with 5.9 % and 2.7 % weightage given to the life cycle indicators. The developed methodology emphasizes the use of LC

parameters in the pre-design stage and in the development stage in order to capture the full impact of the renovation process, especially for the already existing old buildings.

IVADAS

Tyrimo aktualumas, tikslas ir uždaviniai

Statybų sektorius yra labai svarbi sritis tiek nacionaliniam vystymuisi, tiek socialiniam ir kultūriniam augimui bet kurioje žmonių visuomenėje. Antra vertus, gerai žinoma, kad statybų sektorius turi didžiulį poveikį aplinkai, nes šiame sektoriuje sunaudojami dideli kiekiai medžiagų ir energijos išteklių. Šiuo metu apie 35 % pastatų ES yra bent 50 metų senumo, ir net apie 75 % neefektyviai vartojama energija [1]. Europos Sąjunga iškėlė ambicingus tikslus klimato ir energetikos srityje, ragindama šalis nares juos pasiekti per ateinančius metus. Esamų pastatų atnaujinimas tapo esminiu įrankiu siekiant klimato tikslų iki 2050 m., ir tai yra galimybė žymiai pagerinti ne tik pastatų kokybę, bet ir visų europiečių gyvenimo sąlygas. Ispanijoje atlikta analizė parodė, kad dauguma pastatų renovacijos strategijų yra panašios [2]. Didelis dėmesys skiriamas energijos vartojimo efektyvumui, o priemonės pagrįstos daugiausia tik energijos išteklių sąnaudų mažinimu. Pastato, kaip ir miestų, gyvavimo ciklas yra ilgas, todėl tai, kas sukurta ir gaminama šiandien, turės įtakos ateities kartoms. Todėl strategijos turi būti vykdomos nepažeidžiant aplinkos, socialinių ir ekonominių veiksnių [3]. Be to, daug dėmesio įvairiais lygmenimis sulaukia pastangos siekiant tvarios statybos, taip pat ir renovacijos proceso taikant įvairius pastatų tvarumo vertinimo metodus [4]. Tačiau šios priemonės dažnai skirtos tik naujiems pastatams ir su jais susijusiam poveikiui aplinkai bei energijos vartojimo efektyvumui vertinti. Nors renovacijos procesas vyksta nuo pastarojo dešimtmečio, jo studijos yra fragmentiškos ir apsiriboja energijos išteklių analize ir (arba) koncentruojamasi ties eksploatacijos etapu, todėl nenagrinėjamas visas renovacijos procesas kaip visuma. Teigiama, kad trūksta standartizuotų praktikų, politikos priemonių ir reglamentų, kurie būtų konkrečiai skirti renovacijos proceso vertinimui tvarumo ar kokiam nors kitame kontekste [5].

Kaip ir daugelis kitų Europos valstybių, Lietuva susiduria su poreikiu skubiai renovuoti daugiau nei prieš 50 metų pastatytus gyvenamuosius namus. Lietuvoje yra per 37 000 daugiabučių namų, iš jų per beveik 10 metų laikotarpį iki 2021 m. buvo renovuoti 4335 butai [6], o tai sudaro tik 12 % daugiabučių namų. Šių daugiabučių gyvenamųjų namų renovacija vyksta lėtai dėl daugelio įvairių priežasčių, pvz., išteklių trūkumo, gyventojų nepritarimo renovacijai, techninių žinių trūkumo, sociokultūrinių ir kitų priežasčių [7]. Nepaisant to, renovacija prailgina pastatų eksploatacijos laiką, todėl būtina įvertinti gyvenamojo namo renovacijos poveikį, remiantis gyvavimo ciklo požiūriu.

Tyrimo tikslas ir uždaviniai

Tyrimu siekiama sukurti poveikio aplinkai vertinimo metodiką renovuotiems gyvenamiesiems namams taikant gyvavimo ciklo požiūrį. Šiuo tikslu buvo išsikelti tokie uždaviniai:

1. Ištirti esamus pastatų vertinimo metodus bei jų rodiklius ir nustatyti pagrindinius su renovacijos procesu susijusius rodiklius.

2. Įvertinti renovuoto gyvenamojo namo poveikį aplinkai per visą jo gyvavimo ciklą, taikant LCA.

3. Lyginant skirtingus vertinimo metodus, nustatyti esminius renovacijos proceso veiklos vertinimo rodiklius.

4. Parengti ir taikyti renovuojamų namų poveikio aplinkai vertinimo metodiką.

Tyrimo hipotezė

1 hipotezė: aplinkosaugos veiksmingumo įrankiai yra tinkami vertinti gyvenamųjų namų renovacijos efektyvumui, atsižvelgiant į visą gyvavimo ciklo etapą.

2 hipotezė: dabartiniai aplinkosauginio veiksmingumo metodai nepateikia visapusiško daugiabučių namų renovacijos įvertinimo, nes vertinant pastatą netaikomas gyvavimo ciklo metodas.

Tyrimo metodai

Pirmiausia buvo atlikta literatūros analizė, kurią pasitelkus identifikuota problema, tyrimų spragos ir taikyti metodai vertinant renovuotų gyvenamųjų namų poveikį aplinkai. Taip pat atliktas renovuotų pastatų, taikant skirtingas renovacijos technologijas, poveikio aplinkai vertinimas taikant gyvavimo ciklo požiūrį. Dar sukurta apklausos anketa ir atlikta apklausa, siekiant nustatyti veiksnius, susijusius su renovacijos procesu. Pasitelkus daugiakriterius modelius, nustatyti pagrindiniai rodikliai, pasiūlyta konceptuali poveikio aplinkai vertinimo metodika renovuotų gyvenamųjų namų vertinimui taikant gyvavimo ciklo požiūrį. Sukurta poveikio aplinkai vertinimo metodika išbandyta vertinant gyvenamuosius daugiabučius pastatus, tyrimų rezultatai ir išvados publikuoti mokslinėse publikacijose.

Tyrimo objektas

Tai Lietuvoje renovuoti daugiabučiai gyvenamieji pastatai. Eksperimentinei analizei pasirinkti du daugiabučiai namai, kuriuose buvo taikomos skirtingos renovacijos technologijos.

Mokslinis naujumas

Pagrindinis mokslinis naujumas siejamas su poveikio aplinkai metodikos sukūrimu renovuotų daugiabučių gyvenamųjų namų vertinimui taikant gyvavimo ciklo požiūrį. Tyrime pagrindinis dėmesys skiriamas renovuotų pastatų poveikio aplinkai vertinimui, taikant gyvavimo ciklo analizę, neapsiribojant vien tik energetinių išteklių vertinimu. Pirmą kartą pasiūlyta metodika, skirta įvertinti renovuoto daugiabučio gyvenamojo pastato poveikį aplinkai, remiasi daugiakriterine analize ir gyvavimo ciklo vertinimo metodika.

Praktinė vertė

Sukurta metodika gali būti taikoma gyvenamųjų daugiabučių namų renovacijos vertinimui. Svarbu tai, kad sukurta metodika yra išbandyta daugiabučiuose namuose kaip atvejo analizė, kuri galėtų būti naudinga vertinant renovacijos efektyvumą

holistiniu ir gyvavimo ciklo požiūriu viso proceso metu. Siūlomas metodas gali būti taikomas kaip sprendimų priėmimo modelis vertinant pastatų renovacijos efektyvumą nuo pastato planavimo etapo iki kol pastatas po eksploatacijos virsta atliekomis, arba įvertinant atskirus pastato gyvavimo etapus.

Tyrimo rezultatų aprobavimas

Moksliniai rezultatai publikuoti trijuose tarptautinio žurnalo straipsniuose su citavimo indeksu. Du straipsniai paskelbti *WoS* su poveikio koeficientu ir vienas straipsnis paskelbtas *Scopus* su poveikio koeficientu. Pirminiai tyrimų rezultatai pristatyti keturiuose tarptautinėse mokslinėse konferencijose.

Disertacijos struktūra ir turinys

Disertaciją sudaro įvadas, penki skyriai, bendros išvados, literatūros šaltinių sąrašas su 197 literatūros šaltiniais ir mokslinių publikacijų sąrašas. Daktaro disertacijos apimtis – 144 puslapiai, juose yra 19 paveikslų ir 33 lentelės. Disertacija apima medžiagą, anksčiau publikuotą straipsniuose, kurie buvo atgaminti leidėjams sutikus.

1. ESAMŲ PASTATŲ RENOVACIJA

Europoje vyrauja įvairūs pastatai, tačiau didžiąją ploto dalį (75 %) užima gyvenamieji. Pastatai gali būti apibūdinami remiantis tokiomis charakteristikomis: 1) grindų plotas vienam sektoriui; 2) gyvenamieji pastatai pagal konstrukciją; ir 3) pastatų tipologija. Gyvenamųjų namų tipologija taip pat labai skirtinga įvairiose šalyse – vidutiniškai apie 49 % sudaro vienbučiai ir daugiabučiai namai. Nuo pastato tipo ir izoliacinių savybių priklauso energinis pastato naudingumas [10]. Be to, dauguma pastatų statyta prieš įvedant šiluminius standartus, t. y. iki 1970 m., daugiau nei 40 % jų buvo pastatyta iki 1960 m. ir 90 % – iki 1990 m., o dauguma šių pastatų išliks ir 2050 m. Kasmet naujos statybos Europoje sudaro apie 1 % pastatų, o tai reiškia, kad naujesni pastatai pasižymi geresnėmis savybėmis nei esami, anksčiau statyti pastatai [11]. Bendras pastatų kiekis laikui bėgant auga, o naujų pastatų statybos greitis viršija senų pastatų griovimo tempą. Svarbiausia tai, kad tiek griovimo, tiek statybos rodikliai yra žemi. Praėjusį šimtmetį buvo daugiau nugriauinama pastatų, palyginus su esamų pastatų modernizavimo galimybėmis. Taikant griovimo ir statymo metodą, tiek aplinkai, tiek sąvartynams buvo daromas didesnis poveikis, o tai iš esmės nesprendžia pasenusių, neefektyvių pastatų problemų [12]. Taigi buvo prieita prie išvados, kad didelę dalį Europos pastatų reikia atnaujinti.

Lietuva, lyginant su kitomis ES šalimis, atsilieka ir pastatų atnaujinimo (renovacijos) procese. Didžioji dalis Lietuvos pastatų statyta XX a. antrojoje pusėje, 60 % gyventojų gyvena daugiabučiuose, pastatytuose 1961–1990 m. laikotarpiu. Esant ilgiems šildymo sezonams, apie 80 % daugiabučių yra prastos techninės būklės, prastos izoliacijos, neefektyvios šildymo sistemos, dėl kurių patiriami didžiuliai energijos nuostoliai [13, 14]. Siekdama gerinti gyvenimo sąlygas, energijos vartojimo efektyvumą, mažinti iškastinio kuro kiekį, Lietuva įsipareigojo didinti energijos vartojimo efektyvumą, ES finansuojant įvairius pastatų renovacijos projektus [15]. Paprastai pagrindinis dėmesys skiriamas energijos taupymui renovuojant, o tai galima pasiekti renovuojant sienas, stogus, vamzdynus, duris, langus, apšvietimo bei oro kondicionavimo, vandens, energijos bei šildymo tiekimo sistemas ir kt. pastato komponentus. Pasirinkus tinkamą renovacijos priemonę, būtų galima sutaupyti eksploatacijos sąnaudų ir pagerinti įvairius pastato aspektus, tokius kaip energetinės priemonės ir komforto lygis [20–22]. Atsižvelgiant į sutaupytas energijos sąnaudas atnaujinus pastatą, renovacija gali būti klasifikuojama į skirtingas kategorijas. ES pastatų stebėjimo tarnyba pristatė įvairius renovacijos lygius ir priemones, kurias leistų pasiekti tam tikrą energijos efektyvumo lygį (nuo 3 % iki >60 %) [23]. Nepaisant to, renovacijos priemonės neapsiriboja vien tik energijos taupymu ir mažai anglies dioksido į aplinką išskiriančiais pastatais, bet taip pat apima ir gyventojų gerovę, komfortą ir kitus socialinius bei kultūrinius veiksnius [26, 27].

1.1 Teisės aktų sistema

ES politikoje ir strategijose pripažįstama pastatų renovacijos, kaip pagrindinio elemento siekiant ilgalaikių energetikos ir klimato tikslų, svarba, taip pat turinti

teigiamą ekonominį poveikį. Todėl į pastatų sektorių atsižvelgiama visose su energijos, klimato ir išteklių naudojimo efektyvumu susijusiose strategijose [8]. Pastatų energinio naudingumo direktyva (2010/31/ES) ir Energijos vartojimo efektyvumo direktyva (2012/27/ES) – abiejose direktyvose skatinama politika, kad pastatai taptų nulinės emisijos pastatais ir kad pastatai iki 2050 m. būtų dekarbonizuoti [33]. Vadovaujantis nauja renovacijos politikos direktyva [9], nustatomi nauji energinio naudingumo standartai, siekiant sumažinti pastatų sektoriaus išmetamo anglies dioksido kiekį, keičiant energinio naudingumo standartų apibrėžtis (nulinė teršalų emisija, „nuodugni“ renovacija), persvarstant nacionalinius pastatų atnaujinimo planus bei atsižvelgiant į emisijų išmetimą per visą gyvavimo laikotarpį [8, 34] ir Atsinaujinančių išteklių energijos direktyvos (RED) integravimą į renovacijos procesus [35]. Todėl ES šalys turi imtis svarbių veiksmų, siekdamos išspręsti esamų išteklių energijos ir anglies taupymo potencialą, tobulindamos reguliavimo, administracinius ir kt. aspektus. Nors kai kurios iš šių priemonių jau yra taikomos, jos ne visada pakankamai veiksmingos, kad paskatintų renovacijos veiklą, siekiant pakeisti situaciją rinkoje. Nepaisant to, šalys turi daug gerosios patirties, kuria galėtų dalytis, kad būtų lengviau įgyvendinti ilgalaikes strategijas [36].

1.2 Pastatų renovacijos poveikio aplinkos vertinimui metodikos

Pastatų renovacija turi didelį potencialą daryti įtaką poveikio aplinkai mažinimo veiksniams, kad būtų pasiekti klimato kaitos tikslai. Pastatų poveikio aplinkai tyrimui buvo pasiūlyta keletas naujų strategijų ir poveikio aplinkai vertinimo būdų [33, 37]. Gyvavimo (būvio) ciklo vertinimas (GCV/BCV) (angl. *Life cycle assessment (LCA)*) ir aplinkosauginio veiksmingumo vertinimo schemos (angl. *Environmental performance assessment system (EPAS)*) yra du dažniausiai taikomi pastatams apibūdinti tyrimo metodai. Daugeliu atvejų abu metodai buvo derinami siekiant ištirti su pastatais susijusį poveikį aplinkai [38].

Gyvavimo ciklo vertinimas (GCV) renovuojant pastatą yra plačiai taikoma metodika ir pažangiausias įrankis, kuris įvertina galimą visų įvesties ir išvesties srautų poveikį aplinkai per produkto gyvavimo ciklą, nuo žaliavų gavybos iki eksploatavimo pabaigos [39, 40]. Pastatų GCV buvo plačiai ištirta sritis dėl didelio šio sektoriaus poveikio aplinkai ir integruoto požiūrio į poveikio aplinkai vertinimą bei duomenų kokybę [4, 43–45]. Įvairių esamų tyrimų, susijusių su GCV, renovacija ir gyvenamaisiais pastatais, apžvalga apima įvairias pastato energijos analizes, alternatyvias ir efektyvias renovacijos energetikos priemones, renovacijos proceso etapų tarpusavio ryšį, statybinių medžiagų poveikį (sienos, šilumos izoliacija, atitvarai), identifikuojant pastato tipus – vienbučiai ir daugiabučiai pastatai. Įvairiose studijose vertinami ir su renovacijos procesu susiję kriterijai, tačiau dažnai atsižvelgiama į visuotinio atšilimo potencialą, energijos poreikį, eutrofikaciją, rūgštėjimą [20, 51–54]. Daugiau nei pusėje tyrimų buvo analizuojamos sistemos ribos, tačiau transportavimo, statybos ir naudojimo etapai dažnai į tyrimus nebuvo įtraukiami. Ankstesni tyrimai buvo skirti eksploatavimo etapui, ypač energijos taupymui ir šilumos izoliacijos priemonėms įvertinti [17, 49–52]. Nors šiam etapui skiriamas didžiulis dėmesys, kiti aspektai, tokie kaip priežiūra, vandens suvartojimas,

atliekos, neįtraukti nė į vieną tyrimą. Taip pat nepavyko rasti duomenų apie tyrimus, kuriuose būtų nagrinėjami renovacijos aspektai per visą pastato gyvavimo laikotarpį, nors Kamali tyrė tradicinių ir modulinių renovuotų pastatų poveikį aplinkai [55]. Tokių specifinių rodiklių, kaip pastato gyvavimo trukmė, vertinimas duoda įžvalgų būsimiems tyrimams ir suteikia pridėtinės vertės praktiškai. Tačiau nei visas pastato gyvavimo ciklas, nei atskiros poveikio kategorijos nėra įtrauktos į pastato GCV tyrimus. GCV buvo integruota į kitas schemas, pvz., statybos kodeksus ir sertifikavimo sistemas, kad būtų galima palyginti scenarijus planavimo ir projektavimo etapuose, siekiant priimti pagrįstus sprendimus [56].

