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Automated Life Cycle Analysis Tool for Bridge Design: A User-Friendly Model for Sustainability

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ABSTRACT: Large-scale infrastructures including bridges are designed for long lifespans and yet require substantial materials such as concrete and steel, which have high impacts on the environment. Therefore, considering the sustainability requirements early during the design stage is crucial. Life cycle assessment (LCA), which is a systematic and standardized approach for quantifying these environmental impacts, provides designers a better insight to develop eco-friendly solutions that reduce these long-term impacts. It also helps decision-makers to compare different design alternatives and select the one that meets the set sustainability goals. This paper introduces an innovative computer model to minimize the gaps between designing bridges and analyzing their environmental impacts to help engineers investigate and evaluate the design's impact early in the conceiving process. The developed model is a standalone graphical user interface (GUI) that provides a platform to input, process and analyze necessary data for evaluating the environmental impacts across various LCA stages. The development methodology used in this study starts by collecting and storing essential data in a database created for that purpose in Excel and MySQL and thereafter mapping the data with the Life Cycle Inventory (LCI), specifically the Ecoinvent database. Afterwards, the model's implementation and creation of the user interface are fulfilled by using C# programming language and openLCA platform. Finally, the model's generated outcomes are provided to users in graphical and tabulated formats. The said model will offer a practical and efficient solution to integrate sustainability requirements during the early stages of designing bridges and will facilitate making informed decisions to minimize their environmental impacts.

1. INTRODUCTION

Reducing the emissions produced by the construction sector is critical for mitigating climate change, conserving natural resources, protecting human health, and ensuring long-term economic and environmental sustainability. World Health Organization (WHO) (2014) reported that 7 million people died because of exposure to air pollution, which represents one-eighth of the total global deaths. The construction sector is responsible for around 37% of the global operational energy and process-related CO2 emissions (UN Environment Programme UNEP, 2024). Despite the existing variations in the waste production data, it is agreed that the construction sector accounts for 30% to 40% of the global solid waste (Petrović and Thomas, 2024). Life cycle assessment (LCA) is transforming how the construction industry approaches sustainability, enabling stakeholders to make data-driven decisions that reduce environmental impacts. LCA is defined as a systematic methodology to assess the environmental impacts of a project over its entire life cycle. In the construction sector, LCA is gaining prominence as a critical tool for understanding and reducing the environmental footprint of buildings and infrastructure. LCA can be divided into different life cycle stages, including: production stage; construction stage; use stage; end-of-life stage; and beyond end-of-life stage. Beyond the end-of-life stage focuses on evaluating the long-term

environmental impacts, and the net benefits associated with reusing recycled and recovered materials in new projects (Lemperos, 2024). ISO 14040 series identified four phases for any LCA study, which are: goal and scope definition (system boundaries and LOD); inventory analysis (LCI); impact assessment (LCIA); and interpretation (International Organization for Standardization, 2006). LCA is increasingly recognized as a critical tool applied early during the design stages of bridge projects, facilitating the integration of sustainability considerations into the decision-making process. For example, one comparative analysis revealed that epoxy asphalt concrete can be considered as a low-carbon material, reducing life-cycle carbon emissions by 77.6% if compared to Guss asphalt concrete (Zhang et al., 2024).
One of the World's leading LCI databases is Ecoinvent., which was first introduced in 2003 with version 1, then it has been continuously updated, with version 3 released in 2013 (Wernet et al., 2016). Ecoinvent database encompasses a comprehensive range of products, services, and processes ranging from building materials to food and from resource extraction to waste management (Hillege, 2024). Many studies that looked at the integration of BIM with LCA, such as Hollberg et al. (2020), Marrero et al. (2020), and Lima et al (2024), adopted this database as a source of LCI database.
On the other hand, Bridge Information Modeling (BrIM) an extension of Building Information Modeling (BIM) for bridge design and management, is a great tool for visualization, 3D modeling, data management, and centralized data for bridges that enables stakeholders to better coordinate and share project's information. BrIM can facilitate the development of detailed digital models of bridges allowing designers to compare different design alternatives and construction processes. It also provides a platform that enables stakeholders to share and visualize data leading to better communication and collaboration (Jrade et al., 2023).
Although several studies in the literature focused on the integration of BrIM/BIM with LCA for bridge projects (Van Eldik et al., 2020; Kaewunruen et al., 2020; Nahangi et al., 2021; Péntek, G., 2023), there still a need for additional studies for a more accurate, reliable, global and effective sustainable assessment method especially as BrIM/BIM is infrequently adopted for a main goal of environmental assessment and there is a need to change the details and scope of BIM for effective Green House Gas (GHG) assessment (Nahangi et al., 2021). Compared with the building sector it is obvious that there is lack of research on the integration of BrIM, LCA and LCCA in literature for infrastructure although these types of projects are more complex and the need for BrIM to facilitate the implementation of LCA and LCCA is higher. The integration of BIM with LCA and LCCA has received significant attention in the building sector. Jrade et al. (2023) found that there are 329 and 114 articles that integrated BIM with LCA and with LCCA respectively.
This study presents the development of an innovative computer model to bridge the gap between bridge design and environmental impact analysis through the development of a standalone user interface (UI) that allows users to input, process and analyze data across the LCA stages. The development process includes collecting and storing necessary data in Excel and MySQL, mapping the collected data with the Ecoinvent database, developing the UI by using C# programming and openLCA platform, and finally, generating results in graphical and tabulated formats.

