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以 BIM 輔助室內裝修設計碳足跡評估的可視化方法

A BIM-based Visualization of Carbon Footprint Evaluation for Assisting Low Carbon Interior Design

虞佳文

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本論文係 虞佳文 (R09521616) 在國立臺灣大學土木工程學系電腦輔助工程組完成之碩士學位論文，於民國113年7月22日承下列考試委員審查通過及口試及格，特此證明。

The undersigned, appointed by the Department of Civil Engineering (Computer-Aided Engineering) Engineering on July 22nd, 2024 have examined a Master's Thesis entitled above presented by Jiawen Yu (R09521616) candidate and hereby certify that it is worthy of acceptance.

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中文摘要

隨著近年來建築物的能效逐步提高，相比於運營碳排，其隱含碳排逐漸受到更多的關注。室內裝修的碳排放屬於建築隱含碳排的一部分。與建築主結構的碳排放不同，室內裝修的碳排放會在建築物的生命周期內逐漸累積。因此，在設計階段進行室內裝修的碳足跡評估，有助於減少更新維護和廢棄處理階段裝修材料的碳排放，從而實現長期的可持續發展。然而，現有的 BIM-LCA 集成方法在進行生命周期評估時，存在耗時過長、給設計軟件帶來沉重負擔、數據互通性差等問題，且無法將評估結果反饋至設計軟件以輔助低碳室內設計。 為解決這些問題，本研究開發了一種基於 BIM 的碳足跡評估可視化方法，用於輔助低碳室內設計，並整合了台灣低碳建築聯盟提出的室內裝修分項工程碳足跡資料庫。研究中開發了三個插件，用於實現數據提取、整合與評估，並將結果反饋至 Revit 元件中進行 3D 可視化。本研究采用台糖沙崙智慧綠能循環住宅園區的示範屋作爲案例，將方法應用於示範屋的室内裝修碳足跡評估。結果表明，該方法能有效支持低碳室內設計決策，減少 BIM 和 LCA 數據提取與整合所需的時間，並提高 BIM 與 LCA 數據之間的互通性。

關鍵字:碳足跡、室內設計、視覺化、隱含碳、建築信息建模

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ABSTRACT

As buildings become more energy-efficient, embodied carbon has gained increasing attention. The carbon emissions of interior renovation are also included in the embodied carbon. Unlike the carbon emissions from the main structure, the carbon emissions from interior renovation accumulate over the building's lifecycle. Conducting a carbon footprint evaluation of interior renovation during the design stage is beneficial for reducing the carbon emissions of renovation materials during maintenance and disposal stages, achieving long-term sustainability. However, the existing BIM-LCA integrated approaches for life cycle assessment are time-consuming, prone to cause huge burden on design software, have poor data interoperability, and fail to transmit evaluation results back to the design software to assist low-carbon interior design. To address these problems, this study developed a BIM-based visualization of carbon footprint evaluation for assisting low carbon interior design, which integrates the carbon footprint database for interior renovation proposed by the Low Carbon Building Alliance in Taiwan. Three plugins were developed to achieve data extraction, integration, evaluation, feed back to Revit components and 3D visualization. Then the approach was applied in the demo house of the Taisugar Circular Village. The results showed that this approach efficiently supports low-carbon interior design decision-making, reduces the time required for BIM

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and LCA data extraction and integration, and improves interoperability between BIM and LCA data.

Keywords: Carbon footprint, Interior design, Visualization, Embodied carbon, BIM

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Chapter 1 Introduction

The United Nations Environment Programme (UNEP) highlighted in its latest 2022 Global Status Report for Buildings and Construction that the building sector accounts for 37% of global carbon emissions from operational energy and process-related activities (United Nations Environment Programme, 2022). The Operational energy-related carbon emissions, also known as operational carbon, arise from energy consumption during building use, such as heating, cooling, and lighting. The Process-related carbon emissions are associated with building material production, especially in interior design, and are part of embodied carbon, which also includes emissions from material extraction, transportation, installation, maintenance, and disposal (What Is Embodied Carbon?, n.d.).

In previous sustainable design cases, designers focused on reducing the environmental impact of buildings throughout their lifecycle by enhancing energy efficiency. It can effectively reduce operational carbon emissions. However, it has also led to an increased proportion of embodied carbon emissions (Liu et al., 2019). For high-energy-efficiency buildings, embodied carbon emissions can exceed operational carbon emissions, accounting for 50% to 90% of the total carbon emissions of buildings (Röck et al., 2020). Therefore, reducing embodied carbon emissions is a strategic and important approach to achieving net-zero goals, and effective evaluation of embodied carbon is the

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first step in reducing these emissions (Pan & Pan, 2018).

The extraction, transportation, production, installation, maintenance, and disposal of materials such as wall decorations, flooring, and ceilings in interior design generate embodied carbon emissions. However, interior renovation are highly favored by consumers because they can significantly enhance the usability and functionality of a building by updating and optimizing the internal structure and facilities of existing buildings. According to statistics from the Architecture and Building Research Institute of the Ministry of the Interior, R.O.C. (Taiwan) in 2002, with the annual housing transaction volume accounting for approximately 4% to 5% of all households, up to 44.3% of households undertook renovations, indicating that renovation is a more feasible and economical way for most families to meet their housing needs compared to purchasing new houses (住宅裝修市場規模推估方法之研究, 2020). Especially during the COVID-19 pandemic, to cope with the significant rise in housing prices and avoid the high costs associated with buying new houses, many families chose to improve their existing living spaces through interior design to enhance their quality of life (Boesel et al., 2021; De Bruijn et al., 2002). Another important reason for the high demand for interior renovation projects is their ability to effectively respond to changing household needs. For instance, during the COVID-19 pandemic, there was a significant increase in

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the demand for remote work and online learning, and interior renovation projects could meet this demand by transforming home office spaces and study areas (Boesel et al., 2021). In summary, with the rising cost of homeownership and the lifestyle changes brought about by the pandemic, the volume of interior renovation will increase significantly relative to new construction. It will further highlight their importance. Therefore, the embodied carbon emissions of interior design should not be overlooked, they are crucial for achieving more sustainable building practices.

In the cradle-to-gate life cycle of buildings, the embodied carbon of interior renovation accounts for 4% to 22% of the total embodied carbon of buildings. Buildings with larger wall, floor, and ceiling areas have a higher proportion of embodied carbon from interior renovation (*Embodied Carbon Primer*, n.d.). Although the opportunities for reducing the embodied carbon of interior renovation are not as significant as those for the main structure of buildings, the lifespan of interior renovation depends on actual use and maintenance and is usually shorter. For example, in Taiwan, the maximum lifespan of general construction projects is 60 years, while the maximum lifespan of interior renovation is 20 years, meaning that interior renovation can lead to multiple carbon emissions over the building's entire life cycle (Lin, 2018). However, most studies in the field of building embodied carbon today focus only on the carbon emissions of the main

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structure and ignore those of interior renovation (Ashour et al., 2022). This will leads to inaccurate evaluation results of total building carbon, and causing designers to miss opportunities for carbon reduction in interior design.

From another perspective, the renovation of existing buildings has been recognized as a major strategy to reduce the environmental impact associated with construction. Under the influence of government principles advocating reuse and renovation over demolition and new construction, the number of future building renovation projects is bound to increase. Studies have shown that in the same building case, the global warming potential of concrete materials is highest in new construction scenarios, at 38%, while in renovation scenarios, the global warming potential of finishes (including exterior and interior) is highest, at 40% (Hasik et al., 2019). Therefore, the environmental impact of interior renovation will become increasingly significant over time. However, the predominant focus on new construction in most studies of building environmental impact often leads to the oversight of the environmental impact associated with interior renovation in existing buildings (Cabeza et al., 2014). This can result in a biased analysis of a building's environmental impact, causing the long-term environmental effects of the building to be underestimated, which in turn affects long-term sustainability. Thus, incorporating embodied carbon evaluation of interior renovation in the design stage is

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essential.

To address these research gaps, this paper aims to develop a BIM-based visualization of carbon footprint evaluation for assisting low carbon interior design. The objectives of this paper are: (1) to efficiently conduct embodied carbon evaluation for interior design, providing accurate data support for low-carbon interior design decision making; (2) to identify key factors contributing to embodied carbon in interior design for both new construction and renovation of buildings, and to quantify the impact of different interior materials on total carbon emissions through the development of a visualization tool; (3) to offer customized recommendations for low-carbon alternative material selection to interior designers, reducing potential risks that may affect long-term sustainability at the early stages.

Chapter 2 Literature review

2.1 Existing BIM-LCA Approaches and Their Shortcomings

Life Cycle Assessment (LCA) is one of the most suitable methods for analyzing the environmental impact of buildings throughout their entire life cycle (Guinee, 2002; Meex et al., 2018; Lin, 2018). However, the application of LCA in buildings commonly has time consumption, lack of databases, information management, and data interoperability

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issues (Yang et al., 2018).

Building Information Modeling (BIM) has a quantity takeoff function which allows it to effectively integrate and manage the complex data throughout the building lifecycle. And reduces the time and effort required by LCA practitioners for extensive manual input. This has led to an increasing number of researchers attempting to integrate LCA and BIM to assess the embodied environmental impacts of buildings (Cavalliere et al., 2019; Gan et al., 2018; Hollberg et al., 2020; Lai et al., 2023; Nwodo & Anumba, 2019; Santos et al., 2019; Soust-Verdaguer et al., 2018).

Tam et al. (2022) categorized existing BIM-LCA integration approaches into five types: (1) Export the bill of quantities from the BIM model, combine it with environmental impact factors of building components and materials, and conduct the assessment in Excel to obtain results; (2) Export the bill of quantities from the BIM model, integrate it with LCI data (Life Cycle Inventory) from external LCA tools, and conduct the assessment in these external tools to obtain results; (3) Install an LCA plugin containing LCI data within the BIM environment, and conduct the assessment within the plugin to obtain results; (4) Export the bill of quantities from the BIM model, combine it with environmental impact factors of building components and materials, and conduct the assessment in a visual programming environment to obtain results; (5) Integrate LCA data

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into the BIM objects and conduct the assessment within the BIM environment using the Industry Foundation Classes (IFC) format to obtain results. By evaluating these approaches' performances, such as the quality of extracted BIM materials' data and LCA data, the time consumption of assessment, the automation degree of assessment, the operational complexity of assessment, and the skill threshold for practitioners, Tam et al. (2022) considered that the first approach has significant shortcomings in terms of automation, the second approach has notable shortcomings in data quality and operational complexity, and the fifth approach has clear drawbacks in assessment time and technical threshold. In contrast, the third and fourth approaches are the best integration approaches in the detailed design stage. And the fourth approach is the best in the early and construction design stage. However, the representative plugin for the third approach, Tally, is considered to have missing LCA data (Najjar et al., 2017; Schultz et al., 2016). Materials that are either not evaluated or only partially assessed may lead to an underestimation or overestimation of the building's environmental impact, resulting in inaccurate LCA evaluation outcomes. And the fourth approach tends to place huge burden on Revit software (Tam et al., 2023). This is because Dynamo is a visual programming tool outside Autodesk Revit, and unlike the Revit API, it is not built into Revit. This lack of integration with Revit's core functionality can cause delays and resource consumption due to intermediate layers, and prevents direct access to and manipulation of Revit data,

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leading to performance overheads associated with data conversion and processing (Bulchandani, 2024). Moreover, as a node-based graphical programming tool, Dynamo often lacks the flexibility and control necessary for handling complex logic, such as the data extraction, integration, and calculation involved in LCA (*Powerful Features That Differentiate Revit API and Dynamo | eLogicTech Blog*, n.d.). Therefore, compared to Dynamo, the Revit API is more suitable for developing LCA-related tools.

Data interoperability issues, such as missing components when importing models from the BIM environment to the LCA environment, differences in data formats and units between BIM and LCA environments, are commonly occurring in these BIM-LCA integration approaches.

In addition, none of the above five integration approaches have returned the LCA results to the Revit components as parameters. In fact, returning results to Revit not only allows designers access these data directly for efficient design optimization, but also provides an opportunity for visualization of evaluation results. Therefore, it is worth researching whether there are new BIM-LCA integration methods that can improve or solve the problems mentioned above.

2.2 Local Carbon Footprint Evaluation System for Interior

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Renovation

When conducting a carbon evaluation for interior renovation during the design stage, the reliability, completeness, geographical relevance, and technical relevance of the data in the LCA database (British Standards Institution [BSI], 2011) can directly affect the credibility of the assessment results. And it is necessary for LCA practitioners to confirm that the evaluation approach complies with the Carbon Footprint Product Category Rules (CFP-PCR) and its boundaries suitable for the building location before proceeding with the evaluation. Since the CFP-PCR boundaries for building inventories in different countries may vary due to differing environmental policies, building standards, and specific carbon inventory requirements.

To facilitate LCA practitioners in conducting carbon footprint evaluation of interior renovation, the Low Carbon Building Alliance (LCBA) in Taiwan applied to the Ministry of Environment for approval of the interior renovation CFP-PCR in 2017 (Lin, 2018), and established a sub-divisional work carbon footprint database specifically for the interior renovation. This database includes carbon emission data obtained from the materials, construction techniques, and equipment used in sub-divisional works. It is known for its high data quality and clear boundary settings, as well as ensuring the accuracy and credibility of the assessment results. And it is suitable for Taiwan's interior renovation

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CFP-PCR and boundaries (Lin, 2018).

The Interior Renovation Carbon Footprint Evaluation System (ICF System) is an assessment tool also proposed by the Low Carbon Building Alliance in Taiwan, focusing on the carbon reduction benefits of interior renovation design. This system is supported by data from the sub-divisional work carbon footprint database specifically for the interior renovation. It covers five sub-divisional works: partition walls, wall finishes, floor finishes, ceiling finishes, and fixed cabinets. Among them, 'partition walls' refers to newly added partition walls in interior renovation, including screens and partitions, but excluding RC walls, masonry walls, lightweight grouting walls, and existing walls and screen structures. 'Wall finishes' refers to newly added surface finishes fixed to the aforementioned newly added partition walls or existing wall and screen structures in interior renovation, excluding movable objects. 'Floor finishes' refers to finishes newly fixed to the floor structure in interior renovation, and also excludes movable objects. 'Ceiling finishes' refers to finishes newly fixed to the ceiling structure in interior renovation, excluding water and electrical piping, lighting fixtures, chandeliers, and other objects. 'Fixed cabinets' refers to cabinets newly fixed to walls or floors in interior renovation, excluding movable furniture (Lin, 2018). Its assessment includes the carbon footprint of materials and the carbon footprint during the construction process, the repair

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and maintenance process, and the end of life disposal process. The following are the calculation formulas for the evaluation model of this system (Fig. 2. 1):

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- **New Construction Phase Materials and Construction Carbon Footprint ($kgCO_2e$)** :
  $CFmc = CFwc + CFf + CFwd + CFc + CFff$
  - Partition Wall ($kgCO_2e$) :
    $CFwc = \sum CFwci \times Awci$
  - Floor Finishes ($kgCO_2e$) :
    $CFf = \sum CFfi \times Afi$
  - Wall Finishes ($kgCO_2e$) :
    $CFwd = \sum CFwdi \times Awdi$
  - Ceiling Finishes ($kgCO_2e$) :
    $CFc = \sum CFci \times Aci$
  - Cabinets ($kgCO_2e$) :
    - General Panel Cabinets:
      $CFff = \sum (\sum CFBij \times ABij \times Muij + \sum CFDij \times ADij + \sum CFTij \times ATij + \sum CFSij \times ASij)$
    - Metal Tube Cabinets:
      $CFff = \sum (\sum CFBij \times ABij \times Muij)$
- **Renovation and Update Phase Materials and Construction Carbon Footprint ($kgCO_2e$)** :
  $CFrm = \sum CFwdi \times Awdi \times RTwdi + \sum CFfi \times Afi \times RTfi + \sum CFci \times Aci \times RTci + \sum (\sum CFBij \times ABij \times Muij + \sum CFDij \times ADij + \sum CFTij \times ATij + \sum CFSij \times ASij) \times RTbi$
  - Partition Wall ($kgCO_2e$) :
    Due to the durability of partition walls exceeding the entire lifecycle of interior renovation, they are not considered.
  - Wall Finishes ($kgCO_2e$) :
    $\sum CFwdi * Awdi * RTwdi$
  - Floor Finishes ($kgCO_2e$) :
    $\sum CFfi * Afi * RTfi$
  - Ceiling Finishes ($kgCO_2e$) :
    $\sum CFci * Aci * RTci$
  - Cabinets ($kgCO_2e$) :
    - General Panel Cabinets:
      $\sum (\sum CFBij \times ABij \times Muij + \sum CFDij \times ADij + \sum CFTij \times ATij + \sum CFSij \times ASij) \times RTbi$
    - Metal Tube Cabinets:
      Exempt from calculation
- **Demolition Waste Phase Carbon Footprint ($kgCO_2e$)** :
  $CFwr = Wwc + Wwd + Wf + Wc + Wff$
  - Partition Wall ($kgCO_2e$) :
    $Wwc = \sum WDwci \times Awci$
  - Wall Finishes ($kgCO_2e$) :
    $Wwd = \sum WDwdi \times Awdi \times (1 + RTwdi)$
  - Floor Finishes ($kgCO_2e$) :
    $Wf = \sum WDfi \times Afi \times (1 + RTfi)$
  - Ceiling Finishes ($kgCO_2e$) :
    $Wc = \sum WDci \times Aci \times (1 + RTci)$
  - Cabinets ($kgCO_2e$) :
    - General Panel Cabinets:
      $Wff = \sum (\sum WDbij \times ABij \times Muij + \sum WDdij \times ADij + \sum WDtij \times ATij + \sum WDsij \times ASij) \times (1 + RTbi)$
    - Metal Tube Cabinets:
      $Wff = \sum (\sum WDbij \times ABij \times Muij)$