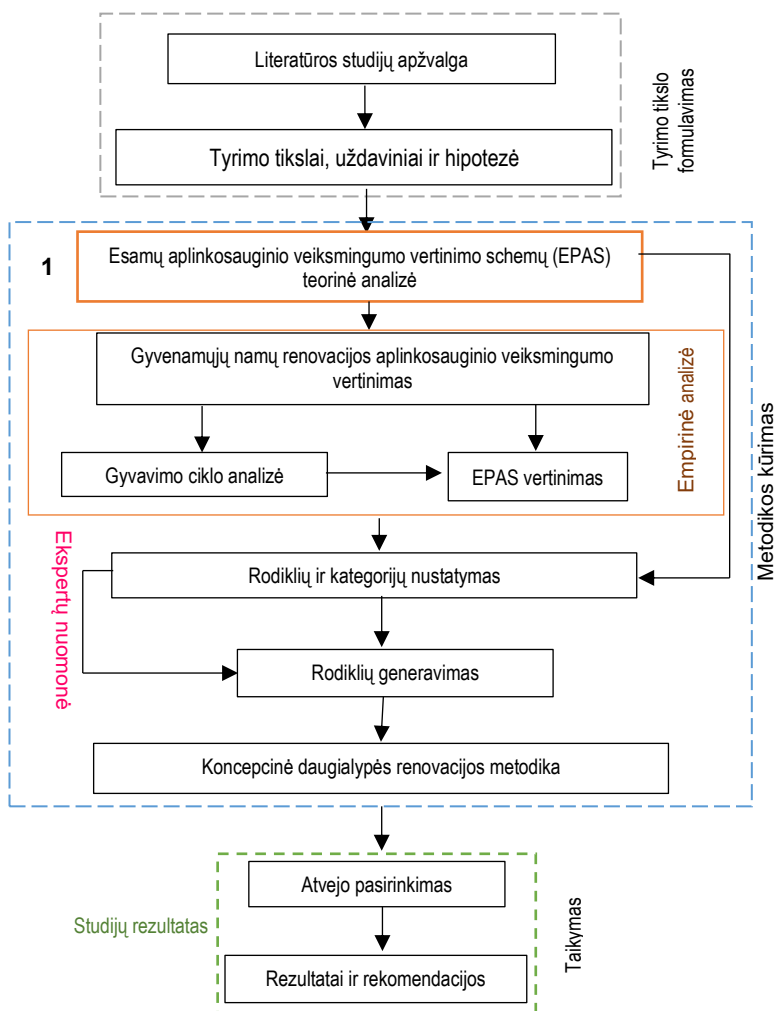
Iš aplinkosauginio veiksmingumo vertinimo atnaujinant pastatus srities pasaulyje taikoma keletas sistemų, tokios kaip BREEAM, LEED, DGNB, HQE ir t. t., kurios įvertina pastato aplinkos tvarumą, taikant išsamius kriterijus, tokius kaip teršalų išmetimas į orą ir vandenį, šiltnamio efektą sukeliančių dujų emisijos, atliekos, medžiagų poveikis, ar kitus specifinius parametrus [69]. Tarptautiniu mastu visuose pasaulio regionuose yra keletas vertinimo priemonių. *Building Research Establishment Environmental Assessment Method* (BREEAM, JK) [70] buvo pirmoji sukurta išsami su pastatų statyba susijusi veiklos rezultatų schema, po kurios atsirado LEED (JAV) [71], CASBEE (Japonija) [72], *Green Star* (Australija) [73], HQE (Prancūzija) [74] ir DGNB (Vokietija) [75]. Illankoon ir kt. [85] palygino aštuonias Australijos sertifikavimo sistemas, panašiai Mattoni ir kt., taip pat Doanas ir kt. palygino apie 10 sistemų, įskaitant regionines [79, 82]. BREEAM, LEED, CASBEE, DGNB yra dažniausiai tyrimams taikomi metodai. Atliekant kai kuriuos tyrimus buvo bandoma apžvelgti tarptautinę sistemą ir rekomenduoti tinkamas išvadas jų regioninei politikai plėtoti [37]. Tyrimuose taip pat iškeltas susirūpinimas dėl bendro šių esamų schemų suderinamumo, todėl pateikiami įvairūs pasiūlymai ir rekomendacijos. Daugumoje analizuotų literatūros šaltinių yra palyginami energijos, medžiagų, vietos ir komforto, kaip pagrindinių su pastatu susijusių aspektų, duomenys. Taip pat atlikus literatūros šaltinių tyrimų analizę buvo nustatyta, kad aplinkosaugos aspektas yra plačiai vertinamas ir svarbus daugumai vertinimo sistemų. Iš visų tyrimų buvo atliktas tik vienas, kuriame daugiausia dėmesio skirta keleivio gerovei ir komfortui. Obrecht ir kt. ištyrė komforto aspektus iš keleivių perspektyvos, taikydama veiklos vertinimo metodus [87]. Nors yra daugybė tyrimų, kuriuose analizuojamas šių metodų visapusiškumas, literatūroje apie BCV/GCV aspektus ir jų įtraukimą to nėra pateikta. Be to, literatūroje nebuvo rasta tyrimų, susijusių su šių metodų įtaka pastato įvairioms gyvavimo fazėms, t. y. projektavimui, medžiagų gavybai, statybai, eksploatacijai, atliekų sutvarkymui ir kt.

Kitų pastatų renovacijos vertinimo metodų apžvalga parodė, kad daugiakriterė analizė (MCA) buvo vis labiau plėtojama siekiant įvertinti tvarumo aspektus statybos sektoriuje ir renovacijos projektuose. Daugiakriterė analizė dažnai taikoma lyginant bei vertinant renovacijos sprendimus ir scenarijus įvairioms suinteresuotosioms šalims. Gervasio ir kt., taip pat Jafari ir kt. taikė MCA optimizuoti pastatų energetiniam naudingumui ir atlikti palyginamajam vertinimui [19, 92], be to, autoriai į savo tyrimus įtraukė ir ekonominius bei socialinius aspektus [19, 93, 94]. Nedaug

tyrėjų savo studijose taip pat dėmesio skyrė socialiniams renovacijos aspektams ir siūlė gaires socialiniam vertinimui [29, 95–97].

Kaip minėta anksčiau, su LCA susiję tyrimai statybų sektoriuje atsirado per pastarąjį dešimtmetį. Antra vertus, ankstesniuose tyrimuose buvo atlikta skirtingų sistemų tyrimų, jungiančių LCA ir MCA, integravimą pastatų vertinimui. LCA taip pat galėtų būti taikomas kaip optimizavimo ir kiekybinio įvertinimo metodas renovacijos procese. Taip pat LCA gali būti integruojamas kartu su LCC, kada būtų galima analizuoti ne tik pastato poveikį aplinkai per visą gyvavimo ciklą, bet ir kiekybiškai įvertinant poveikį aplinkai per ekonominę dedamąją [2]. Panašiai Liu ir Qian sukūrė į sistemą orientuotą aplinkos ir pastatų renovacijos socialinio poveikio metodą taikant MCA ir S-LCA [100]. Remiantis kitų autorių atliktų tyrimų išvadomis, galima teigti, kad buvo bandoma integruoti LCA ir MCA skirtinguose renovacijos etapuose, tačiau nebuvo sukurta ir pasiūlyta metodikų, leidžiančių įvertinti renovuotų pastatų poveikį aplinkai per visą jų gyvavimo ciklą. Dabartiniai tyrimai taip pat rodo, jog daug dėmesio skiriama aplinkos aspektams, kai kurie tyrimai optimizuoja algoritmus, kad įvertintų su renovacija susijusias išlaidas [104]. Bandymas, susijęs su S-LCA, nėra organizuotas ir standartizuotas, skirtingais metodais siūlomas keletas rodiklių, susijusių su socialiniu aspektu, tačiau įvertinančių poveikį aplinkai taikant gyvavimo ciklo požiūrį iki šiol nėra. Literatūros analizė parodė, kad buvo atlikti konkrečiam regionui būdingi atvejų tyrimai, siekiant įvertinti statybos efektyvumą, tačiau atlikti tyrimai fragmentiški, nagrinėjantys tik tam tikrus aspektus.

Kai kurios poveikio aplinkai vertinimo priemonės siūlo savo rodiklius pagal tyrimo pobūdį ir reikalingą kontekstą. Rodiklių, susijusių su statybos veikla, sąrašas yra išsamus, nes apima platų tipologijos, charakteristikų ir susijusių poveikių spektrą. Dažnai šie išsamūs rodikliai skirstomi į kategorijas pagal jų poveikio tipą ir temą, pvz., aplinkos, socialinį, ekonominį ar kultūrinį. Pasaulyje daug vertinimo metodų, todėl yra daugybė rodiklių, kurie konsoliduoti iš literatūros tyrimų. Tyrimų metu konkretūs rodikliai taip pat sugrupuoti pagal jų poveikio kategorijas, kad juos būtų lengviau suprasti ir lengviau įvertinti. Dauguma rodiklių yra „susiję su energija“, kurie dažnai analizuojami, o po to nagrinėjamos išlaidos, nes tai yra svarbus veiksnys atliekant renovaciją. Panašiai dažnai tiriami komforto ir sveikatos aspektai; mažiausiai ištirta pastato istorinė vertė bei ilgaamžiškumas renovacijos metu ir po jos.



1 pav. Disertacinio darbo tyrimo struktūra

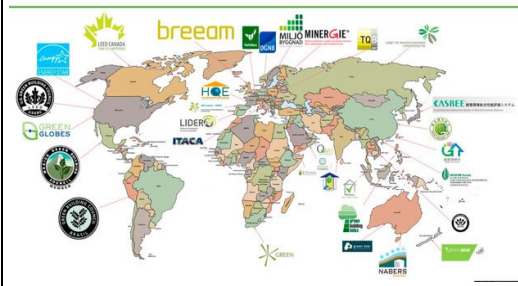
Apskritai per pastaruosius dešimtmečius akademiniėje ir statybų pramonėje atsirado daugybė renovacijos vertinimo priemonių, kurios buvo taikomos įvairiuose renovacijos projektų etapuose. Šie vertinimo metodai plačiai taikomi energiniam naudingumui įvertinti, todėl per visą renovacijos procesą neatsižvelgiama į viso pastato poveikį aplinkai. Nors šiuose vertinimuose taikomas LCA (GCV), renovacijos atveju daugiausia dėmesio skiriama tik energijos komponentui. Todėl buvo atlikta literatūros tyrimų apžvalga aptariant įvairius esamus metodus bei priemones renovacijos ir gyvavimo ciklo požiūriu. Be to, buvo atlikti su gyvenamųjų namų renovacija susiję tyrimai, kurie apsiriboja eksploatacijos etapu, antra vertus, tokios gyvenamosios tipologijos kaip daugiabučiai nagrinėjamos retai. Atlikus literatūros analizę nustatyta, kad esami metodai gali būti taikomi kaip pagalbinė priemonė arba kombinuota metodika renovacijos poveikiui įvairiais lygmenimis įvertinti. Todėl,

siekiant sukurti gyvenamųjų namų renovacijos poveikio aplinkai vertinimo metodiką, kaip pagrindinė tyrimų sritis ir toliau liko aplinkosauginio veiksmingumo vertinimo metodikos, kartu integruojant ir gyvavimo ciklo požiūrio priemones. Be to, kaip tyrimo objektas buvo pasirinkti renovuoti daugiabučiai pastatai, kurių renovacijai buvo taikomos skirtingos technologijos – naudojant atsinaujinančius energijos šaltinius ir taikant įprastines renovacijos technologijas. Toliau pateikiama disertacinio darbo tyrimo eigos struktūrinė schema.

2. VEIKSMŲ VERTINIMO METODŲ LYGINAMOJI ANALIZĖ

Remiantis ankstesniais literatūros tyrimais, toliau analizuoti buvo pasirinktos šios schemas (1 lentelė), siekiant išsiaiškinti, kaip įvairūs aspektai gali prisidėti prie renovacijos proceso metodikos kūrimo. Pasirinktos schemas yra populiariausios ir plačiausiai taikomos visame pasaulyje įvairių tipų pastatams sertifikuoti, šios schemas parenkamos pagal projektų skaičių (daugiau nei 3000) ir jų prieinamumą įvairiuose regionuose. Visame pasaulyje yra apie 600 schemų, iš kurių atrinktos keturios [151]. Pirmiausia buvo išnagrinėti skirtumai tarp kiekvieno kriterijaus pasirinktose schemose, o tada išanalizuotas ryšys su renovacija ir gyvenamaisiais pastatais. Kiekviena schema buvo ištirta dėl LCA įtraukimo, jų paskirstymo ir įgyvendinimo.

1 lentelė. Aplinkosaugos veiksmingumo schemas visame pasaulyje

	Schemas	Ša- lys	Projek- tai	Užbaigtu- mas
	BREEAM	93	31 113	31
	DGNB	20	8700	12
	HQE	26	380 000	29
	LEED	10	80 000	21

2 lentelėje pateikiami visų pasirinktų vertinimo metodų pagrindiniai bruožai. Šie vertinimai taikomi įvairių tipų pastatams, įskaitant švietimo įstaigas, verslo ir gyvenamuosius pastatus, komercines virtuves ir bendruomenes. Siekiant užtikrinti išsamų įvertinimą, kiekvienas vertinimo būdas turi savo modulį ir įvertinimo balus, kurie apima įvairius aspektus.

2 lentelė. Pagrindinės pasirinktų EPAS savybės

Schemas	Kategorijos	Svorinė sistema	Įvertinimo lygis
BREEAM (1990), JK [70]	Energija, atliekos, vanduo, tarša, medžiagos, transportas, ekologija, valdymas, sveikata ir gerovė, inovacijos	Taikoma kiekvienam lygiui	Neklasifikuotas, išlaikytas, geras, labai geras, puikus, nepriekaištingas

DGNB (2007), Vokietija [75]	Ekologinis, ekonominis, techninis, procesinis, socialinis-kultūrinis ir funkcinis, kokybės	Taikoma kiekvienam lygiui	Bronzinis, sidabrinis, auksinis, platininis
HQE (1994), Prancūzija [152]	Ekologinė statyba, ekologinė vadyba, komfortas, sveikata	Nepasiekiamas	Išlaikyta, gerai, labai gerai, puikiai, išskirtinai
LEED (1998), JAV [71, 153]	Energija, medžiagos ir ištekliai, vandens efektyvumas, patalpų kokybė, novatoriškas dizainas, tvartos vietos, regioninis prioritetas	Visi kreditai yra vienodai vertinami	Sertifikuotas, sidabrinis, auksinis, platininis

2.1 EPAS palyginimas

Vertinimai tiriami remiantis: 1) apimtimi; 2) pastato tipologija; 3) gyvavimo ciklo etapais; 4) prieinamumu; 5) rodikliais / kriterijais ir 6) tvarumu. 3 lentelėje pateikiamas išsamus kiekvieno pasirinkto metodo palyginimas, siekiant suprasti jų skirtumus ir aplinkosauginio veiksmingumo vertinimus.

1. Pastato naudojimo sritis ir tipologija: Kiekvienas vertinimo metodas yra unikalus, nes jis taikomas įvairių tipų pastatams, įskaitant pramoninius, komercinius, švietimo, gyvenamuosius pastatus, ir pagrindinis dėmesys skiriamas pastato valdymui, atsižvelgiant į vietinę ir pasaulinę aplinką. Be to, BREEAM, DGNB, HQE ir LEED apima specializuotas schemas, skirtas įvairiems sprendimams, pavyzdžiui, naujiems ar atnaujinamiems pastatams.

2. Gyvavimo ciklo fazės: BREEAM, DGNB, HQE apima keturis pastato gyvavimo ciklo etapus (projektavimas, statyba, eksploatacija ir priežiūra). Išskyrus DGNB, jokia kita priemonė neįvertina pastato griovimo ir dekonstrukcijos etapų. Be to, visi metodai, išskyrus HQE, neapima išankstinio projektavimo etapo.

3. Prieinamumas: Sistemų taikymas ir prieinamumas kitai auditorijai daro sistemą tvirtą ir nustato socialinės įtraukties lygį. Antra vertus, sistemos, tokios kaip BREEAM, DGNB ir LEED, buvo sukurtos remiantis moksliniais tyrimais. Todėl sistema prieinama visiems, norintiems ją taikyti: nuo ekspertų iki pastatų savininkų ir naudotojų. Tačiau visuose vertinimo metoduose siūloma turėti išorinį ekspertą, kuris atliktų pastato eksploatacinių savybių auditą.

4. Rodikliai: Remiantis analize, visos pagrindinės vertinimo sistemos buvo sutelktos į šiuos kriterijus: energijos vartojimą, medžiagas, projektų valdymą, taršą, atliekų tvarkymą ir vandenį. Panašiai ir kitiems rodikliams, tokiems kaip patalpų kokybė, vizualusis komfortas, ekonominis ir kultūrinis bei socialinis identitetas, buvo suteiktas didžiausias prioritetas tvarumo požiūriu. Rodomos kategorijos dažnai apima tuos pačius arba skirtingus elementus tose pačiose arba skirtingose kategorijose. Kartais jie neįvertina tų pačių savybių. Pavyzdžiui, LEED transportas nėra vertinamas kaip atskiras kriterijus, o įtrauktas į vietos

pasirinkimo kategoriją. Taip pat DGNB nevertina transporto, patalpų kokybės ir ekologijos kaip atskirų kategorijų. Jie apibendrinami prie ekologinės kokybės.

