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INTELLIGENT RETROFITS IN RESIDENTIAL BUILDINGS: A KNOWLEDGE -BASED APPROACH

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Abstract

Building Life Cycle Assessment (LCA) is crucial to mitigate the environmental impact of residential retrofits. However, a significant gap exists in evaluating the complexity of building life cycles in the context of residential renovations. The proposed intelligent Knowledge Base System methodology integrates existing building materials, stock data, typologies, and retrofit scenarios, employing a hybrid approach that combines rule-based, case-based, and frame-based systems for comprehensive life cycle assessment. The case study focuses on retrofitting the semi-detached housing typology, transitioning from a boiler to a heat pump, and results in a reduction of total carbon emissions to 184 tCO_2e and 90 tCO_2e over 60 years. This study aids energy policymakers, urban planners, and researchers by offering an intelligent framework to promote eco-friendly renovations and advance sustainable building practices.

Introduction

Buildings are a major source of emissions, accounting for 39% of global energy-related carbon emissions, split between operational emissions (28%) and emissions from materials and construction (11%) (WGBC, 2023). The entire life cycle of a building, from material extraction to demolition, contributes to its carbon footprint. Emissions are categorized into operational (from daily operations) and embodied (from materials, construction, transportation, and demolition) (Fenner et al., 2020). Addressing these emissions is crucial for achieving near-zero carbon targets, requiring effective methods and strategies to assess and reduce carbon emissions throughout a building life cycle assessment (LCA).

A big challenge in applying LCA during initial design or retrofitting is the scarcity or complexity of data (Kadrić et al., 2023; Roberts et al., 2020). This complexity hinders stakeholders from developing and implementing effective retrofit measures (Zuo et al., 2017; Najjar et al., 2019). Conducting LCAs to upgrade residential building stock is crucial, as it allows for assessing long-term environmental and cost impacts throughout the buildings' lifespan, as discussed previously, and all subsequent phases. Despite the widespread adoption and standardization of LCA methodologies and the growing availability of data through tools like Environmental Product Declarations (EPD), a significant research gap still needs to be addressed. This gap mainly lies in integrating and interpreting complex data for specific scenarios. The complexity increases when dealing with residential renovations, where factors such as renovation type, materials used, and the building's operational phase add complexity (Roberts et al., 2020).

Furthermore, despite the benefits of sustainably retrofitted buildings, key stakeholders often lack a system to generate new knowledge while incorporating the entire lifecycle of a building. This includes selecting sustainable materials and transferring related information between stages. However, integrating complex data across different LCA phases and needing a flexible and scalable solution represents a significant research gap in Building LCA (Hollberg et al., 2021).

The importance of comparing different existing LCA analyses of buildings has been widely acknowledged. For instance, Röck et al. (2020) analyzed 238 buildings from 54 scientific articles, focusing on embodied and operational emissions. They emphasized the need for comparative LCA studies due to varying energy performance standards. Previous research has concentrated on implementing LCA frameworks in buildings to assess environmental impacts. Waldman et al. (2020) proposed a methodology for assessing construction materials during the specification and procurement stages of LCA. Balouktsi et al. (2020) explored the level of designers' awareness of environmental performance assessments and LCA in buildings. A study by Sharma et al. (2011) demonstrated large discrepancies in LCA results for 13 buildings, highlighting that commercial buildings have a greater environmental impact than residential ones. Similarly, Säynäjoki et al. (2017) reviewed 116 buildings and compared their GHG emissions during pre-use life cycle stages, finding significant inconsistencies in LCA results, ranging from 0.03 to 2.00 tons of CO_2 eq. per m^2. Data reliability and geographic relevance are crucial for accurate LCA methodologies across different buildings. Another challenge is the lack of collaboration among LCA practitioners, including designers, architects, building consultants, and engineers. Bridging this gap and promoting collaboration is a key objective of this study.