(a) The carbon footprint calculation formula of the sub-divisional works

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- **Total Carbon Footprint of Interior Renovation throughout the Life Cycle ($kgCO_2e$):**
  TCF = CFmc + CFrm + CFwr
- **Design Project Carbon Footprint Indicator ($kgCO_2e$ / m^2. yr):**
  CFI = TCF ÷ AI ÷ LC
- **Benchmark Project Carbon Footprint Indicator ($kgCO_2e$ / m^2. yr):**
  CFI' = TCF' ÷ AI ÷ LC
- **Design Project Carbon Footprint Reduction Percentage:**
  CFR = (CFI - CFI') ÷ CFI'

CFwci: The Materials and Construction Carbon Footprint Density of Partition Wall i
CFwdi: The Materials and Construction Carbon Footprint Density of Wall i
CFfi: The Materials and Construction Carbon Footprint Density of Floor i
CFci: The Materials and Construction Carbon Footprint Density of Ceiling i
Awci: The Area of Partition Wall i
Afi: The Area of Floor i
Awdi: The Area of Wall i
Aci: The Area of Ceiling i
CFBij: Cabinet i Body j Material and Construction Carbon Footprint Density
CFDij: Cabinet i Door j Material and Construction Carbon Footprint Density
CFTij: Cabinet i Countertop j Material and Construction Carbon Footprint Density
CFSij: Cabinet i Panel j Material and Construction Carbon Footprint Density
ABij: Cabinet i Body j Elevation Area
ADij: Cabinet i Door j Area
ATij: Cabinet i Countertop j Area
ASij: Cabinet i Panel j Area
Muij: Cabinet i Body j Material Ratio
RTwdi: The Life Cycle Update Standard of Wall Finishes i
RTfi: The Life Cycle Update Standard of Floor Finishes i
RTci: The Life Cycle Update Standard of Ceiling Finishes
RTbi: The Life Cycle Update Standard of Cabinet i Body Finishes
WDwci: The Disposal Carbon Footprint Density of Partition Wall i
WDwdi: The Disposal Carbon Footprint Density of Wall i
WDfi: The Disposal Carbon Footprint Density of Floor i
WDci: The Disposal Carbon Footprint Density of Ceiling i
WDbij: The Disposal Carbon Footprint Density of Cabinet i Body j
WDdij: The Disposal Carbon Footprint Density of Cabinet i Door j
WDtij: The Disposal Carbon Footprint Density of Cabinet i Countertop j
WDsij: The Disposal Carbon Footprint Density of Cabinet i Panel j
AI: Total Floor Area of Interior Renovation Projects
LC: The Life Cycle Standard of Interior Renovation

(b) Main evaluation formulas and variables

Fig. 2. 1 Formulas and variables in the ICF system calculation model.

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In the above formulas, apart from the area of various building components and the material ratio of cabinet bodies, which need to be extracted from the revit model. The carbon footprint density, the life cycle update standard for sub-divisional works, and the life cycle standard of interior renovation can all be obtained by querying the database.

The carbon footprint density in the database includes design and its baseline two parts. The carbon footprint density of the design case component depends on the material usage information in the actual sub-divisional work design of the Revit model, while the carbon footprint density of the baseline case component is based on the most commonly used or representative materials in the sub-divisional work. The carbon footprint density of the baseline case refers to the benchmark for the design case. During the assessment process, these data are used to calculate the carbon footprint indicators of the baseline and design cases, as well as the carbon reduction percentage of the design case.

The ICF system divides buildings into 3 types: buildings with high deterioration rate, buildings with medium deterioration rate, and buildings with low deterioration rate, and set the life cycle standard for them respectively in 5, 10, and 20 years. These standards have gained industry consensus, and are part of the interior renovation CFP-PCR rules. Based on this, the ICF system has calculated corresponding sub-divisional work update standards for these three types of buildings, which are incorporated into the ICF

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calculation model during the assessment process to obtain the total carbon footprint of the interior renovation throughout the life cycle and the carbon reduction percentage of the design case (*低碳建築聯盟 LCBA (Low Carbon Building Alliance)*, n.d.; Lin, 2018).

Although the ICF System complies with Taiwan's interior renovation CFP-PCR and its boundaries, and the data used in the assessment process are reliable, complete, geographically relevant, and technically relevant, the calculation method is manual. Since the ICF system's calculation process involves extensive data collection, organization, and analysis, manually assess the carbon footprint can lead to time consuming and human errors.

2.3 The Presentation Format of the LCA Results

According to the content of the ICF System, its evaluation results only provide the total carbon footprint of the interior renovation throughout the life cycle (TCF) and the carbon reduction percentage of the design case (CFR). Although these data can be used for the rating of low-carbon interior renovation design (*低碳建築聯盟 LCBA (Low Carbon Building Alliance)*, n.d..; Lin, 2018), they cannot directly assist designers in decision-making during the actual design process. Designers often need more detailed and intuitive results, such as 3D visualization, to consider carbon emissions when

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selecting materials.

In previous research, the results of building life cycle assessments were normally presented in the form of data and graphs (Asare et al., 2020; Najjar et al., 2019; Xu et al., 2022). In contrast, presenting the LCA results in 3D content creation suites outside of the design platform Autodesk Revit was relatively less common (Kulahcioglu et al., 2012). And there are only one study added the evaluation results to the building component properties and presented the results in 3D visualization in Autodesk Revit (van Eldik et al., 2020). However, this method is only applicable to the environmental impact assessments in infrastructure design projects and cannot be directly used for carbon footprint evaluation of interior renovation in Taiwan.

The LCA results in previous research were typically presented in the form of data and graphs because visualizing LCA results generally requires very detailed and comprehensive data, including environmental impact baseline for each building component. However, since different components serve various functions and purposes within a building, obtaining and integrating this data to support fair and accurate comparisons is often highly complex. For example, while data and graphs can be used to compare the carbon emissions of certain types of building components, visualizing these results would require carbon emission data for each component. Although this data can

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be easily obtained, the components' different roles, such as load-bearing, insulation, and waterproofing, require varying requirements for material strength, durability, and cost. Directly comparing their embodied carbon emissions might overlook these functional differences, leading to unfair comparisons. Furthermore, visualizing LCA results also needs linking this data to specific building model components, which presents technical challenges and requires advanced programming skills. Therefore, while LCA result visualization is theoretically feasible, it is relatively difficult to implement in practice, which has led most past research to rely on data and graphs for presenting LCA outcomes.

A number of points can be derived from this review. First, the manual calculation model proposed by the ICF System, which meets the CFR-PCR standards for interior renovation, is time-consuming and prone to errors, emphasizing the need for a more automated approach. Second, though the BIM-LCA integration approach using the visual programming language environments shows promise, it places a heavy burden on Revit. This highlights the potential of Revit API for tool development to enhance stability. Third, existing BIM-LCA integration methods often face data interoperability issues, which similarly affect the carbon footprint evaluation of interior design. This presents the necessity for improved data management solutions. Lastly, there is a distinct lack of studies that integrate LCA results back into Revit components for visualization, which

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limits the ability to use these results in practical design optimization. Therefore, this study proposes a BIM-based visualization of carbon footprint evaluation for assisting low carbon interior design by providing accurate, actionable data to support effective decision-making and long-term sustainability.

Chapter 3 Methods

This study aims to accurately evaluate the embodied carbon emissions in the interior design through a BIM-based visualization for carbon footprint evaluation, providing reliable data, charts, and 3D visualization support for low-carbon interior design decision-making. Through this approach, interior designers can not only efficiently identify carbon hotspots in new construction and renovation interior design, including the sub-items of interior renovation sub-divisional works and the materials used for components in the interior renovation, but also gain a clear understanding of the impact of different sub-divisional works on the total carbon emissions across various life cycle phases. Consequently, this approach offers customized recommendations for low-carbon alternative materials to support low-carbon design.

To achieve these objectives, this study developed a systematic approach comprising six main modules (Fig. 3. 1): (1) LCA data preparation, (2) BIM data extraction, (3) BIM

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and LCA data integration, (4) Interior Design Carbon Footprint Evaluation and Analysis, and Low-Carbon Design Alternatives Customization, (5) Carbon footprint evaluation data feedback, and (6) Carbon footprint evaluation data visualization. These modules are closely integrated, forming a comprehensive and effective process for assessing and reducing embodied carbon emissions in interior design. The following sections will provide a detailed description of the functionality and implementation of each module, and explain how they collectively support the core objectives of this study.

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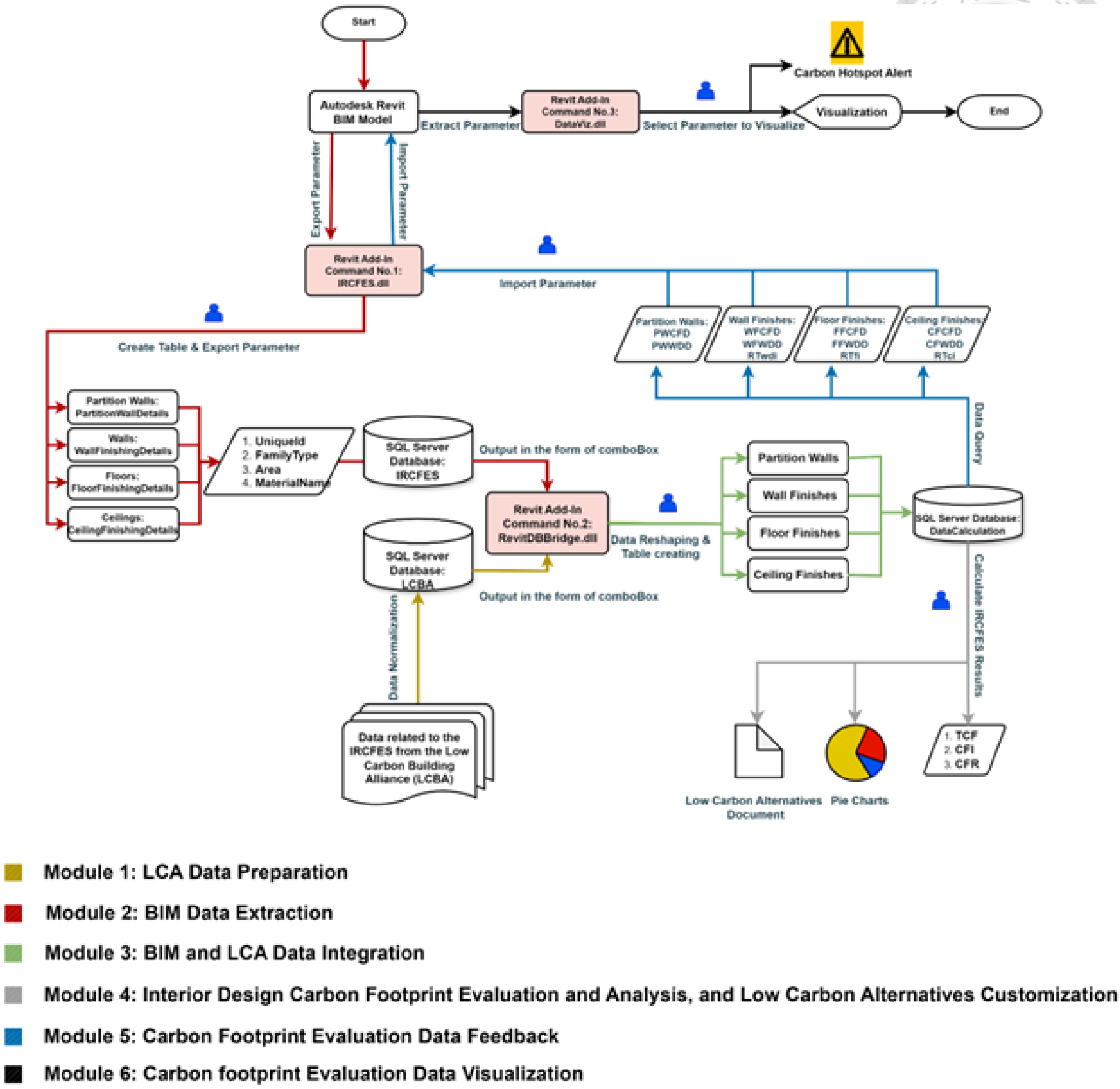

Fig. 3. 1 Flowchart of the developed systematic approach.

3.1 Module 1: LCA Data Preparation

First, to support the integration of BIM and LCA data, the sub-divisional work carbon footprint database for interior renovation proposed by LCBA was normalized. This process involved restructuring and optimizing the data using Microsoft SQL Server,

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creating a more digitized and structured database to ensure data integrity and consistency, to enhance the efficiency of subsequent queries and analyses.

Although the database provided by LCBA offers fundamental data on carbon footprint density and lifecycle standards, its primary presentation in paper-based tables (LCBA Taiwan Low Carbon Building Alliance, n.d.; Lin, 2018). And the limitations in data organization and querying (Fig. 3. 2) often lead to complexities and risks of errors in the querying process. To address these issues, this study applied normalization to the original data, transforming it into a structured and easily manageable digital format.

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The sub-item is transitively dependent on the sub-divisional work

Sub-divisional Works	Sub-items of the Sub-divisional Works		Building with high deterioration rate		Building with medium deterioration rate		Building with low deterioration rate	
The Life Cycle Standard of Interior Renovation Projects LCi (yrs)			5		10		20	
The Life Cycle Standard of Subdivisional Work LCi and The Life Cycle Update Standard of Subdivisional Work RTi			LCi	RTi	LCi	RTi	LCi	RTi
1. Partition Wall (Only the newly added partition walls in the renovation are calculated; existing structural partitions are excluded. Finishes on partition walls are counted separately under interior wall finishes.)			5	0	10	0	20	0
2. Wall Finishes	Wall Finishes (Exclude base cement mortar plastering)	Wallpaper (Well-Ventilated Environment)	5	0	10	0	10	1
		Wallpaper (Humid Environment)	2.5	1	5	1	5	3
		Paint (Well-Ventilated Environment)	5	0	10	0	10	1
		Paint (Humid Environment)	2.5	1	5	1	5	3
		Wood and Bamboo Paneling (Well-Ventilated Environment)	5	0	10	0	20	0
		Wood and Bamboo Paneling (Humid Environment)	2.5	1	5	1	10	1
		Cement, Ceramic Tile, Stone, Metal, Glass Panel	5	0	10	0	20	0
3. Floor Finishes	Grass, Bamboo, Carpet, Plastic (Well-Ventilated Environment)		2.5	1	5	1	10	1
	Grass, Bamboo, Carpet, Plastic (Humid Environment)		2.5	1	2.5	3	5	3
	Cork Board (Well-Ventilated Environment)		5	0	10	0	20	0
	Cork Board (Humid Environment)		2.5	1	5	1	10	1
	PU, Epoxy Resin, Hardwood Board and Other Flooring Material PU、Epoxy		5	0	10	0	20	0
	Cement, Ceramic Tile, Stone, Metal, Glass Panel		5	0	10	0	20	0
4. Ceiling Finishes	Wallpaper (Well-Ventilated Environment)		5	0	10	0	10	1
	Wallpaper (Humid Environment)		2.5	1	5	1	5	3
	Paint (Well-Ventilated Environment)		5	0	10	0	10	1
	Paint (Humid Environment)		2.5	1	5	1	5	3
	Wood and Bamboo Paneling (Well-Ventilated Environment)		5	0	10	0	20	0
	Wood and Bamboo Paneling (Humid Environment)		2.5	1	5	1	10	1
	Metal and Glass Panel		5	0	10	0	20	0

Data is not atomic. It includes 2 values: the sub-item of the sub-divisional work and the environmental type

If we assume sub-divisional work and sub-item as a composite primary key, the LCi and RTi values in Buildings with high/medium/low deterioration rates depend on the building types and the specific sub-items, rather than the composite primary key.