2. LITERATURE REVIEW

The integration of BrIM and LCA represents a significant advancement in the field of sustainable infrastructure. This section highlights the current state of research on this integration, identifying the methodologies, benefits, and challenges associated with integrating BrIM and LCA for bridge projects. Incorporating LCA assessment into the design process can help support making decisions related to sustainable bridges (Soust-Verdaguer et al., 2023). Tam et al. (2023) identified that the early design stage has a significant impact on the final performance of the project, while Forth et al., (2023) believed that targeting this stage would help designers optimize the environmental outcomes when the design choices are still flexible and can be easily adjusted. However, there is still during this stage lack of sufficient and detailed information about the project (Tam et al., 2023).
Not many studies focused on the integration of BrIM and LCA for bridge projects such as the studies done by Van Eldik et al., 2020; Kaewunruen et al., 2020; Nahangi et al., 2021; Jrade et al., 2023; and Péntek, G., 2023. Van Eldik et al. (2020) developed a BIM-based LCA framework to integrate and automate the environmental assessment during the design stage. The proposed framework allows designers to assess the environmental impact of different design choices in real time by calculating the Environmental Impact Scores (EIS) for the design elements and visualizing them directly in the BIM model. Moreover, Péntek, G.

(2023) proposed a BIM-based framework to assess the environmental impacts of a bridge at the early design stage with a case study from the Netherlands. The methodology of integrating data was through dynamo within BIM environment.

Jrade et al. (2023) conducted a comprehensive literature review focusing on the integration of BrIM with LCA and LCCA. Reviewing 102 selected articles, the authors noted that integrating LCA and LCCA with BrIM enhances the decision-making process by providing designers with detailed economic and environmental information throughout the project life cycle. Another study conducted by Kaewunruen et al. (2020) highlighted a contemporary 6D BIM approach for life cycle bridge management, 3D model information, 4D time scheduling, 5D cost estimating, and 6D carbon footprint assessment. Whereas, Nahangi et al. (2021) conducted a comparison between BIM-based GHG assessments and conventional assessments based on quality assurance and quality control (QA/QC) reports. 63% and 47% extra concrete volume delivered to the site based on QA/QC reports compared to initial estimation from the BIM model and preconstruction estimators, respectively. This would lead to a significantly different outcome of GHG emissions based on the BIM model and real situations. The concrete quantity based on the BIM model is 1507m3, 1664m3 predicted by estimators, and 2,452m3 were in reality delivered to the site.

One important finding by Jrade et al. (2023) is that they identify six main methods to integrate LCA with BIM, which have been listed in the literature, as follows: exporting the Bill of Quantity (BOQ) into Excel; exporting BOQ into exclusive LCA software; the use of LCA plugins in BIM software; using visual programming tool such as Dynamo; use IFC to transfer the data to an LCA software; incorporate LCA data directly to the elements in BIM model.

The integration of BrIM and LCA offers numerous benefits that enhance the efficiency, accuracy, and sustainability of infrastructure projects. The integration of LCA with BrIM allows for a more holistic approach to environmental impact assessment, enabling engineers and decision-makers to visualize and analyze the sustainability of bridge projects in real time (Van Eldik et al., 2020). By integrating LCA into BrIM, stakeholders can evaluate the environmental impacts of various design alternatives early in the project's lifecycle, optimizing design and efficiently presenting results to clients, thus facilitating more sustainable choices (Van Eldik et al., 2020). It improves the decision-making process by providing designers during the design and construction stages with detailed economic and environmental information (Jrade et al. 2023). Péntek, G. (2023) was able to efficiently present LCA bridge elements with environmental outcomes, visualizations and graphs, which helped make sustainable decisions at the early stage of the project. It reduces the interoperability problems between software packages and limits human errors during the normal assessment process. It can save time, reduce errors during pre-construction and construction stages, better visualization, and promote cooperation among project stakeholders (Kaewunruen et al., 2020).

Despite the clear advantages, challenges remain in the integration of LCA and BrIM. One significant barrier is the need for standardized methodologies for the connection between environmental databases and BrIM tools. Additionally, expanding the applicability of the developed frameworks to other geographical contexts is also another hurdle (Van Eldik et al., 2020).

The main challenge, however, lies in the data transition during the integration process (Jrade et al., 2023). To address this, Jrade et al. (2023), recommended to conduct more analysis and evaluation to guide researchers in developing prototype models to integrate BrIM with LCA and LCCA. Another issue is the higher compatibility of BIM with building standards if compared to BrIM (Kaewunruen et al., 2020).

After reviewing 34 articles from 2013 to 2017, Crippa et al. (2020) highlighted three primary challenges in the literature: the lack of interoperability of BIM and LCA tools; the time-consuming process of manual data input; and the lack of information in databases about specific materials. Similarly, Safari and Azari Jafari (2021) mentioned that most of the BIM-LCA studies focused on manual and semi-automatic approaches of data integration at the initial design stages. Furthermore, Chen et al. (2024), after reviewing 152 articles, they listed some of the challenges, which include: inefficient data exchange between BIM and LCA tools; lack of standardized formats for data sharing; time-consuming process of mapping the LCA database with materials manually; and variability of level of details (LOD) provided by BIM.