5. **Tvarumas:** Turint tiek daug galimybių ir neatsilikant nuo pasaulinių atnaujinimų, buvo sukurta daug metodų, skirtų įtraukti tvarumo aspektus. Todėl šio kriterijaus tikslas – išanalizuoti pasirinktas EPAS sritis, atitinkančias tvarumo apibrėžimą. Pastebima, kad kiekviena EPAS sistema priskyrė kategorijoms ir subkategorijoms svorį. Taip pat suprantama, kad visuose EPAS metoduose vadovaujamosi skirtingais vertinimo modeliais ir skirtingu rodiklių išdėstymu pagal kategorijas.

3 lentelė. Kiekvienos schemos rodiklių palyginimas

Rodikliai	BREEAM	DGNB	HQE	LEED
Energijos efektyvumas	✓	✓	✓	✓
Šiltnamio efektą sukeliančių dujų emisija	✓	×	✓	✓
Susisiekimas viešuoju transportu	✓	✓	×	✓
Žaliosios transporto priemonės	✓	✓	×	✓
Statybinių atliekų tvarkymas	✓	×	×	✓
Triukšmo tarša	✓	×	×	✓
Šviesos tarša	✓	×	×	✓
Oro tarša	✓	×	×	✓
Vandens kokybė	✓	×	✓	✓
Patalpų oro kokybė	×	✓	×	✓
Šiluminis komfortas	✓	✓	✓	✓
Akustinė tarša	×	✓	✓	✓
Vizualusis komfortas	✓	×	✓	✓
Atsakingas pirkimas	✓	✓	✓	×
Žemės naudojimas ir ekologija	✓	✓	✓	×
Vietinis poveikis aplinkai	×	✓	✓	×
Svetainės vertinimo kūrimas	✓	×	✓	×
Pavojai	✓	✓	✓	×
Lauko erdvių kokybė	×	×	✓	✓
Paleidimas ir perdavimas	✓	✓	×	✓
Inovacijos	✓	×	×	✓
Prisitaikymas	✓	✓	×	×
Gyvavimo ciklo poveikis	✓	✓	×	✓
✓ Įskaitant; × Neįtrauktos.				

Aplinka yra pagrindinis visų metodų aspektas. Daugiau nei 75 % rodiklių priimami remiantis aplinkosaugos aspektais, vidutiniškai 60 % visų metodų yra orientuoti į aplinkos veiksnį. Didžiausia reikšmė teikiama energijos vartojimo efektyvumui, vandens naudojimui ir aplinkosaugos kategorijos medžiagų aptarimui.

2.2 LCA integracijos EPAS tyrimas

Pirma, reikia pažymėti, kad LCA (GCV) metodas ir rodikliai yra integruoti į veiklos vertinimo metodus. Informacija, susijusi su LCA komponentais, buvo renkama naudojant įvairius duomenų šaltinius, pavyzdžiui, techninius duomenis, mokslinių tyrimų duomenis ir t. t. Atlikta analizė remiantis standartizuota LCA metodika: tyrimų tikslas, apimtis, LCA rodikliai, siekiant parodyti jų naudingumo ir svarbos lygį.

Ryšys su LCA visuose metoduose leidžia suprasti rodiklių integravimo lygį sistemoje. DGNB vertinimo sistema apima visą pastatą ir visas fazes, o BREEAM ir LEED – tik medžiagų lygiu. BREEAM atveju rodiklių (medžiagų ir energijos) įskaitymas nėra visiškai skaidrus kiekviename proceso etape. DGNB ir HQE visi šie metodai daugiausia remiasi statybinių produktų EPD, kad būtų suteiktas kreditas LCA komponentui. HQE suteikiami kreditai, tačiau tai nebūtinai grindžiama LCA rezultatų vertinimu, aiškiai neįgyvendina LCA ir nenurodo techninių kriterijų. Palyginti su kitais metodais, DGNB yra išsamiausias gyvavimo ciklo poveikio požiūriu, nes atsižvelgia į pastato energijos poreikį per visą jo eksploatavimo laiką, įskaitant statybos, renovacijos ir eksploatavimo etapus. DGNB yra pati visapusiškiausia sistema, paremta LCA požiūriu.

Tačiau tikrasis klausimas yra tai, kiek šie rodikliai apskaičiuoja faktinį poveikį ir parodo absoliutų poveikio rodiklio sumažėjimą, nes pateiktose analizėse trūksta konkretumo [159, 160]. Be to, šie rodikliai yra santykinai mažesni nei su energija susiję rodikliai, ir dauguma jų yra kokybinio pobūdžio. Atliktų tyrimų analizė padėjo nustatyti esamų metodikų spragas, susijusias su pagrindinėmis vertinimo schemomis. Be to, buvo analizuojami vertinimui taikomi rodikliai, siekiant suprasti jų pasiskirstymą įvairiuose renovacijos etapuose.

3. GYVENAMŲJŲ PATALPŲ ATNAUJINIMO APLINKOSAUGINIS VERTINIMAS

3.1 Objektas

2015 m. buvo renovuoti du daugiabučiai gyvenamieji pastatai, kuriuose yra 54 butai, ir kurie yra identiški savo išvaizda bei erdve. Šie pastatai buvo pastatyti naudojant gelžbetonio plokštes, kurios sudaro sienas, cokolį ir stogą, o jų bendras naudingasis plotas yra 3469,24 m². Norint aiškiai suprasti du objektus, šie du namai buvo pavadinti *A* ir *B* pastatais. *A* ir *B* pastatai modernizuoti kompleksškai, apšiltinant sienas ir stogus, pakeičiant medinius arba senus plastikinius langus naujais plastikiniais langais. Be to, *B* pastate buvo įrengtas karšto vandens stovas, saulės kolektoriai ir šilumos siurbliai. Pagal Lietuvos energetikos standartus, pasirinktas pastatas prieš renovacijos procesą buvo sertifikuotas kaip „E klasės“ energetinio efektyvumo pastatas. Po renovacijos pastatas buvo priskirtas „C klasei“, nes visi renovuoti daugiabučiai turi pasiekti minimalią C klasę [161].



2 pav. Renovuotas daugiabutis namas

3.2 Daugiabučio namo gyvavimo ciklo vertinimas

Tikslas, taikymo sritis ir sistemos ribos

Atliktas renovuoto gyvenamojo namo vertinimas, kuris apėmė statybą, priežiūrą, vėdinimo bei šildymo sistemos eksploatavimą ir eksploatacinę energiją. Tyrimu siekiama įvertinti renovuojamų daugiabučių namų poveikį aplinkai, nustatant ir analizuojant galimą poveikį aplinkai prieš ir po renovacijos. Remiantis tyrimo charakteristikomis, funkciniu vienetu laikomas visas pastatas, kurio eksploatacijos laikas yra 40 metų.

Sistemos ribos yra produkto gyvavimo ciklo etapai ir komponentai, peržiūrėti ciklo vertinimo metu. Į kitas charakteristikas, tokias kaip vandens sunaudojimas, patalpų oro kokybė, akustika ir ekonominė vertė, šiame funkcinio bloko tyrime neatsižvelgiama. Tyrimo ribos buvo pagrįstos Vilches ir kt. atliktu tyrimu, kuriame autorius išnagrinėjo pastato atnaujinimo proceso galimybes su skirtingomis sistemos ribomis, atsižvelgdamas į standartinius pastato vertinimo modulius gyvavimo ciklo vertinimui pagal standartą EN15804:2012 [4]. Tyrimo sistemos ribos yra tokios:

- pagrindinės statybinės medžiagos, naudotos statant ir renovuojant daugiabutį;
- procesai ir energijos suvartojimas, reikalingi statybinėms medžiagoms gaminti [duomenys iš *Ecoinvent* duomenų bazės];
- šiluminės energijos sąnaudos pastato patalpoms šildyti ir karšto vandens ruošimui per pastato gyvavimo ciklą (t. y. vidutinis 40 metų šilumos energijos suvartojimas).

Tyrimas atliktas pasitelkus *SimaPro 8.0* programinę įrangą. Programinė įranga naudoja *Ecoinvent 3.0* duomenų bazę [167]. Paprastai duomenų rinkiniai priimami remiantis aplinkosaugos produktų deklaracijomis (EPD), šiuo atveju EPD nebuvo, todėl bendrieji duomenys buvo perimti iš *Ecoinvent* duomenų bazės.

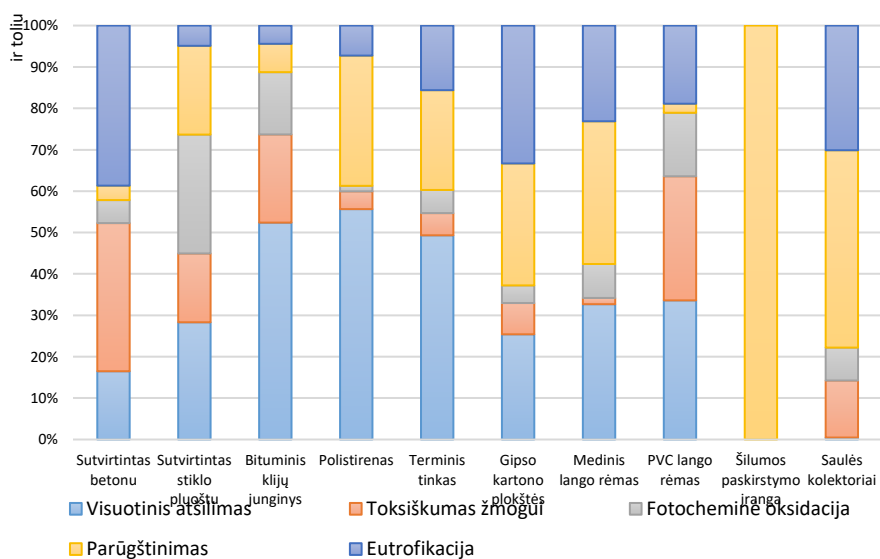
Rezultatai

Programine įranga *SimaPro 8.0* buvo sumodeliuoti trys gyvavimo ciklo scenarijai:

- nerenovuotas daugiabutis;
- renovuotas daugiabutis (*A* pastatas);
- modernizuotas daugiabutis, aprūpintas atsinaujinančiais energijos šaltiniais, saulės kolektoriais ir šilumos siurbliu (*B* pastatas).

Pastatų poveikis aplinkai įvertintas skaičiuojant pagrindinių statybinių medžiagų kiekius ir šilumos energijos sąnaudas buto eksploatacijos metu (numatomas pastato gyvavimo ciklas – 40 metų).

Medžiagos atlieka svarbų vaidmenį nustatant pastatų poveikį aplinkai. Toliau pateiktame 3 paveiksle parodytas skirtingų medžiagų, naudojamų statant pastatą – prieš ir po renovacijos – pasiskirstymas. Rodikliai parinkti remiantis literatūros šaltiniais ir atsižvelgiant į galimą poveikį, t. y. visuotinį atšilimą (GWP100a), žmonių sveikatą, fotocheminę oksidaciją, rūgštėjimą, eutrofikaciją.



3 pav. Medžiagų poveikio aplinkai pasiskirstymas

Bendras daugiabučio namo poveikio aplinkai vertinimas

Poveikis aplinkai remiantis gyvavimo ciklo požiūriu įvairiais aspektais buvo apskaičiuotas taikant CML metodą, kurio metu buvo įvertintos reikšmingiausios vidurio taškų kategorijos statybų sektoriuje. Rodiklis parinktas atsižvelgiant į pasirinktą galimą poveikį, t. y. visuotinį atšilimą (GWP100a), žmonių sveikatą, fotocheminę oksidaciją, rūgštėjimą, eutrofikaciją. Šios kategorijos seno pastato poveikis aplinkai yra:

- apie 1,14 karto didesnis nei įprastai atnaujinto pastato (t. y. apšildintos pastato fasado sienos, antžeminė cokolio dalis, stogas ir langai);
- apie 2 kartus didesnis nei atnaujinto pastato, kuriame naudojami atsinaujinantys energijos šaltiniai.

Klimato kaitos kategorijos namo įtaka po įprastinio pastato atnaujinimo gali būti sumažinta iki 12 %. Renovuojant gyvenamąjį namą ir įrengus saulės elementus bei šilumos siurbį (*B* pastatas), neigiamą poveikį klimato kaitai galima sumažinti iki 48 %. Šie skirtumai atsiranda dėl energijos vartojimo efektyvumo ir sumažėjusio šiluminės energijos suvartojimo, todėl sumažėja šiltnamio efektą sukeliančių dujų emisija naudojant iškastinį kurą. Be to, renovuotame daugiabutyje galima sutaupyti šilumos energijos, vartojamos patalpoms šildyti ir karštam vandeniui ruošti, atitinkamai 25 %, 40 % po įprastinės renovacijos (*A* pastatas) ir renovacijos taikant atsinaujinančius energijos šaltinius (*B* pastatas).

3.3 EPAS diegimas daugiabučiuose namuose

Renovuojami pastatai dažnai yra sertifikuojami pagal jų energinį naudingumą ir vadinami nurodant jų energinio naudingumo sertifikatą (EPC). Kaip išsamiai ištirta, visame pasaulyje yra keletas schemų, tokių kaip BREEAM, LEED, DGNB, HQE ir pan. Lietuvoje kol kas dažniausiai taikomos sistemos BREEAM ir LEED [169]. Šiai analizei buvo pasirinktas renovuotas daugiabutis namas, kad būtų galima toliau ištirti skirtingų schemų reikšmę.

4 lentelė. Daugiabučio namo renovacijos įvertinimas ir kriterijų reikšmės – BREEAM

Kategorijos	Svoris (%)	Kriterijaus reikšmė	<i>A</i>	<i>B</i>
Valdymas	12	11	6	6
Sveikata ir gerovė	17	12	4,5	4,5
Energija	43	29	7,5	12
Vanduo	11	4	2,5	2,5
Medžiagos	8	45	19	19
Atliekos	5	5	2	2
Tarša	6	8	3	3
Inovacijos	10	10	4	5
Iš viso		110	48,5	54
Įvertinimas			Gera	Labai gera

Bendras BREEAM balas renovuotiems *A* ir *B* pastatams yra 48,5 ir 54, o tai atitinka gerą ir labai gerą klasifikaciją. Abu atrinkti pastatai buvo renovuoti (maža ir didelė kriterijų reikšmė), energinis naudingumas ir papildomas atsinaujinančios energijos šaltinis lėmė gerą *B* pastato eksploatacinių savybių balą. Tačiau bendras balas tarp dviejų pastatų yra nežymus, nedaug skiriasi kitose kategorijose, išskyrus energijos suvartojimą ir atsinaujinančių energijos šaltinių įrengimą.

5 lentelė. Daugiabučio namo renovacijos įvertinimas ir kriterijų reikšmės – LEED

Kategorijos	Kreditai	Svoris (%)	Pasiecta	
			A	B
Vieta ir transportas	16	14,54	6	6
Tvarios svetainės	10	9,091	6	6
Vandens efektyvumas	11	10	5	5
Energija ir atmosfera	33	30	9	15
Medžiagos ir ištekliai	13	11,82	6	7
Vidaus aplinkos kokybė	16	14,54	8	8
Inovacijos	6	5,45	1	2
Regioninis prioritetas	4	3,63	1	1
Iš viso surinktų taškų	110	100	43	50
Įvertinimai	-		Sertifikuotas	Sidabrinis

Apskritai pastato eksploatacinės savybės buvo apskaičiuotos taškais, suteikiančiais 43 balus ir 50 balų už A ir B pastatą pagal LEED schemą. Vadinasi, B pastatas sertifikuotas kaip „sidabrinis“ pagal schemą, o tai reiškia geresnes eksploatacines savybes.

3.4 LCA įgyvendinimas EPAS

Šioje dalyje siekiama palyginti visų pasirinktų schemų LCA aspektus ir jų rodiklius. Be to, apskaičiuojant svorinę reikšmę, pasirinktas etaloninis pastatas svorinėms reikšmėms suteikti ir įvertinti, kad būtų galima suprasti LCA apimtį. Originalus pastatas (naudojamas kaip etalonas) lygina BREEAM ir LEED svertinius koeficientus, kad būtų paskirstyti balai pagal LCA kreditus schemose (6 lentelė) tarp originalaus ir renovuoto pastato (B pastatas). Namas B laikomas renovuotu pastatu, nes buvo atlikta pastato kapitalinė renovacija (įskaitant atsinaujinančius energijos šaltinius). Originalus pastatas (nerenuotas) pasirinktas kaip bazinis modelis, siekiant atskirti du scenarijus.

6 lentelė. LCA pasiskirstymas pasirinktose schemose

	BREEAM	LEED
Ištirtas modulis	Buitinių pastatų atnaujinimas	Daugiabučiai gyvenamieji namai
LCA kriterijai ir kreditai	Ene 02 (4) Ene 03 (7) Mat 01 (25)	EA (18) MRc1 (5)
Galimi LCA kreditai	36	23
Originalus pastatas Rezultatas	0 (Ene 02) 0 (Ene 03) 2 (Mat 01)	0 (EA) 0 (MRc1)
Renovuotas pastatas	2 (Ene 02)	14 (EA)

balas	1 (Ene 03) 9,5 (Mat 01)	3 (MRc1)
-------	----------------------------	----------

BREEAM ir LEED schemas taip pat įvertina gyvavimo ciklo rodiklius; tačiau jose atskiriama gaminio medžiagų stadija ir eksploataavimo fazė. BREEAM turi išskirtinį renovacijos standartų metodą visiems pastatams, kuriems atliekama nedidelė ar kapitalinė renovacija. Naudojant EPD, BREEAM poveikio vertinimui taikomos skirtingos metodikos [170]. Tai reiškia, kad LCA rodikliai nustatomi remiantis statybos produktais, o ne LCA rezultatais. Be to, BREEAM ir LEED nebūtini su LCA susiję kriterijai, išskyrus energijos vartojimo efektyvumą kaip minimalų standartą arba būtiną sąlygą. LEED medžiagos arba gaminiai yra kritiškai peržiūrimi remiantis EPD ir klasifikuojami pagal gaminio gyvavimo ciklą [171].

