Article

Integrating BIM-LCA to Enhance Sustainability Assessments of Constructions

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Abstract: The need for sustainable practices in the construction sector has never been more pressing, as the sector seeks to mitigate its carbon footprint, water consumption, and waste generation. The integration of building information modeling (BIM) and life-cycle assessment (LCA) emerges as a promising solution for rapidly and accurately evaluating the environmental impact of construction. This integration has the potential to empower stakeholders to make informed decisions, paving the way for a more environmentally conscious future in the construction sector. However, there are still challenges to overcome before this is a standard procedure. Data interoperability and standardized classifications necessitate ongoing research. To understand the potential of BIM–LCA integration in minimizing carbon emissions in constructions, this study focuses on a hypothetical renovation project, unraveling the mechanics of BIM–LCA integration and exploring its challenges and opportunities. While the existing literature acknowledges the potential benefits of BIM–LCA integration, few research efforts delve into the specific issues that practitioners may face. Our approach seeks to fill this gap by presenting a holistic view of the integration process, highlighting the practical steps and addressing the intricacies involved. The results show that the most relevant information when performing a BIM–LCA integration using Revit® (v 2022) and OneClick LCA (OCL) is the name-property given to the materials within Revit®. Despite the advances made by this semi-automated approach, interoperability and data accessibility challenges remain. The results show that automated material identification relies on Revit® classifications and necessitates careful modeling practices to prevent impact-calculation redundancy.

Keywords: building information modeling; life cycle assessment; data interoperability

1. Introduction

In a world where the construction sector is responsible for around 40% of global carbon emissions, utilizes 14% of the planet's water resources, and generates approximately 60% of total waste [1], the urgency for adopting sustainable construction practices has never been more evident. To achieve the Sustainable Development Goals (SDGs) [2] and shape a future in which societal advancement coexists harmoniously with environmental well-being, the construction industry stands at a pivotal juncture of transformation.

Traditionally, the life-cycle assessment (LCA) has been the preferred approach for determining the environmental impact of construction and making informed decisions [3]. An LCA analyzes the environmental implications of construction activities, from the raw materials extraction stage to disposal, providing a framework for comprehending the complex interconnection of environmental factors associated with construction.

However, the conventional methods of conducting an LCA suffer from inefficiencies and inaccuracies. Manual data collection and the absence of standardized protocols, as well as oversimplified assumptions, spatial variability, and varying impact assessment methods, etc., culminate in prolonged analysis timelines and unreliable conclusions [4]. Additionally,

the complexity of construction exacerbates these challenges, revealing the constraints of established methodologies.

The potential solution for these limitations lies in digitalization [5]. Leveraging the potential of advanced modelling technologies and data-driven solutions, digitalization offers precision, efficiency, and scalability in navigating environmental impact assessments [6].

The prospect of integrating building information modeling (BIM) [7,8] and LCA presents a potentially transformative phase for environmental analysis [9,10]. By combining BIM's digital representation of the built environment with LCA's comprehensive evaluation, a dynamic workflow is created that captures design details and quantifies their environmental impacts. This synergy has the potential to modernize assessments, enhance data exchange, and elevate the accuracy and scope of outcomes.

For Dalla Mora et al. [1], the use of BIM allows the integration of complex information cohesively, providing accelerated LCA analyses. In the publication, the authors conduct a literature analysis of articles published over the last decade, focusing on BIM–LCA integration methodologies. The review seeks to outline work methodologies and the factors considered in applying BIM–LCA integration, revealing recurring parameters and measures. By summarizing diverse approaches and shared methods, the review contributes to a deeper understanding of successful BIM–LCA integration, emphasizing the significance of level of development (LOD) databases, in addition to software tools for environmental assessments. (For the purposes of the present publication, it is important to note that the terms LOD and LOIN are to be interpreted interchangeably, as some authors and software applications still employ the older terminology, i.e., LOD.) However, the review highlights the need for further development aimed at standardizing processes. This will ensure that BIM–LCA integration becomes an approach that is streamlined, efficient, and user-friendly for sustainable decision-making in construction.

Based on these findings by Dalla Mora et al. [1], it is evident that the majority of BIM–LCA integration studies to date have relied on tools such as MS Excel, Athena, or Simapro for conducting LCA analyses. This observation highlights a prevailing trend in which environmental assessments are predominantly carried out manually, lacking automated tools to streamline the process and minimize potential human errors in impact calculations.

Boje et al. [6] propose a novel approach that harnesses data from BIM and digital twins (DT) to enhance LCA for buildings. The research reviews existing practices, and introduces a methodological framework based on established standards. In summary, the authors state that BIM and DT are promising tools for enhancing the sustainability assessment. However, they also acknowledge existing challenges, highlighting the necessity for constant refinement and advancement in this domain.

Researchers widely acknowledge the potential of BIM to automate modeling tasks and act as a key information source for LCA [11–13]. Despite some existing studies, the integration of BIM and LCA remains in the developmental stage. Defining a workflow and gaining a deeper understanding of how inputs and outputs are inserted and provided are critical aspects that necessitate further research [14–17]. This underscores the importance of addressing challenges related to data interoperability, standardized classifications, seamless stakeholder communication, and the identification of appropriate evaluation tools.