The integration of LCA with BrIM represents a transformative approach to advancing sustainability in the infrastructure sector. By combining the rich data capabilities of BrIM with the analytical power of LCA, stakeholders can optimize designs, reduce environmental impacts, and meet climate goals efficiently. Although challenges remain, advancements in technology, standardization, and stakeholder engagement promise a future where BrIM-LCA integration becomes a standard practice in sustainable infrastructure.

While previous studies explored BrIM-LCA integration, many remain limited when it comes to practical application. A key gap in the existing literature is the lack of user-friendly platforms that allow non-expert users to conduct LCA. Additionally, few existing models support automated workflows where they rely more on manual processes (e.g., Kaewunruen et al., 2020). Furthermore, some studies have excluded important life cycle stages such as maintenance from their assessments (e.g., Kim et al., 2024) and also focused on limited impact categories (e.g., Kaewunruen et al., 2020). These limitations reduce the usability and scalability of their studies. In response to these gaps, this study introduces an automated, standalone and user-friendly user interface that covers all life cycle stages, a wide range of materials and analyzes nine distinct environmental impact categories.

3. METHODOLOGY

This study presents an integrated framework to integrate BrIM and LCA. The methodology consists of sequential phases including data collection; data mapping; database development; user interface (UI) development; and finally, LCA results generation and visualization. This approach integrates a developed knowledge-based database with a user-friendly interface to facilitate bridge's impact analysis. The key steps of the process are shown in Figure 1.

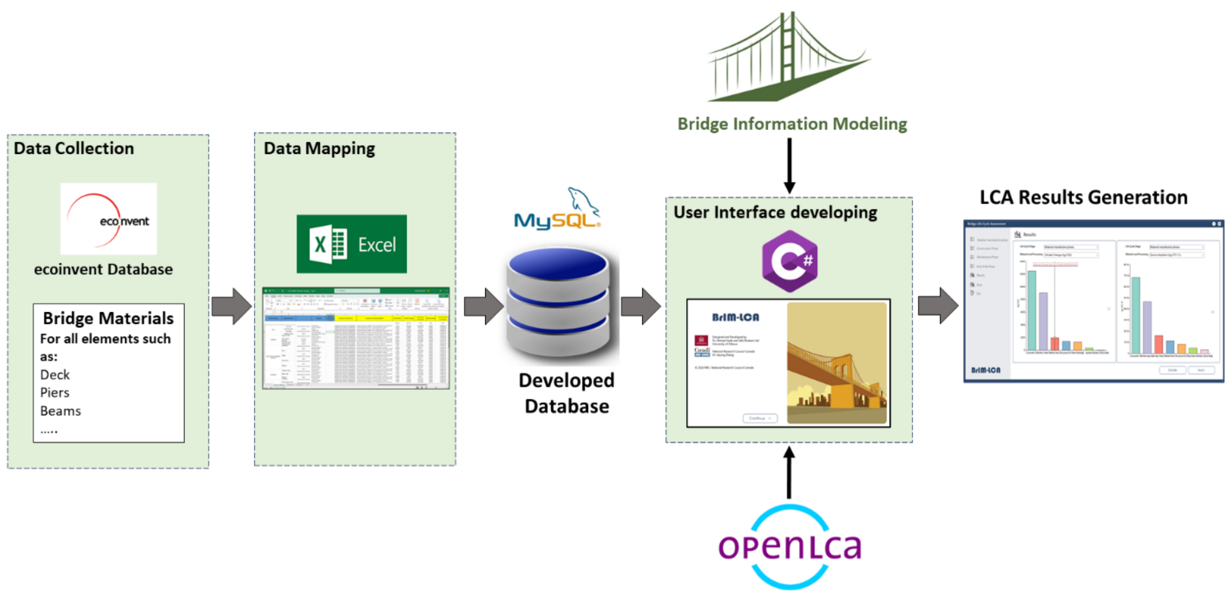

Figure 1: Model Development Process Flow

3.1 Data Collection

The first step starts by collecting data related to bridge materials for various bridge elements such as decks, piers, beams, foundations and coatings. Then, Ecoinvent database, as an LCI database, is used to extract the environmental impact data of various materials that can be used in infrastructure projects. Ecoinvent is one of the most comprehensive and widely used LCA databases that provide comprehensive environmental datasets regarding various materials and processes. Ecoinvent offers impact factors for material extraction, processing, transportation, and disposal.

3.2 Data Mapping

The second step focuses on mapping the collected data with their corresponding entries in the Ecoinvent database. This step is a crucial stage of the development, which ensures that the environmental impact of each material is accurately represented. Microsoft Excel is used for this purpose while the mapping process is conducted manually. The created spreadsheet includes different columns for the collected data and categorizes them as the bridge elements' names, sub-elements and related materials on one side and then cross-referenced with the Ecoinvent existing materials. The data related to the Ecoinvent database includes Ecoinvent Inventory ID, Ecoinvent Inventory Material and all the common LCA impact categories' data including climate change, Acidification, Ozone depletion, Human toxicity, Ecotoxicity, etc., as shown in Figure 2.

3.3 Database Development

Upon completing the previous step, MySQL is used to develop a structured database and store the mapped data. This database includes various material types and specifications, Mapped environmental impact values from Ecoinvent, and user-defined material properties. Creating this database is crucial for the developed system as it allows fast retrieval of the information, comparison and analysis of the materials' impacts.