4. GYVENAMŲJŲ PASTATŲ POVEIKIO APLINKAI VERTINIMO, TAIKANT GYVAVIMO CIKLO METODĄ, KONCEPCINĖS METODIKOS KŪRIMAS

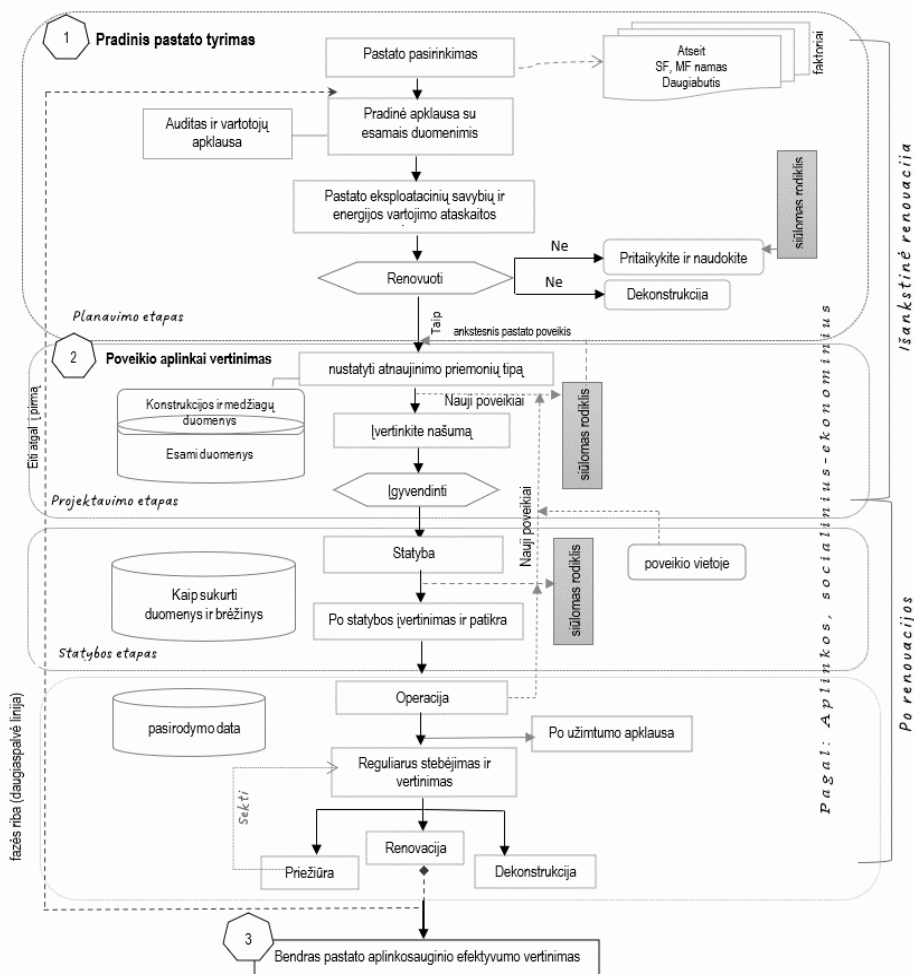
4.1 Daugiabučių namų renovacijos konceptuali metodika

Renovacijos procesui reikalingos įvairios naujos statybinės medžiagos ir technologijos. Atlikti renovaciją daug sudėtingiau, ypač kai pastatas senesnis, nes tai kelia didesnę finansinę ir aplinkos riziką [129]. Todėl renovacijos procesas turėtų būti vykdomas kompleksškai, įvertinant visus veiksnius visuose renovacijos etapuose. Buvo pasiūlyta konceptuali daugiabučio renovacijos metodika, įvertinus ekspertų išvadas, išsamią literatūros apžvalgą ir atlikus renovacijos atvejų taikant gyvavimo ciklo požiūrį analizę. Apskritai renovacijos procesą galima suskirstyti į keturis etapus: išankstinis projektavimas, projektavimas, statyba ir eksploatacija.

Pirmajame etape pradinis pastato tyrimas apima išsamų patikrinimą, pradinę padėtį ir vartotojų apklausą, o pastato išankstinė diagnostika atliekama intensyviai renkant duomenis ir įvertinant eksploatacines savybes. Auditas gali būti taikomas analizuojant energijos duomenis, kad būtų galima geriau suprasti energijos vartojimą, nustatyti sritis, kuriose jis yra perteklinis, laikantis patalpų klimato ir kitų priežiūros reikalavimų, kad būtų pasiūlytos renovacijos priemonės. Projektavimo etape buvo nustatytos tinkamiausios pastatų atnaujinimo priemonės ir alternatyvos. Remiantis rezultatais, pasirinktos medžiagos ir technologijos pagrįstos atitinkamais su energija susijusiais ir nesusijusiais veiksniais. Trečiasis etapas – statybos, pasirinktos priemonės įgyvendintos atnaujinamo pastato vietoje. Paskutiniame etape sudaromos pastato renovacijos ataskaitos, kad būtų aiškūs pastato atnaujinimo duomenys, taip pat atliekama apklausa, siekiant suprasti gyventojų atsiliepimus.

Renigiant atnaujintų pastatų vertinimo ataskaitas pastebėta, kad renovacijos dėka pastato eksploatacinės išlaidos žymiai pasikeitė, ypač tai atsiliepė energijos sąnaudų priskiriamiesiems kaštams. Renovuojant esamą pastatą buvo atsižvelgiama į naujus poveikius kartu su „sukauptu“ seno pastato poveikiu, kai kuriais atvejais į senesnių pastatų sukauptą poveikį praktiškai neatsižvelgiama. Paprastai naujų statybinių medžiagų papildymo ir atnaujinimo scenarijai dažnai analizuojami dėl poveikio

aplinkai, taip apskaičiuojant naujų medžiagų poveikį; tačiau neįskaitant viso transportavimo proceso ciklo, rezultatų vietoje, esamo pastato „sukaupto poveikio“, galimo esamų medžiagų panaudojimo ir kt. [158]. Šios metodikos rengimo tikslas – reprezentuoti kompleksinį daugiabučių namų renovacijos metodą ir renovacijos proceso sprendimų priėmimo palaikymą. Ši metodika pateikia skirtingus žingsnius renovacijos proceso metu ir siūlo rodiklius prieš / po renovacijos, atsižvelgiant į aplinkos, ekonominius ir socialinius veiksniai. Todėl renovacijos proceso poveikio aplinkai vertinimo metu tiriamas ne tik poveikis aplinkai taikant gyvavimo ciklo požiūrį, bet gali būti vertinamas poveikis darnaus vystymosi kontekste.



5 pav. Konceptinė daugiabučių namų renovacijos metodika derinant efektyvumą ir gyvavimo ciklą

Tyrimo metu sukurta metodika gali būti taikoma apibūdinant kritines sritis ir veiksmus, kai siekiama visapusiškos pastato renovacijos. Surinkti duomenys, susiję

su pagrindiniais veiksniais ir rodikliais, suteikia esminį bei platų renovacijos projekto supratimą ir apskritai atskleidžia, ar pastatas turi potencialo būti renovuotas palankiame aplinkai kontekste. Nors buvo pasiūlyti 26 rodikliai, atsižvelgiant į unikalios pastatų charakteristikas, metodika yra lanksti pridėdant arba išbraukiant (ne)tinkamus rodiklius pagal tikslus. Tam reikalingos visos duomenų rinkimo pastangos, įskaitant pakartotines peržiūras, pastatų fizinius įvertinimus, tyrimų duomenis, apklausas ir bendravimą su pagrindinėmis suinteresuotosiomis šalimis. Taigi, ši metodika gali būti taikoma atliekant pradinį vertinimą, tiriant galimas vertinimo spragas ir analizuojant bei stebint įvairias taikytas atnaujinimo priemones, siekiant nustatyti konkrečią jų svarbą, kuri kiekvienu atveju skiriasi, taip pat įvertinti veiklos rezultatus.

4.2 Siūlomi daugiakriteriai renovacijos vertinimo rodikliai

Naujai siūlomi rodikliai apibrėžiami keturiose kategorijose, o iš viso taikant tyrimo metodiką buvo atsižvelgta į 26 pagrindinius kriterijus. Remiantis ekspertų pateiktomis įžvalgomis ir atliktais renovacijos proceso tyrimais, šie rodikliai buvo pripažinti kaip ypač efektyvūs. Nors galutiniai rezultatai rodo minimalius bendruosius kategorijų skirtumus, kaip aptarta duomenų analizėje, rodiklių svoriai taip pat rodo nedidelius skirtumus daugelyje kategorijų. Tai, kad respondentai priskyrė santykinis rodiklių svarbos skirtumus, gali būti susiję su jų profesine patirtimi, esama kiekvieno respondento praktika ir vietos reikalavimais.

7 lentelė. Siūlomų rodiklių sąrašas

Kategorija	Rodikliai	Apibūdinimas
Komfortas ir gera savijauta (CW)	Vidaus gyvenimo sąlygos (CW1)	Kokybė, vartotojo patogumas ir pasitenkinimas renovacija
	Šiluminis komfortas (CW2)	Kambario temperatūros kontrolės kokybė
	Atsparumas ir prisitaikymas (CW3)	Faktinis / numatomas prisitaikymas prie klimato kaitos
	Akustinis triukšmas (CW4)	Efektyvi triukšmo kontrolė
Ištekliai (R)	Vietinis medžiagų tiekimas (R1)	Padidinkite vietoje prieinamų medžiagų naudojimą
	Biologinės įvairovės praradimas (R2)	Žala vietinei aplinkai
	Kaupiamasis energijos poreikis (R3)	Neatsinaujinančių pirminių energijos išteklių kaip žaliavų naudojimas
	Energijos efektyvumas (R4)	Tobulinti energinio naudingumo priemones
	Kaupiamasis vandens naudojimas (R5)	Santykinio sunaudoto vandens kiekio rodiklis
	Toksiškų medžiagų mažinimas (R6)	Toksiška ir nepavojinga medžiaga
	Pakartotinis esamų konstrukcijų naudojimas (R7)	Veiksmingas pakartotinis išmestų komponentų panaudojimas esamose konstrukcijose
	Perdirbimo potencialas (R8)	Galimybė perdirbti medžiagas mažiau kenkiant aplinkai

	Išmontavimo paprastumas (R9)	Komponentų išmontavimo / išmontavimo ir perdirbimo nuostata
Tarša (P)	Šiltnamio efektą sukeliančių dujų emisija (P1)	CO ₂ emisija, matuojama kv. m per metus
	Parūgštinimas (P2)	Emisija į orą, matuojama kv. m per metus
	Eutrofikacija (P3)	Emisija į vandenį, matuojama kv. m per metus
	Ozono sluoksnio ardymas (P4)	Išmetimai į orą, kg
	Fotocheminis ozono susidarymas (P5)	Atskirų medžiagų išmetimas į orą, kg
	Toksiškumas žmogui (P6)	Į aplinką išmetamų toksinių medžiagų poveikis žmonėms
	Atliekų šalinimas (P7)	Atliekų išvežimas per metus
Kainos ir funkcionalumas (CF)	Transportas ir mobilumas (CF1)	Lengvai pasiekiamas alternatyviu transportu
	Socialinė ir kultūrinė įtrauktis (CF2)	Asmens saugumo ir kultūrinės pagarbos gerinimas
	Kokybiška lauko aplinka (CF3)	Kokybiška aplinka
	Ilgamžiškumas (CF4)	Patvari statybinė konstrukcija ir medžiagos
	Gyvavimo ciklo išlaidos (CF5)	Pastato ekonomiškumas
	Galimas sutaupymas (CF6)	Galimas energijos taupymas

a. Metodikos taikymas pavyzdžiui ir rezultatams

Analizei pasirinkti pastatai yra tipiniai daugiaaukštės statybos pastatai. Tyrimui pasirinkti 9 aukštų namai, kuriuose yra 54 butai, renovuoti 2015 m. ir 1991 m. [195]. Apskritai atrinktiems daugiabučiams reikėjo renovacijos dėl prasto energinio naudingumo.

8 lentelė. Atvejo analizės pastatų būklės ir atnaujinimo priemonių aprašymas

Apibūdinimas	A pastatas (1 scenarijus)	B pastatas (2 scenarijus)
Statybos metai: Išdėstymas: Plotas: Butų Nr.: Renovacijos metai:	1983 2 pastatai, 9 aukštai 3469,24 m ² 54 2015	1949 2 pastatai, 7 aukštai 5630 m ² 48 1991
Struktūra:	Surenkamos betoninės plokštės, betonas ir plieninė armatūra	Mūrinės sienos, betono plokštė ir medinis stogas
Vėdinimas:	Centralizuotas šildymas, radiatoriai Natūrali ventiliacija	Centralizuotas šildymas, radiatoriai Natūrali ventiliacija
Renovacijos priemonės:	Išorės ir vidaus izoliacija Mažo šilumos laidumo langų keitimas Šilumos siurblio montavimas Saulės elementai	Išorės ir vidaus izoliacija Šilumos siurblys

Pagal gautus rezultatus, pasiūlyta metodika įvertinamas pastato poveikis, šiuo atveju buvo svarstomas renovuotas pastatas, o įvestis yra įtraukta į LCA programinę įrangą, kad būtų galima suprasti pastato poveikį pagal skirtingas kategorijas. Iš ankstesnio rezultato, kurį atliko autorius, LCA tyrimas atskleidė, kad didžiausią įtaką energijos tiekimui turi nerenovuoti pastatai, o energijos nuostoliai sumažinti 25 % ir 40 % įdiegus atnaujinimo priemones (langų keitimą, stogų, sienų ir vamzdžių izoliacija, vėdinimas, saulės elementai) *A* ir *B* pastatams. Taikant siūlomą metodiką, suvestinis pirminis pasiūlytų kriterijų balas ir dviejų pastatų palyginimas parodė 31 % ir 46 % naudingumo įverčius, o tai reiškia žemą ir vidutinį našumo lygį. Tačiau šiuo atveju pasirinktuose pastatuose buvo atlikta tokia pati renovacija, išskyrus atsinaujinančios energijos pakeitimą. Todėl kiekvienu atveju svorio skirtumas nėra didelis. Išsamiau LCA ir pasiūlyta metodika pagrįsti rezultatai rodo, kad, remiantis įgyvendintomis priemonėmis, atnaujinto pastato eksploatacinės savybės gerėja. Siūlomi metodikos rezultatai yra nereikšmingi, nes rezultatai per daug nesiskiria daugeliu kriterijų, kurie buvo įvertinti. Šiam tyrimui pasirinktame objekto pavyzdyje buvo atlikta dalinė ir pagrindinė renovacija (įskaitant šilumos siurblius, saulės fotoelementus ir vėdinimo pakeitimus). Metodus buvo pritaikytas konkrečioms sąlygoms, atsižvelgiant į pasirinktą atvejį. Taip gali būti dėl tyrimui pasirinkto objekto pobūdžio, išskyrus energijos mažinimą, reikšmingų rezultatų nepastebėta, iš tikrųjų *B* pastatas rodo 46 % našumo balą. Metodika turėtų būti taikoma įvairiuose pastatuose ir viso renovacijos proceso metu, kad būtų patikrinti visi jo rezultatai. Ši metodika gali būti taikoma tiek visam pastatui kaip visumai, tiek atskiriems jo gyvavimo ciklo etapams.

Apklausos rezultatai. Apklausą atskleidė, kokių veiksmų būtina imtis po renovacijos proceso. Remiantis ekspertų nuomone, siūloma metodika taip pat rekomenduojamas nuolatinis kasmetinis stebėjimas naudojimo etape [176]. Nuolatinis stebėjimas gali būti labai naudingas siekiant tikslų, nes stebėseną suteikia galimybę suformuluoti tinkamą priežiūrą ar dėmesį ankstyvoje stadijoje, kurią būtų lengviau planuoti ir prireikus pasirinkti tolesnes renovacijos proceso priemones [193]. Be to, apklausą atskleidė, kad vartotojų pasitenkinimo apklausose retai gali būti klausimų apie patalpų aplinkos kokybę. Tai patvirtino tyrimas, kad nė viena statybų organizacija prieš renovacijos projektą neatliko jokios specialios nuomininkų apklausos [194]. Metodika taip pat primygtinai rekomenduojama prieš renovuojant ir po pastato renovacijos atlikti vartotojų apklausą. Tokių klausimų pridėjimas galėtų būti veiksminga priemonė surinkti gyventojų nuomones ir nustatyti tobulinimo sritis [31, 194].