A pivotal question emerges: Can the integration of BIM–LCA, by solely extracting the Bill of Materials from a 3D model, ensure precise environmental impact quantification? This study seeks to explore the potential of a BIM–LCA methodology within the construction industry, aiming to provide a comprehensive understanding of the critical factors involved in this integration process. The novelty lies in identifying essential parameters and enhancing workflow consolidation, focusing on a semi-automated process using a specific tool: OneClick LCA (OCL).

The recent emergence of BIM–LCA highlights its role in improving LCA analysis and refining information extraction from models. Notably, existing studies predominantly concentrate on the design phase [11–13], often overlooking the building's lifespan and maintenance requirements. In contrast, this study adopts a holistic approach, considering

crucial maintenance aspects, assessing scenarios like material recycling and reuse, and exploring the construction workflow from diverse perspectives, encompassing both the current state of the building and a proposed renovation project. Consequently, this investigation delves into the intricacies of the workflow and input considerations within a BIM–LCA integration.

Our study primarily focuses on the interoperability and information exchange between Revit® and OCL. Using a hypothetical 211-square-meter building in Southern Portugal as a case study, we explore the practicalities and challenges of this integration. This exploration includes a detailed analysis of data input requirements, error reduction strategies, and the overall efficiency of this approach in sustainable decision-making. Our objective is to contribute to the evolving landscape of construction sustainability, providing insights and recommendations that enhance the effectiveness of BIM–LCA integration in reducing environmental impacts and achieving the Sustainable Development Goals (SDGs). This study not only addresses current challenges but also aims to pave the way for more streamlined, accurate, and user-friendly sustainable construction practices.

2. Materials and Methods

2.1. Objectives of the Study

The project presented compares the environmental impacts of different construction phases (before and after renovation) of a fictional building to be renovated in a Portuguese city. However, the primary objective of this study is not merely the measurement of the construction's carbon footprint; rather, it aims to thoroughly examine the interoperability process and the information exchange among software systems. Furthermore, this research includes a comprehensive analysis of the behavior of inputs and outputs in this context.

The goal is to merge BIM tools with LCA to enhance the automation of environmental analyses, fostering a more comprehensive and optimized approach of assessing environmental impacts by streamlining interdisciplinary project management and information flow. To achieve this, the interoperability between two software applications is leveraged: Autodesk Revit® for BIM modeling [18] and OCL [19].

This work involved collaboration with multiple disciplines. The first step to be carried out was the architectural design for the 'existing' and 'proposed' phases of a building in Portugal of approximately 211.8 m^2 which is to be renovated for educational purposes, as shown in Figure 1.
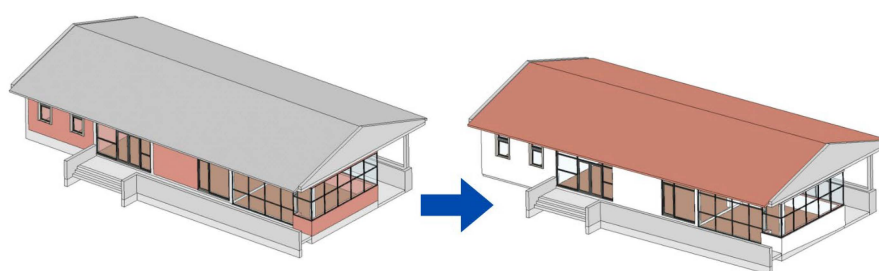

Figure 1. 3D model of the 'existing' building and its 'proposed' renovation in Revit®.

In the subsequent sections, we elaborate on the workflow, software selection process, step-by-step integration procedures, and identification of inputs and outputs, detailing the intricacies of each aspect.

2.2. Software and BIM Tools Utilized

The 3D project is modeled in Revit® 2022.

In order to facilitate a more efficient sustainability analysis, BIM 360 is used as a common data environment (CDE) to share updates between stakeholders while they are collaboratively working on the models. This allowed for continuous feedback in order to optimize the carbon-emission analysis process.