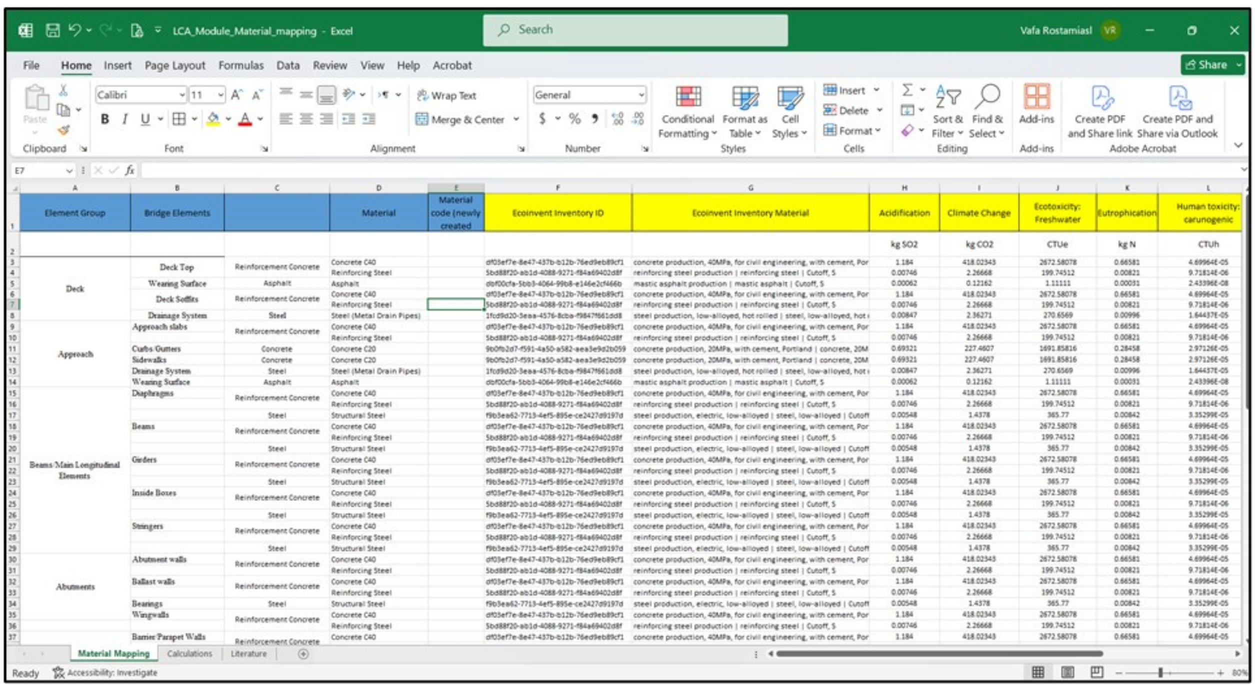

Figure 2: Data Mapping Sample Spreadsheet

3.4 User Interface Development and Integration with openLCA

After developing the database and storing the data, a graphical user interface (GUI) is developed. GUI is a visual way that allows users to interact with the model easily by using controls such as buttons, menus, and icons instead of text-based commands, which makes it more user-friendly and intuitive. C# programming language is used for this development due to its several advantages. It is well-suited for creating Windows-based applications with GUIs, offers efficient integration with MySQL and Excel to store and retrieve data when needed, and provides effective Application Programming Interface (API) support to handle external data processing. The developed GUI allows users to enter data and interact with the application easily. These input parameters include, but are not limited to, Bridge Element Category (structural components such as deck, girder, pier,…); Sub-element or Items (reinforced concrete slab, asphalt layer, steel beam,…); Material Type (concrete, steel,…); and quantities. Currently, users have to enter the materials information and their associated quantities manually but the authors are working on automating the process to import the Bill of Quantities (BOQ) directly from the 3D model that is designed in BrIM tool. Selecting the materials is designed in a flexible way so that users can view and select pre-mapped materials that are stored in the database or select the closest alternatives based on their needs. The GUI suggests a wide range of materials to the user based on the data entry if the exact material is not available in the database otherwise the system selects the matching material automatically. For the LCA calculations, the developed model is integrated with openLCA. In this study, all impact values and their units for the stored material are extracted from openLCA and stored in the MySQL database to be used for the impact analysis automatically. openLCA is a leading open-source software for conducting environmental impact assessments and was selected due to its compatibility with the Ecoinvent database. It allows users to conduct detailed impact analysis by using standardized LCA methodologies. Upon entering all the materials, the system calculates the impacts for the different categories and generates the results in the form of tables and graphs within the user interface. This system allows users to interpret and analyze the results of the environmental impact easily and effectively.