Apribojimai: Pasirinktas tyrimams pastatas jau buvo renovuotas, todėl duomenų prieš renovaciją nebuvo, dalis duomenų paimta iš ankstesnės literatūros ir darytos papildomos prielaidos. Informacija apie pastatą, tokia kaip geografinė vieta, pastato tipas, dydis, pastato amžius, eksploatacija ir priežiūra, energijos šaltiniai, komunalinių paslaugų tarifų struktūra, pastato struktūra ir paslaugų sistema, turi įtakos renovacijos efektyvumui. Be to, šiame tyrime naudojami duomenys yra svarbūs ES, ne visi duomenys buvo naudojami regioniniame ES kontekste. Ypač kalbant apie senesnius pastatus, duomenų, susijusių su ankstesniu statybos etapu (nerenuovotas pastatas), prieinamumas yra beveik nulinis, nebent remiantis naudotojų duomenimis, daugeliu

atvejų vertinimas toli gražu nėra tikslus. Lyginant su kitais vertinimais, siūlomo metodo pranašumas yra tas, kad jis sujungia LCA metodą ir MCDA, kuris leidžia gauti skirtingus vertinimo balus, atsižvelgiant į skirtingas suinteresuotųjų šalių nuostatas [99].

IŠVADOS

1. Tyrimo metu buvo nustatytos pagrindinės spragos, susijusios su gyvenamųjų namų renovacijos vertinimu. Pasitelkus literatūrą, išanalizuotas ir konsoliduotas išsamus rodiklių sąrašas ir metodai, kuriais vertinama gyvenamųjų namų renovacija. Aplinkosauginio veiksmingumo schemos ir gyvavimo ciklo vertinimo metodai yra plačiausiai taikomi ir atrenkami renovuoto pastato veiksmingumui įvertinti. Be to, buvo pasirinktas daugiakriteris vertinimo metodas, siekiant priskirti pirmenybę vertinimo rodikliams taikant naują metodiką. Todėl literatūros studija padėjo suformuluoti tyrimo metodiką ir rodiklius, kaip atlikti pastatų renovacijos poveikio aplinkai vertinimą.

2. Pasirinkti metodai: gyvavimo ciklo vertinimo ir aplinkosauginio veiksmingumo schemos taikomos renovuotam daugiabučiui, siekiant suprasti faktinį poveikį ir kreditų paskirstymą tarp dviejų metodų. (a) LCA rezultatai atskleidė, kad *A* ir *B* pastatai sutaupė apie 12 % ir 48 % energijos, atsižvelgiant į renovacijos tipą. Po renovacijos galimas šiluminės energijos sutaupymas patalpoms šildyti ir karštam vandeniui ruošti yra 25 % ir 40 % po įprastinės renovacijos ir renovacijos naudojant atsinaujinančios energijos priemones. (b) Vertinant EPAS ir lyginant LEED ir BREEAM, abi sistemos parodė gerą *B* pastato našumą, suteikdamos 50 balų LEED ir 54 balus BREEAM, o tai atitinka gerą ir labai gerą našumą. Be to, LCA suteikimas abiejose schemose sudaro apie 11,5 % galutinio BREEAM balo ir 15,4 % LEED balo.

3. Sukurta gyvenamųjų namų renovacijos LCA metodu vertinimo metodika. Ji sukurta remiantis gyvavimo ciklo vertinimo metodo ir aplinkosauginio veiksmingumo schemų integravimu, siekiant įvertinti renovacijos efektyvumą nuo pradinio proceso etapo. Metodika gali būti taikoma faktiniam esamam projektui, siekiant suprasti esamą našą aplinkai, būsimą poveikį ateityje ir poveikį vietoje per visą pastato etapą (išankstinis projektavimas ir eksploatavimo etapas), atsižvelgiant į pasirinktus rodiklius. Sukurta metodika tokia, kad nuo pat renovacijos proceso pradžios būtų galima taikyti holistinį požiūrį ir įvertinti daugiau tvarumo bei cirkuliacijos aspektų.

4. Sukurta metodika pritaikyta pasirinktam pastatui, o rezultatai gauti su keturiomis kategorijomis ir 26 rodikliais. Remiantis gautais rezultatais, pasiūlyta metodika, suvestinis pirminis pasiūlytų kriterijų balas ir dviejų pastatų palyginimas parodė 45 % ir 47 % našumo balus, kurie reiškia žemą ir vidutinį našumo lygį. Sukurta metodika apibendrina apie 10 % rodiklių, susijusių su gyvavimo ciklo parametrais, paskirstytų per visas gyvavimo ciklo fazes, palyginti su BREEAM ir LEED, kurių gyvavimo ciklo rodikliams skiriama 5,9 % ir 2,7 % svorio. Sukurtoje metodikoje akcentuojamas *LC* parametrų naudojimas priešprojektiniame ir pačiame kūrimo etape, siekiant užfiksuoti visą renovacijos proceso poveikį, ypač esamiems seniems pastatams.

LITERATURE

1. European Commission Energy Performance of Buildings 2019.
2. Pombo, O.; Allacker, K.; Rivela, B.; Neila, J. Sustainability Assessment of Energy Saving Measures: A Multi-Criteria Approach for Residential Buildings Retrofitting—A Case Study of the Spanish Housing Stock. *Energy and Buildings* **2016**, *116*, 384–394, doi:10.1016/j.enbuild.2016.01.019.
3. Wallentén, P.; Mjörnell, K. SiRen: An Applied Framework for a Sustainable Renovation Process. *Sustainability* **2021**, *13*, doi:10.3390/su13105412.
4. Vilches, A.; Garcia-Martinez, A.; Sanchez-Montañes, B. Life Cycle Assessment (LCA) of Building Refurbishment: A Literature Review. *Energy and Buildings* **2017**, *135*, 286–301, doi:10.1016/j.enbuild.2016.11.042.
5. Thuvander, L.; Femenías, P.; Mjörnell, K.; Meiling, P. Unveiling the Process of Sustainable Renovation. *Sustainability* **2012**, *4*, 1188–1213, doi:10.3390/su4061188.
6. Housing Energy Efficiency Agency BETA-Housing Energy Efficiency Agency Available online: <http://www.betalt.lt/en> (accessed on 1 April 2022).
7. Biekša, D.; Šiupinskas, G.; Martinaitis, V.; Jaraminiene, E. Energy Efficiency Challenges in Multi-Apartment Building Renovation in Lithuania. *Journal of Civil Engineering and Management* **2011**, *17*, 467–475, doi:10.3846/13923730.2011.622408.
8. Energy Performance of Buildings Directive Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en#documents (accessed on 13 June 2022).
9. European Commission A Renovation Wave for Europe - Greening Our Buildings, Creating Jobs, Improving Lives 2020.
10. EU Buildings Factsheets Available online: https://ec.europa.eu/energy/eu-buildings-factsheets_en (accessed on 22 November 2020).
11. Building Performance Institute Europe Energy Performance Certificates Available online: <http://www.bpie.eu/publication/97-of-buildings-in-the-eu-need-to-be-upgraded/> (accessed on 1 September 2020).
12. Nick, Baker. *The Handbook of Sustainable Refurbishment*; CRC Press, 2009; ISBN 1-136-57351-8.
13. Perednis, E.; Valančius, R.; Černeckienė, J.; Stasiulienė, L.; Vaičiūnas, J. Analysis of the Criteria for Selecting Heating Systems for Residential Buildings in Cold Climate. *Journal of Sustainable Architecture and Civil Engineering* **2018**, *23*, doi:10.5755/j01.sace.23.2.21359.
14. Raslanas, S.; Alchimoviene, J. Assessment of the Sustainability of the Renovation of Multi-Apartment Buildings in Residential Areas/Daugiabuciu Namu Lietuvoje Atnaujinimo Darnumo Ivertinimas. *Engineering Structures and Technologies* **2012**, *4*, 145–145.
15. Lithuania - Support Energy Efficiency in the Housing Sector Available online: <https://www.greengrowthknowledge.org/big-e/lithuania-support-energy-efficiency-housing-sector> (accessed on 27 June 2019).
16. Hasik, V.; Escott, E.; Bates, R.; Carlisle, S.; Faircloth, B.; Bilec, M.M. Comparative Whole-Building Life Cycle Assessment of Renovation and New Construction. *Building and Environment* **2019**, *161*, 106218, doi:10.1016/j.buildenv.2019.106218.
17. Renovation v Refurbishment v Retrofit Available online: https://www.designingbuildings.co.uk/wiki/Renovation_v_refurbishment_v_retrofit (accessed on 4 August 2022).
18. Eames Tim Dixon Simon Lannon Miriam Hunt Carla De Laurentis Simon Marvin Mike Hodson Peter Guthrie Maria Christina Georgiadou Illustrations, M.; Frodsham, C.; Phillips, D.; Newton, A.; Jones, K.; Sinclair, B.; Hume, R. *Retrofit 2050: Critical*

Challenges for Urban Transitions Retrofit 2050: Critical Challenges for Urban Transitions Authors; 2014; ISBN 978-1-899895-12-0.

19. Jafari, A.; Valentin, V. An Optimization Framework for Building Energy Retrofits Decision-Making. *Building and Environment* **2017**, *115*, 118–129, doi:10.1016/j.buildenv.2017.01.020.
20. Dahlström, O.; Sørnes, K.; Eriksen, S.T.; Hertwich, E.G. Life Cycle Assessment of a Single-Family Residence Built to Either Conventional- or Passive House Standard. *Energy and Buildings* **2012**, *54*, 470–479, doi:10.1016/j.enbuild.2012.07.029.
21. Wallhagen, M.; Glaumann, M.; Malmqvist, T. Basic Building Life Cycle Calculations to Decrease Contribution to Climate Change – Case Study on an Office Building in Sweden. *Building and Environment* **2011**, *46*, 1863–1871, doi:10.1016/j.buildenv.2011.02.003.
22. Lidberg, T.; Olofsson, T.; Trygg, L. System Impact of Energy Efficient Building Refurbishment within a District Heated Region. *Energy* **2016**, *106*, 45–53, doi:10.1016/j.energy.2016.03.043.
23. Anne Esser; Allison Dunne; Tim Meeusen; Simon Quaschnig; Denis Wegge; Andreas Hermelink; Sven Schimschar; Markus Offermann; Ashok John; Pohl, A.; et al. *Comprehensive Study of Building Energy Renovation Activities and the Uptake of Nearly Zero-Energy Buildings in the EU*; European Commission - DG for Energy: Belgium, 2019; p. 102;.
24. Liang, J.; Qiu, Y.; James, T.; Ruddell, B.L.; Dalrymple, M.; Earl, S.; Castelazo, A. Do Energy Retrofits Work? Evidence from Commercial and Residential Buildings in Phoenix. *Journal of Environmental Economics and Management* **2018**, *92*, 726–743, doi:10.1016/j.jeem.2017.09.001.
25. Dall'O', G.; Galante, A.; Pasetti, G. A Methodology for Evaluating the Potential Energy Savings of Retrofitting Residential Building Stocks. *Sustainable Cities and Society* **2012**, *4*, 12–21, doi:10.1016/j.scs.2012.01.004.
26. Jagarajan, R.; Abdullah Mohd Asmoni, M.N.; Mohammed, A.H.; Jaafar, M.N.; Lee Yim Mei, J.; Baba, M. Green Retrofitting – A Review of Current Status, Implementations and Challenges. *Renewable and Sustainable Energy Reviews* **2017**, *67*, 1360–1368, doi:10.1016/j.rser.2016.09.091.
27. Richard Paradis *Retrofitting Existing Buildings to Improve Sustainability and Energy Performance | WBDG - Whole Building Design Guide*; 2016;
28. Jensen, P.A.; Maslesa, E.; Brinkø Berg, J. Sustainable Building Renovation: Proposals for a Research Agenda. *Sustainability* **2018**, *10*, doi:10.3390/su10124677.
29. Mjörnell, K.; Boss, A.; Lindahl, M.; Molnar, S. A Tool to Evaluate Different Renovation Alternatives with Regard to Sustainability. *Sustainability* **2014**, *6*, doi:Pons,.
30. Ma, Z.; Cooper, P.; Daly, D.; Ledo, L. Existing Building Retrofits: Methodology and State-of-the-Art. *Energy and Buildings* **2012**, *55*, 889–902, doi:10.1016/j.enbuild.2012.08.018.
31. Gohardani, N.; Bjork, F.; Jensen, P.; Maslesa, E.; Kanarachos, S.; Fokaides, P. Stakeholders and the Decision Making Process Concerning Sustainable Renovation and Refurbishment in Sweden, Denmark and Cyprus. *Architecture & Environment* **2013**, *1*, 21, doi:10.12966/ae.09.01.2013.
32. Jagarajan, R.; Abdullah Mohd Asmoni, M.N.; Mohammed, A.H.; Jaafar, M.N.; Lee Yim Mei, J.; Baba, M. Green Retrofitting – A Review of Current Status, Implementations and Challenges. *Renewable and Sustainable Energy Reviews* **2017**, *67*, 1360–1368, doi:10.1016/j.rser.2016.09.091.

33. Energy Performance of Buildings Directive | Energy Available online: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed on 9 June 2020).
34. Updating the Energy Performance of Buildings Directive Available online: <https://www.interregeurope.eu/news-and-events/news/updating-the-energy-performance-of-buildings-directive> (accessed on 22 June 2022).
35. European Commission Renewable Energy Directive Available online: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en (accessed on 12 June 2022).
36. Jarich (Rick) Dijkstra Optimizing the Large-Scale Renovation Strategy. Master Thesis, University of Twente: Netherlands, 2018.
37. Markelj, J.; Kuzman, M.; Zbasnik-Senegacnik, M. A review of building sustainability assessment methods. *AR : Architecture, Research* **2013**, *XIV*, 22–31.
38. Bernardi, E.; Carlucci, S.; Cornaro, C.; Bohne, A.R. An Analysis of the Most Adopted Rating Systems for Assessing the Environmental Impact of Buildings. *Sustainability* **2017**, *9*, doi:10.3390/su9071226.
39. Cabeza, L.F.; Rincón, L.; Vilarinho, V.; Pérez, G.; Castell, A. Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) of Buildings and the Building Sector: A Review. *Renewable and Sustainable Energy Reviews* **2014**, *29*, 394–416, doi:10.1016/j.rser.2013.08.037.
40. Kashkooli, A.; Altan, H. *Critical Building Life-Cycle Assessment Methodology: Developing a Simple Tool*; 2010;
41. International Organization for Standardization ISO (2006b) Environmental Management - Life Cycle Assessment - Requirements and Guidelines Available online: <https://archive.org/details/gov.in.is.iso.14044.2006/page/n3/mode/2up> (accessed on 29 January 2019).
42. International Organization for Standardization ISO (2006a) Environmental Management - Life Cycle Assessment - Principles and Framework Available online: <https://archive.org/details/gov.in.is.iso.14040.2006/page/n25/mode/2up> (accessed on 29 January 2019).
43. Khasreen, M.M.; Banfill, P.F.G.; Menzies, G.F. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability* **2009**, *1*, 674–701, doi:10.3390/su1030674.
44. Sharma, A.; Saxena, A.; Sethi, M.; Shree, V.; Varun Life Cycle Assessment of Buildings: A Review. *Renewable and Sustainable Energy Reviews* **2011**, *15*, 871–875, doi:10.1016/j.rser.2010.09.008.
45. Abd Rashid, A.F.; Yusoff, S. A Review of Life Cycle Assessment Method for Building Industry. *Renewable and Sustainable Energy Reviews* **2015**, *45*, 244–248, doi:10.1016/j.rser.2015.01.043.
46. Birgisdóttir, H.; Rasmussen, F.N. *Introduction to LCA of Buildings*; Energy and Indoor Environment; 1st ed.; Trafik-og Byggestyrelsen: Copenhagen, Denmark, 2016; ISBN 978-87-90661-59-5.
47. Blom, I.; Itard, L.; Meijer, A. Environmental Impact of Building-Related and User-Related Energy Consumption in Dwellings. *Building and Environment* **2011**, *46*, 1657–1669, doi:10.1016/j.buildenv.2011.02.002.
48. Motuzienė, V.; Gediminas, V. **2013**.
49. Ramírez-Villegas, R.; Eriksson, O.; Olofsson, T. Life Cycle Assessment of Building Renovation Measures—Trade-off between Building Materials and Energy. *Energies* **2019**, *12*, doi:10.3390/en12030344.