In pursuit of a comprehensive sustainability analysis, several opportunities for software and tool integration have been previously explored. The emphasis is on understanding the flow of information necessary for conducting a thorough assessment of the building's life cycle. Based on this context, the following approaches are identified (Figure 2):
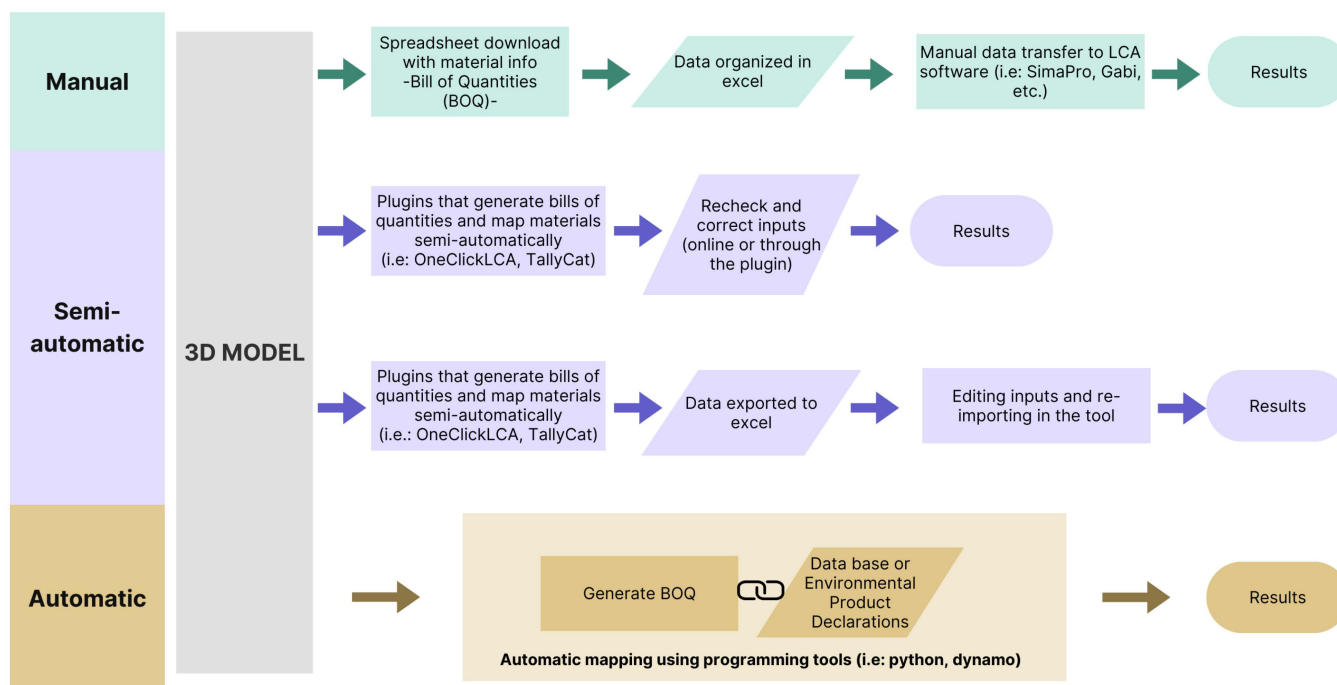

Figure 2. Possibilities for the exchange of information using the BIM–LCA approach.

From the options researched, the OCL plugin/software was chosen to perform the carbon-emission analysis. This choice was motivated by its capability to export quantities and material classification data directly from the BIM model without requiring extensive programming knowledge. OCL, along with Tally Cat, is one of the few tools that offer this functionality. With a user-friendly interface, the software interprets imported data and automatically assigns datasets to materials used in the model. Additionally, OCL provides access to an extensive database which not only contains datasets from the prominent life-cycle analysis database Ecoinvent but also allows for the use of EPDs (Environmental Product Declarations) for materials and elements, as declared by specific suppliers. Consequently, the software enables a more detailed environmental analysis through specific dataset mapping.

Compared to similar tools like TallyCat [20], OCL features more comprehensive geographic datasets, as TallyCat's database concentrates on material production in North America. Considering the project's execution within European territory, the decision was made to use the OneClick LCA software (building version 4.0.6).

2.3. Process Map

Typically, the information flow required for conducting LCA with BIM as the source of quantifiable data follows a structured sequence. It originates from the 3D model generated in Revit®, undergoes interpretation by the OCL plugin within the Revit® environment, and is subsequently exported to the OCL cloud-based platform. This cloud version offers a more user-friendly interface, providing users with the capability to establish connections with datasets from diverse sources, including EPDs. Following this data integration, a comprehensive understanding of the overall information flow can be achieved, as shown in Figure 3.
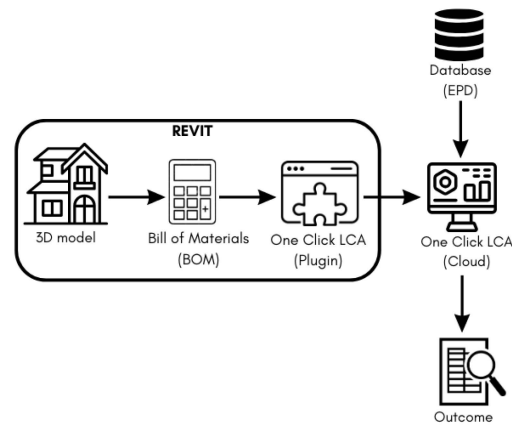
Figure 3. BIM–LCA information flow.

Although this is not recommended, the nomenclature and the level of information needed (LOIN) were refined as the architectural project progressed. The analysis is conducted following the iterative PDCA (plan–do–check–act (or adjust)) management method. Consequently, the assessment is continuously carried out in a loop until the architectural model is considered suitable, ensuring that the elements and materials used in the project are accurately mapped by OneClick LCA. The resulting process map can be seen below (Figure 4):
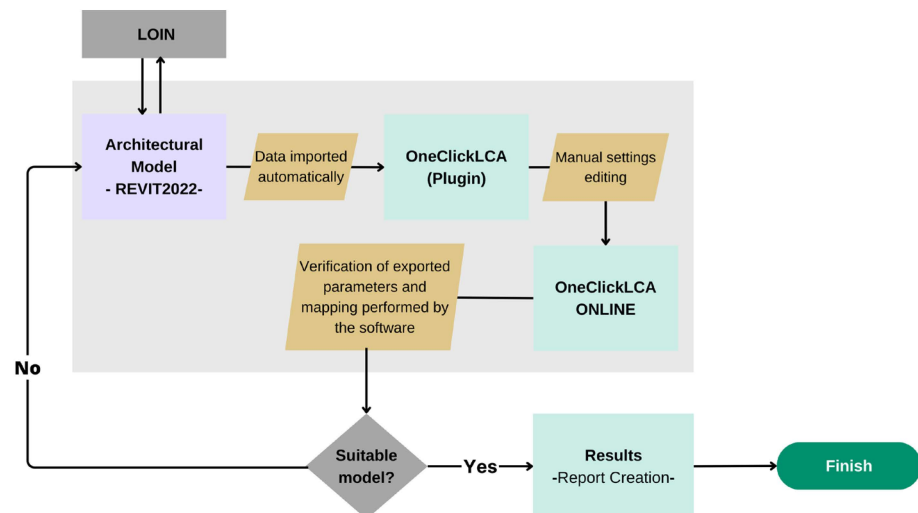

Figure 4. Workflow process mapping.