A survey by Jusselme et al. (2020) highlighted the time-consuming nature of LCA in the design stage, ranging from 18 to 33 hours from data collection to result interpretation. This adds to the time and cost of the process. Identifying strategies for efficient LCA analysis is therefore crucial. Various LCA databases, such as One Click LCA, Eco Invent, SimaPro, and the ULSCI database, offer different strengths and weaknesses. Each database, like Eco Invent v3 with its 10,000 interlinked datasets, or SimaPro, suitable for cradle-to-grave assessments, has unique features

(Wernet et al., 2016). Mohammadpourkarbasi et al. (2023) performed a comparative study of retrofit approaches for life cycle carbon assessment of decarbonizing UK's hard-to-treat homes. However, integrating data from multiple databases, establishing relationships, and reducing redundancies and discrepancies can greatly benefit decision-makers and stakeholders. Furthermore, studies rely on predefined retrofit scenarios and require intelligent solutions to recommend environmentally friendly retrofit scenarios for buildings based on their requirements.

The aim of this study is to propose a methodology for an intelligent Knowledge Base System (iKBS) for residential building LCA. The knowledge-base system integrates and analyzes complex, various data sources using knowledge acquisition, knowledge pre-processing (transforming unstructured data into structured data), and knowledge management. A novel feature of this system is knowledge inference, specifically tailored to generate new pieces of information from existing data. Furthermore, this research compares various knowledge-based approaches, such as rule-based, case-based, and frame-based systems for building LCA. This comparative analysis led to the development of a recommendation system for stakeholders that provides deep insights into the embodied energy aspects of residential renovations, a critical factor in understanding and improving the environmental performance of the building stock. The semi-detached housing typology case study shows that combining various knowledge leads to low-energy, cost-effective retrofit material recommendations.

Traditional LCA methods often rely on static, linear approaches to assess the environmental impacts of building projects. These methods may not adequately capture the complexities and interdependencies inherent in building life cycles, particularly for residential renovations. They typically struggle with dynamically incorporating new data or adjusting to novel scenarios without substantial manual intervention that accounts for updates during the life cycle. This can lead to inaccuracies in modeling the environmental impacts of different materials, processes, and retrofit options. In contrast, iKBS offers a dynamic, adaptive, and comprehensive framework for LCA. iKBS is built upon a hybrid model that combines the strengths of rule-based, case-based, and frame-based reasoning to handle diverse data types and complex analysis scenarios. The iKBS is capable of automating the data acquisition, preprocessing, and analysis processes, significantly reducing the time and effort required while enhancing the accuracy and relevance of the assessments. This integration allows for the sophisticated handling of diverse data types and complex analysis scenarios, facilitating the assimilation and processing of vast amounts of building material, stock data, residential typologies, and retrofit scenarios. the proposed intelligent framework can adapt and learn from new information, providing a more nuanced understanding of environmental impacts and facilitating the generation of actionable recommendations tailored to specific renovation projects.

The paper follows a structured format, with Section 2 presenting the methodology employed in the research. Section 3 examines a comprehensive Irish case study, providing real-world context for the study's findings. Finally, Section 4 concludes the paper and outlines potential avenues for future research.

Methodology

This paper presents a comprehensive methodology for an intelligent Knowledge-based System to facilitate detailed Life Cycle Impact (LCI) Assessments for the building and construction sector, integrating environmental and economic performance metrics for sustainable decision-making (Figure 1). The proposed development for residential building stock, based on the ISO 14040/44 standards (Principles and Framework for Life Cycle Assessment), comprises four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. Each phase is crucial and builds upon the previous one, ensuring a comprehensive and systematic approach to assessing the environmental impacts of residential building renovations.

The proposed methodology encompasses several key steps: 1. Goal and Scope Definition to outline the study objectives, 2. Development of a Knowledge-based System for LCI to gather relevant data or knowledge; 3. Integration of Life Cycle Impact Assessment via an Inference Engine, and 4. Creation of an LCA Interface for Recommendations, facilitating informed decision-making. This comprehensive approach ensures thorough analysis and informed choices throughout the lifecycle assessment process, emphasizing requirements, steps, and effective implementation strategies.