Fig. 3. 2 The lifecycle and update standard table for interior renovation subdivisional works.

This process was based on the three normal forms of data normalization (Fong & Wong Ting Yan, 2021), aiming to eliminate data redundancy, ensure data integrity and consistency, and simplify the interdependencies between data. As a result, an optimized sub-divisional work carbon footprint database for interior renovation was established, consisting of 19 simplified tables linked by primary or foreign key relationships (Fig. 3. 3). This database can effectively supports the efficient integration of BIM and LCA data,

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providing the RevitDBBridge.dll plugin with a streamlined, efficient, and reliable querying capability.

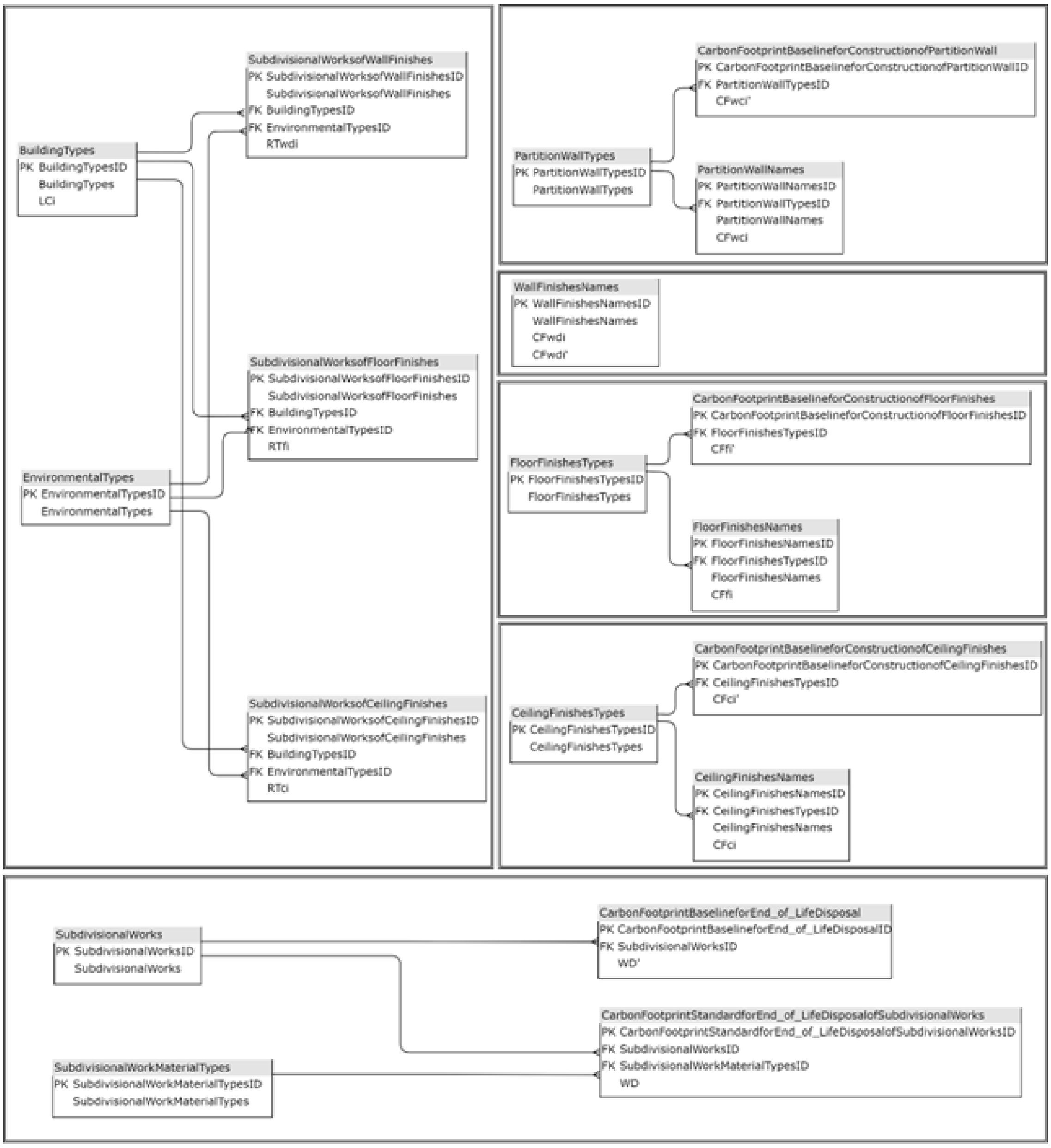

Fig. 3. 3 The relationship diagram of database LCBA.

3.2 Module 2: BIM data extraction

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Subsequently, to achieve effective integration of BIM and LCA data, this study developed a plugin named IRCFES.dll (Fig. 3. 4), designed to automatically extract BIM data from Revit models. This data includes each component's unique identifier (GUID), family type, material name, and area (with units: m^2). The extracted data is stored in a dedicated database, IRCFES, to support subsequent carbon footprint evaluation and analysis.

The carbon footprint evaluation approach developed in this study focuses on four sub-divisional works: partition walls, wall finishes, floor finishes, and ceiling finishes. This focus was chosen because many users now prefer to purchase prefabricated cabinets from furniture stores rather than custom-making them during renovation. This means that the carbon footprint from the production, transportation, and installation of fixed cabinets should be categorized under furniture, not interior renovation. Therefore, the approach excludes fixed cabinet carbon footprint calculations from the interior renovation evaluation. Instead, it focuses on the fixed components that are integral to the interior renovation process, ensuring accuracy and relevance in the evaluation. The IRCFES.dll plugin automatically extracts and organizes the BIM data required for evaluation. This information not only supports the precise matching of LCA data in the carbon footprint evaluation but also enhances data transparency and traceability in the design process.

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Through a systematic data processing approach, this study ensures that the extracted BIM data is highly complete and consistent. The retention of the GUID in the extracted BIM data enhances cross-platform compatibility and supports the precise linkage of subsequent evaluation results to BIM model components (van Eldik et al., 2020). The combination of family type and material name provides detailed descriptions of the components' structure, type, and specific material composition, facilitating the association of LCA data in the carbon footprint evaluation with specific elements. The area data directly supplies the necessary input for the partition wall, wall finish, floor and ceiling areas in the carbon footprint evaluation. To ensure the accuracy and precision of the data, the IRCFES.dll plugin imposes strict controls on the data extraction process, to make sure that each piece of data accurately reflects the actual design in the Revit model.

Moreover, considering that partition walls and wall finishes are both categorized under the wall category (OST_Walls) in Revit models, this method incorporates a filtering condition based on the component parameter ‘Coarse Scale Fill Pattern’ during the export of partition wall data, to accurately identify partition wall components (Fig. 3. 5). This approach not only improves the accuracy of data extraction but also ensures that carbon footprint evaluations in complex modeling environments are based on correct data inputs.

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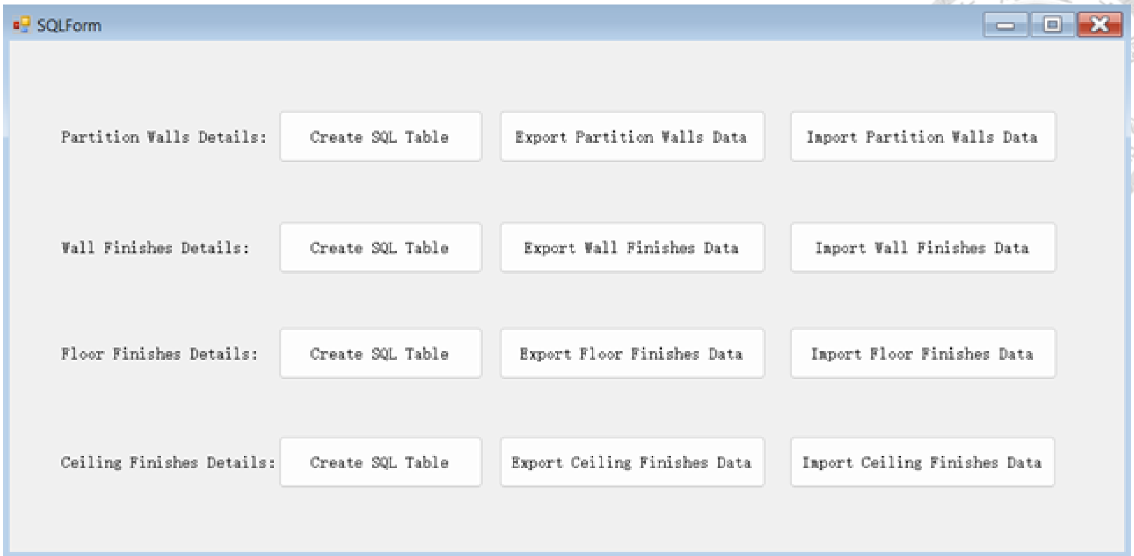

Fig. 3. 4 The relationship diagram of database LCBA.

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```
// Export partition wall data
private void btnExportPWData_Click(object sender, EventArgs e)
{
    IList<Element> partitionwalls = new FilteredElementCollector(Doc)
        .OfCategory(BuiltInCategory.OST_Walls)
        .WhereElementIsNotElementType()
        .ToElements();

    string setQuery = "INSERT INTO PartitionWallDetails(UniqueId, FamilyType, Area, MaterialName)" +
        " VALUES(@param1, @param2, @param3, @param4)";

    foreach (Element ele in partitionwalls)
    {
        // Get Coarse Scale Fill Pattern
        Parameter coarseScaleFillPattern = Doc.GetElement(ele.GetTypeId())
            ?.LookupParameter("Coarse Scale Fill Pattern");
        if (coarseScaleFillPattern != null)
        {
            string fillPatternValue = coarseScaleFillPattern.AsValueString();
            if (fillPatternValue.Contains("隔間牆") || fillPatternValue.Contains("分間墙") ||
                fillPatternValue.Contains("Partition wall") ||
                fillPatternValue.Contains("PartitionWall") ||
                fillPatternValue.Contains("Partition Wall"))
            {
                string area = ele.LookupParameter("Area").AsValueString();
                ICollection<ElementId> materialIds = ele.GetMaterialIds(false);
                string mName = "";

                foreach (ElementId materialId in materialIds)
                {
                    Material material = Doc.GetElement(materialId) as Material;
                    if (material != null)
                    {
                        mName = material.Name;
                    }
                    break;
                }

                using (SqlCommand command = sqlConnection.Query(setQuery))
                {
                    try
                    {
                        command.Parameters.AddWithValue("@param1", ele.UniqueId);
                        command.Parameters.AddWithValue("@param2", ele.Name);
                        command.Parameters.AddWithValue("@param3", area);
                        command.Parameters.AddWithValue("@param4", mName);
                        command.ExecuteNonQuery();
                    }
                    catch (Exception ex)
                    {
                        TaskDialog.Show("SQL Insert Error", ex.ToString());
                    }
                }
            }
        }
    }