By utilizing the Revit® plugin, project information is automatically transferred to the online version of OCL. There, the information is mapped to generate a carbon-emissions report. Both the plugin and online versions allow users to adjust certain settings to cluster or divide elements based on their level of detail. Additionally, it is possible to modify the functional unit of each material to optimize the mapping process.

2.4. Exchange Information Requirement (EIR)

To enhance the efficiency of analyzing embedded and operational carbon emissions in buildings, it is essential to define the level of detail and precision associated with the required information (LOIN). The LOIN determines the extent of development and comprehensiveness of information within a BIM model. This approach ensures that the data within the BIM model are suitable for meeting the requirements necessary for conducting environmental impact analyses, enabling stakeholders to access accurate and sufficient information to carry out their tasks efficiently and effectively.

According to EN 17412-1 standard [21], the level of information can encompass a combination of geometric, alphanumeric, and/or document data. The geometric information of an individual object or a group of objects should include aspects such as detail, dimensions, location, appearance, and parametric behavior. The standard also suggests defining an information delivery milestone and addressing questions such as "Who should request/provide the information?", "Why?", "When?", and "What should be detailed?".

For the purpose of conducting the environmental impact analysis, a decision was made to focus on the architectural model only, excluding the HVAC models, electrical models, hydraulic models, etc. As a result, the assessment of embedded carbon is limited to the materials used and the level of detail defined in the architectural design.

Information exchange with the architectural experts in order to conduct LCA is facilitated through the Plannerly application. This establishes the LOIN required for the data to be incorporated into the 3D model. The necessary parameters for performing the environmental analysis are presented below.

Information about the building:

- Building type;
- Area;
- Location;
- Estimated energy consumption.

Specific information about materials used:

- Description of elements/materials;
- Category, family, type;
- Dimensions and quantities;
- GUID.

The LOIN is closely tied to the construction development phase. As the proposed renovation project in this study is still in the design phase, the details regarding specific suppliers or materials to be used are not detailed.

Considering the LOD specified in the software [22], it is apparent that this work adheres to LOD 200-300. This indicates that all building materials are included, except installations. Moreover, all objects have been appropriately classified, avoiding the use of generic models or inaccurate classifications. Specific labeling has also been established to streamline material recognition, ensuring a precise and organized approach.

2.5. Life-Cycle Assessment
Scope of Study and System Boundaries

To conduct the life-cycle analysis, it is essential to define the construction phases included in the analysis and, therefore, the inputs requested by OCL. In this study the European standard EN 15804 [23] is used as a guideline for establishing the principles to be applied in the environmental analysis of the renovated building throughout both construction phases. The analysis considers the environmental impacts of the building's construction, from raw material extraction, transportation, and production (A1–A3) to the end of the building's life. The construction phase details considered within this analysis are described below.

- A1–A3 (Raw material extraction, transportation, and production): Included. Automatically attributed when an EPD is applied to each material dataset.
- A4 (Transportation): Included. Distances were manually inserted based on the ones informed in the EPD.
- A5 (Construction): Excluded in this study.
- B1 (Use): Excluded. (There is no specific field in OCL for inserting this information.)
- B2 (Maintenance): Excluded. (There is no specific field in OCL for inserting this information, but the field to inform repairment can be utilized.)
- B3 (Repair): Excluded. There is a specific field to be filled in to communicate annual repairs given to a product or material. This value is given as a percentage. Therefore, if

there is a window over a total of ten in a building to be repaired in a year, the number to be provided is 2%. In this study, these blank spaces were left empty for both of the projects (before and after).

- B4–B5 (Replacement and refurbishment): Included. OCL automatically defines the service life of products and materials, enabling the automatic calculation of their impacts. The lifespan of the building is set to the standard 60 years established by EN 15978 [24] and EN 15804 [23]. Considering that some materials have shorter lifespans, the automatically defined lifespan provided by the software is adopted. Similarly, default values for waste, transportation distance, and end-of-life processing of materials configured by the system were adhered to. It is crucial to acknowledge that information on the longevity of products is often scarce; in many cases, even the manufacturers may not have precise data on the durability of their products. Therefore, the necessity for accurate and comprehensive EPD becomes evident, not only for selecting appropriate datasets for specific projects, but also to ensure that the life expectancies of products are accurately reported. This approach is vital for enhancing decision-making processes in sustainable construction, aligning with broader goals of environmental, social, and economic impact mitigation.
- B6 (Operational energy use): Included (demanded by OCL). This is calculated with Insight and Green Building Studio (GBS); to perform the carbon-emissions analysis for the building, OCL requires the estimated annual energy consumption and the lifespan of the building. For defining the building's energy consumption, Revit® is used in conjunction with the GBS [25] and Insight [26] tools. The calculated annual energy consumption is 36,711 kWh/year for the existing construction and 30,744 kWh/year for the proposed version.
- B7 (Operational water use): Excluded.
- C1 (Demolition): Excluded.
- C2 (Transport): Excluded.
- C3–C4 (Waste processing and disposal): Included. OCL allows the user to define the EOL of the products. The options vary between 'do nothing', 'reuse', 'backfilling and landfilling' for inert materials, and 'recycling'. The program suggests specific EOL depending on the EPD selected for the material. Concrete, mortar, and bricks, for example, are automatically set to be crushed and used as aggregate in subbase layers.
- D (Re-use, recovery and recycling potential): Included. In OCL it is possible to define whether the material is to be reused. This field is used to model the project after renovation, since most of the elements of the building were maintained.