Goal and Scope Definition

The methodology begins with defining the goal and scope of the building life cycle assessment. The goals are to understand its initiation reasons, identify potential applications, and specify the target audience. The scope includes specifying the application, approach, data requirements, study period, functional unit, and system boundary. These parameters are essential for guiding the overall development process and ensuring the assessment aligns with the intended purpose. The goal and scope definition serves as the foundation for developing an iKBS to strategically identify areas for enhancement in the building's environmental performance. Furthermore, the methodology is beneficial in determining the best retrofit options, providing in-depth cost-benefit analysis, and conducting comprehensive sustainability assessments by defining proper goals and requirements.

Knowledge-based System for LCI Development

Life Cycle Inventory (LCI) is a core step of LCA and represents the quantification of inputs and outputs for a product throughout its life cycle (Wernet et al., 2016). In the

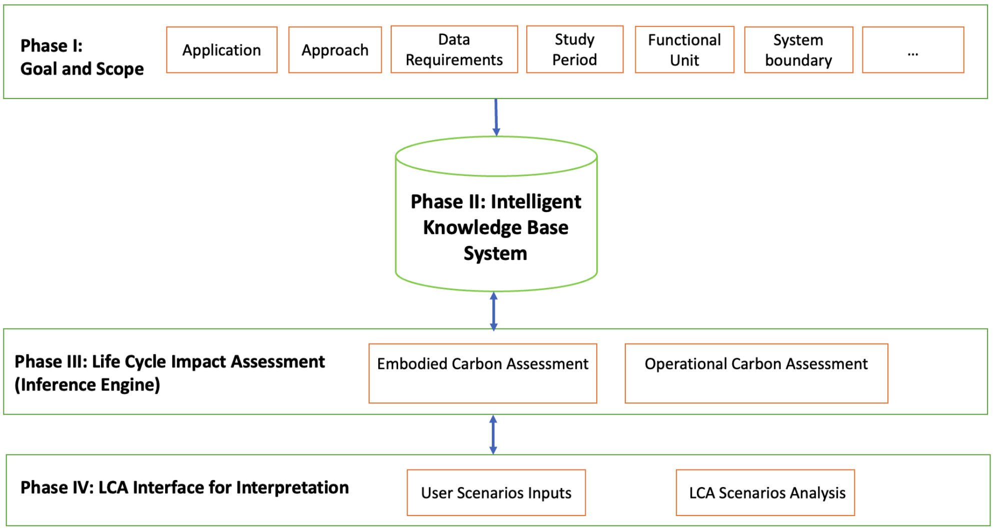

Figure 1: Methodology for intelligent Knowledge-based system for comprehensive life cycle assessment of residential buildings

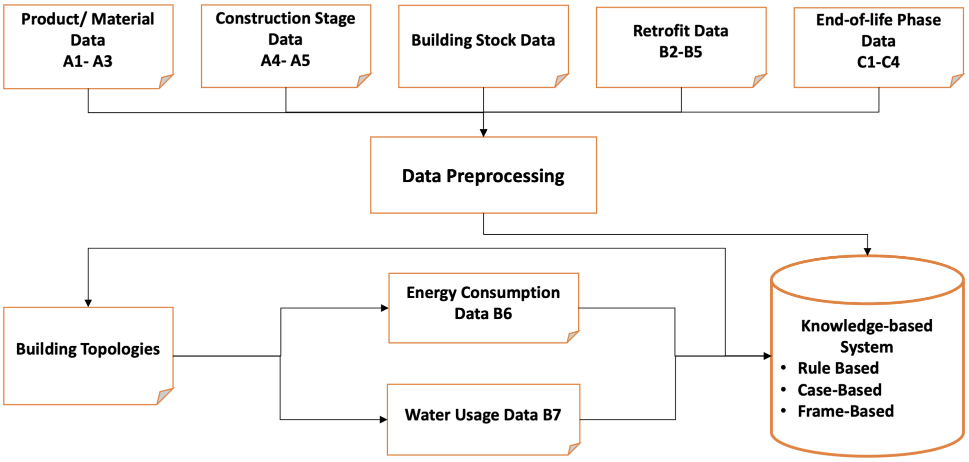

Figure 2: Sub-methodology for knowledge-based system for life cycle inventory development