3.5 LCA Result Generation and Visualization

The final step is generating and visualizing the LCA results. The system calculates the environmental impacts automatically by using the collected data, as mentioned in the previous steps, and presents the findings in graphical and tabular formats. The results include impact indicators such as Acidification ($KgSO_2$), represents the emissions, such as sulfur dioxide, that cause acid rain and affect the ecosystems and built infrastructure; Climate Change ($KgCO_2$), measures the greenhouse gas emissions, such as carbon dioxide, that lead to global warming; Ecotoxicity: Freshwater (CTUe), refers to the toxic effects of pollutants on freshwater ecosystems; Eutrophication (kg N), is the excess nutrients, such as nitrogen and phosphorus, in water that lead to algae growth; Human toxicity: carunogenic and non-carunogenic (CTUh), The health risks, including cancer and non-cancer, from exposure to toxic substances; Ozone depletion (kg CFC-11), refers to emissions that cause the thinning of the ozone layer and increase UV radiation exposure; Particulate matter formation (kg PM2.5), indicates the emission of small particles that affect the air quality and human health (respiratory and cardiovascular diseases); and Photochemical oxidant formation (kg O_3), refers to emissions that lead to smog formation and impact human health and vegetation. These categories are organized alphabetically in the UI for convenient selection. The user can select different LCA stages and impact categories, and then the model conducts the analysis automatically and presents them for visualization. The model is flexible in terms of generating results based on the user's needs where the user can compare different materials, different stages and different impact categories.

This methodology integrates BrIM and LCA effectively by employing a structured database, a user-friendly interface and an LCA tool. This integration, coupling with Ecoinvent and openLCA provides a reliable and accessible environmental impact evaluation to help users enhancing their decision-making at the early design stage.

4. MODEL DEVELOPMENT AND TESTING

For testing and validating the developed model, the authors did not have access to information about an actual bridge project, therefore, a synthesized typical bridge BOQ was used to assess the functionality and usability of the system. The typical BOQ was constructed based on a sample of quantities and materials used in a bridge and includes elements such as deck slabs, girders, piers and abutments. The data is illustrative and used to show the model's usability and functionality, and visualize the output. This is one of the limitations of this study, hence there is a need for future testing by using data of actual bridge projects. Another limitation of the current model is that the materials and their representative quantities are entered manually. Upon running the model, the main dashboard opens. This dashboard provides access to several modules including the LCA module, which is the primary focus of this study. Upon selecting the LCA module, a new window with several LCA stage options including A1-A5 (material production and construction), B2 (maintenance), and C1-C4 (end-of-life processes) appears. This paper focuses on the material manufacture phase (A1-A3). Figure 3 provides screenshots of the different LCA phases as developed in the UI. The UI is designed to be flexible by allowing users to navigate through the LCA stages sequentially or by selecting specific stages independently based on their needs.

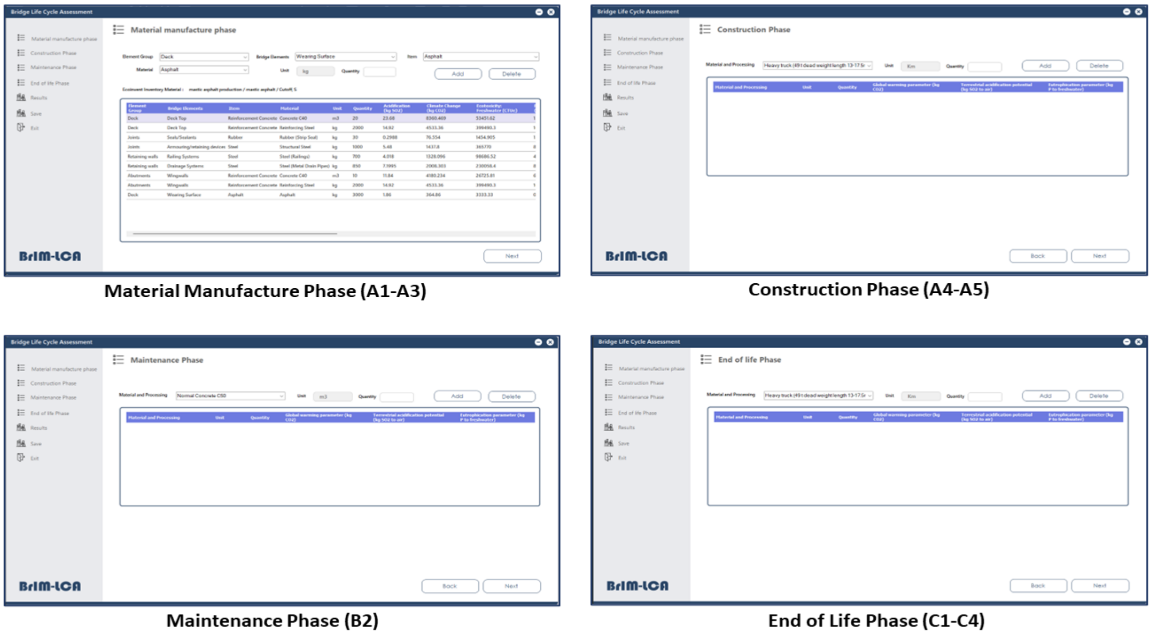

Figure 3: Different LCA Phases Developed in the UI

Upon opening the “Material Manufacture Phase” window, users are first required to select an element such as abutments, barriers, coating, decks, etc. They are arranged in alphabetical order for easy access. Then, they can select related sub-elements. For example, if they select decks as an element, they have options such as deck soffits, deck tops, drainage systems and wearing surfaces to select. Then, the users can select the related materials based on the sub-elements. Then, they can enter the quantities into the designated field and add them to the table for further analysis. The rows in the table can be deleted or modified by clicking on them and selecting the “Delete” button or modifying the entered data. This phase is a crucial component of the developed model, as it is the base component for assessing environmental impacts. Figure 4 shows a screenshot of the “Material Manufacture Phase” window with sample data.