    TaskDialog.Show("Partition Wall Details Export", "Partition Wall Details added!");
}
```

Fig. 3. 5 The code for exporting partition wall data.

3.3 Module 3: BIM and LCA Data Integration

To achieve effective integration of BIM and LCA data, this study developed the

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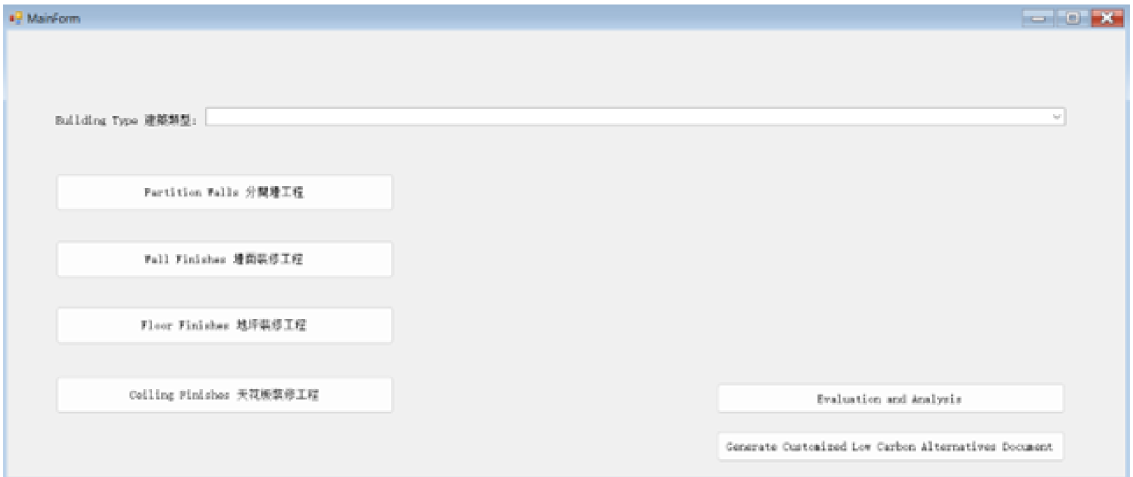
RevitDBBridge.dll plugin, which assists users in establishing the connections between BIM data and LCA data during the interior renovation carbon footprint evaluation process. The plugin's user interface consists of a main interface and four sub-interfaces, corresponding to the four sub-divisional works: partition walls, wall finishes, floor finishes, and ceiling finishes (Fig. 3. 6). Through these interfaces, users can easily select the BIM component material information that needs to be linked, along with the corresponding material names, categories, sub-items of interior renovation sub-divisional works, building types, and environmental types from the LCBA database. The system will then automatically query and rapidly integrate the relevant BIM and LCA data.



(a) Main interface

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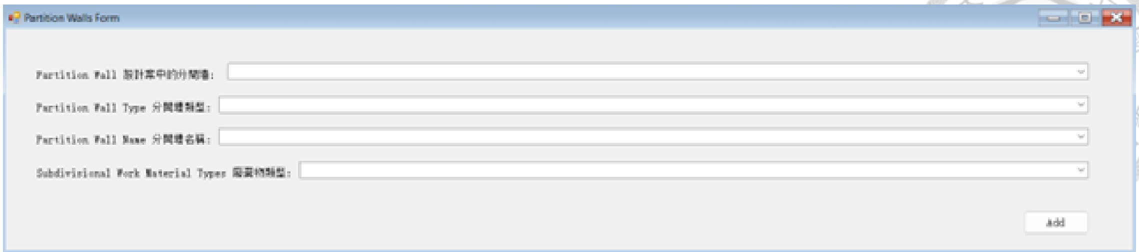
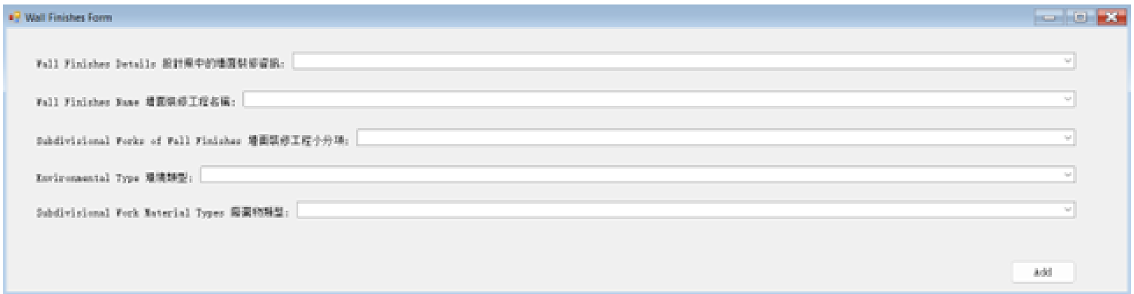
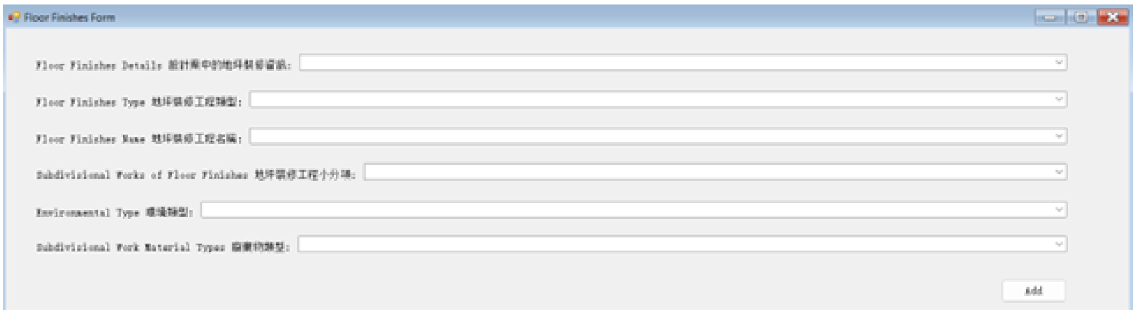


(b) Partition walls interface



(c) Wall finishes interface



(d) Floor finishes interface

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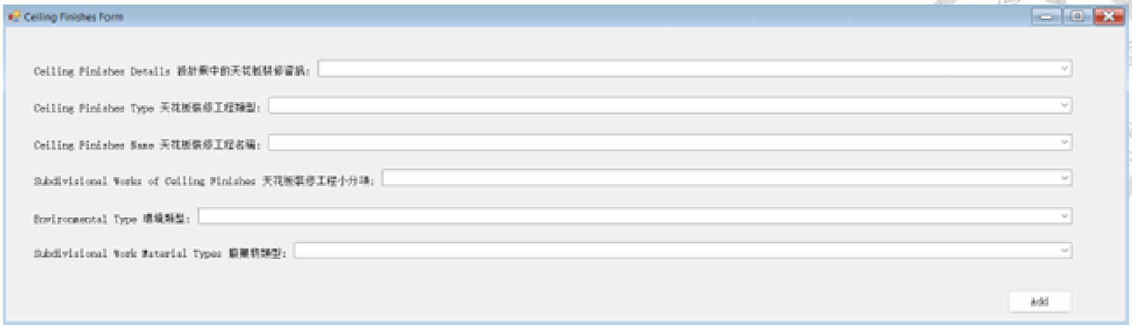

(e) Ceiling finishes interface

Fig. 3. 6 The user Interfaces of RevitDBBridge plugin.

During the data integration process, the main interface provides a function to select the building type. Users can choose the corresponding building type from the LCBA database via a dropdown menu. The plugin automatically retrieves the building type ID and lifecycle standard (LCi) and utilizes this information in subsequent carbon footprint evaluations. The four sub-divisional work selection buttons allow users to access the corresponding sub-interfaces. In these sub-interfaces, the plugin automatically extracts the relevant LCA data from the LCBA database based on the user's selection, including carbon footprint density, the baseline of the carbon footprint density, and the lifecycle update standards for the sub-items of interior renovation sub-divisional works (except for partition walls, which do not have this standard). These data are then integrated with the corresponding BIM component information to calculate the difference between each component's carbon footprint density and its baseline ($kgCO_2e/m^2$). This automated process ensures seamless integration between BIM and LCA data.

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To achieve efficient integration, RevitDBBridge.dll uses programmatic SQL queries to extract the necessary data and imports the integrated results into a dedicated database, Data Calculation. Throughout the data integration process, RevitDBBridge.dll not only simplifies the integration of BIM and LCA data but also reduces human errors through automated data processing, thereby enhancing data reliability. This integration process provides an accurate and consistent data foundation for subsequent carbon footprint evaluations. And also ensures the scientific validity of the evaluation results.

3.4 Module 4: Interior Design Carbon Footprint Evaluation and Analysis, and Low-Carbon Design Alternatives Customization

After the semi-automated integration of BIM and LCA data, the RevitDBBridge.dll plugin can automatically evaluate the total carbon footprint (TCF, in $kgCO_2e$) generated during the interior renovation, the carbon footprint indicator (CFI, in $kgCO_2e/m^2 \cdot yr$) of the design case, and the carbon reduction percentage (CFR). These calculations consider multiple dimensions of data input, including the area of building components, the carbon footprint density of materials, lifecycle update standards, the total floor area of the building, and the lifecycle standards of the interior renovation project. The results are presented to the user in a dialog box, assisting in the preliminary evaluation of the design scheme's carbon emissions and providing data support for design optimization.

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In addition, the RevitDBBridge.dll plugin automatically generates carbon emission analysis charts, including the carbon footprint contribution of different sub-divisional works, various life cycle phases, and the distribution of carbon footprint across sub-divisional work in different lifecycle phases. These charts, presented as pie charts, visually highlight the key points of high carbon footprint, and enables interior designers to quickly identify and prioritize points for optimization.

To further support low-carbon interior design decisions, RevitDBBridge.dll can also automatically generate low-carbon alternative materials for designers based on the analysis results. These alternatives are produced through data integration and automated analysis and compiled into a document. When combined with visualization results from subsequent modules, this document provides specific material optimization suggestions, which can assist the low-carbon design.

All the above-mentioned evaluations, analyses, and the customization of low-carbon alternatives for interior design can be executed with a single click of a button on the plugin's main interface. This not only significantly enhances the efficiency of interior renovation carbon footprint evaluation and analysis but also reduces the complexity of the operation, making the evaluation and analysis of carbon footprint in interior design more convenient.

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3.5 Module 5: Carbon footprint evaluation data feedback

Although in Module 4 users can require the results of the total carbon footprint (TCF), carbon footprint Indicator (CFI), and carbon reduction percentage (CFR) through the main interface's calculation button, these data do not directly indicate the carbon reduction hotspots in the design to interior designers. In contrast, specific data in the Data Calculation database, such as the lifecycle update standards of the sub-items of interior renovation sub-divisional works (with the exception of partition walls) and the difference between each component's carbon footprint density and its baseline($kgCO_2e/m^2$), more intuitively reflect which materials require higher maintenance and update frequency throughout the lifecycle and which materials have significantly higher carbon footprint densities than its baseline. By feeding back and visualizing these data into the Revit model, it becomes possible to visually represent high carbon emission areas, which refers to the carbon reduction hotspots in the design. To achieve this, this study uses the IRCFES.dll plugin to return these critical data as new parameter values to the Revit model.

The plugin's user interface provides four data feedback buttons, corresponding to the four sub-divisional works. The plugin adds new shared parameters to the model components within each sub-divisional work, feeding the evaluation results back into the components. The advantage of this approach is that all elements belonging to the same

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category share these parameters and display the relevant data when needed. Although some wall elements (e.g., non-partition walls) may have additional parameter values, these values are empty and do not affect subsequent data visualization. Because these parameters will not be used in unrelated elements (Fig. 3. 7).

```
private bool setNewParameterToTypeWall(UIApplication app)
        {
            Document doc = app.ActiveUIDocument.Document;
            bool result = true;

            DefinitionFile myDefinitionFile = app.Application.OpenSharedParameterFile();
            DefinitionGroup myGroup = myDefinitionFile.Groups.get_Item("IRCFESWall") ??
            myDefinitionFile.Groups.Create("IRCFESWall");

            CategorySet myCategories = app.Application.Create.NewCategorySet();
            Category myCategory = doc.Settings.Categories.get_Item(BuiltInCategory.OST_Walls);
            myCategories.Insert(myCategory);

            TypeBinding typeBinding = app.Application.Create.NewTypeBinding(myCategories);
            BindingMap bindingMap = doc.ParameterBindings;

            result &= CreateAndBindDefinition("CarbonFootprintDifferenceforConstruction",
            ParameterType.Number, myGroup, typeBinding, bindingMap, doc);
            result &= CreateAndBindDefinition("CarbonFootprintDifferenceforEnd_of_LifeDisposal",
            ParameterType.Number, myGroup, typeBinding, bindingMap, doc);
            result &=
            CreateAndBindDefinition("StandardforRenewalTimesofSubdivisionalWorksofWallFinishesRTwdi",
             ParameterType.Number, myGroup, typeBinding, bindingMap, doc);
            result &=
            CreateAndBindDefinition("CarbonFootprintDifferenceforConstructionofPartitionWall",
            ParameterType.Number, myGroup, typeBinding, bindingMap, doc);
            result &=
            CreateAndBindDefinition("CarbonFootprintDifferenceforEnd_of_LifeDisposalofPartitionWall",
             ParameterType.Number, myGroup, typeBinding, bindingMap, doc);

            return result;
        }
```

Fig. 3. 7 The code for setting new parameters to walls.

During the data feedback process, the plugin connects to the Data Calculation database, automatically retrieves and reads the corresponding parameter values, and then assigns these values to the relevant components in the Revit model. Ultimately, users can visually observe the carbon emission-related parameter values of each component in the

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design through the Revit interface, which allow them to identify and optimize carbon reduction hotpots. This method not only effectively feeds evaluation results back into the BIM model but also enhances the efficiency and accuracy of data feedback through automated data extraction and parameter settings.

3.6 Module 6: Carbon footprint evaluation data visualization

The visualization of evaluation data in this study is handled by the DataViz.dll plugin. Through a user-friendly interface, this plugin assists designers in intuitively viewing carbon footprint evaluation results, thereby identifying and optimizing carbon reduction hotpots in the design scheme. The interface is designed to be simple, with two dropdown menus and a ‘Visualize’ button. The first dropdown menu allows users to select one of the four sub-divisional works of interior renovation, and the second dropdown menu loads the corresponding parameter names based on the first menu's selection (Fig. 3. 8).

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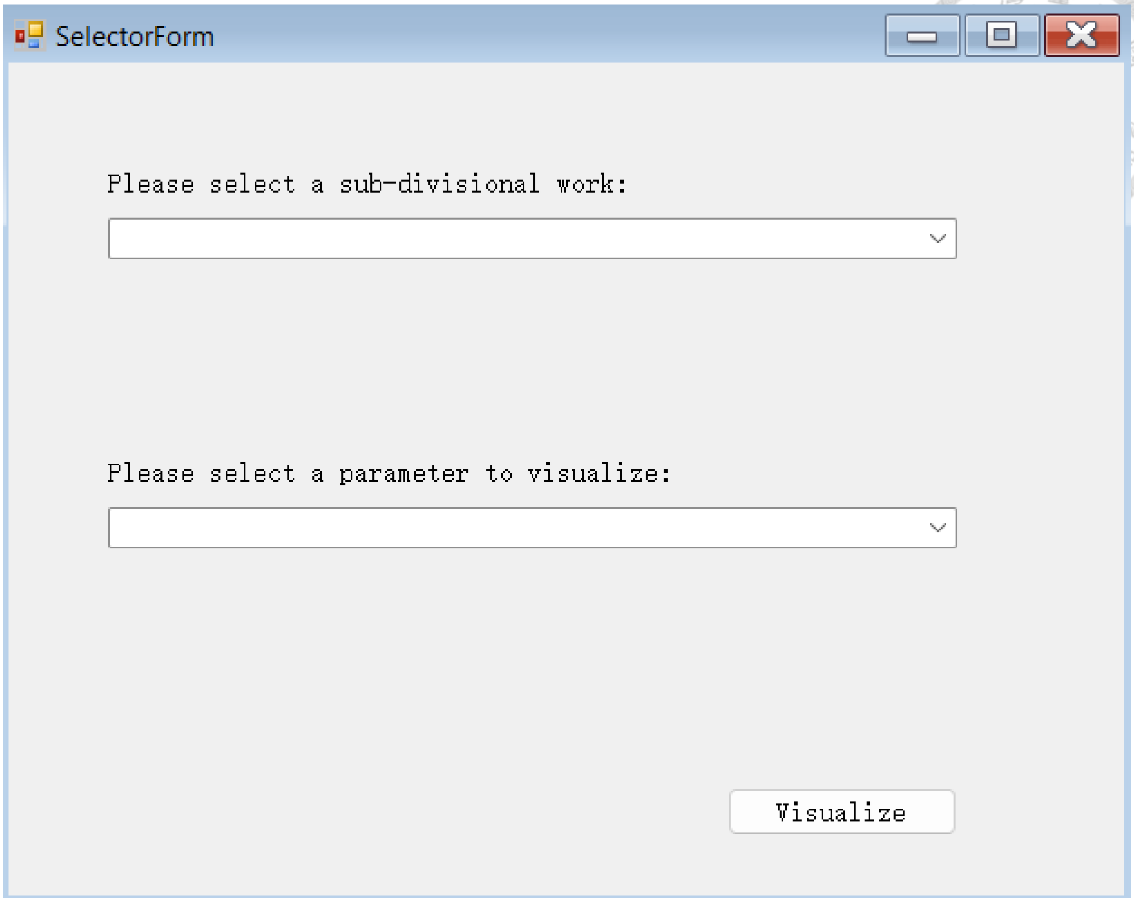

Fig. 3. 8 The user Interface of DataViz plugin.

Once users complete the selection of sub-divisional work and parameters, they can click the 'Visualize' button to generate the corresponding parameter visualization. The entire visualization process involves several 6 steps:

1. **Retrieving Unique Parameter Values**: A filter is created based on the selected sub-divisional work and parameters, extracting the parameter values of all relevant components and constructing a set of unique parameter values.

2. **Mapping Values to Colors**: Parameter values are mapped to colors (Fig. 3. 9).

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This method uses red and green as the two extremes of the color range for visualization. Red indicates that the parameter value exceeds the reference value, such as when the lifecycle update standard is greater than zero or the component's carbon footprint density is higher than its baseline, suggesting that the component has a relatively high carbon emission during the interior renovation lifecycle and may require material optimization. Green indicates that the parameter value is below the reference value, such as when the lifecycle update standard is less than zero or the component's carbon footprint density is lower than its baseline, suggesting that the component has a relatively low carbon emission, and the material selection is optimized. When the parameter value equals the reference value, such as when the lifecycle update standard is zero or the component's carbon footprint density equals its baseline, the component is displayed in white. This indicates that the component's carbon emissions match the industry benchmark, neither higher nor lower than expected. Additionally, in the code of the DataViz.dll plugin, the extreme values of the color range can be set. For example, if ‘12’ is used as the extreme value, the component will be displayed in pure red when the parameter value equals 12, and in pure green when the parameter value equals ‘-12’. Parameter values greater than ‘-12’ but less than zero will gradually transition from green to white, while values greater than zero

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but less than ‘12’ will transition from white to pure red.