context of buildings, LCI data include the energy, materials, and emissions associated with the construction, operation, maintenance, and eventual deconstruction of buildings. Several databases provide LCI data with embodied carbon values for various construction materials and processes, such as the Inventory of Carbon and Energy (ICE) database from the University of Bath (ICE, 2024), which can be used exclusively for calculating embodied energy from a prospective perspective, and Ecoinvent (Ecoinvent, 2024) considered to be the largest transparent unit-process. Similarly, various regions and organizations maintain databases of EPDs, which provide standardized LCA-based reports for specific products, including many construction products (Feng et al., 2023). Generally, Building LCA is categorized into different stages: A1-A3 for material extraction and transport, A4-A5 for construction and waste management, B1-B7 for use and renovation, C1-C4 for end-of-life disposal, and D for the environmental benefits of recovery. The process consists of multiple steps: Knowledge Acquisition and Preprocessing, Building Typologies, Knowledge-Based System Development, and Inference Engine for assessments (Figure 2).

Knowledge Acquisition and Preprocessing

The knowledge Acquisition phase for the iKBS involves gathering a wide range of information to create a comprehensive understanding of various aspects of building construction and maintenance. The knowledge acquisition in this phase is segmented into various categories:

- Product/Material Data (A1-A3): This involves gathering data on all materials and products used in the construction process, from extraction to processing.
- Construction Stage Data (A4-A5): Data related to the construction activities, including transportation and on-site processes.
- Building Stock Data: Information on the existing buildings, including their types, ages, and materials.
- Retrofit Data (B2-B5): Information on any renovation or updates made to existing buildings.

- End-of-life Phase Data (C1-C4): Data concerning the demolition, waste processing, and disposal or recycling of building materials or products.

The acquired knowledge undergoes a pre-processing stage to ensure it is consistent, accurate, and relevant for developing the iKBS. The methodology uses different data pre-processing methods such as data cleaning, data transformation, and data integration. The fuzzy-based method is used for identifying and merging records that refer to the same entities across different databases. This step is crucial to ensure the iKBS can effectively use the knowledge for intelligent decision-making in construction projects, sustainability assessments, and lifecycle management of buildings.

Building Typologies

Buildings often share common characteristics and can be classified into a building typology. This can also be referred to as a reference building, which is a representative structure capturing the typical characteristics and performance of a specific category or group of buildings within a larger building stock. This data can be sourced from established national building stock databases, such as TABULA or EPC databases (Ali et al., 2024). Building typologies data is further used for the B1 stage, which evaluates the building's performance in terms of energy and water usage. These data can also be generated using a thermal simulation engine such as EnergyPlus and IES for the generation of energy and water consumption data based on retrofit scenarios (Ali et al., 2024).

Intelligent Knowledge-based System Development

The proposed iKBS is an advanced framework to analyze the complex decision-making process. This process integrates pre-processed and simulated data from the Life Cycle Inventory Development, accommodating the vast array of data and variables in assessing a building's life cycle. The system comprises various intelligent knowledge representation and recommendation methods, including Rule-Based, Case-Based, and Frame-Based systems. Rule-based systems express knowledge concepts as a conjunction of conditions and conclusions (Santos et al., 2020). A rules-based system can be developed for LCA in residential buildings to evaluate environmental impacts based on specific criteria, such as material selection. For instance, a rule might state, *"If a building's construction year is old, then the materials used in the building are of low performance."* Case-based reasoning solves new problems by extracting and applying solutions previously adopted for similar problems (Zhao et al., 2019). In the context of LCA, past LCA studies or available data from similar residential buildings can be used to predict the environmental impact of a new building project. Frame-based systems use structured templates or frames to represent knowledge and infer new information based on existing structures and relationships within the frames (Nazaruks and Osis, 2021). These systems use detailed, available data in structured frames or templates. Each frame can represent different aspects of LCA, like materials, energy efficiency, or water usage, with slots for specific attributes and values.