3. Interoperability between Revit® and OneClick LCA

Working with two distinct software platforms involves deciphering how inputs from one, namely Revit®, are interpreted by the other, OCL.

While the export of quantities and materials from Revit® to OCL was a known objective from the outset, the challenge lay in identifying the key fields within Revit® that would serve as vital inputs. A question arose as to how this information could then be transformed into meaningful outputs, mapping materials and products from Revit® to specific datasets reflecting real-world environmental impacts. To streamline this process and create a standardized workflow, we introduced a labeling pattern for materials within Revit®. This pattern ensured clarity in the exported information when integrated into OCL. The subsequent sections show details of this labeling process and elucidate the ensuing procedures employed throughout the entire analysis, facilitating a seamless transition between the two software environments.

3.1. Nomenclature

Guides provided by the OCL software company (Helsinki, Finland) [27] advocate detailed labeling and note the possibility of performing late-stage manual mapping edits.

However, considering that the aim of this project is to automate the LCA process as efficiently as possible, several questions needed to be addressed:

1. Which language should be adopted? Portuguese or English?
2. What level of detail should be adopted in the material labels?
3. What information needs to be visible and immediately comprehensible?
4. Sequence of information within the material property?

To enhance the LCA, it is crucial that all materials and elements modeled in BIM tools adhere to the established agreement. Due to its international character, English is designated as the primary language for this study.

In conducting life-cycle analysis, it is essential to pre-identify which elements should be considered, avoiding excessive object-modeling details. Otherwise, the file may become so large that it is difficult to share, and the list of elements to be mapped may grow significantly, extending the analysis time, particularly if reviews and manual editing are involved, rendering the process unfeasible.

From the perspective of environmental impacts, it is paramount to focus on elements present in greater quantities, rather than on overly specific details (such as screws and nuts, for example), which would rarely have a substantial impact in the overall construction context. However, prior knowledge about higher-environmental-impact materials (like concrete and steel) that are regularly used in construction is required. This approach would allow for a prior segregation of materials and the establishment of the LOIN necessary for consideration in the analysis.

To facilitate material identification when exported from Revit® to OCL, the following sequence of information is defined:

Class: WALL
Family: WALL_EXT_E
Type: WALL_EXT_CERAMIC_E
Material: CERAMICBRICK_HOLLOW_25_E

When conducting mapping, the material label in Revit® is essential for identifying the information on OCL (either the online version or plugin). Initially, details such as class/family and material type were included to the material name (e.g., Material: WALL_EXT_CERAMICBRICK_HOLLOW_25_E), resulting in different material labels for the same material. Therefore, it is advisable to only write the name of the material used and its relevant specifications.

Either in the 'Type' or 'Material' field, information such as the material dimensions or geometric information (e.g., MULLION_FRAME_10 × 5_E) is added. The dimensions were standardized and listed in the order: length × width × height (or depth), using centimeters as unit of measurement.

Considering that this project involved two construction phases, an 'E' for Existing phase and a 'P' for Proposed phase were added to the end of the 'Type' and 'Material' fields. Therefore, when a material list is generated in Revit® or OCL, it is possible to identify which materials are to be replaced and which not.

3.2. Step-by-Step

By using the OCL plugin, it is possible to export quantities, modeled elements, and material-related information. The first decision to be made in the OCL plugin is the selection of the database for mapping purposes. Here, the software's recommendation is embraced, opting for the impact assessment methodology mandated by European standards EN 15978 [24] and EN 15804 [23], which is known as CML [28]. This methodology includes a database of characterization factors essential for life-cycle impact assessment (LCIA).

The grouping mode for construction elements available in the OCL plugin is an integral field for deliberation. It allows for the combination of materials from the same family, streamlining the analysis. For instance, a wall may consist of bricks, plaster, and paint. Opting for this approach facilitates the selection of specific EPDs [26] that encompass the entire family.

However, determining the availability of datasets for each family in advance can be difficult, necessitating periodic checks using the OneClick LCA Online version.

An alternative within this field is 'Split family types into materials', which effectively fragments families into individual materials. This theoretically eliminates the need to verify compatible EPDs, as most construction materials can be found in the program's libraries. This alternative is particularly advisable when pursuing a more detailed analysis of environmental impacts. Nevertheless, it is important to note that, depending on the precision of the Revit® modeling, large projects might grow intricate due to the numerous datasets assigned to each distinct material.