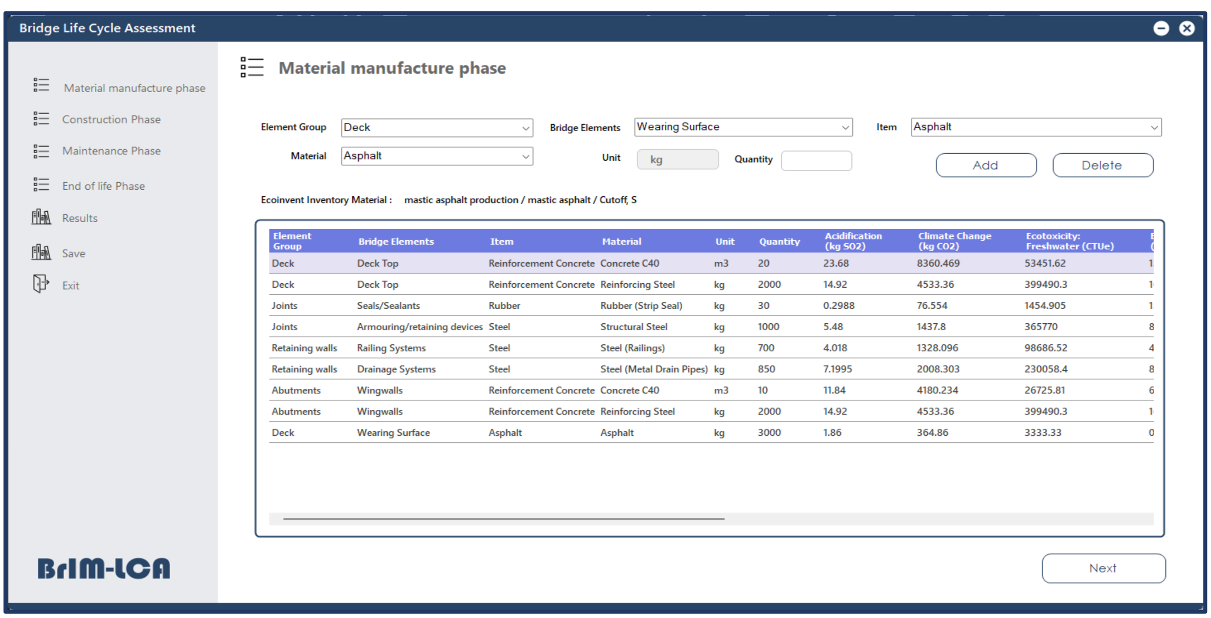

Figure 4. Material Manufacture Phase Data Entry

After completing the material manufacture phase and entering all the necessary data, users can proceed with the next stages by clicking on the “Next” button or simply selecting a specific stage from the left-side menu as needed. Once all the necessary data has been entered, users can proceed to the results window at any stage by selecting the “Result” button on the left-side menu. In the result window, users can select the relevant LCA stage and environmental impact category from available options. By default, the model shows results for the material manufacture phase, with "Climate Change" and "Ozone Depletion" as the default impact categories. Users can select up to two impact categories for comparison. Once a selection is made, the UI generates the results and presents them in the designated areas. Users can hover over bars in the graph to reveal the corresponding values as seen in Figure 5. For a more comprehensive analysis, the model can provide an overview of all the LCA impact categories in a single graph. This is accessible by clicking on the “Detail” button as shown in Figure 6. The model uses the stored data in the developed database and openLCA to process the input data and to generate results. The model provides users with valuable insights about the sustainability considerations during the early design stages of bridge projects.

The developed model helps designers, planners and decision-makers to evaluate the environmental impacts of various bridge designs and material selections at the early design stage. It enables quick comparison, such as comparing two different materials or two maintenance strategies. This supports the selection of the more sustainable alternative or scenario, improves stakeholders' communications, and facilitates decision-making for bridge projects.