Typically, KBS (Knowledge-Based Systems) stores all data in databases such as PostgreSQL and MySQL for structured data with well-defined schemas, and MongoDB, Cassandra, or Couchbase for unstructured or semi-structured data. In this paper, MongoDB and Python are used to implement a hybrid approach of Rule-Based, Case-Based, and Frame-Based systems that store different types of unstructured or semi-structured data.

This study comprehensively assesses each system based on accuracy, complexity, flexibility, and scalability. However, due to the complex nature of building lifecycle assessment and data requirements, this study proposes a hybrid approach for effective life cycle assessment. Furthermore, the hybrid approach offers a comprehensive, adaptable, and flexible method to handle unique scenarios, making it a robust solution for sustainable building practices.

Life Cycle Impact Assessment (Inference Engine)

An inference engine that evaluates the environmental implications of a building throughout its life cycle. Environmental performance assessment focuses on embodied energy (energy used in the production of the building materials) and operational energy (energy used during the building's operation).

LCA Interface for Recommendation

Stakeholders can input or query different scenarios to the inference engine to see how changes might affect the life cycle impacts. The inference engine gives recommendations based on input or query to analyze various scenarios to help decision-making. The system provides a comprehensive analysis that enables users to accurately interpret the life cycle impacts of buildings. It allows for assessing different scenarios and helps make informed decisions to improve environmental and economic performance.

The LCA interface empowers stakeholders to input or query diverse scenarios into developed iKBS using an intelligent inference engine. Furthermore, the interface provides a detailed and comprehensive analysis of environmentally sustainable and efficient materials. The IKBS is a pivotal tool in driving eco-friendly viable building and infrastructure development practices.

Case Study

This case study focuses on analyzing the impact of renovation on the life cycle of an Irish semi-detached building. This study demonstrates the application of an Intelligent Knowledge-based System (iKBS) for detailed residential building LCA (Figure 3).

Intelligent Knowledge-based System Development

This case study aims to evaluate the environmental impact of existing Irish semi-detached typology and recommend the best materials and components for retrofits. The scope encompasses assessing embodied energy, operational en-

Table 1: Data knowledge requirement for Irish case study knowledge-base development

knowledge Requirement	Irish Case Study
Product/ Material Data A1- A3	ICE, Ecoinvent, TM65, Irish National Material database
Construction Stage Data A4- A5	ICE, Ecoinvent, TM65,Irish National Material database
Building Stock Data	Ireland BER database
Retrofit Data B2-B5	Irish Building Regulation, Irish Retrofit Scenarios
End-of-life Phase Data C1-C4	ICE, Ecoinvent, TM65, Irish National Material database
Building Typologies	Irish TABULA, EnergyPlus

ergy, and potential retrofitting options for energy efficiency improvement. The study targets policymakers, contractors, and homeowners to provide insights into sustainable building practices. The scope of this case study includes specifying the application, approach, data requirements, study period, functional unit, and system boundary.

The knowledge-based development phase involves an extensive collection and analysis of knowledge for the life cycle of buildings, focusing on the context of Ireland. This process uses a variety of sources, including the Irish Energy Performance Certificate (EPC) database, the Irish database for embodied energy and materials, the International ICE database, and retrofit scenarios data relevant to Ireland (Table 1).