```
private int Clamp(int value, int min, int max)
        {
            return (value < min) ? min : (value > max) ? max : value;
        }

        private System.Drawing.Color GetColorFromValue(double value)
        {
            if (value == 0)
            {
                return System.Drawing.Color.FromArgb(255, 255, 255);
            }

            int red, green, blue;

            if (value > 0)
            {
                // Scale the color for positive values (0 < value <= 12)
                red = 255;
                green = 255 - Clamp((int)(255 * value / 12), 0, 255);
                blue = 255 - Clamp((int)(255 * value / 12), 0, 255);
            }
            else
            {
                // Scale the color for negative values (-12 <= value < 0)
                red = 255 + Clamp((int)(255 * value / 12), -255, 0);
                green = 255;
                blue = 255 + Clamp((int)(255 * value / 12), -255, 0);
            }

            return System.Drawing.Color.FromArgb(red, green, blue);
        }
```

Fig. 3. 9 The code for mapping values to colors.

3. **Collecting Relevant Elements**: A collection of all relevant model components is created to ensure that each component is included in the subsequent visualization process.

4. **Graphical Override Settings**: Graphical override settings are applied to each component, combining the color mapping from the parameter values with the

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graphical properties of the components to ensure clear visual presentation.

5. **Applying Color Overrides**: The graphical override settings are applied to the relevant components to complete the color overlay, allowing designers to intuitively identify carbon hotspots.
6. **Carbon Hotspot Alert**: A dialog box will display the information about components where the lifecycle update standard exceeds zero or the component's carbon footprint density is higher than its baseline, which can save designers time and effort in manually searching for component information.

Through this visualization method, the DataViz.dll plugin provides designers with a powerful tool for identifying carbon hotspots during the design phase. This approach not only improves the transparency and comprehension of carbon footprint evaluation but also provides clear guidance for optimizing low-carbon interior design.

Overall, this BIM-based LCA integration approach accurately assesses carbon emissions during interior design and provides reliable data, charts, and 3D visualization support for design decision makings. This method effectively combines the strengths of BIM and LCA data, playing a crucial role in advancing low-carbon interior design practices.

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Chapter 4 A case study using the developed method

4.1 Case building description

The case study in this research is the demo house at the Taisugar Circular Village (TCV), Located in Tainan City. It received Taiwan's Diamond Level Building Carbon Footprint Accreditation in 2020 and was completed and put into use in 2021(*低碳建築聯盟 LCBA (Low Carbon Building Alliance)*, n.d.). It is the first residential building in Taiwan to implement the concept of a circular economy (Corporation, 2024). The BIM model of the demonstration house (Fig. 4. 1) is a Revit model consisting of 2503 elements, including 101 different element types (Family and Type) and 68 different materials. This model focuses on interior design and renovation, providing detailed material information for walls, floors, and ceiling elements. Therefore, it is highly suitable for assessing the carbon footprint of interior renovation and visualizing the evaluation results.

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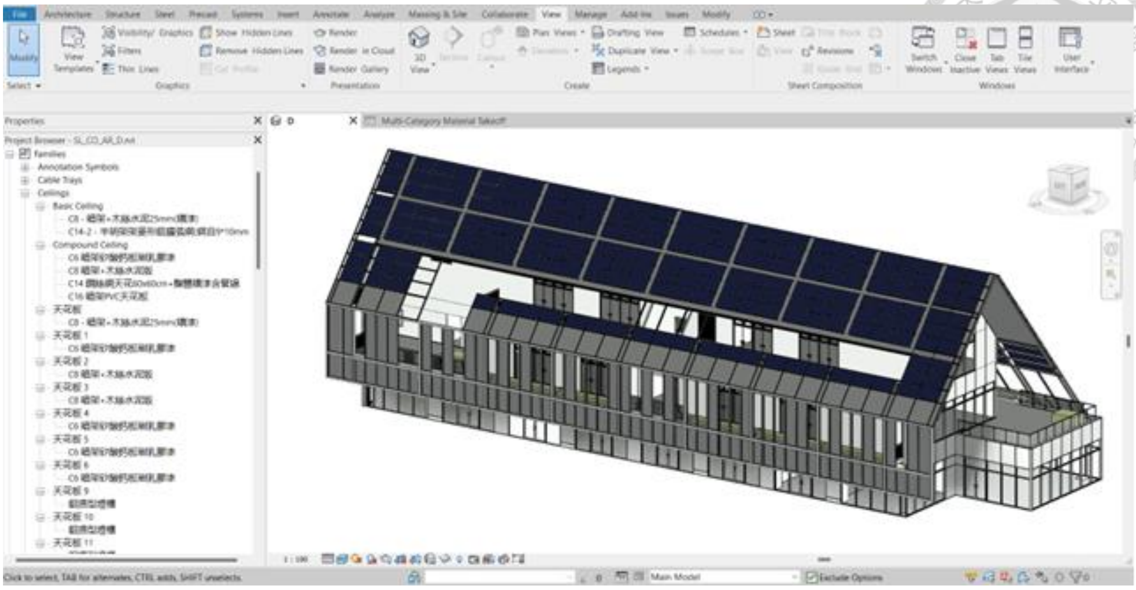

Fig. 4. 1 The Revit model of the demo house.

4.2 Application of the developed method

The developed approach in this study was successfully applied to the case. All LCA data related to the carbon footprint evaluation of interior renovation were included in the LCBA database. Unique identifiers, family types, areas, and material names of components in various sub-divisional works from the BIM model were exported to the IRCFES database. Specifically, there are 83 rows of partition wall information, 658 rows of wall finish information, 33 rows of floor finish information, and 44 rows of ceiling finish information. Fig. 4. 2 illustrates an example of the extraction results for unique identifiers, family types, areas, and material names of ceiling finish components from the model.

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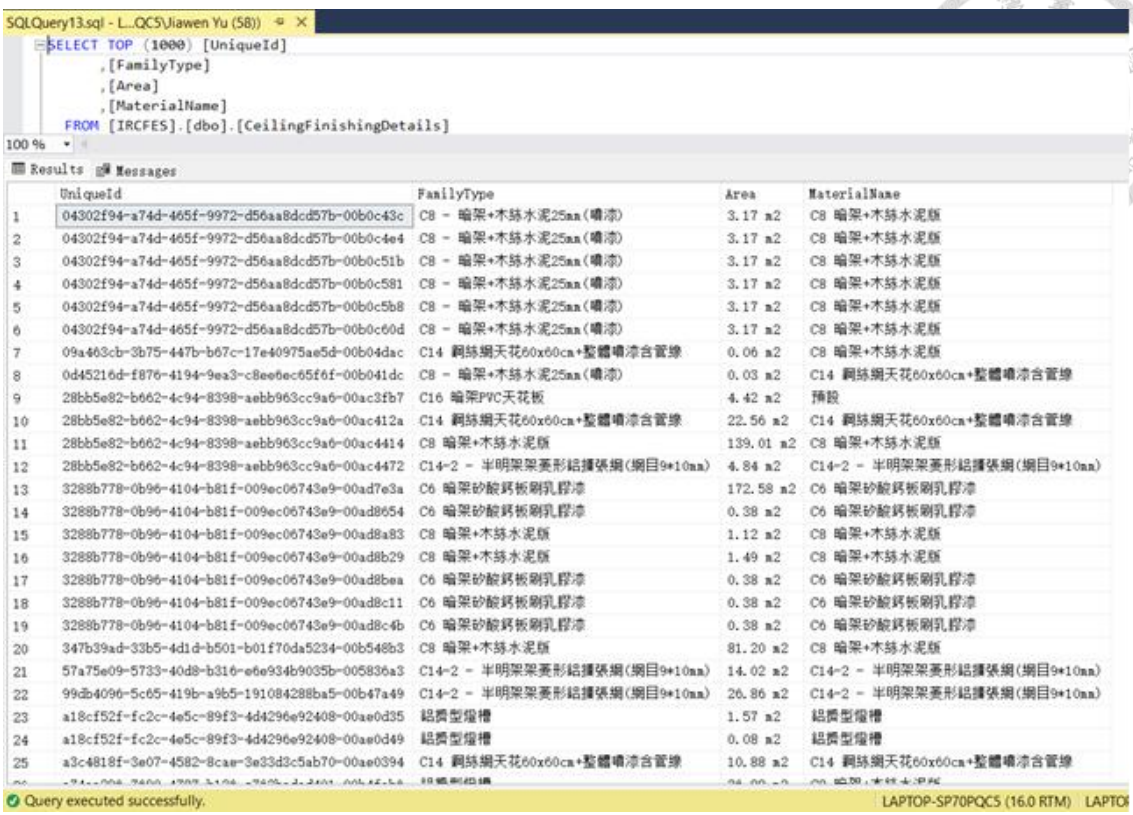

SQLQuery13.sql - L...QC5\Jiawen Yu (58))