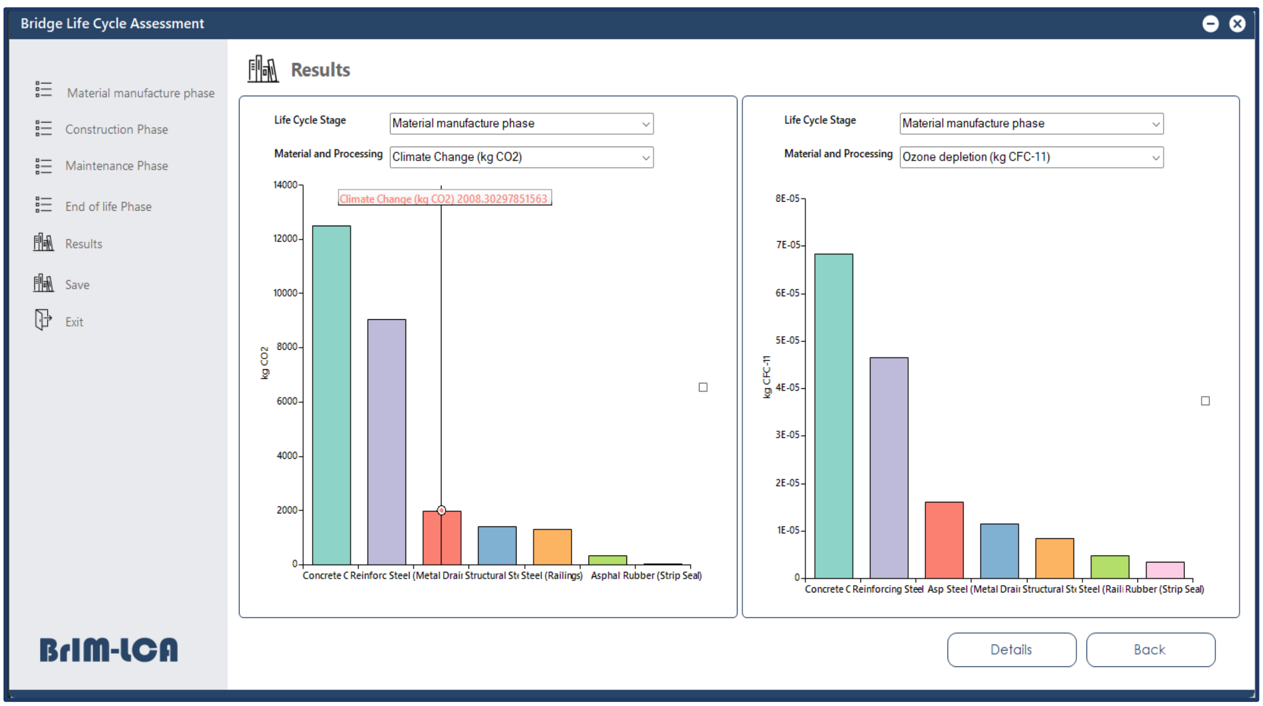

Figure 5. Result Generation and Comparison Ability of the Developed Model

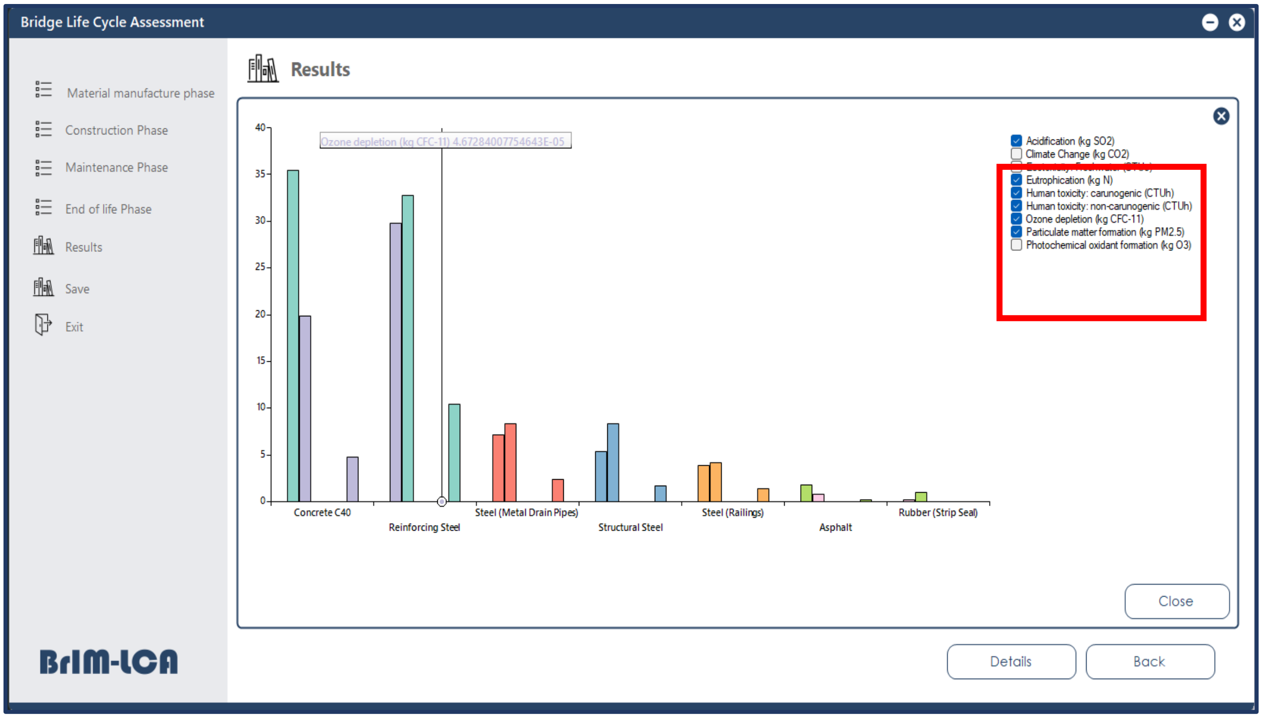

Figure 6. Generating Comparison Graph

5. CONCLUSIONS

This study introduced the development of an innovative computer model in the form of a stand-alone application that integrates LCA into the bridge design at the early stage. The model consists of a user-friendly interface for entering data, processing, and analyzing different LCA stages easily by using the stored data in a developed MySQL database, mapping them with the Ecoinvent database and processing the information using openLCA. The model was implemented by using C# programming language. This model can generate results in the form of graphs and tables to provide users with an overview of the environmental impact and support decision-making for sustainable bridge design. However, despite its advantages, this study has some limitations. One of the limitations is the lack of a real-world bridge project to validate the model. The authors used example values to assess the usability and functionality of the model. Furthermore, currently, users must manually enter the data from the BOQ into the model, which is time-consuming and prone to human errors. Future work focuses on automating the data entry process directly from BrIM tool to enhance efficiency and usability. In addition, the primary focus of this study is the materials manufacturing phase and the authors plan to expand the model to incorporate other LCA stages to have a more comprehensive assessment of bridges throughout their entire lifespan.