The knowledge of building materials for constructing Irish houses encompasses stages A1-A5 or C1-C5, ranging from raw material production to end of life. This information is gathered from the Irish National Material Database, the ICE, Ecoinvent, and TM65 databases. (ICE, 2024; Ecoinvent, 2024). These databases contained embodied energy and carbon emissions associated with different materials that contribute to global warming and climate change and information related to the transportation of materials and the actual on-site construction processes (Table 1). The building stock knowledge component offers detailed information about existing houses in Ireland, including their age, construction materials, and build type. This knowledge is collected from the Irish EPC database of 1 million buildings. Retrofit scenarios encompass information about renovations to enhance building energy efficiency collected from existing retrofit schemes in Ireland nationally (Figure 3)(CAP, 2024).

The study used typologies of existing residential buildings in Ireland from the TABULA project. These typologies aid in evaluating the buildings' energy and water usage, focusing on the usage data generation. TABULA provides typological data for the 34 Irish dwelling types across 10 age bands. The Irish TABULA project also provides baseline knowledge for building elements, such as exterior walls, roofs, windows, and floors. The baseline knowledge helps to identify recommended retrofit scenarios for target buildings. This study uses the EnergyPlus simulation engine for energy and water consumption, as well as B6 and B7 usage data generation based on retrofit scenarios.

The integration of acquired Irish knowledge within the iKBS begins with a critical pre-processing stage designed to ensure the accuracy and consistency of the data. This foundational step is crucial for preparing the information for sophisticated analysis and decision-making processes. The iKBS integrates pre-processed data and typologies knowledge using Rule-Based, Case-Based, and Frame-Based systems for intelligent decision-making. These knowledge-based approaches, commonly used based on existing studies, are considered optimal for Knowledge-Based Systems (Santos et al., 2020; Zhao et al., 2019; Nazaruks and Osis, 2021). In this study, MongoDB is used for storing knowledge because of its ability to handle unstructured or semi-structured data. This system enables the evaluation of environmental impacts based on criteria such as material selection and energy efficiency.

The Rule-Based system is pivotal in identifying construction materials used in typology, considering various attributes such as layers, thickness, conductivity, and cost. The Frame-Based system facilitates the retrieval of all data in frames, simplifying interaction with the inference engine for estimating total embodied energy and U-values. This study also compares the embodied carbon of materi-

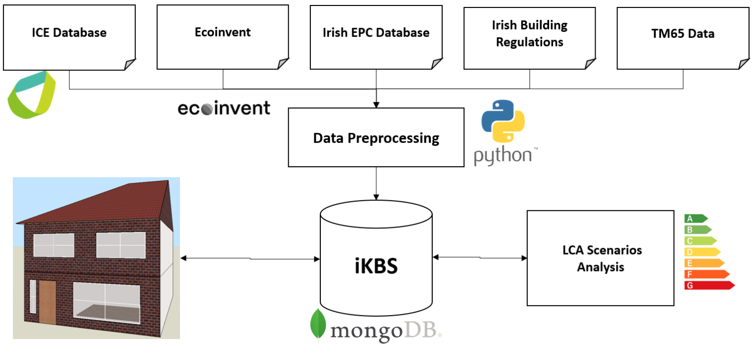

Figure 3: Irish case study knowledge-based development process diagram for LCA analysis