The subsequent step involves the selection of the model to be subjected to analysis. Considering the presence of two models, the 'existing' and the 'proposed', the most effective approach to selecting the desired project phase is opting for the 'Active model' selection. This mitigates any information interference between phases and enhances clarity regarding the analyzed project phase. However, it is important to note that if an element is in 'hidden' mode, the OneClick LCA plugin will not identify it, potentially affecting the model's analysis.

Within the plugin, specifically under the 'Detailed Scope' tab, the functional unit of measurement for analysis can be defined. However, it can be observed that this selection only extends to the level of element type, allowing the definition of a separate functional unit for an element like 'door', for instance. However, if the field 'split family types into materials' is chosen, the element is then divided into various parts, such as door leaf, lock, and frame. Even if each requires distinct functional units, these units can't be attributed at the material level. Consequently, when materials are mapped in the online version, functional units are often inaccurately assigned.

Opting to 'keep family types grouped' within the grouping field leads the software to cluster elements, which hinders automated mapping due to the existence of a diversity of composite materials. This approach does not aid unit assignment, but it at least reduces the number of elements requiring mapping.

While materials appear in different units in the plugin mode, when exported to the online model, the dataset unit options are limited, contingent on the plugin selections. Since it is not possible to assign units at the material level in the 'Detailed Scope' tab, an element with 'area' selected as the functional unit will often only have 'area' and 'volume' options for its components.

Despite the 'Detailed Scope' tab being the field inside the plugin designated for the modification of units, the optimal place for defining material units is within the 'Materials' tab, where specific material units can be specially assigned. This way, when data are exported to the online version, materials can be organized and grouped, thereby facilitating mapping. However, each time the model is updated, the changes in the unit must be performed again manually, compromising the automation process.

Within the plugin, materials are grouped according to the assigned source category in Revit®. The list and quantity of materials extracted from Revit® appear in the 'Materials' tab, and are categorized into 13 groups: Ceilings, Curtain Panels, Curtain Wall Mullions, Doors, Exterior Walls, Floors, Interior Walls, Roofs, Stairs, Structural Columns, Structural Foundations, Structural Framings, and Windows.

The program demands the creation of an initial project design and definition of parameters, including the project name, development phase (selected: 'design development'), project type (selected: 'renovation of an existing building'), and structure type (the program prompts the user to select 'not applicable' if it is not a new construction). Then, the available tool 'Level(s) life-cycle assessment EN 15804 + A1' [26] is selected. Level(s) is a European approach to assessing and reporting building sustainability performance throughout the entire life-cycle of the building, as compliant with EN 15978 [25]. Version +A1 exclusively utilizes the CML database [27,28].

The software exports the 'Family' classification assigned in Revit® to the online version. The previously inserted information and the classifications can be edited and modified. However, the options are more limited, compared to the plugin version or Revit® itself. For

instance, elements like stairs need to be classified as 'others', curtain walls fall under the 'wall' classification, and interior walls, even though correctly mapped in the plugin version, are always read as 'exterior' walls in the online version.

Evidently, the plugin uses the 'function' parameter assigned in Revit® to define the 'interior wall' classification (see Supplementary Materials Figure S1), while in the online version, only the general 'wall' classification is exported, and the software categorizes all walls as 'exterior' ones. In OCL review tab, despite manually modifying the wall category, the internal walls still appear in the external category (see Supplementary Materials Figure S2), which indicates possible interoperability problems within the OCL plugin and online version.

In order to maintain clustered identical elements and update the mapping process, the option to cluster by 'type' is deselected. In this manner, certain elements, e.g., doorknobs and door locks, could be grouped into a single item.

When the mapping is finally conducted, only 60% of the material volume used in the existing phase was automatically mapped by the software. It is possible to observe that not all materials were automatically mapped, and some of them were inaccurately mapped. During the configuration setup, it is possible to define whether the used materials should be clustered or separated, thereby improving the software's recognition of different materials.

However, as shown in Supplementary Materials Figure S3, doors of different types had their components mapped unevenly. The wooden door leaf is mapped as 'plywood', whereas the glass pane belonging to another door is categorized as if it were the entire door ('steel door with glass'), thus accounting for the environmental impact of the frame as well.

Similarly, if elements like door frames or window frames are modeled as part of the 'door' or 'window' element and the option to 'not split materials' is selected, the entire set of materials used (including the frames) is accounted for, making the mapping even more complex. Hence, careful attention is necessary to avoid double-mapping of an element.

According to the EN 15804 + A1 specification, the cutoff criteria for input data should be 1% of the primary renewable and non-renewable energy use and 1% of the total mass input of that unit process. The total neglected input flows per module (A1–A3, A4–A5, B1–B5, B6–B7, C1–C4, and module D) should not exceed 5% of energy and mass consumption. To reduce the number of inputs and simplify the analysis, OCL allows the elimination of inputs that, when combined, constitute less than 1% of the total mass. This leads to a reduction of the number of inputs and, consequently, a smaller number of elements to be mapped.

The remaining inputs were manually mapped using datasets produced in Portugal or Spain.

During the process it was observed that the automated material mapping process was closely tied to the description associated with the names (see Supplementary Materials Figure S4). It was observed that the category of the element was typically stated before the actual material name, as the software did not recognize this automatically. For instance, the term "wall" was mentioned first, followed by the desired element "ceramic brick."