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REFERENCES

Chen, Z., Chen, L., Zhou, X., Huang, L., Sandanayake, M., & Yap, P. S. (2024). Recent technological advancements in BIM and LCA integration for sustainable construction: a review. Sustainability, 16(3), 1340.

Crippa, J., Araujo, A. M., Bem, D., Ugaya, C. M., & Scheer, S. (2020). A systematic review of BIM usage for life cycle impact assessment. Built Environment Project and Asset Management, 10(4), 603-618.
Forth, K., Hollberg, A., & Borrmann, A. (2023). BIM4EarlyLCA: An interactive visualization approach for early design support based on uncertain LCA results using open BIM. Developments in the Built Environment, 16, 100263.
Hillege, L. (2024 June 10). “What is ecoinvent? – Meet the LCI Database”. Ecochain. https://ecochain.com/blog/what-is-ecoinvent/
Hollberg, A., Genova, G., & Habert, G. (2020). Evaluation of BIM-based LCA results for building design. Automation in construction, 109, 102972.
International Organization for Standardization 14040:2006; Environmental Management–Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 07 December 2024).
Jrade, A., Jalaei, F., Zhang, J. J., Jalilzadeh Eirdmousa, S., & Jalaei, F. (2023). Potential Integration of Bridge Information Modeling and Life Cycle Assessment/Life Cycle Costing Tools for Infrastructure Projects within Construction 4.0: A Review. Sustainability, 15(20), 15049.
Kaewunruen, S., Sresakoolchai, J. and Zhou, Z. (2020) 'Sustainability-Based lifecycle Management for bridge infrastructure using 6D BIM,' Sustainability, 12(6), p. 2436. https://doi.org/10.3390/su12062436.
Kim, H., Roh, S., & Kim, J. (2024) ‘Embodied carbon of BIM bridge models according to the application of off-site prefabrication: Precast concrete applied to superstructure and substructure,’ Developments in the Built Environment, 20, 100550. https://doi.org/10.1016/j.dibe.2024.100550.
Lemperos, X. (2024). The stages of LCA. Anavitor. Available online: https://anavitor.ai/en/ecobuild-lca-perspectives-for-the-built-environment/the-stages-of-lca. (Accessed on 07 December 2024)
Lima, M. S. S., Duarte, S., Exenberger, H., Fröch, G., & Flora, M. (2024). Integrating BIM-LCA to Enhance Sustainability Assessments of Constructions. Sustainability, 16(3), 1172.
Marrero, M., Wojtasiewicz, M., Martínez-Rocamora, A., Solís-Guzmán, J., & Alba-Rodríguez, M. D. (2020). BIM-LCA integration for the environmental impact assessment of the urbanization process. Sustainability, 12(10), 4196.
Nahangi, M., Guven, G., Olanrewaju, B., & Saxe, S. (2021). Embodied greenhouse gas assessment of a bridge: A comparison of preconstruction Building Information Model and construction records. Journal of Cleaner Production, 295, 126388.
Péntek, G. 2023. Implementation of a stochastic LCA method into BIM environment at infrastructure design projects - a case study of a bridge (Master's thesis, University of Twente).
Petrović, E. K., & Thomas, C. A. (2024). Global Patterns in Construction and Demolition Waste (C&DW) Research: A Bibliometric Analysis Using VOSviewer. Sustainability, 16(4), 1561.
Safari, K., & AzariJafari, H. (2021). Challenges and opportunities for integrating BIM and LCA: Methodological choices and framework development. Sustainable Cities and Society, 67, 102728.
Soust-Verdaguer, B., Gutiérrez Moreno, J. A., & Llatas, C. (2023). Utilization of an automatic tool for building material selection by integrating life cycle sustainability assessment in the early design stages in BIM. Sustainability, 15(3), 2274.
Tam, V. W., Zhou, Y., Shen, L., & Le, K. N. (2023). Optimal BIM and LCA integration approach for embodied environmental impact assessment. Journal of Cleaner Production, 385, 135605.
UN Environment Programme (UNEP) (2024). Not yet built for purpose: Global building sector emissions still high and rising. https://www.unep.org/news-and-stories/press-release/not-yet-built-purpose-global-building-sector-emissions-still-high
Van Eldik, M.A. et al. (2020) 'BIM-based environmental impact assessment for infrastructure design projects,' Automation in Construction, 120, p. 103379. https://doi.org/10.1016/j.autcon.2020.103379.
World Health Organization (WHO) (2014). 7 million premature deaths annually linked to air pollution. Available online: https://www.who.int/news/item/25-03-2014-7-million-premature-deaths-annually-linked-to-air-pollution (accessed on 14 December 2024)
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The Ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21, 1218-1230.
Zhang, Z. H., Huang, W., Lu, G. Y., & Luo, S. (2024). A holistic life cycle assessment of steel bridge deck pavement. Renewable and Sustainable Energy Reviews, 200, 114575.