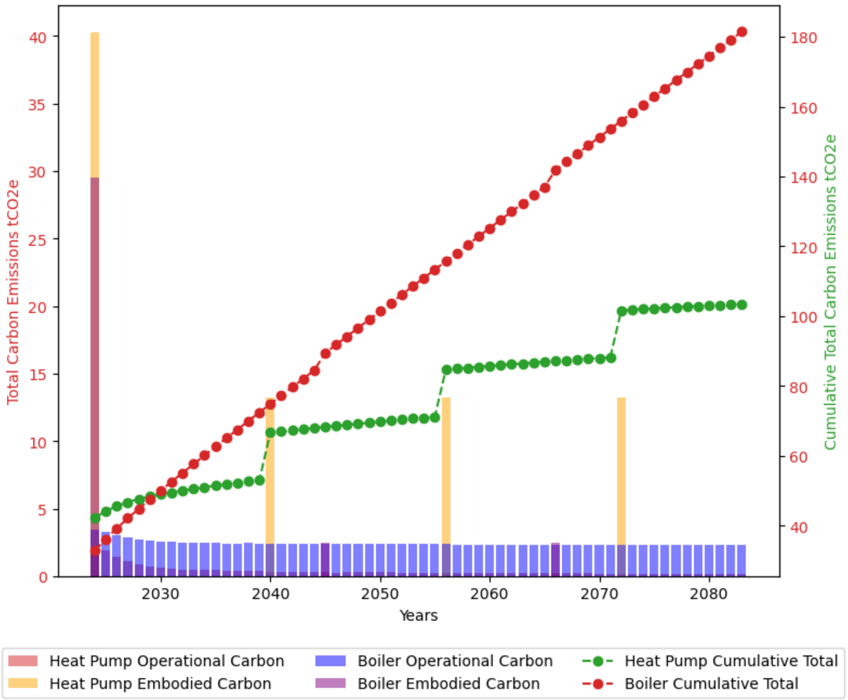

Figure 4: Long-Term impact of retrofitting measures on CO_2e emissions in semi-detached topology residential buildings: A 60-year lifecycle assessment

Table 2: Pre and post-retrofit scenarios for the semi-detached topology building for LCA analysis

	Pre-Retrofit	Post-Retrofit (Boiler)	Post-Retrofit (Heat Pump)
Wall U-value	0.6	0.21	0.21
Roof U-value	0.4	0.13	0.13
Floor U-value	0.64	0.21	0.21
Window U-value	3.1	1.6	1.6
Heating Efficiency/COP	0.7	0.9	3
EUI	290	148	78
Energy Rating	D2	B3	B1

als with those in the Irish material database and other available databases, such as ICE and Ecoinvent. The frame-based system organizes and stores data in a structured format known as frames, which facilitates the efficient retrieval and analysis of information related to construction materials.

Furthermore, the Case-Based system develops recommendations for stakeholders to find insulation materials with minimal embodied carbon. This system identifies similar cases using a fuzzy string-matching approach, helping to find materials by name or category. The fuzzy approach is the most robust in handling variations in input data and string matching, based on existing studies (Zhao et al., 2019). The case-based system uses historical knowledge of insulation materials to recommend options with minimal embodied carbon for new construction projects.

Overall, the hybrid approach is used in the inference engine to assess the environmental and economic impacts of the buildings. This integration offers a robust framework for intelligent decision-making, providing flexibility, adaptability, and comprehensive analysis. The system provides recommendations and a comprehensive analysis of existing and retrofit material, allowing users to explore various scenarios for improved environmental performance.

LCA for Semi-detached typology using iKBS

The case study of the semi-detached typology demonstrates how iKBS can lead to recommendations for materials with minimal embodied energy or operational energy for retrofitting. The typology of a semi-detached house built between 1983 and 1993 features cavity walls and pitched roofs with a floor area of 106.27 m^2. The pre-retrofit typology U-values are 0.6 $W/(m^2 \cdot K)$ for walls, 0.4 $W/(m^2 \cdot K)$ for roofs, and 0.64 $W/(m^2 \cdot K)$ for floors, with double-glazed, PVC-framed windows at 3.1 $W/(m^2 \cdot K)$, and a boiler efficiency of 70%, leading to an energy rating of D2 and a total Energy Use Intensity (EUI) of 290 $kWh/(m^2.yr)$. These figures indicate significant potential for improvement. The iKBS recommended various insulation materials based on their thermal conductivity and embodied energy values to enhance the U-values of the walls, roof, floor, and window (Table 2).

The iKBS recommends various insulation materials, including Extruded Polystyrene (XPS) and mineral wool, to improve the U-values of building structures such as walls, roofs, and floors. These recommendations based on Low thermal conductivity ensure that materials like XPS offer superior insulation performance, effectively reducing heat transfer through walls and floors. Furthermore, these materials enhance a building's energy efficiency and contribute to a more stable and comfortable indoor environment. On the other hand, mineral wool is highlighted for roof insulation due to excellent thermal resistance and ability to manage moisture, further optimizing the building's thermal performance. The iKBS aims to promote sustainable construction practices that minimize energy consumption and carbon footprint, aligning with broader environmental conservation efforts.