Therefore, a final test was conducted to verify whether modifying the material names would facilitate the software's recognition of the material:

By modifying the material names (see Supplementary Materials Figure S5), the percentage of automatically mapped elements increased to 84.59%. This time, the majority were mapped to datasets compatible with the intended material.

The bricks that previously went unrecognized by the software were automatically mapped to datasets compatible with the material in this test (see Supplementary Materials Figure S6). Previously, it was thought that the software utilized the Revit® classification, in addition to a few other parameters, to identify and subsequently "auto-map" materials. However, after the name modifications, it became apparent that the way the material name is written is equally, if not more, crucial as the classification in Revit® for achieving optimal mapping.

A few unmapped elements, such as the ceramic roof and the insulation material (see Supplementary Materials Figure S7), were not automatically mapped because the material names were not written exactly as they appear in the program's database. For instance, the ceramic roof, written as 'ceramic tile,' would only be mapped if the term 'roofing tile' were

used. The same applies to the insulation material, which was written exactly in the manner recorded in the database, but without a space between the words 'Rock' and 'Wool,' and it included a comma before the word 'insulation,' exactly as presented in the program.

3.3. Proposed Phase

Despite the availability of a tool that allows for visualizing changes to the project using distinct colors, the material identification process faced complications while mapping the proposed phase; it was difficult to differentiate between materials that were retained, refurbished, added, or replaced.

As a result, some materials and elements had to be renamed once again within Revit®, taking into consideration the alterations made in the proposed design:

- Ceilings: Only in the 'Proposed' version.
- Curtain Panels: Modified.
- Curtain Wall Mullions:
  - Casings: Retained.
  - Frames: Modified.
- Doors:
  - Interior: Retained but sanded, painted, and varnished.
  - Exterior: Modified.
- Walls:
  - Interior: Retained, but painted and refurbished (bathroom tiles).
  - Exterior: Retained, but painted and refurbished (external insulation system).
- Floors: Modified.
- Roof: Modified.
- Stairs: Retained.
- Structural Elements: Retained.
- Windows: Modified.

For this version, materials to be used in ceilings (absent in the previous version), for instance, were identified by adding the letter 'A' to signify elements added to the model. Materials used in the interior doors, which were refurbished (polished and painted), were identified with the letter 'R' at the end. Elements and materials demolished in the existing phase were marked with the letter 'D' at the end.

Elements in the proposed phase that were completely renovated while remaining extant in the existing phase, such as curtain walls and exterior doors, were labeled with a 'P'. Materials and elements that were in good condition in the existing model and were therefore retained and not renovated were marked with an 'E'.

The initial idea was to rename materials by adding the representative letter at the end to assign the same datasets to retained elements in both phases. However, it was observed that, before finalizing the mapping in OCL, it is possible to download an Excel file containing a list of all materials extracted from Revit®, along with the quantities and classification information (see Supplementary Materials Figure S8 (1)). After mapping (see Supplementary Materials Figure S8 (2)), the material fields are filled in using the mapped datasets. This means that the added material names are removed, making their identification impossible. This information is crucial, because the unchanged elements in the proposed version must have the same dataset as those used in the existing version in order to enable a comparison of the environmental impacts of the modifications made. Nonetheless, the comment field available in the Excel file generated by OCL contains information corresponding to the designated family names in Revit®. This field was subsequently manually edited in Excel to identify added, demolished, existing, proposed, and refurbished materials. The following sequence of actions was followed:

1. Export Revit® data to OCL (plugin and online).

2.   Map elements in the proposed phase (employing low-impact datasets for refurbished materials).
3.   Download the Excel file after mapping.
4.   Manually edit the comment field to classify existing, added, proposed, and refurbished elements.
5.   Filter existing elements to determine which datasets used in the existing phase should remain unchanged.
6.   Map the existing phase using datasets that might not necessarily be correct (opting for relatively higher impact datasets for material fields in the existing phase to be altered).
7.   Download the Excel file after this second mapping.
8.   Edit the comment field again to identify existing and refurbished elements, referring to the Excel file from the proposed phase.
9.   Transfer unchanged datasets from the proposed to the existing phase.
10. Upload both Excel files to the online version of OCL (existing and proposed phases).
11. Examine the results in the online version of OCL.

4. Results and Discussions

Challenges and Best Practices

In Revit®, there is a recurring issue which pertains to the double-counting of intersection areas between elements, which is particularly noticeable with overlapping elements like walls or slabs. This discrepancy arises when, for instance, a wall includes two layers of 2 cm plaster and a layer of brick, causing the software to overlook the intersection area between walls. Consequently, an erroneous duplication of plaster quantities occurs, impacting the accuracy of the life-cycle analysis in OCL. To rectify this, it is essential to ensure precise modeling, avoiding unnecessary intersections and potentially reducing the automatically calculated material waste in OCL.

A notable discrepancy in window quantities between OCL and Revit® was also identified at a specific mapping stage. OCL listed 28 windows, while the Revit® model only accounted for 11. The root cause was traced to windows being modeled as curtain walls, inadvertently inflating the window count due to the inclusion of curtain wall components. To mitigate such issues, a meticulous review of counting and the use of appropriate tools for element creation, such as specifying 'windows' for windows and 'doors' for doors, is recommended.