50. Swing Gustafsson, M.; Gustafsson, M.; Myhren, J.A.; Dotzauer, E. Primary Energy Use in Buildings in a Swedish Perspective. *Energy and Buildings* **2016**, *130*, 202–209, doi:10.1016/j.enbuild.2016.08.026.
51. Zhang, W.; Tan, S.; Lei, Y.; Wang, S. Life Cycle Assessment of a Single-Family Residential Building in Canada: A Case Study. *Building Simulation* **2014**, *7*, 429–438, doi:10.1007/s12273-013-0159-y.
52. Motuziene, V.; V Gediminas Environmental Performance of Energy Efficient Residential Building—a Case Study of Lithuania. *Proc. of the Sustainable Buildings—Construction Products and Technologies* **2013**, 25–28.
53. Palacios-Munoz, B.; Peuportier, B.; Gracia-Villa, L.; López-Mesa, B. Sustainability Assessment of Refurbishment vs. New Constructions by Means of LCA and Durability-Based Estimations of Buildings Lifespans: A New Approach. *Building and Environment* **2019**, *160*, 106203, doi:10.1016/j.buildenv.2019.106203.
54. Muneron, L.M.; Hammad, A.W.A.; Najjar, M.K.; Haddad, A.; Vazquez, E.G. Comparison of the Environmental Performance of Ceramic Brick and Concrete Blocks in the Vertical Seals’ Subsystem in Residential Buildings Using Life Cycle Assessment. *Cleaner Engineering and Technology* **2021**, *5*, 100243, doi:10.1016/j.clet.2021.100243.
55. Kamali, M.; Hewage, K.; Sadiq, R. Conventional versus Modular Construction Methods: A Comparative Cradle-to-Gate LCA for Residential Buildings. *Energy and Buildings* **2019**, *204*, 109479, doi:10.1016/j.enbuild.2019.109479.
56. Markelj, J.; Kuzman, M.K.; Grošelj, P.; Zbašnik-Senegačnik, M. A Simplified Method for Evaluating Building Sustainability in the Early Design Phase for Architects. *Sustainability (Switzerland)* **2014**, *6*, 8775–8795, doi:10.3390/su6128775.
57. Bastos, J.; Batterman, S.A.; Freire, F. Life-Cycle Energy and Greenhouse Gas Analysis of Three Building Types in a Residential Area in Lisbon. *Energy and Buildings* **2014**, *69*, 344–353, doi:10.1016/j.enbuild.2013.11.010.
58. Zygomalas, I.; Baniotopoulos, C. Life Cycle Assessment Environmental Data for Structural Steel Construction in Greece. *International Journal of Sustainable Engineering* **2014**, *7*, 13–23, doi:10.1080/19397038.2012.756951.
59. Lasvaux, S.; Favre, D.; Périsset, B.; Bony, J.; Hildbrand, C.; Citherlet, S. Life Cycle Assessment of Energy Related Building Renovation: Methodology and Case Study. *Energy Procedia* **2015**, *78*, 3496–3501, doi:10.1016/j.egypro.2016.10.132.
60. Balasbaneh, A.T.; Marsono, A.K.B.; Khaleghi, S.J. Sustainability Choice of Different Hybrid Timber Structure for Low Medium Cost Single-Story Residential Building: Environmental, Economic and Social Assessment. *Journal of Building Engineering* **2018**, *20*, 235–247, doi:10.1016/j.jobbe.2018.07.006.
61. Weerasinghe, A.S.; Ramachandra, T. Economic Sustainability of Green Buildings: A Comparative Analysis of Green vs Non-Green. *Built Environment Project and Asset Management* **2018**, *8*, 528–543, doi:10.1108/BEPAM-10-2017-0105.
62. Piroozfar, P.; Pomponi, F.; El-Alem, F. Life Cycle Environmental Impact Assessment of Contemporary and Traditional Housing in Palestine. *Energy and Buildings* **2019**, *202*, 109333, doi:10.1016/j.enbuild.2019.109333.
63. Bielek, V.; Hanák, T. LCC Estimation Model: A Construction Material Perspective. *Buildings* **2019**, *9*, doi:10.3390/buildings9080182.
64. Moran, P.; O’Connell, J.; Goggins, J. Sustainable Energy Efficiency Retrofits as Residential Buildings Move towards Nearly Zero Energy Building (NZEB) Standards. *Energy and Buildings* **2020**, *211*, 109816, doi:10.1016/j.enbuild.2020.109816.
65. Tokbolat, S.; Nazipov, F.; Kim, J.R.; Karaca, F. Evaluation of the Environmental Performance of Residential Building Envelope Components. *Energies* **2020**, *13*, doi:10.3390/en13010174.

66. Alhazmi, H.; Alduwais, A.K.; Tabbakh, T.; Aljamlani, S.; Alkahlan, B.; Kurdi, A. Environmental Performance of Residential Buildings: A Life Cycle Assessment Study in Saudi Arabia. *Sustainability* **2021**, *13*, 3542, doi:10.3390/su13063542.
67. Mercader-Moyano, P.; Esquivias, P.M.; Muntean, R. Eco-Efficient Analysis of a Refurbishment Proposal for a Social Housing. *Sustainability* **2020**, *12*, doi:10.3390/su12176725.
68. Petrović, B.; Zhang, X.; Eriksson, O.; Wallhagen, M. Life Cycle Cost Analysis of a Single-Family House in Sweden. *Buildings* **2021**, *11*, doi:10.3390/buildings11050215.
69. Markelj, J.; Kitek Kuzman, M.; Grošelj, P.; Zbašnik-Senegačnik, M. A Simplified Method for Evaluating Building Sustainability in the Early Design Phase for Architects. *Sustainability* **2014**, *6*, 8775–8795, doi:10.3390/su6128775.
70. Building Research Establishment Ltd BREEAM Available online: <https://www.breeam.com/> (accessed on 1 June 2022).
71. LEED Rating System Available online: <https://www.usgbc.org/leed> (accessed on 4 April 2022).
72. Comprehensive Assessment System for Built Environment Efficiency (CASBEE) Available online: <https://www.ibec.or.jp/CASBEE/english/> (accessed on 1 January 2019).
73. Green Star Available online: <https://new.gbca.org.au/green-star/rating-system/design-and-built/> (accessed on 25 January 2019).
74. Certifications Available online: <http://www.hqegbc.org/home/> (accessed on 1 June 2019).
75. DGNB - Deutsche Gesellschaft Für Nachhaltiges Bauen Available online: <https://www.dgnb.de/en/topics/climate-action/framework/?> (accessed on 1 April 2022).
76. Gama, E.; Papadopoulos, A.M. Sustainable Building Management: Overview of Certification Schemes and Standards. *null* **2012**, *6*, 242–258, doi:10.1080/17512549.2012.740905.
77. Mancik, S.; Růžicka, J. Multicriterion Assessment of Existing Buildings in ReSBToolCZ. *International Journal of Sustainable Construction* **2012**, *1*, 73–81.
78. Energy Available online: https://www.breeam.com/BREEAMInt2016SchemeDocument/content/06_energy/energy.htm (accessed on 20 August 2019).
79. Doan, D.T.; Ghaffarianhoseini, A.; Naismith, N.; Zhang, T.; Ghaffarianhoseini, A.; Tookey, J. A Critical Comparison of Green Building Rating Systems. *Building and Environment* **2017**, *123*, 243–260, doi:10.1016/j.buildenv.2017.07.007.
80. Gobbi, S.; Puglisi, V.; Ciaramella, A. A Rating System for Integrating Building Performance Tools in Developing Countries. *Energy Procedia* **2016**, *96*, 333–344, doi:10.1016/j.egypro.2016.09.156.
81. Zimmermann, R.K.; Skjelmose, O.; Jensen, K.G.; Jensen, K.K.; Birgisdottir, H. Categorizing Building Certification Systems According to the Definition of Sustainable Building. *IOP Conference Series: Materials Science and Engineering* **2019**, *471*, 092060, doi:10.1088/1757-899x/471/9/092060.
82. Mattoni, B.; Guattari, C.; Evangelisti, L.; Bisegna, F.; Gori, P.; Asdrubali, F. Critical Review and Methodological Approach to Evaluate the Differences among International Green Building Rating Tools. *Renewable and Sustainable Energy Reviews* **2018**, *82*, 950–960, doi:10.1016/j.rser.2017.09.105.
83. Ferreira, J.; Pinheiro, M.D.; de Brito, J. Portuguese Sustainable Construction Assessment Tools Benchmarked with BREEAM and LEED: An Energy Analysis. *Energy and Buildings* **2014**, *69*, 451–463, doi:Castellano.

84. Ophelia CHU Ka-waia; Richard CHEUNG Yun-hing A Comparison on Two Certification Systems: Leadership in Energy and Environmental Design (LEED) And Building Environmental Assessment Method (BEAM) On Green Building in Hong Kong. In Proceedings of the Track 3: Advancing SBE Assessments; HongKong, 2017; pp. 1022–1030.
85. S. ILLANKOON, I.M.C.; W. Y. TAM, V.; LE, K.N.; TRAN, C.N.N.; MA, M. Review on Green Building Rating Tools Worldwide: Recommendations for Australia. *Journal of Civil Engineering and Management* **2019**, *25*, 831–847, doi:https://doi.org/10.3846/jcem.2019.10928.
86. Rastogi, A.; Choi, J.-K.; Hong, T.; Lee, M. Impact of Different LEED Versions for Green Building Certification and Energy Efficiency Rating System: A Multifamily Midrise Case Study. *Applied Energy* **2017**, *205*, 732–740, doi:10.1016/j.apenergy.2017.08.149.
87. Potrc Obrecht, T.; Kunič, R.; Jordan, S.; Dovjak, M. Comparison of Health and Well-Being Aspects in Building Certification Schemes. *Sustainability* **2019**, *11*, 2616, doi:10.3390/su11092616.
88. Usman, A.; Abdullah, K. Comparative Study on the Malaysian Sustainable Building Rating Systems. *International Journal of Integrated Engineering* **2018**, *10*.
89. Gero, J.S.; D'Cruz, N.; Radford, A.D. Energy in Context: A Multicriteria Model for Building Design. *Building and Environment* **1983**, *18*, 99–107, doi:10.1016/0360-1323(83)90001-X.
90. Tupenaite, L.; Kaklauskas, A.; Voitov, I.; Trinkunas, V.; Gudauskas, R.; Naimaviciene, J.; Kanapeckiene, L. Multiple Criteria Assessment of Apartment Building Performance for Refurbishment Purposes. *International Journal of Strategic Property Management* **2018**, *22*, 236–251, doi:10.3846/ijspm.2018.3679.
91. Addy, M.; Adinyira, E.; Ayarkwa, J. Identifying and Weighting Indicators of Building Energy Efficiency Assessment in Ghana. *Energy Procedia* **2017**, *134*, 161–170, doi:10.1016/j.egypro.2017.09.554.
92. Gervasio, H.; Dimova, S.; Pinto, A. Benchmarking the Life-Cycle Environmental Performance of Buildings. *Sustainability* **2018**, *10*, 1454, doi:10.3390/su10051454.
93. Belucio, M.; Rodrigues, C.; Antunes, C.; Freire, F.; Dias, L. Eco-Efficiency in Early Design Decisions: A Multimethodology Approach. *Journal of Cleaner Production* **2020**, *283*, 124630, doi:10.1016/j.jclepro.2020.124630.
94. Galimshina, A.; Moustapha, M.; Hollberg, A.; Padey, P.; Lasvaux, S.; Sudret, B.; Habert, G. Statistical Method to Identify Robust Building Renovation Choices for Environmental and Economic Performance. *Building and Environment* **2020**, *183*, 107143, doi:10.1016/j.buildenv.2020.107143.
95. Wandahl, S.; Lund, L.; Neve, H.; Jensen, S.R. Social Sustainability in Modelling of Value Creation in Housing Refurbishment. In *10th Nordic Conference on Construction Economics and Organization*; Lill, I., Witt, E., Eds.; Emerald Reach Proceedings Series; Emerald Publishing Limited, 2019; Vol. 2, pp. 383–391 ISBN 978-1-83867-051-1.
96. Lami, I.M.; Mecca, B. Assessing Social Sustainability for Achieving Sustainable Architecture. *Sustainability* **2021**, *13*, doi:10.3390/su13010142.
97. Dwijendra, N.K.; Akhmadeev, R.; Tumanov, D.; Kosov, M.; Shoar, S.; Banaitis, A. Modeling Social Impacts of High-Rise Residential Buildings during the Post-Occupancy Phase Using DEMATEL Method: A Case Study. *Buildings* **2021**, *11*, doi:10.3390/buildings11110504.
98. Kaklauskas, A.; Zavadskas, E.K.; Raslanas, S. Multivariant Design and Multiple Criteria Analysis of Building Refurbishments. *Energy and Buildings* **2005**, *37*, 361–372, doi:10.1016/J.ENBUILD.2004.07.005.

99. Hu, M. Building Impact Assessment—A Combined Life Cycle Assessment and Multi-Criteria Decision Analysis Framework. *Resources, Conservation and Recycling* **2019**, *150*, 104410, doi:10.1016/j.resconrec.2019.104410.
100. Liu, S.; Qian, S. Evaluation of Social Life-Cycle Performance of Buildings: Theoretical Framework and Impact Assessment Approach. *Journal of Cleaner Production* **2019**, *213*, 792–807, doi:10.1016/j.jclepro.2018.12.200.
101. Cetiner, I.; Edis, E. An Environmental and Economic Sustainability Assessment Method for the Retrofitting of Residential Buildings. *Energy and Buildings* **2014**, *74*, 132–140, doi:10.1016/j.enbuild.2014.01.020.
102. Cellura, M.; Di Gangi, A.; Longo, S.; Orioli, A. An Italian Input-Output Model for the Assessment of Energy and Environmental Benefits Arising from Retrofit Actions of Buildings. *Energy and Buildings* **2013**, *62*, 97–106, doi:10.1016/j.enbuild.2013.02.056.
103. Risholt, B.; Time, B.; Hestnes, A.G. Sustainability Assessment of Nearly Zero Energy Renovation of Dwellings Based on Energy, Economy and Home Quality Indicators. *Energy and Buildings* **2013**, *60*, 217–224, doi:10.1016/j.enbuild.2012.12.017.
104. Fraile-Garcia, E.; Ferreira-Cabello, J.; Sodupe, E.; Sanz García, A. Combined Assessment of the Environmental, Economic and Social Impacts of Structural Solutions for Residential Construction. *Informes de la Construcción* **2015**, *067*, e101.
105. Asdrubali, F.; Baldinelli, G.; Bianchi, F.; Sambuco, S. A Comparison between Environmental Sustainability Rating Systems LEED and ITACA for Residential Buildings. *Building and Environment* **2015**, *86*, 98–108, doi:10.1016/j.buildenv.2015.01.001.
106. Castellano, J.; Ribera, A.; Ciurana, J. Integrated System Approach to Evaluate Social, Environmental and Economics Impacts of Buildings for Users of Housings. *Energy and Buildings* **2016**, *123*, 106–118, doi:10.1016/j.enbuild.2016.04.046.
107. Awadh, O. Sustainability and Green Building Rating Systems: LEED, BREEAM, GSAS and Estidama Critical Analysis. *Journal of Building Engineering* **2017**, *11*, 25–29, doi:10.1016/j.job.2017.03.010.
108. Florez-Perez, L. Sustainability and Green Building Rating Systems: A Critical Analysis to Advance Sustainable Performance. *Encyclopedia of Renewable and Sustainable Materials* **2020**, doi:10.1016/B978-0-12-803581-8.11411-0.
109. Tang, K.H.D.; Foo, C.Y.H.; Tan, I.S. A Review of the Green Building Rating Systems. *IOP Conference Series: Materials Science and Engineering* **2020**, *943*, 012060, doi:10.1088/1757-899x/943/1/012060.
110. Cellura, M.; Di Gangi, A.; Longo, S.; Orioli, A. An Italian Input-Output Model for the Assessment of Energy and Environmental Benefits Arising from Retrofit Actions of Buildings. *Energy and Buildings* **2013**, *62*, 97–106, doi:10.1016/j.enbuild.2013.02.056.
111. Cetiner, I.; Edis, E. An Environmental and Economic Sustainability Assessment Method for the Retrofitting of Residential Buildings. *Energy and Buildings* **2014**, *74*, 132–140, doi:10.1016/j.enbuild.2014.01.020.
112. Maleki, B.; Casanovas Rubio, M. d M.; Hosseini, S.M.A.; de la Fuente Antequera, A. Multi-Criteria Decision Making in the Social Sustainability Assessment of High-Rise Residential Buildings. *IOP Conference Series: Earth and Environmental Science* **2019**, *290*, 012054, doi:10.1088/1755-1315/290/1/012054.
113. Janjua, S.Y.; Sarker, P.K.; Biswas, W.K. Development of Triple Bottom Line Indicators for Life Cycle Sustainability Assessment of Residential Buildings. *Journal of Environmental Management* **2020**, *264*, 110476, doi:10.1016/j.jenvman.2020.110476.
114. Ignjatović, D.; Bojana, Z.; Ćuković Ignjatović, N.; Đukanović, L.; Radivojević, A.; Rajčić, A. Methodology for Residential Building Stock Refurbishment Planning—