In this study, two heating system scenarios are considered for post-retrofit scenarios, such as employing a condensing boiler with 90% efficiency and an air source heat pump with a Coefficient of Performance (COP) of 3.0 (Table 2). The life cycle assessment of retrofitting measures in a semi-detached building, analyzed over a 60-year life span, highlights the significant environmental benefits of retrofitting despite initial increases in total CO_2 emissions due to embodied carbon from materials and heat pump installations (Figure 4). The analysis reveals a significant reduction in operational emissions post-retrofit when compared to both boiler and heat pump heating systems, validating the efficacy of retrofitting in reducing operational carbon.

Despite the initial environmental cost indicated by the surge in total emissions due to the heat pump (40 tCO_2e) and boiler installation (30 tCO_2e), the operational savings quickly compensate for these impacts, leading to a considerable reduction in the building's carbon footprint over the long term. The periodic accounting for the embodied emissions of heat pumps every 15 years and boilers every 20 years takes into account the replacement cycles of the equipment, underscoring the necessity of long-term sustainability planning.

Overall, the LCA demonstrates that retrofitting significantly contributes to environmental sustainability by lowering operational emissions, emphasizing the long-term benefits of such interventions in residential building management. Retrofitting with a boiler decreases the EUI from 290 to 149 $kWh/(m^2.yr)$, enhancing the energy rating from D2 to B3, with a 184 tCO_2e emission. Similarly, Retrofitting with a heat pump reduces the Energy Use Intensity (EUI) from 290 to 78 $kWh/(m^2.yr)$, upgrading the energy rating from D2 to B1 and resulting in a reduction of 90 tCO_2e emission.

This case study demonstrated the effective application of an iKBS in the context of Irish housing stock. The study provided valuable insights into sustainable building practices by integrating comprehensive data sources, highlighting areas for embodied energy efficiency improvements and potential retrofit options. The approach underscores the importance of detailed life cycle assessments in guiding sustainable decision-making in the building and construction sector.

The results show that iKBS enabled the quantification of energy and emissions savings with greater specificity, demonstrating significant improvements in energy use intensity and carbon emissions reductions through various retrofit scenarios. Traditional methods might not fully capture the nuanced impacts of different retrofit options due to complex interactions between various building materials, usage patterns, and lifecycle stages. This methodology offers a more dynamic and comprehensive tool for policymakers, urban planners, and researchers aiming to optimize residential renovations for sustainability and climate mitigation.

Conclusions

This study bridged a significant gap in Building LCA for residential renovations by integrating diverse data sources such as existing building stock data, residential typologies, retrofit scenarios, and building materials data into an intelligent Knowledge Base System (iKBS). This research has advanced the understanding of the environmental impacts of residential renovations. Knowledge-based system development represents a novel approach to assessing building life cycles, particularly in the national residential building stock context.

The comparative analysis of various KBS approaches, including rule-based, case-based, and frame-based systems, has provided valuable insights into operational and embodied energy aspects. This work is particularly noteworthy for contributing to eco-friendly renovation practices and advancing sustainable building methodologies. The findings of this study are a valuable resource for energy policymakers, urban planners, and researchers, offering a new and intelligent framework for promoting sustainable practices in the building sector.

Future work would expand the methodology's applicability by encompassing diverse geographic regions building typologies and retrofit scenarios thereby enhancing its utility and relevance. Furthermore, integrating emerging technologies such as machine learning and big data analytics could further refine the accuracy and efficiency of the LCA process. Collaborating with industry stakeholders and policymakers will be vital in implementing these advanced tools in practical scenarios. Finally, the ongoing evolution of this research can significantly contribute to the global effort to create sustainable and eco-friendly buildings.

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