```
SELECT TOP (1000) [UniqueId]
      ,[FamilyType]
      ,[Area]
      ,[MaterialName]
  FROM [IRCFES].[dbo].[CeilingFinishingDetails]
```

100 %

Results | Messages

	UniqueId	FamilyType	Area	MaterialName
1	04302f94-a74d-465f-9972-d56aa8dcd57b-00b0c43c	C8 - 暗架+木絲水泥25mm(噴漆)	3.17 m2	C8 暗架+木絲水泥版
2	04302f94-a74d-465f-9972-d56aa8dcd57b-00b0c4e4	C8 - 暗架+木絲水泥25mm(噴漆)	3.17 m2	C8 暗架+木絲水泥版
3	04302f94-a74d-465f-9972-d56aa8dcd57b-00b0c51b	C8 - 暗架+木絲水泥25mm(噴漆)	3.17 m2	C8 暗架+木絲水泥版
4	04302f94-a74d-465f-9972-d56aa8dcd57b-00b0c581	C8 - 暗架+木絲水泥25mm(噴漆)	3.17 m2	C8 暗架+木絲水泥版
5	04302f94-a74d-465f-9972-d56aa8dcd57b-00b0c5b8	C8 - 暗架+木絲水泥25mm(噴漆)	3.17 m2	C8 暗架+木絲水泥版
6	04302f94-a74d-465f-9972-d56aa8dcd57b-00b0c60d	C8 - 暗架+木絲水泥25mm(噴漆)	3.17 m2	C8 暗架+木絲水泥版
7	09a463cb-3b75-447b-b67c-17e40975ae5d-00b04dac	C14 鋼絲網天花60x60cm+整體噴漆含置線	0.06 m2	C8 暗架+木絲水泥版
8	0d45216d-f876-4194-9ea3-c8ee6ec65f6f-00b041dc	C8 - 暗架+木絲水泥25mm(噴漆)	0.03 m2	C14 鋼絲網天花60x60cm+整體噴漆含置線
9	28bb5e82-b662-4c94-8398-aebb963cc9a6-00ac3fb7	C16 暗架PVC天花板	4.42 m2	預設
10	28bb5e82-b662-4c94-8398-aebb963cc9a6-00ac412a	C14 鋼絲網天花60x60cm+整體噴漆含置線	22.56 m2	C14 鋼絲網天花60x60cm+整體噴漆含置線
11	28bb5e82-b662-4c94-8398-aebb963cc9a6-00ac4414	C8 暗架+木絲水泥版	139.01 m2	C8 暗架+木絲水泥版
12	28bb5e82-b662-4c94-8398-aebb963cc9a6-00ac4472	C14-2 - 半明架菱形鋁擴張網(網目9*10mm)	4.84 m2	C14-2 - 半明架菱形鋁擴張網(網目9*10mm)
13	3288b778-0b96-4104-b81f-009ec06743e9-00ad7e3a	C6 暗架矽酸鈣板刷乳膠漆	172.58 m2	C6 暗架矽酸鈣板刷乳膠漆
14	3288b778-0b96-4104-b81f-009ec06743e9-00ad8654	C6 暗架矽酸鈣板刷乳膠漆	0.38 m2	C6 暗架矽酸鈣板刷乳膠漆
15	3288b778-0b96-4104-b81f-009ec06743e9-00ad8a83	C8 暗架+木絲水泥版	1.12 m2	C8 暗架+木絲水泥版
16	3288b778-0b96-4104-b81f-009ec06743e9-00ad8b29	C8 暗架+木絲水泥版	1.49 m2	C8 暗架+木絲水泥版
17	3288b778-0b96-4104-b81f-009ec06743e9-00ad8bea	C6 暗架矽酸鈣板刷乳膠漆	0.38 m2	C6 暗架矽酸鈣板刷乳膠漆
18	3288b778-0b96-4104-b81f-009ec06743e9-00ad8c11	C6 暗架矽酸鈣板刷乳膠漆	0.38 m2	C6 暗架矽酸鈣板刷乳膠漆
19	3288b778-0b96-4104-b81f-009ec06743e9-00ad8c4b	C6 暗架矽酸鈣板刷乳膠漆	0.38 m2	C6 暗架矽酸鈣板刷乳膠漆
20	347b39ad-33b5-4d1d-b501-b01f70da5234-00b548b3	C8 暗架+木絲水泥版	81.20 m2	C8 暗架+木絲水泥版
21	57a75e09-5733-40d8-b316-e6e934b9035b-005836a3	C14-2 - 半明架菱形鋁擴張網(網目9*10mm)	14.02 m2	C14-2 - 半明架菱形鋁擴張網(網目9*10mm)
22	99db4096-5c65-419b-a9b5-191084288ba5-00b47a49	C14-2 - 半明架菱形鋁擴張網(網目9*10mm)	26.86 m2	C14-2 - 半明架菱形鋁擴張網(網目9*10mm)
23	a18cf52f-fc2c-4e5c-89f3-4d4296e92408-00ae0d35	鋁質型擋槽	1.57 m2	鋁質型擋槽
24	a18cf52f-fc2c-4e5c-89f3-4d4296e92408-00ae0d49	鋁質型擋槽	0.08 m2	鋁質型擋槽
25	a3c4818f-3e07-4582-8cae-3e33d3c5ab70-00ae0394	C14 鋼絲網天花60x60cm+整體噴漆含置線	10.88 m2	C14 鋼絲網天花60x60cm+整體噴漆含置線

Query executed successfully. LAPTOP-SP70PQC5 (16.0 RTM) LAPTO

Fig. 4. 2 The example of the extraction result for ceiling finishes details.

The plugin RevitDBBridge.dll allows the dropdown menus of main interface and the sub-interfaces to automatically query and load data from the LCBA and IRCFES databases. After the user makes their selections, the plugin correctly builds the relationships among these data and eventually imports the data into the Data Calculation database for further evaluation and visualization. Fig. 4. 3 presents part of the results of the data integration for ceiling finishes, as well as two new parameters related to the difference between ceiling finishes component's carbon footprint density and its baseline ($kgCO_2e/m^2$). To avoid an excessive number of columns, as the Ceiling Finishes table has

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24 columns, the table in the figure was split into four smaller tables. After the evaluation is completed, the user can add the new parameters back to the Revit model with a single click. Fig. 4. 4 provides an example of the new parameter results for a type of ceiling.

CeilingFinishes

UniqueId	FamilyType	MaterialName	Area
04302f94-a74d-465f-9972-d56aa8dcd57b-00b0c43c	C8 - [illegible]25mm([illegible])	C8 [illegible]	3.17 m2
09a463cb-3b75-447b-b67c-17e40975ae5d-00b04dac	C14 [illegible]60x60cm+[illegible]	C8 [illegible]	0.06 m2
0d45216d-f876-4194-9ea3-c8ee6ec65f6f-00b041dc	C8 - [illegible]25mm([illegible])	C14 [illegible]60x60cm+[illegible]	0.03 m2
28bb5e82-b662-4c94-8398-aebb963cc9a6-00ac412a	C14 [illegible]60x60cm+[illegible]	C14 [illegible]60x60cm+[illegible]	22.56 m2
28bb5e82-b662-4c94-8398-aebb963cc9a6-00ac4472	C14-2 - [illegible](網目9*10mm)	C14-2 - [illegible](網目9*10mm)	4.84 m2
3288b778-0b96-4104-b81f-009ec06743e9-00ad7e3a	C6 [illegible]	C6 [illegible]	172.58 m2
57a75e09-5733-40d8-b316-e6e934b9035b-005836a3	C14-2 - [illegible](網目9*10mm)	C14-2 - [illegible](網目9*10mm)	14.02 m2
99db4096-5c65-419b-a9b5-191084288ba5-00b47a49	C14-2 - [illegible](網目9*10mm)	C14-2 - [illegible](網目9*10mm)	26.86 m2
a3c4818f-3e07-4582-8cae-3e33d3c5ab70-00ae0394	C14 [illegible]60x60cm+[illegible]	C14 [illegible]60x60cm+[illegible]	10.88 m2
b9b5198d-70e0-41a1-a7d2-3f792781a92d-00b0bbea	C8 - [illegible]25mm([illegible])	C8 [illegible]	3.17 m2
db3ad6c2-c274-4d7f-9155-733b828e5d91-00ae234d	C6 [illegible]	C6 [illegible]	4.48 m2

(a) Ceiling finishes table part 1

CeilingFinishes (Continued)

CeilingFinishesTypesID	CeilingFinishesTypes	CeilingFinishesNamesID	CeilingFinishesNames	CFci	CFcf
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	00e114ad-1e1b-49bc-be15-0e1a34076298	Concealed Frame Lightweight Steel Ceiling System (12mm Gypsum Board)	8.83	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	00e114ad-1e1b-49bc-be15-0e1a34076298	Concealed Frame Lightweight Steel Ceiling System (12mm Gypsum Board)	8.83	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	00e114ad-1e1b-49bc-be15-0e1a34076298	Concealed Frame Lightweight Steel Ceiling System (12mm Gypsum Board)	8.83	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	00e114ad-1e1b-49bc-be15-0e1a34076298	Concealed Frame Lightweight Steel Ceiling System (12mm Gypsum Board)	8.83	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	6e86c124-566a-43e2-8187-edb52249c302	Metal Grid Exposed Frame Lightweight Steel Ceiling System (Aluminum Square Tube)	7.93	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	80d746a2-6fc7-4969-84c9-86814041bcad	Concealed Frame Lightweight Steel Ceiling System (6mm Calcium Silicate Board)	7.18	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	6e86c124-566a-43e2-8187-edb52249c302	Metal Grid Exposed Frame Lightweight Steel Ceiling System (Aluminum Square Tube)	7.93	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	6e86c124-566a-43e2-8187-edb52249c302	Metal Grid Exposed Frame Lightweight Steel Ceiling System (Aluminum Square Tube)	7.93	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	00e114ad-1e1b-49bc-be15-0e1a34076298	Concealed Frame Lightweight Steel Ceiling System (12mm Gypsum Board)	8.83	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	00e114ad-1e1b-49bc-be15-0e1a34076298	Concealed Frame Lightweight Steel Ceiling System (12mm Gypsum Board)	8.83	10.61
09afc02f-8746-4d38-a48e-ae5e6ff0ad06	Light steel frame ceiling	80d746a2-6fc7-4969-84c9-86814041bcad	Concealed Frame Lightweight Steel Ceiling System (6mm Calcium Silicate Board)	7.18	10.61

(b) Ceiling finishes table part 2

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CeilingFinishes (Continued)

SubdivisionalWorksofCeilingFinishes	EnvironmentalTypes	EnvironmentalTypes	BuildingTypesID	BuildingTypes	RTci
Paint	139c6cad-2c1e-44f2-ba0c-2fc875844f68	Humid Environment	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	3
Paint	139c6cad-2c1e-44f2-ba0c-2fc875844f68	Humid Environment	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	3
Paint	139c6cad-2c1e-44f2-ba0c-2fc875844f68	Humid Environment	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	3
Paint	139c6cad-2c1e-44f2-ba0c-2fc875844f68	Humid Environment	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	3
Metal and Glass Panel	a9fc55f6-efd7-4a72-9886-68aa41afa358	null	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	0
Paint	139c6cad-2c1e-44f2-ba0c-2fc875844f68	Humid Environment	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	3
Metal and Glass Panel	a9fc55f6-efd7-4a72-9886-68aa41afa358	null	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	0
Metal and Glass Panel	a9fc55f6-efd7-4a72-9886-68aa41afa358	null	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	0
Paint	139c6cad-2c1e-44f2-ba0c-2fc875844f68	Humid Environment	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	3
Paint	139c6cad-2c1e-44f2-ba0c-2fc875844f68	Humid Environment	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	3
Paint	139c6cad-2c1e-44f2-ba0c-2fc875844f68	Humid Environment	29a99089-dc12-44e0-a9f0-c2ccc0133df4	Building with low deterioration rate	3

(c) Ceiling finishes table part 3

CeilingFinishes (Continued)

SubdivisionalWorkMaterialTypesID	SubdivisionalWorkMaterialTypes	SubdivisionalWorksID	SubdivisionalWorks	WDci	WDci'	CFci-CFci'	WDci-WDci'
559dd13c-d677-4385-96a4-64dbae92fc0f	Fabric Paper Coating and Painting	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-1.78	-4.95
559dd13c-d677-4385-96a4-64dbae92fc0f	Fabric Paper Coating and Painting	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-1.78	-4.95
559dd13c-d677-4385-96a4-64dbae92fc0f	Fabric Paper Coating and Painting	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-1.78	-4.95
559dd13c-d677-4385-96a4-64dbae92fc0f	Fabric Paper Coating and Painting	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-1.78	-4.95
0918ae4c-6c56-457a-b101-de014cfd9b32	Metal and Glass Work	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-2.68	-4.95
559dd13c-d677-4385-96a4-64dbae92fc0f	Fabric Paper Coating and Painting	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-3.43	-4.95
0918ae4c-6c56-457a-b101-de014cfd9b32	Metal and Glass Work	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-2.68	-4.95
0918ae4c-6c56-457a-b101-de014cfd9b32	Metal and Glass Work	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-2.68	-4.95
559dd13c-d677-4385-96a4-64dbae92fc0f	Fabric Paper Coating and Painting	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-1.78	-4.95
559dd13c-d677-4385-96a4-64dbae92fc0f	Fabric Paper Coating and Painting	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-1.78	-4.95
559dd13c-d677-4385-96a4-64dbae92fc0f	Fabric Paper Coating and Painting	c3fe02a3-0bbb-474c-a571-952f11c90ba0	Ceiling Finishes	0.05	5	-3.43	-4.95

(d) Ceiling finishes table part 4

Fig. 4. 3 Part of the BIM-LCA data relationship structuring result for ceiling finishes.

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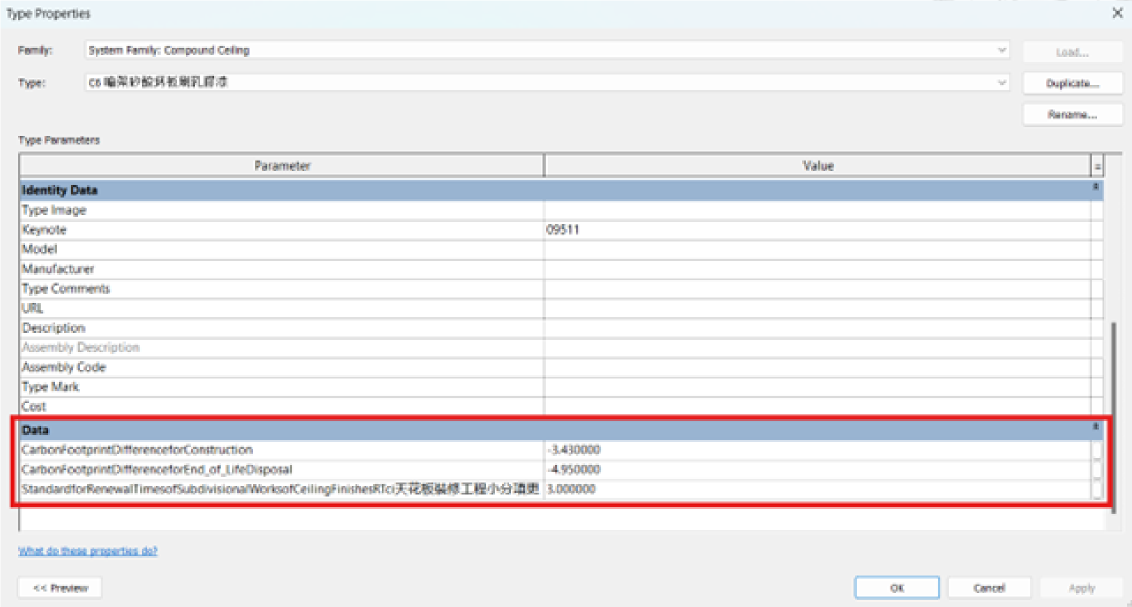

Fig. 4. 4 The example of the parameter adding results for a type of ceilings.

4.3 Interior Design Carbon Footprint Evaluation and Analysis, and Low-Carbon Design Alternatives Customization Results of the Case Building

The carbon footprint evaluation results for the interior renovation of the case study are shown in Fig. 4. 5. The total carbon footprint of interior renovation throughout the life cycle is 103,638 (with units: $kgCO_2e$), with a design case carbon footprint indicator of 2.97 (with units: $kgCO_2e/m^2 \cdot yr$) and a carbon reduction percentage of 52.9%.

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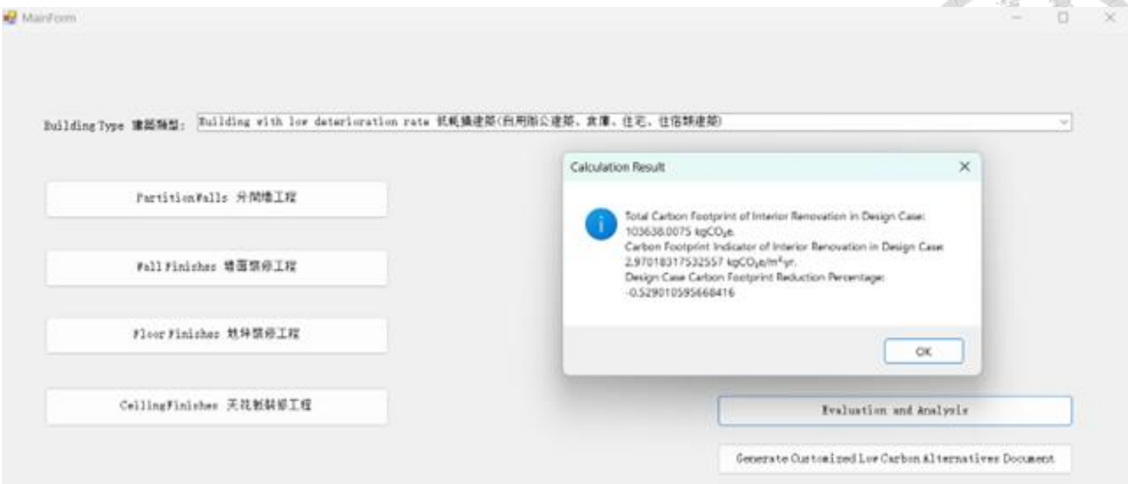

Fig. 4. 5 The carbon footprint evaluation results of the interior renovation for the demo house.

Furthermore, the LCBA classifies the low-carbon interior renovation certification into 5 levels: Qualified, Bronze, Silver, Gold, and Diamond. For design cases involving general renovation amounts, such as accommodations, public assembly, commercial entertainment, and office service buildings, the relationship between classification and CFR is as follows (Lin, 2018):

- Qualified: 10% < CFR ≤ 20%
- Bronze: 20% < CFR ≤ 30%
- Silver: 30% < CFR ≤ 40%
- Gold: 40% < CFR ≤ 50%
- Diamond: 50% < CFR

The higher the CFR, the more the interior renovation project reduces carbon compared

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to its baseline case, indicating a more environmentally friendly design.

The case used in this study is classified as an accommodation building. Therefore, according to the above classification levels, the CFR the case falls within the '50% < CFR' range, qualifying for the Diamond-level low-carbon interior renovation certification.

Based on the carbon footprint analysis of the case's interior design, three pie charts illustrating the distribution of carbon footprint were generated (Fig. 4. 6). The distribution of carbon footprint across the four sub-divisional works throughout the entire lifecycle of the interior renovation is as follows: floor finishes account for 41.98%, ceiling finishes for 24.08%, wall finishes for 21.29%, and partition walls for 12.65%. The distribution of carbon footprint across different lifecycle phases of the interior renovation is: the construction phase accounts for 62.37%, the maintenance phase for 29.25%, and the demolition phase for 8.37%. Among the sub-divisional works in different lifecycle phases, the top three contributors to carbon footprint are: floor finishes during the construction phase (36.99%), ceiling finishes during the maintenance phase (17.69%), and wall finishes during the maintenance phase (11.56%). Designers can prioritize optimizing the materials of high-carbon components in these specific sub-divisional works and lifecycle phases based on this carbon footprint distribution pie charts and the visualization results.

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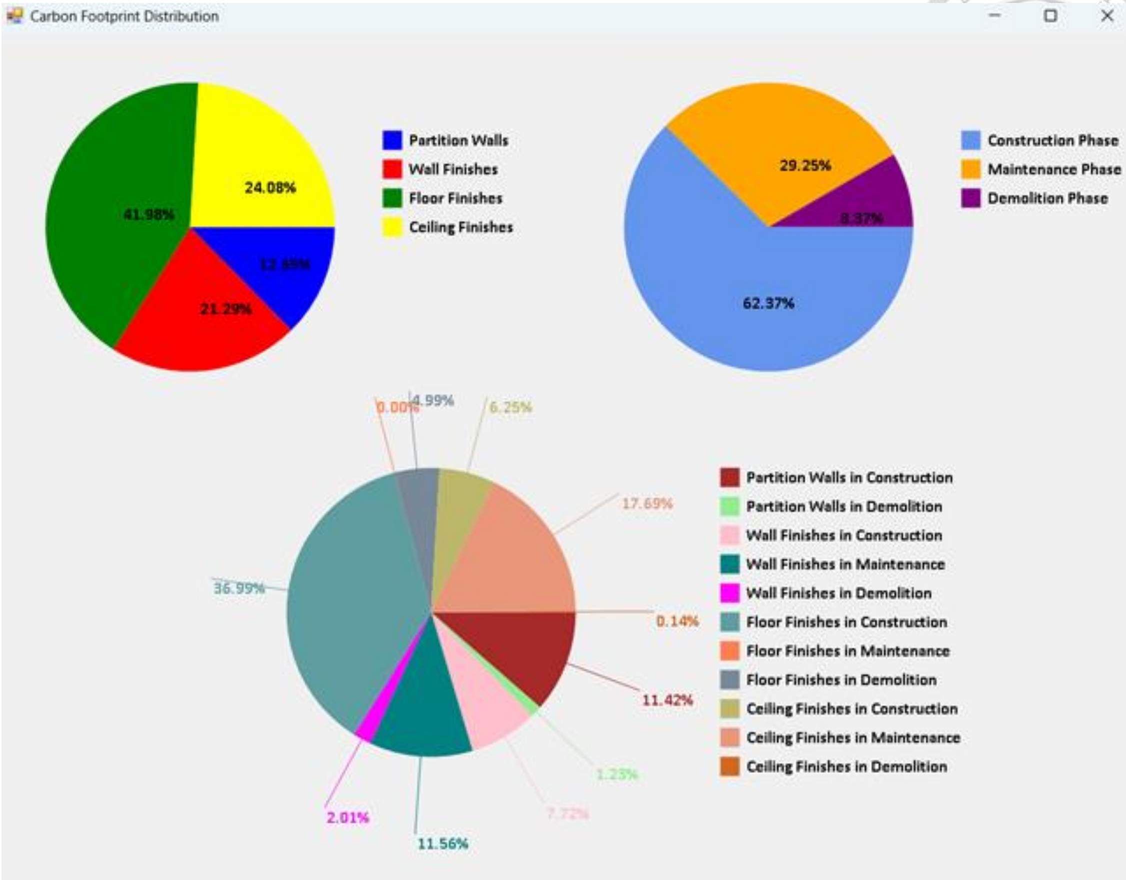

Fig. 4. 6 The three pie charts generated by the carbon footprint analysis of the case's interior design.

Furthermore, the customized low-carbon alternatives document, tailored to the case, displays the materials within each sub-divisional work component that can be optimized. The list of low-carbon alternatives for each material to be optimized is customized according to the building type, environmental type, the sub-divisional work the component belongs to, and the carbon emission-related data of the material in the case (Fig. 4. 7). Interior designers can choose the low-carbon alternatives they wish to replace

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based on the recommendations in the document. If the alternatives are strictly followed, when the original material's lifecycle update standard is greater than zero and its carbon footprint density exceeds its baseline, the new material's lifecycle update standard will be less than or equal to zero, and its carbon footprint density will be less than or equal to its baseline; if the original material's lifecycle update standard is greater than zero but its carbon footprint density is less than or equal to its baseline, the new material's lifecycle update standard will be less than or equal to zero, and its carbon footprint density will be less than or equal to that of the original material and also less than or equal to the baseline of itself; if the original material's lifecycle update standard is equal to zero but its carbon footprint density exceeds its baseline, the new material's lifecycle update standard will be equal to zero, and its carbon footprint density will be less than or equal to its baseline.