- Development of Local Building Typologies. *Sustainability* **2021**, *13*, doi:10.3390/su13084262.
115. Pinzon Amoroch, J.A.; Hartmann, T. A Multi-Criteria Decision-Making Framework for Residential Building Renovation Using Pairwise Comparison and TOPSIS Methods. *Journal of Building Engineering* **2022**, *53*, 104596, doi:10.1016/j.job.2022.104596.
 116. Zhang, H.; Lei, S.L. An Assessment Framework for the Renovation of Existing Residential Buildings Regarding Environmental Efficiency. *Procedia - Social and Behavioral Sciences* **2012**, *68*, 549–563, doi:10.1016/j.sbspro.2012.12.248.
 117. Rajiv Bhatt; J.E.M. Macwan; Darshana Bhatt; Vipul Patel Analytic Hierarchy Process Approach for Criteria Ranking of Sustainable Building Assessment: A Case Study. *World Applied Sciences Journal* **2010**, *8*, 881–888.
 118. Kabak, M.; Kose, E.; Kırılmaz, O.; Burmaoğlu, S. A Fuzzy Multi-Criteria Decision Making Approach to Assess Building Energy Performance. *Energy and Buildings* **2014**, *72*, 382–389, doi:10.1016/j.enbuild.2013.12.059.
 119. Taillandier, F.; Mora, L.; Breyse, D. Decision Support to Choose Renovation Actions in Order to Reduce House Energy Consumption – An Applied Approach. *Building and Environment* **2016**, *109*, 121–134, doi:10.1016/j.buildenv.2016.09.019.
 120. Perera, P.; Hewage, K.; Alam, M.S.; Mèrida, W.; Sadiq, R. Scenario-Based Economic and Environmental Analysis of Clean Energy Incentives for Households in Canada: Multi Criteria Decision Making Approach. *Journal of Cleaner Production* **2018**, *198*, 170–186, doi:10.1016/j.jclepro.2018.07.014.
 121. Al-Jebouri, M.F.A.; Saleh, M.S.; Raman, S.N.; Rahmat, R.A.A.B.O.K.; Shaaban, A.K. Toward a National Sustainable Building Assessment System in Oman: Assessment Categories and Their Performance Indicators. *Sustainable Cities and Society* **2017**, *31*, 122–135, doi:10.1016/j.scs.2017.02.014.
 122. Kanapeckiene, L.; Tupenaite, L.; Jucienė, G.; Geipele, I. Sustainability Assessment of the Residential Construction Projects in Lithuania. *Engineering Structures and Technologies* **2021**, *12*, 53–60, doi:10.3846/est.2020.14933.
 123. Abdel-Basset, M.; Gamal, A.; Chakraborty, R.K.; Ryan, M.; El-Saber, N. A Comprehensive Framework for Evaluating Sustainable Green Building Indicators under an Uncertain Environment. *Sustainability* **2021**, *13*, doi:10.3390/su13116243.
 124. Yu, W.; Li, B.; Yang, X.; Wang, Q. A Development of a Rating Method and Weighting System for Green Store Buildings in China. *Renewable Energy* **2015**, *73*, 123–129, doi:10.1016/j.renene.2014.06.013.
 125. Mulliner, E.; Smallbone, K.; Maliene, V. An Assessment of Sustainable Housing Affordability Using a Multiple Criteria Decision Making Method. *Omega* **2013**, *41*, 270–279, doi:10.1016/j.omega.2012.05.002.
 126. Maslesa, E.; Jensen, P.A.; Birkved, M. Indicators for Quantifying Environmental Building Performance: A Systematic Literature Review. *Journal of Building Engineering* **2018**, *19*, 552–560, doi:10.1016/j.job.2018.06.006.
 127. Ardda, N.; Mateus, R.; Bragança, L. Methodology to Identify and Prioritise the Social Aspects to Be Considered in the Design of More Sustainable Residential Buildings—Application to a Developing Country. *Buildings* **2018**, *8*, doi:10.3390/buildings8100130.
 128. Ferreira, M.; Almeida, M. Benefits from Energy Related Building Renovation beyond Costs, Energy and Emissions.; Elsevier; Vol. 00, pp. 000–000.
 129. Anand, C.K.; Amor, B. Recent Developments, Future Challenges and New Research Directions in LCA of Buildings: A Critical Review. *Renewable and Sustainable Energy Reviews* **2017**, *67*, 408–416, doi:10.1016/j.rser.2016.09.058.

130. Gholami Rostam, M.; Abbasi, A. A Framework for Identifying the Appropriate Quantitative Indicators to Objectively Optimize the Building Energy Consumption Considering Sustainability and Resilience Aspects. *Journal of Building Engineering* **2021**, *44*, 102974, doi:10.1016/j.jobe.2021.102974.
131. Ho, A.M.Y.; Lai, J.H.K.; Chiu, B.W.Y. Key Performance Indicators for Holistic Evaluation of Building Retrofits: Systematic Literature Review and Focus Group Study. *Journal of Building Engineering* **2021**, *43*, 102926, doi:10.1016/j.jobe.2021.102926.
132. Rajabi, S.; El-Sayegh, S.; Romdhane, L. Identification and Assessment of Sustainability Performance Indicators for Construction Projects. *Environmental and Sustainability Indicators* **2022**, *15*, 100193, doi:10.1016/j.indic.2022.100193.
133. Arukala, S.R.; Pancharathi, R.K.; Pulukuri, A.R. Evaluation of Sustainable Performance Indicators for the Built Environment Using AHP Approach. *Journal of The Institution of Engineers (India): Series A* **2019**, *100*, 619–631, doi:10.1007/s40030-019-00405-8.
134. Nair, A.; Nayar, S. Key Performance Indicators of Sustainability. *IOP Conference Series: Earth and Environmental Science* **2020**, *491*, 012047, doi:10.1088/1755-1315/491/1/012047.
135. Hossain, Md.U.; Ng, S.T. Strategies for Enhancing the Accuracy of Evaluation and Sustainability Performance of Building. *Journal of Environmental Management* **2020**, *261*, 110230, doi:10.1016/j.jenvman.2020.110230.
136. Wang, R.; Lu, S.; Feng, W.; Zhai, X.; Li, X. Sustainable Framework for Buildings in Cold Regions of China Considering Life Cycle Cost and Environmental Impact as Well as Thermal Comfort. *Energy Reports* **2020**, *6*, 3036–3050, doi:10.1016/j.egyr.2020.10.023.
137. McGinley, O.; Moran, P.; Goggins, J. An Assessment of the Key Performance Indicators (KPIs) of Energy Efficient Retrofits to Existing Residential Buildings. *Energies* **2022**, *15*, 334, doi:10.3390/en15010334.
138. Mbugua, M.; Ajwang', P.O.; Winja, M.M.O. Identification and Ranking of Key Performance Indicators in Building Construction Projects in Kenya. *Eng. Technol. Appl. Sci. Res.* **2021**, *11*, 6668–6673, doi:10.48084/etasr.3912.
139. Kamari, A.; Corrao, R.; Kirkegaard, P. Sustainability Focused Decision-Making in Building Renovation. *International Journal of Sustainable Built Environment* **2017**, *6*, doi:10.1016/j.ijbsbe.2017.05.001.
140. Gopikrishnan, S.; Topkar, V.M. Attributes and Descriptors for Building Performance Evaluation. *HBRC Journal* **2017**, *13*, 291–296, doi:10.1016/j.hbrj.2015.08.004.
141. Olakitan Atanda, J. Developing a Social Sustainability Assessment Framework. *Sustainable Cities and Society* **2019**, *44*, 237–252, doi:10.1016/j.scs.2018.09.023.
142. Khalil, N.; Kamaruzzaman, S.N.; Baharum, M.R. Ranking the Indicators of Building Performance and the Users' Risk via Analytical Hierarchy Process (AHP): Case of Malaysia. *Ecological Indicators* **2016**, *71*, 567–576, doi:10.1016/j.ecolind.2016.07.032.
143. Almeida, M.; Barbosa, J.; Ferreira, M.; Rodrigues, A. *Benefits of Energy Related Building Renovation in Residents Comfort and Well-Being – Vila d'Este Case Study*; **2016**.
144. Javiri, F.; Aminullah, A.; Triwiyono, A. Assessment System of Condition of Typical Building Infrastructure Using Fuzzy Analitical Hierarchy Procces (FAHP) Method. *MATEC Web of Conferences* **2019**, *258*, 03006, doi:10.1051/mateccconf/201925803006.
145. Liu, Y.; Eckert, C.M.; Earl, C. A Review of Fuzzy AHP Methods for Decision-Making with Subjective Judgements. *Expert Systems with Applications* **2020**, *161*, 113738, doi:10.1016/j.eswa.2020.113738.

146. Işık, Z.; Aladağ, H. A Fuzzy AHP Model to Assess Sustainable Performance of the Construction Industry from Urban Regeneration Perspective. *Journal of Civil Engineering and Management* **2016**, *23*, 1–11, doi:10.3846/13923730.2016.1210219.
147. Elshafei, G.; Katunský, D.; Zelenáková, M.; Negm, A. Opportunities for Using Analytical Hierarchy Process in Green Building Optimization. *Energies* **2022**, *15*, doi:10.3390/en15124490.
148. Bruce-Hyrkäs, T.; Pasanen, P.; Castro, R. Overview of Whole Building Life-Cycle Assessment for Green Building Certification and Ecodesign through Industry Surveys and Interviews. *Procedia CIRP* **2018**, *69*, 178–183, doi:10.1016/j.procir.2017.11.127.
149. Lifecycle Initiative Environmental LCA Available online: <https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/environmental-lca/> (accessed on 2 January 2019).
150. Chau, C.K.; Leung, T.M.; Ng, W.Y. A Review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on Buildings. *Applied Energy* **2015**, *143*, 395–413, doi:10.1016/j.apenergy.2015.01.023.
151. Tebbouche, H.; Bouchair, A.; Grimes, S. Towards an Environmental Approach for the Sustainability of Buildings in Algeria. *Energy Procedia* **2017**, *119*, 98–110, doi:10.1016/j.egypro.2017.07.053.
152. Virginia Valentini HQE (Haute Qualité Environnementale) Certification for Buildings in Operation: How Does It Compare on Health and Wellbeing? Available online: <https://evoraglobal.com/news/sustainability/hqe-certification/> (accessed on 14 February 2020).
153. Vazquez, E.; Haddad, A.; Evangelista, A. LEED and HQE Certifications Assessment in Sustainable Construction. **2014**, *145*, 1743–3509, doi:10.2495/ICBEEE20130451.
154. S.E. Ismaeel, W. Midpoint and Endpoint Impact Categories in Green Building Rating Systems. *Journal of Cleaner Production* **2018**, *182*, doi:10.1016/j.jclepro.2018.01.217.
155. Anders Schmidt *Analysis of Five Approaches to Environmental Assessment of Building Components in a Whole Building Context*; eurima: Denmark, **2012**; p. 58;.
156. Rezaallah, A.; Bolognesi, C.; Afghani Khoraskani, R. *LEED and BREEAM; Comparison between Policies, Assessment Criteria and Calculation Methods*; **2012**;
157. Polli, G.H.B. A Comparison about European Environmental Sustainability Rating Systems: Breeam UK, DGNB, LiderA, ITACA and HQE. *U.Porto Journal of Engineering* **2020**, *6*, 45–57, doi:10.24840/2183-6493_006.002_0005.
158. Collinge, W.O.; Thiel, C.L.; Campion, N.A.; Al-Ghamdi, S.G.; Woloschin, C.L.; Soratana, K.; Landis, A.E.; Bilec, M.M. Integrating Life Cycle Assessment with Green Building and Product Rating Systems: North American Perspective. *Procedia Engineering* **2015**, *118*, 662–669, doi:10.1016/j.proeng.2015.08.500.
159. Schlegl, F.; Gantner, J.; Traunsperger, R.; Albrecht, S.; Leistner, P. LCA of Buildings in Germany: Proposal for a Future Benchmark Based on Existing Databases. *Energy and Buildings* **2019**, *194*, 342–350, doi:10.1016/j.enbuild.2019.04.038.
160. Politi, S.; Antonini, E.; Wilkinson, S. *Overview of Building LCA from the Sustainability Rating Tools Perspective*; **2018**.
161. UAB Statybos Birža Apartment Renovation Building Available online: <https://statybukonkursai.lt/lt/constructions/21564> (accessed on 1 August 2021).
162. Norvaišienė, R.; Karbauskaitė, J.; Bruzgevičius, P. *Energy Performance Certification in Lithuanian Building Sector. Book of Abstracts.*; 2014;
163. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent Developments in Life Cycle Assessment. *Journal of Environmental Management* **2009**, *91*, 1–21, doi:10.1016/j.jenvman.2009.06.018.

164. Gustavsson, L.; Joelsson, A. Life Cycle Primary Energy Analysis of Residential Buildings. *Energy and Buildings* **2010**, *42*, 210–220, doi:10.1016/J.ENBUILD.2009.08.017.
165. Ramesh, T.; Prakash, R.; Shukla, K.K. Life Cycle Energy Analysis of Buildings: An Overview. *Energy and Buildings* **2010**, *42*, 1592–1600, doi:10.1016/j.enbuild.2010.05.007.
166. Scheuer, C.; Keoleian, G.A.; Reppe, P. Life Cycle Energy and Environmental Performance of a New University Building: Modeling Challenges and Design Implications. *Energy and buildings* **2003**, *35*, 1049–1064.
167. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The Ecoinvent Database Version 3 (Part I): Overview and Methodology. *The International Journal of Life Cycle Assessment [online]* **2016**, *9*, 1218–1230.
168. CML_Department of Industrial Ecology CML_IA Characterisation Factors Available online: <https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors> (accessed on 8 May 2018).
169. Apanavičienė, R.; Maliejus, K.; Fokaides, P. Sustainability Assessment of the Building Construction Stage Using Building Sustainability Assessment Schemes (BSAS). *IOP Conference Series: Earth and Environmental Science* **2020**, *410*, 012064, doi:10.1088/1755-1315/410/1/012064.
170. Oviir, A. Life Cycle Assessment (LCA) in the Framework of the Next Generation Estonian Building Standard Building Certification as a Strategy for Enhancing Sustainability. *Energy Procedia* **2016**, *96*, 351–362, doi:10.1016/j.egypro.2016.09.159.
171. Sartori, T.; Drogemuller, R.; Omrani, S.; Lamari, F. A Schematic Framework for Life Cycle Assessment (LCA) and Green Building Rating System (GBRS). *Journal of Building Engineering* **2021**, *38*, 102180, doi:10.1016/j.jobe.2021.102180.
172. Mateus, R.; Bragança, L. Sustainability Assessment and Rating of Buildings: Developing the Methodology SBToolPT–H. *Building and Environment* **2011**, *46*, 1962–1971, doi:10.1016/j.buildenv.2011.04.023.
173. Castro, M. de F.; Mateus, R.; Bragança, L. Development of a Healthcare Building Sustainability Assessment Method – Proposed Structure and System of Weights for the Portuguese Context. *Journal of Cleaner Production* **2017**, *148*, 555–570, doi:10.1016/j.jclepro.2017.02.005.
174. Golić, K.; Kosorić, V.; Lau, S.-K. A Framework for Early Stages of Socially Sustainable Renovation of Multifamily Buildings with Occupants' Participation. *Sustainability* **2020**, *12*, doi:10.3390/su12218823.
175. Wiprächtiger, M.; Haupt, M.; Heeren, N.; Waser, E.; Hellweg, S. A Framework for Sustainable and Circular System Design: Development and Application on Thermal Insulation Materials. *Resources Conservation and Recycling* **2020**, *154*, doi:10.1016/j.resconrec.2019.104631.
176. BUILD UPON2: Creating a Renovation Framework Available online: <https://www.worldgbc.org/build-upon2-project> (accessed on 1 June 2022).
177. Marique, A.-F.; Rossi, B. Cradle-to-Grave Life-Cycle Assessment within the Built Environment: Comparison between the Refurbishment and the Complete Reconstruction of an Office Building in Belgium. *Journal of environmental management* **2018**, *224*, 396–405, doi:10.1016/j.jenvman.2018.02.055.
178. Alwisy, A.; BuHamdan, S.; Gül, M. Criteria-Based Ranking of Green Building Design Factors According to Leading Rating Systems. *Energy and Buildings* **2018**, *178*, 347–359, doi:10.1016/j.enbuild.2018.08.043.
179. Malmgren, L.; Mjörnell, K. Application of a Decision Support Tool in Three Renovation Projects. *Sustainability* **2015**, *7*, doi:10.3390/su70912521.

180. Hu, X.; Lei, D.; Li, L.; Leng, Y.; Yu, Q.; Wei, X.; Lo, W.L.A. Quantifying Paraspinal Muscle Tone and Stiffness in Young Adults with Chronic Low Back Pain: A Reliability Study. *Scientific Reports* **2018**, *8*, 14343, doi:10.1038/s41598-018-32418-x.
181. Gani, A.; Asjad, M.; Talib, F. Prioritization and Ranking of Indicators of Sustainable Manufacturing in Indian MSMEs Using Fuzzy AHP Approach. *Materials Today: Proceedings* **2021**, *46*, doi:10.1016/j.matpr.2021.04.101.
182. Hashim, M.; Nazam, M.; Abrar, M.; Hussain, Z.; Nazim, M.; Shabbir, R. Unlocking the Sustainable Production Indicators: A Novel TESCO Based Fuzzy AHP Approach. *null* **2021**, *8*, 1870807, doi:10.1080/23311975.2020.1870807.
183. Milošević, D.M.; Milošević, M.R.; Simjanović, D.J. Implementation of Adjusted Fuzzy AHP Method in the Assessment for Reuse of Industrial Buildings. *Mathematics* **2020**, *8*, doi:10.3390/math8101697.
184. Ebrahimigharehbaghi, S.; Qian, Q.K.; de Vries, G.; Visscher, H.J. Application of Cumulative Prospect Theory in Understanding Energy Retrofit Decision: A Study of Homeowners in the Netherlands. *Energy and Buildings* **2022**, *261*, 111958, doi:10.1016/j.enbuild.2022.111958.
185. Official Statistics Portal Database of Indicators Available online: <https://osp.stat.gov.lt/statistiniu-rodikliu-analize#/> (accessed on 29 March 2022).
186. Cradle to Cradle Certified Product Standard Version 3.1 **2018**.
187. Ben Kubbinga; Max Bamberger; Edwin van Noort; Dirk van den Reek; Merlijn Blok; Gerard Roemers; Justin Hoek; Kees Faes A Framework for Circular Buildings - Indicators for Possible Inclusion in BREEAM 2018.
188. Ratnasabapathy, S.; Perera, S.; Alashwal, A. *A review of construction waste data and reporting systems used in Australia*; **2019**.
189. Mesa, J.; González-Quiroga, A.; Maury, H. Developing an Indicator for Material Selection Based on Durability and Environmental Footprint: A Circular Economy Perspective. *Resources, Conservation and Recycling* **2020**, *160*, 104887, doi:10.1016/j.resconrec.2020.104887.
190. *Long Term Renovation Strategy of Lithuania*; Government of the Republic of Lithuania, 2021; p. 127;.
191. Chandrasekaran, V.; Dvarionienė, J. A Review of the Environmental Impact of Buildings with an Emphasis on Performance Assessment Tools and Their Incorporation of LCA. *Advances in Civil Engineering* **2022**, *2022*, 9947920, doi:10.1155/2022/9947920.
192. PRé Sustainability. SimaPro-LCA Software for Fact-Based Sustainability Available online: <https://simapro.com/> (accessed on 21 November 2021).
193. Pons-Valladares, O.; Nikolic, J. Sustainable Design, Construction, Refurbishment and Restoration of Architecture: A Review. *Sustainability* **2020**, *12*, doi:10.3390/su12229741.
194. Olsson, S.; Malmqvist, T.; Glaumann, M. Managing Sustainability Aspects in Renovation Processes: Interview Study and Outline of a Process Model. *Sustainability* **2015**, *7*, doi:10.3390/su7066336.
195. Antonov, Y. I.; Heiselberg, P.; Flourentzou, F.; and Pomianowski, M. Z., Methodology for Evaluation and Development of Refurbishment Scenarios for Multi-Story Apartment Buildings, Applied to Two Buildings in Denmark and Switzerland. *Buildings* **2020**, *10*(6), 102, doi.org/10.3390/buildings10060102.
196. Serrano-Lanzarote, B.; Ortega-Madrigal, L.; García-Prieto-Ruiz, A.; Soto-Francés, L.; Soto-Francés, V.M. Strategy for the energy renovation of the housing stock in Comunitat Valenciana (Spain). *Energy Build.* **2016**, *132*, 117–129.