Classification systems like Secclass [29] and CoBie [30] were also explored and revealed limited relevance in simplifying the mapping process or optimizing dataset allocation. Initially, there was also an assumption that the Industry Foundation Classes (IFC) file format would play a role in the process of element identification complementary to that of OCL. However, after conducting tests, it was found that OCL relies on classifications defined in the Revit® modeling software itself to categorize and identify materials. Details such as Category, Family, Type, and Material proved to be of paramount importance, both for the analysis of elements and to simplify the allocation of datasets in OCL. Hence, avoiding generic or uncategorized objects is also relevant in ensuring better interoperability between the software.

Despite the expansive capabilities of parametric modeling, OCL relies predominantly on basic information, such as labels, classification, and quantities, for material mapping. The limitation becomes apparent when parameters like conservation status and pathologies are not automatically incorporated, impacting the accurate assessment of potential renovation needs. Furthermore, nuanced details, such as whether materials are painted, often escape OCL's notice unless manually inserted as an additional layer. This underscores how the modeling process significantly shapes dataset mapping, highlighting the importance of meticulous cross-checks.

To ensure effective automation in the material-identification process using OCL, the current best practice involves breaking down elements into their respective material compositions. This approach significantly enhances the software's recognition of materials.

However, during the mapping stage, many datasets often extend to cover the entire element. For example, when considering a window broken down into materials like aluminum (frame) and glass, it may happen that a dataset for the entire window is automatically linked to one of the materials. This scenario results in the duplication of environmental impacts and compromises the results. Therefore, a meticulous analysis of the mapped elements and materials is necessary to ensure their full compatibility with the chosen dataset.

In general, the proper naming of materials and elements plays a fundamental role in facilitating the correct recognition and automatic mapping by OCL. The company responsible for OCL advocates the use of nomenclature aligned with the EPD dataset used in the mapping stage. However, this information is only accessible at the end of the mapping process. This would imply an overly time-consuming process of searching for the necessary datasets in advance and subsequently renaming them in Revit®. To optimize the automation of mapping by OCL, it is recommended to designate elements in a way that accurately reflects the material used, avoiding special characters in material names and preferably opting for English language designations.

Environmental analyses in the early stages of a project often present limitations in levels of detail, which, on one hand, restricts the precise quantification of impacts but, on the other hand, provides a degree of flexibility in exploring more sustainable possibilities. In contrast, the final stages of a project are often associated with less editing freedom and higher levels of detail. However, a higher LOIN does not necessarily determine a more accurate quantification of environmental impacts. This is because highly detailed materials, including details as to information about specific suppliers, for example, do not always have corresponding datasets available in databases. In the end, the used dataset, obtained through a database like Ecoinvent or approximated based on geographic location using EPDs, often turns out to be more generic.

When implementing different phases in a project, the most effective strategy for discerning elements and materials at each stage proved to be associated with the assignment of indicators to nomenclature. In this study, the practice of incorporating indicators (both in material designations and in the 'Observations' field), such as 'A' for added elements, 'R' for refurbished, and 'D' for demolished, among others, is adopted.

Unfortunately, in this context, the automation of BIM–LCA integration is affected due to the need to identify a single dataset to be assigned to both phases. As a result, manual manipulation through Excel spreadsheets became necessary. This not only hindered the automation of the process but also raised questions about the inherent complexity of identifying identical datasets in different phases, especially in large-scale projects.

5. Conclusions

This study underscores the crucial role played by precise material labels in enhancing dataset mapping within the Revit®-OCL framework. Challenges arise when material titles in the 3D model diverge from those in the EPD, making synonyms or equivalent labels ineffective. This highlights the imperative need for a standardized nomenclature across both platforms, ensuring seamless integration and accuracy in environmental impact assessments.

Exploring uncertainties in the Bill of Materials generated by 3D model software emphasizes the importance of accurate quantification for reliable measurements of environmental impacts. This task becomes particularly challenging in projects with intricate details. The correctness of the project design is pivotal, underscoring the need to stress the significance of using correct categories within software like Revit® and implementing thorough checks to maintain data consistency.

To tackle these challenges, a multifaceted approach is essential. The emphasis on accurate and standardized modeling practices forms the foundational step, fostering clear communication through the establishment of a detailed LOIN for harmonious collaboration with third-party modelers. Rigorous checks for quantities and mapping, combined

with a proactive stance in seeking out software updates, significantly contribute to the reliability of the integration process. Additionally, exploring programming capabilities offers tailored solutions, enabling the incorporation of custom parameters to meet specific project requirements and overcome software limitations.

In conclusion, optimizing the integration process necessitates a holistic strategy that seamlessly blends standardized practices, effective communication, and technological enhancements. Proactive measures, such as defining LOIN and leveraging programming for custom parameters, play a crucial role in achieving a more accurate and efficient environmental impact assessment. This aligns seamlessly with the overarching goal of fostering sustainable decision-making in construction projects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16031172/s1. Figure S1: Scheme of input/output information given in Revit®and OCL; Figure S2: Internal walls correctly mapped in the plugin and manually modified in the online version appear as 'external walls' in the final mapping step; Figure S3: The automatic mapping can lead to duplicated environmental impact; Figure S4: The unidentified materials: names are crucial to enable automatic mapping; Figure S5: Names given to the materials inside Revit®2022; Figure S6: OCL mapping after correcting names in Revit®; Figure S7: Some unidentified materials after name correction. Figure S8: Material quantities and classification information: (1) Before mapping (selecting the respective datasets for each material); (2) After mapping.

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