```
Design Recommendations For Floor Finishes:
--------------------------------------------------------------------------------
Replaceable Material Name:
Family and Type: F3, Material Name: F3 - 60*120霧面石英磚

Types and Names of Low-Carbon Alternatives ( Please select based on the recommendations for Floor Finishes Material Types and Sub-items of Floor Finishes! ):
Floor Finishes Type: Elevated Flat Lay Flooring 架高平鋪, Floor Finishes Name: Island-Type Flooring 海島型地板
Floor Finishes Type: Flat or Straight Lay Flooring 平鋪或直鋪, Floor Finishes Name: Flat-Laid Island-Type Flooring 平鋪式(海島型地板)
Floor Finishes Type: Japanese Style Raised Flooring 和室高架, Floor Finishes Name: Island-Type High-Durability Flooring 海島型超耐磨地板
Floor Finishes Type: Elevated Flat Lay Flooring 架高平鋪, Floor Finishes Name: High-Durability Flooring 超耐磨地板
Floor Finishes Type: Mud Work Flooring 泥作地坪, Floor Finishes Name: Stone Surface Flooring (Hard Base) 貼石材地坪(硬底)
Floor Finishes Type: Mud Work Flooring 泥作地坪, Floor Finishes Name: Stone Surface Flooring (Soft Base) 貼石材地坪(軟底)
Floor Finishes Type: Mud Work Flooring 泥作地坪, Floor Finishes Name: Plastic Flooring / Square Carpet Tiles 貼塑膠地板/方塊地毯
Floor Finishes Type: Flat or Straight Lay Flooring 平鋪或直鋪, Floor Finishes Name: Floating Direct Lay (2cm PS Board) 漂浮直鋪式(2cmPS板)
Floor Finishes Type: Japanese Style Raised Flooring 和室高架, Floor Finishes Name: Solid Hardwood Flooring 硬實木地板
Floor Finishes Type: Elevated Flat Lay Flooring 架高平鋪, Floor Finishes Name: Island-Type High-Durability Flooring 海島型超耐磨地板
Floor Finishes Type: Flat or Straight Lay Flooring 平鋪或直鋪, Floor Finishes Name: Flat-Laid Solid Hardwood Flooring 平鋪式(硬實木地板)
Floor Finishes Type: Mud Work Flooring 泥作地坪, Floor Finishes Name: Cement Mortar Flooring 水泥砂漿地坪
Floor Finishes Type: Japanese Style Raised Flooring 和室高架, Floor Finishes Name: Soft Hardwood Flooring 軟實木地板
Floor Finishes Type: Flat or Straight Lay Flooring 平鋪或直鋪, Floor Finishes Name: Floating Direct Lay (2mm PE Foam) 漂浮直鋪式(2mmPE泡棉)
Floor Finishes Type: Elevated Flat Lay Flooring 架高平鋪, Floor Finishes Name: Soft Hardwood Flooring 軟實木地板
Floor Finishes Type: Japanese Style Raised Flooring 和室高架, Floor Finishes Name: High-Durability Flooring 超耐磨地板
Floor Finishes Type: Japanese Style Raised Flooring 和室高架, Floor Finishes Name: Island-Type Flooring 海島型地板
Floor Finishes Type: Mud Work Flooring 泥作地坪, Floor Finishes Name: Carpet Flooring 地毯地坪
Floor Finishes Type: Network Raised Flooring 網路高架, Floor Finishes Name: Flat Laid without Base Layer (HPL Surface FRP) 平鋪無基層(HPL面FRP)
Floor Finishes Type: Mud Work Flooring 泥作地坪, Floor Finishes Name: Tiled Flooring (Soft Base) 貼磁磚(軟底)
Floor Finishes Type: Mud Work Flooring 泥作地坪, Floor Finishes Name: PU/Epoxy/Embossed/Hardened Film/Acrylic Resin/Paper Mold PU/Epoxy/壓花/硬化膜/壓克力樹脂/紙模板
Floor Finishes Type: Elevated Flat Lay Flooring 架高平鋪, Floor Finishes Name: Solid Hardwood Flooring 硬實木地板
Floor Finishes Type: Flat or Straight Lay Flooring 平鋪或直鋪, Floor Finishes Name: Flat-Laid Soft Hardwood Flooring 平鋪式(軟實木地板)

Recommended Floor Finishes Material Types:
Metal and Glass Work 金屬玻璃作
Cement and Natural Brick/Stone Work 水泥與天然磚石作

Recommended Sub-items of Floor Finishes:
Cement, Ceramic Tile, Stone, Metal, Glass Panel 水泥磁磚石材金屬玻璃板類
PU, Epoxy Resin, Hardwood Board and Other Flooring Material PU、Epoxy樹脂類、硬木板與其他地板材類
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```

Fig. 4. 7 The customized low-carbon alternatives document of the case building.

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4.4 Visualization of results

The visualization of the case evaluation results is categorized into four sub-divisional works, as shown in Fig. 4. 8. When the user clicks the 'Visualize' button, if the selected sub-divisional work parameter exceeds its reference value—such as when the lifecycle update standard of a component's material is greater than zero or its carbon footprint density surpasses its baseline—the user will receive a carbon hotspot alert (Fig. 4. 9). For instance, when the user selects the carbon footprint difference of construciton as the floor finishes visualization parameter, the carbon hotspot alert indicates that two materials, 'F3 - 60*120 Matte Quartz Tile' and 'F4-1 - 30*60 Rock Surface Quartz Tile', have carbon footprint densities that exceed their baselines by 8.12 $kgCO_2e/m^2$. Additionally, the alert provides the total number of components using these materials, such as nine components with 'F3 - 60*120 Matte Quartz Tile' and four components with 'F4-1 - 3060 Rock Surface Quartz Tile.' These carbon hotspot alerts correspond to components displayed in red in the visualization interface. And the value 8.12 determines the component's color intensity.

Combined with the carbon footprint analysis and low-carbon alternatives document for the case study, designers should prioritize optimizing the floor finishes materials 'F3 - 60*120 Matte Quartz Tile' and 'F4-1 - 30*60 Rock Surface Quartz Tile' used in the

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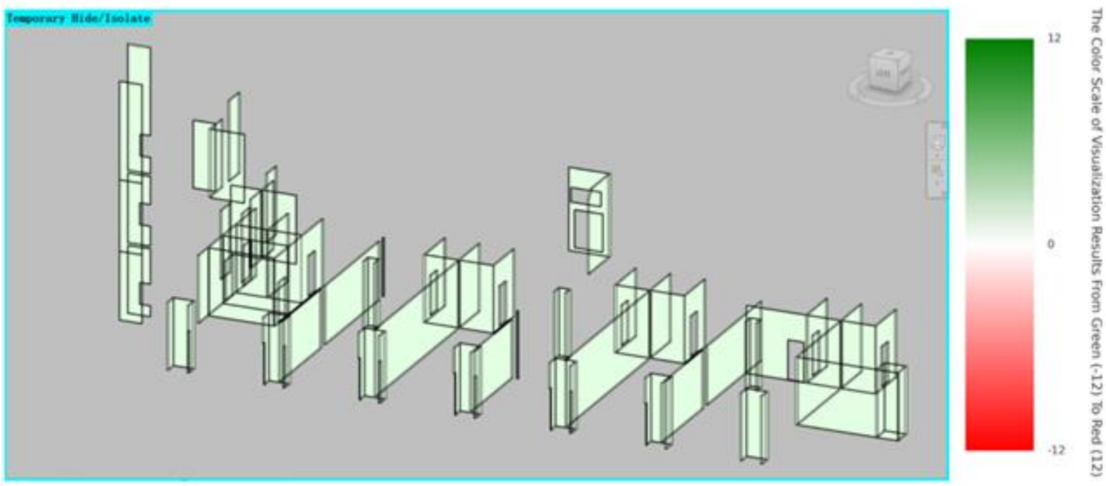
construction phase. Taking the material ‘F3 - 60120 Matte Quartz Tile’ as an example, if the designer follows the recommendations for Floor Finishes Material Types and Sub-items of Floor Finishes from the document, they could select alternatives from the Mud Work Flooring category, such as Stone Surface Flooring (Hard Base), Stone Surface Flooring (Soft Base), Cement Mortar Flooring, or Tiled Flooring (Soft Base). These alternative materials would ensure that all components using ‘F3 - 60*120 Matte Quartz Tile’ are optimized to have a lifecycle update standard of zero and a carbon footprint density less than or equal to the baseline. Furthermore, it would ensure that these components do not display in red during the three parameter visualization processes for floor finishes, thereby avoiding classification as carbon hotspots.



(a) The visualization results of the difference in material and construction carbon footprints between the design case and the baseline case for partition walls.

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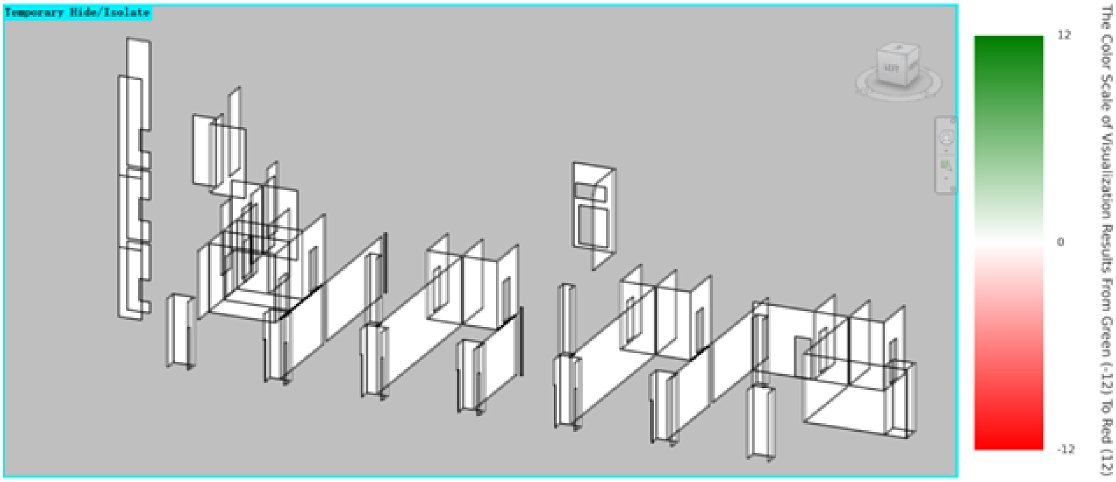
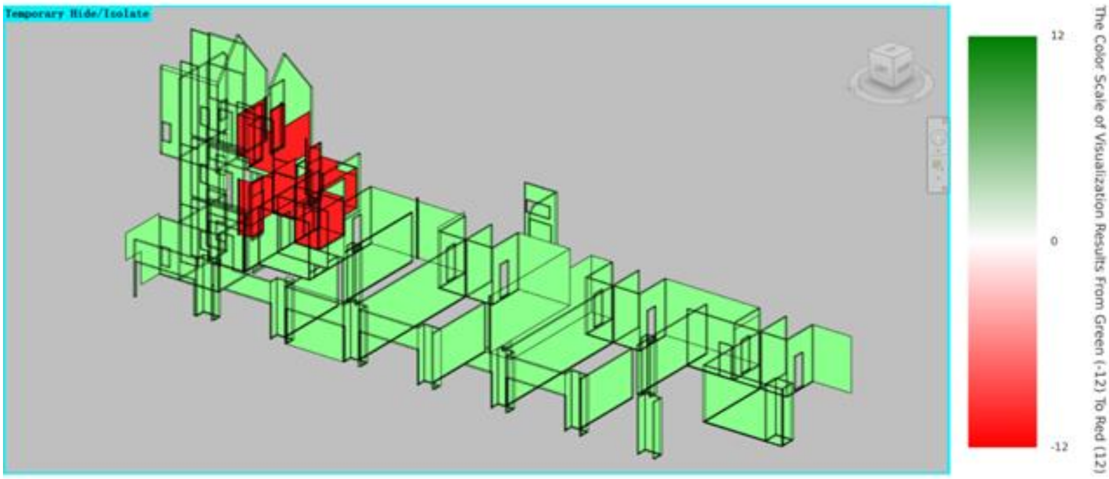


(b) The visualization results of the difference in end-of-life disposal carbon footprint between the design case and the baseline case for partition walls.



(c) The visualization results of the difference in material and construction carbon footprints between the design case and the baseline case for wall finishes.

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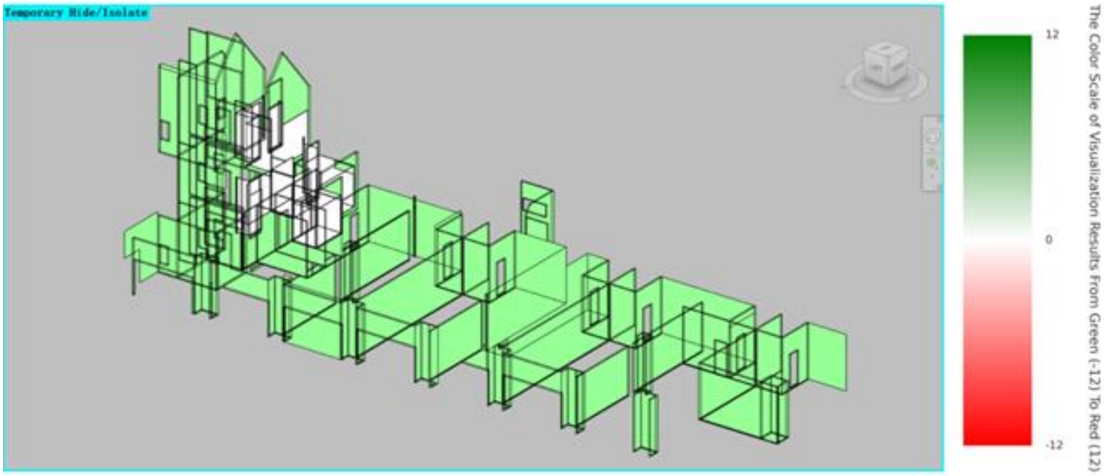
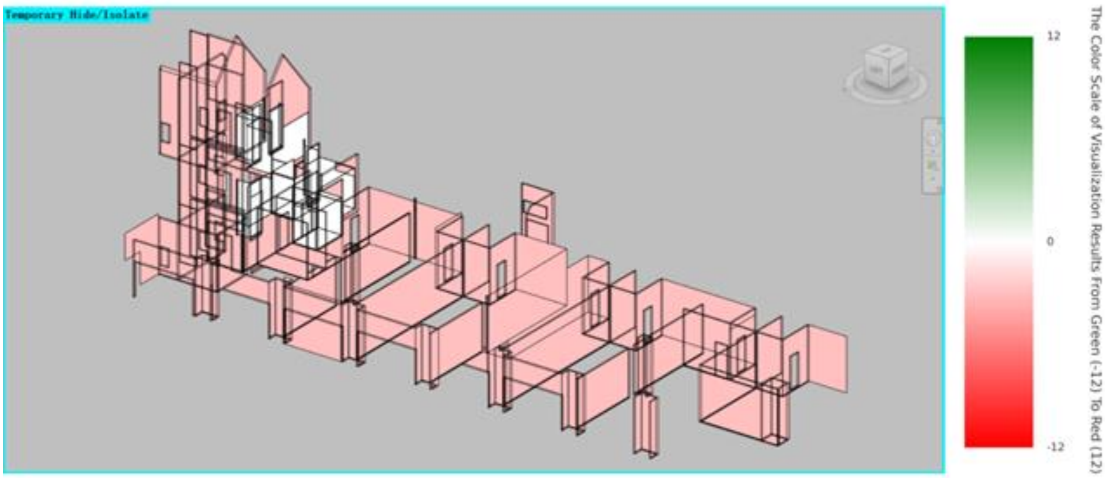


(d) The visualization results of the difference in end-of-life disposal carbon footprint between the design case and the baseline case for wall finishes.



(e) The visualization results of the lifecycle update standard for wall finishes.

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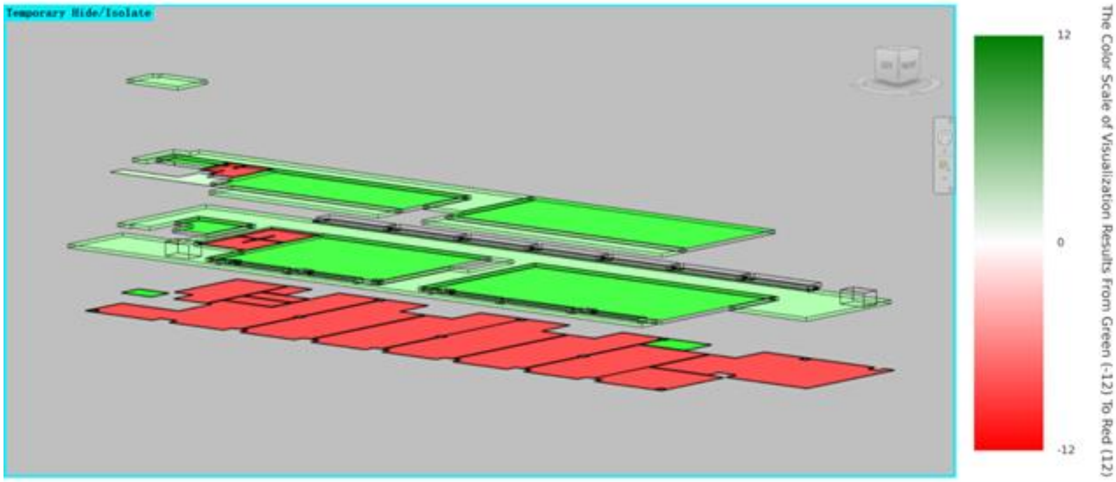
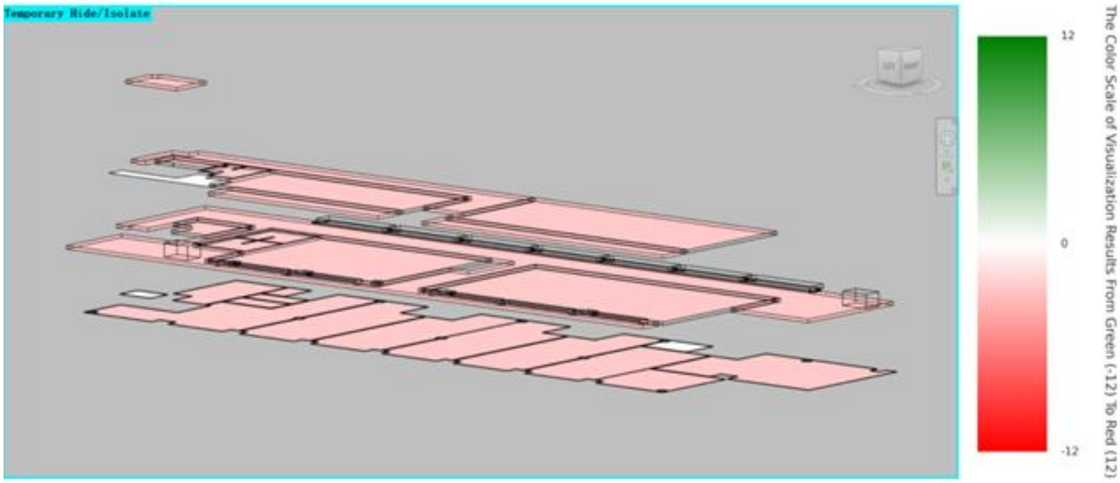


(f) The visualization results of the difference in material and construction carbon footprints between the design case and the baseline case for floor finishes.