197. Liu, J.; Bengtsson, B.; and Staffansson-Pauli, K., A Theoretical Framework of Sustainable Housing Renovation: A System Perspective and Innovation Approach', presented at the 8th Real Estate Workshop, Malmö, Sweden (9-10 may 2019), **2019**.

CURRICULUM VITAE

Vidhyalakshmi Chandrasekaran
vidhyalakshmi.chandrasekaran@ktu.lt

Education:

2007–2010 Bachelor's in Physics
2010–2012 Master's in Environment Sciences
2016–2018 Master's in Environmental Engineering
2018–2023 PhD in Environmental Engineering

Professional experience:

2012–2016 Assistant Project Manager, Solid Waste Management, Hand in Hand India, India.

Areas of research interest:

Life cycle assessment, environmental impact assessment, sustainability, chemicals management, waste management.

Scientific papers related to the topic of dissertation:

Publications in Web of Science Journals with citation index

1. **Chandrasekaran V.**; Dvarionienė, J.; Vitkute, A.; Gecevicius, G. Environmental Impact Assessment of Renovated Multi-Apartment Building Using LCA Approach: Case Study from Lithuania. *Sustainability* 2021, 13, 1542. <https://doi.org/10.3390/su13031542>
2. **Chandrasekaran V.**; Dvarionienė J., A Review of the Environmental Impact of Buildings with an Emphasis on Performance Assessment Tools and Their Incorporation of LCA, *Advances in Civil Engineering*, 2022, 22 pages, vol. 2022. <https://doi.org/10.1155/2022/9947920>

Publications in other journals with citation index

1. **Chandrasekaran V.**; Dvarionienė J. A conceptual methodology for renovation of multi-apartment buildings with a combined performance and lifecycle approach, *Journal of Environmental Research Engineering and Management*, 2022, vol. 78 (3), 7-21. <https://doi.org/10.5755/j01.erem.78.3.32023>.

Scientific conferences:

1. LCA4Regions-Interreg Europe: Environment and Resource Efficiency, “Environmental impact assessment of renovated multiapartment building using LCA – A case study from Lithuania”, 15 January 2020.
2. BUP Research Forum: Research and Innovation for a Sustainable Baltic Sea Region, Urban and Rural Development, *Environmental Life Cycle Assessment of residential buildings*, 25–26 August 2020.

3. Advanced Construction and Architecture 2020, Raw Materials and Circular Economy in the Built Environment, *Life cycle assessment of renovated multi-apartment buildings*, 23–25 September 2020.
4. FSLCI-LCSS: Lifecycle Approaches for Sustainable Regional Development, *A conceptual methodology as a support tool for environmental impact assessment in residential buildings using lifecycle approach*, 30 September 2021.

ACKNOWLEDGEMENTS

With the generous assistance and support of many people, this thesis is made a reality. I would like to extend my sincere gratitude to all of them.

Foremost, I am deeply grateful to my supervisor **Prof. Dr. Jolanta Dvarionienė** for her immeasurable patience and unwavering encouragement and feedback throughout my PhD study. Her immense knowledge and plentiful experience have inspired me throughout my whole academic research and daily life. I want to sincerely thank the **members of the advisory** of the **Institute of Environmental Engineering** for their generous time to offer me insightful criticism toward improving my work.

Getting through my dissertation required more than academic support, and I have many, many people to thank for listening to me and at times, having to tolerate me over the past five years of this journey. I cannot begin to express how grateful I am for their friendship and their priceless time. *Gabrielė Čepeliauskaitė* has been unwavering in her personal and professional support during the time I spent at the University. I am lucky to have met her, and I thank her for her friendship, kindness, love, and unyielding support while I adapted to a new culture. I must thank *Pavithra Suresh*, *Rathna Muruganatham*, *Manonmani Natarajan*, *Roshini Das*, and *Mantas Deksnys* for many amazing nights out and for keeping me young, funny, and humorous, and for not getting lost in my life. I cannot forget a friend who went through hard times together, cheered me on, and celebrated each accomplishment, *Dr. Rama Krishna Reddy* for his assistance, kindness, and support. Additionally, I would like to thank all my friends from India, *Jyothi*, *Uppili*, *Anirudh*, *Vishnu* and *Kaushik* for their constant motivation, emotional support, and for not letting me go, despite my failing correspondence. I apologize to anyone whose names I have left out, but I am sincerely appreciative to all the friends and colleagues who have helped and inspired me along the way.

Most importantly, none of this could have been possible without my family. I would like to dedicate this thesis to my mother, *Chandra Naganathan*, and my late father, *Chandrasekaran Abiraman*, both of whom instilled in me the perserverence and determination that always rendered me to pursue my aspirations. I am extremely grateful to my brother, *Swaminathan Chandrasekaran* and my sister-in-law for their unrelenting trust, timely encouragement, and unending patience. Finally, I would like to thank with love to *Vivek*, my husband, for being the person who best understands me and has supported me throughout my journey with his tremendous patience and energy. I would like to express my gratitude to my mother-in-law and brother-in-law for their unfailing emotional support and their heart-warming kindness.

Last but not least, I would like to dedicate my thanks to **God**, for letting me through all the challenges and stumbling blocks, this would not be possible without his blessings.

ANNEXES

Annex 1. List of environmental performance assessment schemes across globe

Region	Country	Rating Tools	Year	Name of the green building council	Websites
Africa	South Africa	Green Star SA	2008	Green Building Council South Africa	https://gbc.sa.org.za/certify/green-star-sa/
Americas	Argentina	LEED-Argentina	N/A	Argentina Green Building Council	https://www.argentinagbc.org.ar/leed/
	Brazil	LEED-Brazil	2004	Green Building Council Brazil	https://www.gbcbrasil.org.br/
		GBC Brasil	N/A		
	Canada	LEED Canada	2009	Canada Green Building Council	https://www.cagbc.org/CAGBC/LEED/Why_LEED/CAGBC/Programs/LEED/_LEED.aspx?hkey=5d7f0f3e-0dc3-4ede-b768-021835c8ff92
	USA	LEED	2000	US Green Building Council	http://leed.usgbc.org/leed.html
		Green Globes	2000		https://thegbi.org/
Asia-Pacific	Hong Kong	BEAM-Plus	1996	Hong Kong Green Building Council	https://www.beamsociety.org.hk/en_index.php
	India	LEED-India	2011	Indian Green Building Council	https://igbc.in/igbc/redirectHtm.html?redVal=showAboutusnosign
		TERI_GRIHA	2007		https://www.grihaindia.org/about-griha
	Japan	CASBEE	2004	Japan Sustainable Building Consortium	http://www.ibec.or.jp/CASBEE/english/
	Korea	GBCC	2000	Korean Green Building Council	http://esci-ksp.org/wp/wp-content/uploads/2012/07/Korean-Green-Building-Certification-Criteria.pdf
	Malaysia	Green Building Index	2009	Malaysia Green Building Confederation	https://www.researchgate.net/publication/328556644_Review_of_Green_Building_Index_in_Malaysia_Existing_Work_and_Challenges
	Singapore	Green Mark	2005	Singapore Green Building Council	https://www.bca.gov.sg/greenmark/green_mark_buildings.html
	Taiwan	EEWH	1999	Taiwan Green Building Council	http://twgbcqanda.com/english/e_tgbr.php?Type=2%26menu=e_tgbr_class%26pic_dir_list=0
Europe	Austria	DGNB	2009	Austrian Sustainable Building Council	https://www.dgnb-system.de/en/system/international/austria/
		LEED-AT	N/A		http://leed.usgbc.org/leed.html
		BREEAM-AT	N/A		https://www.breeam.com/worldwide/

Belgium	LEnSE	2008	Belgian Building Research Institute	https://www.bbri.be/homepage/download.cfm?lang=en&dtype=bbri&doc=Katrien_Putzeys.pdf
Czech Republic	SBToolCZ	2010	Czech Green Building Council	https://www.czgbc.org/en/workgroups/certifications
	BREEAM	N/A		
	LEED	N/A		
Denmark	BEAT 2002	2002	Danish Building Research Institute	https://www.irbnet.de/daten/iconda/CIB4368.pdf
	DGNB	2011	Danish Green Building Council	https://www.dk-gbc.dk/
Estonia	BREEAM - EE	2012	Estonian Green Building Council	http://www.gbc.ee/gbc_eng.html
Finland	PromisE	2006	Green Building Council Finland	https://figbc.fi/en/green-building-council-finland/
France	HQE	2005	France Green Building Council	http://www.hqegbc.org/home/
Germany	DGNB	2009	German Sustainable Building Council	https://www.dgnb-system.de/en/system/index.php
	BREEAM	2012	DIFNI	https://difni.de/breem/breem-de/
	LEED	2012	German Green Building Council	https://www.german-gba.org/en/systems-ggba/
	WELL	2019		
Hungary	DGNB	2010	Hungary Green Building Council	https://www.hugbc.hu/english?lang=en
Italy	LEED	2006	Green Building Council Italy	https://www.gbccitalia.org/web/guest/leed
	<i>Protocollo ITACA</i>	2005		https://www.gbccitalia.org/web/guest/home
Latvia	BREEAM-LV	2012	Latvian Sustainable Building Council	https://conqual.rtu.lv/about-the-conference/
Lithuania	LEED	2014	Lithuanian Green Building Council	https://www.lzpt.lt/about-us/
	BREEAM	2014		https://www.breem.com/tag/lithuania/
	DGNB	2014		https://www.lzpt.lt/about-us/
	LBSAS	2014		https://www.lzpt.lt/wp-content/uploads/2019/06/Lithuanian-building-sustainability-assessment-system.pdf
Netherlands	BREEAM-NL	2011	Dutch Green Building Council	https://www.breem.nl/
Norway	BREEAM - NOR	2012	Norwegian Green Building Council	https://byggalliansen.no/sertifisering/breem/om-breem-nor/
	Økoprofil	1999		https://www.arkitektur.no/?nid=155686&pid0=155001
Poland	DGNB	2008		

		BREEA M	2008	Polish Green Building Council	https://plgbc.org.pl/zrownowa-zone-budownictwo/certyfikacje-wielokryterialne/
		LEED	2008		
		HQE	2019		
		WELL	2019		
	Spain	VERDE	2006	Green Building Council Espana	http://www2.gbce.es/en/pagina/verde-certificate
		LEED	N/A		http://www.spaingbc.org/web/detalle-noticia.php?id=91
		BREEA M	2010		http://www.breem.es/
	Sweden	Green Building	2014	Sweden Green Building Council	https://www.sgbc.se/certifiering/
		Miljöbyggnad	2011		
		BREEA M SE	2013		
	Swiss	SNBS	2013	Green Building Switzerland	https://www.greenbuilding.ch/partner-labels
		MINERGIE	1998		
		LEED	2013		
		BREEA M CH	2012		
		DGNB	2010		https://www.dgnb-system.de/en/system/international/index.php
	UK	BREEA M	1990	UK Green Building Council	https://www.breem.com/
Middle East and North Africa	Turkey	DGNB	2010	Turkish Green Building Council	https://cedbik.org/en
	United Arab Emirates	LEED	N/A	Emirates Green Building Council	https://emiratesgbc.org/about/
		BREEA M	N/A		
Oceania	Australia	Green Star	2003	Green Building Council Australia	https://new.gbca.org.au/
		NABERS	2001		https://www.nabers.gov.au/
	New Zealand	Green Star	2007	New Zealand Green Building Council	https://www.nzgbc.org.nz/GreenStar

Annex 2. List of preliminary indicators selected based on literature studies

Indicators	Grouping	Aspects	Description
Energy performance	Energy	En	Improve energy performance measures
Greenhouse Emissions		En	Reduce greenhouse gas from all building performance
Renewable energy		En	Reduce fossil fuel consumption in the building
Energy conservation		En/Sc	Reducing the energy consumption without compromising thermal comfort

Construction Waste Management	Pollution	En	Implement construction waste program with provision for reuse, recycling measures
Noise Pollution		En	Minimize noise with efficient acoustics
Light Pollution		En	Install efficient lighting systems and provision for daylight source
Air Pollution		En	Air Pollution Index (API) report meets the standard
Flooding			Flooding and adaptation strategy for high-risk zones
Waste		En	Provision for managing household wastes
Water Consumption & Monitoring		En	Installation of efficient water monitoring system
Water Quality		En	Improve water quality through efficient measures
Potable Water & demand		En	Minimize water consumption
Wastewater		En	Utilize wastewater treatment systems
Acidification		En	Emissions to air measured in sq. m per year
Eutrophication		En	Emissions to water measured in sq. m. per year
Ozone depletion		En	Emissions to air in kg
Photochemical ozone formation		En	Emissions to air of the individual substances in kg
Indoor air quality	Health and comfort	En/Sc	Compliance to Indoor Air Quality Standards
Thermal Comfort		En/Sc	Room temperature control quality
Acoustic Performance		En/Sc	Efficient noise control in the site
Visual Comfort		En/Sc	Sufficient lighting
Olfactory comfort		En/Sc	Limiting Excessively strong or distinct odors
User comfort & Satisfaction		En/Sc	User comfort and satisfaction of indoor quality and renovation
Smoke Control		En/Sc	Efficient smoke control systems
Humidity control		En/Sc	Efficient ventilation control systems
Hazards		En/Sc	Plan and mitigation of natural hazards
Quality of Outdoor spaces		En/Sc	Provision of green spaces and quality surroundings
Human toxicity		En	Impact on humans of toxic substances emitted to the environment
Responsible Procurement	Resources and Materials	En/Ec	Procurement of environmentally friendly products
Fundamental Material Safety		En	Hazardous free building products as per EU compliance
Toxic material reduction		En	Toxic and hazardous free material
Land-use & ecology		En	Minimize ecological and damage to local site during renovation process
Reuse of existing structures		En	Efficient reuse of discarded components to existing structures
Local Environment Impact		En	Minimize ecological and overall impact to environment during renovation process
Life cycle impacts		En	Environment performance of a building over its entire life
Depletion of fossil fuels		En	Indicator of the depletion of natural fossil fuel resources.

Cumulative energy demand		En	Use of non-renewable primary energy resources as raw materials in MJ
Loss of biodiversity		En	Damage to local environment
Cumulative water consumption		En	Indicator of the relative amount of water used
Life cycle costs	Costs and functionalities	Ec	Economic performance of a building over its entire life
Potential savings		Ec	Promote a higher value of the building stock and establish solutions in line with the circular economy
Deconstruction		En/Ec	Provision for deconstruction and recycling of components
Public transport accessibility		En/Sc	Easily accessible to public commutation
Alternative Transportation		En/Sc	Alternate commutation – trams, railway, etc
Quality design		Sc/En	Integrated smart and quality design
Innovation		Sc/En/Ec	To support innovation within the construction and refurbishment
Safety, Security, and cultural aspects		Sc/En	Maximize personal safety and security, respect cultural aspects
Durability and resilience		Sc/En	Durable and resilient building structure and materials
Accessibility to workspace		Sc	Commutation from residence to workplace
Home office		Sc	Accessibility of workspace at home
Security of the neighborhood		Sc	Secured and safe neighborhoods
Aesthetic appearance		Sc	Appeal and aesthetic design of the building structure
Innovation		En/Sc/Ec	Innovation in construction through sustainability benefits
Bicycling path/storage		En/Sc	Promoting bicycling/storage for bicycles
Waste disposal	Waste	En	Disposal of waste per year
Recycling potential		En	Recycling potential in percentage per year
En – Environment ; Sc – Social; Ec – Economic			

UDK 502.174+502.131.1+69.059](043.3)

SL 344. 2023-xx-xx, xx leidyb. apsk. I. Tiražas xx egz. Užsakymas xxx.
Išleido Kauno technologijos universitetas, K. Donelaičio g. 73, 44249 Kaunas
Spausdino leidyklos „Technologija“ spaustuvė, Studentų g. 54, 51424 Kaunas