(g) The visualization results of the difference in end-of-life disposal carbon footprint between the design case and the baseline case for floor finishes.

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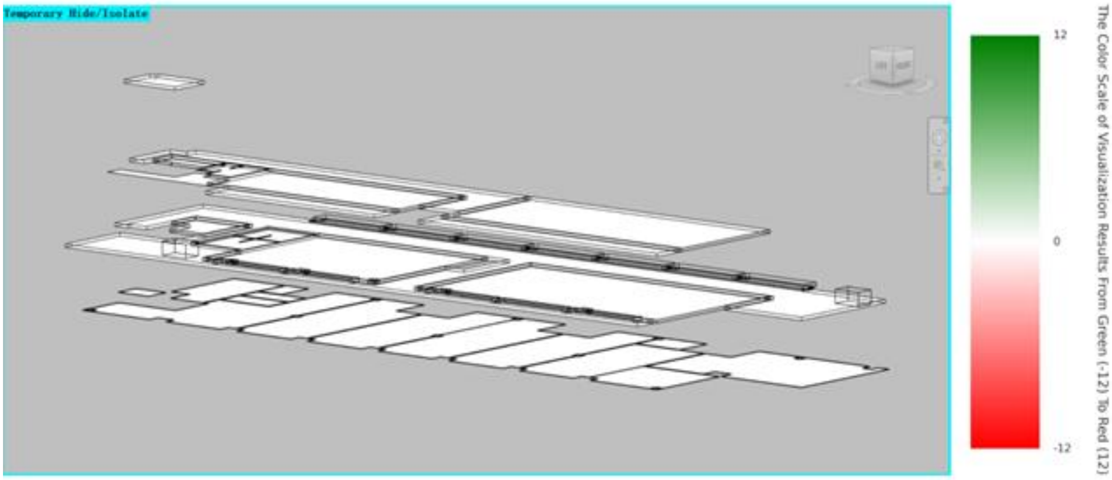
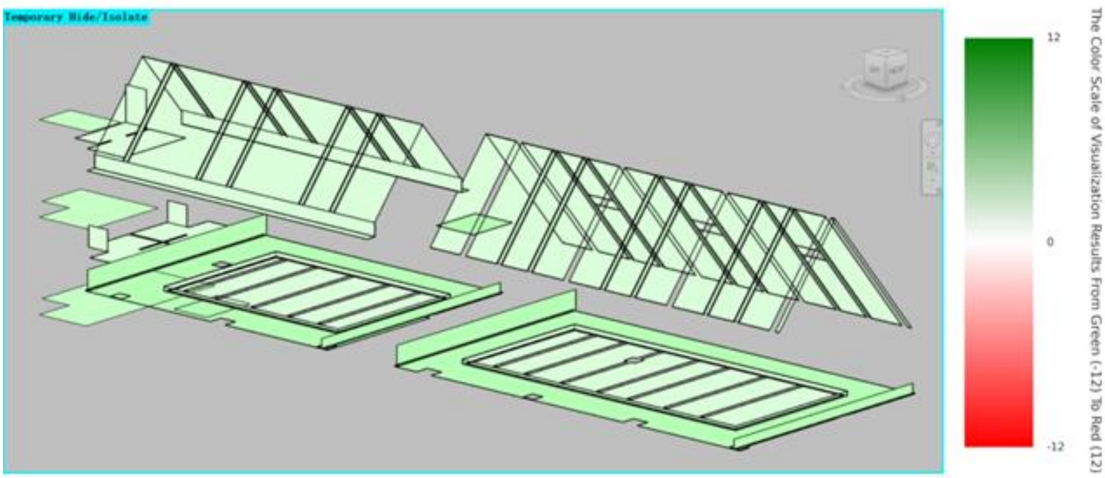


(h) The visualization results of the lifecycle update standard for floor finishes.



(i) The visualization results of the difference in material and construction carbon footprints between the design case and the baseline case for ceiling finishes.

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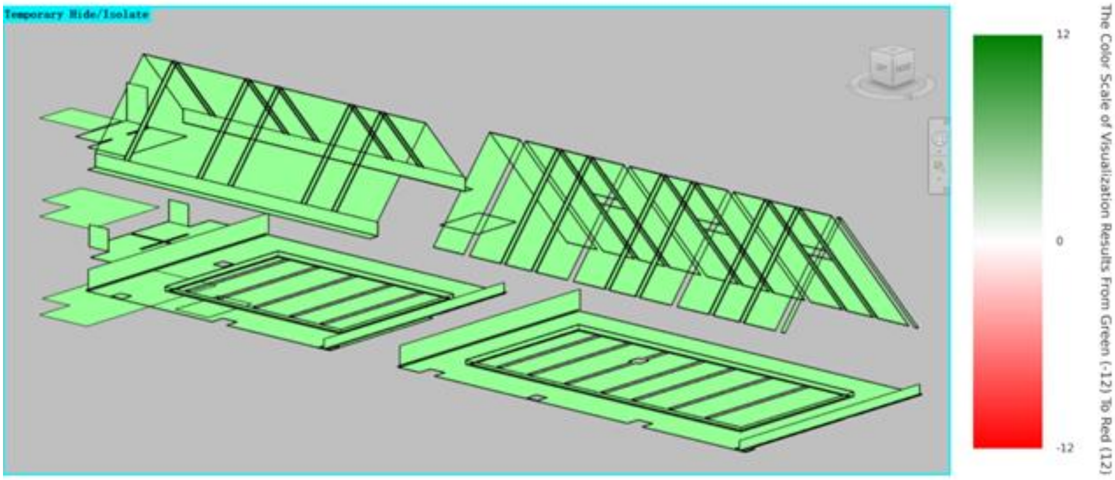
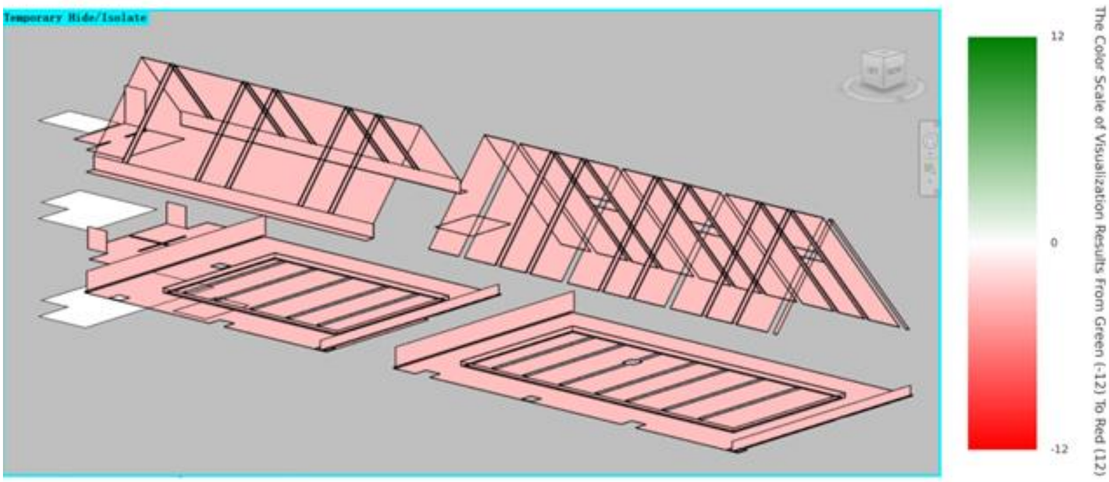


(j) The visualization results of the difference in end-of-life disposal carbon footprint between the design case and the baseline case for ceiling finishes.



(k) The visualization results of the lifecycle update standard for ceiling finishes.

Fig. 4. 8 The Revit visualization results of the interior design carbon footprint evaluation for the case building.

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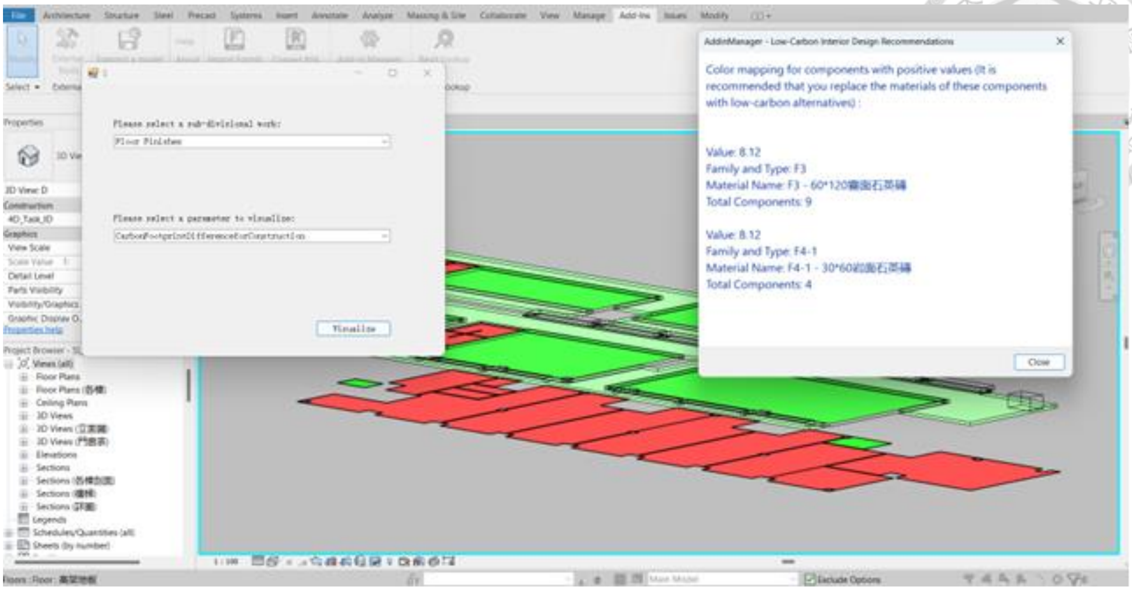

Fig. 4. 9 The example of carbon hotspot alert.

Chapter 5 Discussion

This study proposes a BIM-based visualization of carbon footprint evaluation for assisting low carbon interior design, specifically applicable to the detailed design and construction design phases of new constructions and renovations. The innovative aspects of this approach are highlighted as follows:

First, the new approach automates all necessary BIM and LCA data queries through plugins, significantly reducing the data collection time. It streamlines LCA data by normalizing the LCBA database, simplifying data structures, and improving LCA data query efficiency. The method also provides users with an intuitive BIM plugin interface,

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containing only dropdown menus and buttons, allowing users to import BIM data into the database, integrate new parameters into BIM components, and complete the calculation of the total carbon footprint generated during the interior renovation, the carbon footprint indicator of the design case, and the carbon reduction percentage with a single click. This method is similar to the third approach summarized by Tam et al. (2022), which also installs plugins in the BIM environment and completes the LCA assessment within the plugin, offering the advantage of reduced evaluation time. The ICF system proposed by LCBA involves extensive collection, organization, and analysis of BIM and LCA data (Lin, 2018). Without the new approach developed in this study, LCA practitioners would need to manually collect, organize, and analyze BIM and LCA data. And they also need to export quantities from the Revit model, searching for related LCA data, and manually inputting formulas into Excel to obtain the final evaluation results. Clearly, the new approach outperforms traditional manual assessments in terms of evaluation time.

Second, the plugins in this study were developed using Autodesk's official programming interface, Revit API, which integrates directly with Revit's core functions, ensuring stable and efficient operations. Compared to the fourth method summarized by Tam et al. (2022), which uses Dynamo, the approach developed in this study reduces delays and resource consumption (Autodesk University, n.d.), and is particularly flexible

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when handling complex database queries and calculations. Overall, the plugins developed in this study run more stably and impose a lower burden on users' equipment compared to Dynamo-based plugins.

Third, the new approach ensures smooth integration and efficient interoperability between BIM and LCA data through three measures. The first measure normalizes LCA data by establishing the LCBA database, to ensure data accuracy and completeness. The second measure involves developing data transmission and semi-automated data integration plugins, enabling BIM data to be exported in native Revit format and adjusted semi-automatically to the structure required by the LCA model before being imported into the Data Calculation database. This measure establishes a secure integration bridge between BIM and LCA data. It effectively avoids data loss and attribute and type mapping issues commonly seen during the Revit to IFC conversion process (Moreau, 2018) and the problem of inconsistent data structures between BIM and LCA data (Rezaei et al., 2019). The third measure includes an area unit adjustment code in the evaluation button. It ensures unit consistency between BIM and LCA data before calculating evaluation results, thus avoiding inaccuracies due to unit adjustments (Yang et al., 2018).

Fourth, the new approach successfully adds parameters related to interior renovation carbon footprint evaluation results to the Revit components and visualizes these results

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directly in the Revit model by mapping parameter values to colors and applying overrides. In previous carbon footprint assessment approaches, evaluations typically concluded with data or graphs, with results rarely being fed back into the main design platform, Autodesk Revit, for 3D visualization (Hussain et al., 2023; Tam et al., 2023; Zhang et al., 2022). This transition from numerical and 2D chart data to 3D visualization enables interior designers to intuitively understand the carbon footprint evaluation results of interior design and more easily identify carbon reduction hotspots, promoting low-carbon design in Taiwan's interior renovation sector. Visualizing these results in the Revit model and generating low-carbon alternative files can become more effective communication tools between designers, clients, and contractors, encouraging the adoption of low-carbon interior renovation materials. Moreover, since most interior designers and LCA practitioners are not familiar with each other's works, this method also has educational significance. By using the plugins developed in this study, designers can better grasp low-carbon interior design practices, and LCA practitioners can gain a deeper understanding of interior design processes, helping to establish more suitable low-carbon design standards for interior design.

However, it should be noted that the new approach developed in this study requires the Revit model's LOD level to be no less than 350, and the model needs to use the

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‘Coarse Scale Fill Pattern’ in the ‘Graphics’ property to mark partition wall components, thereby ensuring the program runs successfully.

Chapter 6 Conclusion

The carbon emissions from interior renovation are a significant part of a building's embodied carbon emissions but are often overlooked in favor of focusing on the main structure. The current carbon footprint evaluation approaches for interior renovation are time-consuming, prone to human error, have high technical barriers, low BIM-LCA data interoperability, and do not have results backhaul and visualization. To address these issues, this study developed a BIM-based visual assessment approach featuring a standardized database, automated data query functions, semi-automated data transfer and integration assessment functions, and the capability to achieve 3D visualization of assessment results in Revit through the preservation of unique element identifiers, numerical color mapping, and graphical overlays.

The approach was demonstrated through a case study of a demo house at the Taisugar circular village inTaiwan. The results showed the approach's advantages in improving evaluation efficiency, reducing the frequency of human errors, lowering user technical barriers, enhancing BIM-LCA data interoperability, and providing data feedback. The

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visualization of evaluation results and the customized low carbon alternatives document also aids designers' decision-making, enhances communication efficiency between designers and clients, and promotes the education of carbon footprint evaluation in interior design.

In future work, the study aims to improve the approach in the following areas: 1) Incorporating cost assessment of interior design to assist designers in providing optimal low-carbon interior renovation designs for clients; 2) Developing a multi-level database for interior design to accommodate models of different LOD levels; 3) Achieving full automation of data import and export; 4) Adding a comparison function for design changes.

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