Mixed Reality-based Digital Twinning of Building Circularity: A Co-Design Approach for Sustainable Buildings

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Abstract –

Sustainability in construction practices is becoming the need of the day, and the construction sector is getting adoptive to the integration of digital tools to explore the opportunities for enhancing sustainability and circular economy applications, offering significant benefits to both industry and society. To achieve this goal, this article discusses a sustainability framework combining Digital Twin (DT), Mixed Reality (MR), and Life-Cycle Assessment (LCA) to align with circular economy principles in building construction.

A case study of a single-family house in Kelowna, BC, Canada is conducted to demonstrate the potential of this integration for comprehensive LCA of buildings. The LCA analysis of the building is performed using OneClick LCA– an LCA platform. The results of LCA account for the embodied carbon, improved material circularity, life cycle cost efficiency, etc. A DT Dashboard (DTD) of the building's circularity model is also developed, which monitors and optimizes the whole life cycle of the building. The DTD is then deployed to MR hardware – Microsoft HoloLens for enabling onsite circularity analysis of the building. This not only allows for immersive visualization of LCA data but also enhances stakeholders' collaboration and decision-making. This way the study showcases how immersive DT can potentially be a game-changer for sustainable construction and provides an industrially replicable model.

Keywords –
Mixed Reality (MR), Circular Economy (CE), Life-Cycle Assessment (LCA), Digital Twin (DT), Data Fusion.

1 Introduction

Circular Economy (CE) has become prominent in the construction industry as a way of responding to challenges of sustainability through reduced waste and resource extraction. The underlying rationale of this concept is a closed-loop use of materials, which is somewhat contrary to the traditional linear model of "take, make, dispose [1] [2]." On the one hand, it is agreed that using CE tools and practices earlier in the project can reduce the negative environmental impacts constructions can have [1]. On the other hand, it is also highlighted that adopting circular practices during the demolition phase in construction can significantly reduce waste, where most materials are currently discarded due to lack of reuse potential [3]. There are other strategies such as adaptive reuse and selective disassembly that are in line with CE principles and extend the life of building components by maximizing material recovery [4].

Furthermore, a collaboration of CE with Life-Cycle Assessment (LCA) is to be considered while designing an optimum building for sustainability in terms of reuse, recycling, and reduction of any kind of waste in the whole life cycle.

Also, advanced technologies such as Digital Twin (DT) are essential to assist in the use of these strategies, as real-time monitoring and data-driven decision-making capabilities can effectively manage resources. Digital Twin technology empowers several industries to dynamically create replicas of actual running systems. By continuously synchronizing data between the physical and digital worlds, replicas are extremely helpful for performance optimization and predicting upcoming problems [5]. The concept of Digital Twin was first proposed by Michael Grieves in 2002 and was officially named and applied by NASA in 2010 for real-time simulation and monitoring of space missions. It then developed into a key tool for Industry 4.0 applications [6]. Digital Twin can enhance decision-making and reduce operational inefficiencies by integrating Internet of Things (IoT) sensors and Building Information Modelling (BIM) [7], and can also collect and analyze data continuously, to enable predictive maintenance, optimize the processes, and improve resource management in complex construction projects [6]. Owing to its powerful advantages, Digital Twin is playing a more and more crucial role in the construction industry.

To make digital data more accessible and interactable for stakeholders, Mixed Reality (MR) is another powerful technology to apply in construction projects. MR merges the physical world with the digital one to create an immersive environment. The users can interact with both real and virtual objects at the same time using MR technology. It has shown great potential so far in making the construction processes better by enhancing visualization and interaction with real-time data on-site [8]. MR integrates digital overlays into the physical environment, thus making communication among stakeholders easier and allowing for more intense collaboration and quicker decision-making [9]. For example, Wu et al. (2022) [10] did some research on developing MR-based systems to enhance safety by offering real-time visual warnings about potential hazards on a construction site to workers, thus reducing various accidents and improving safety protocols. In addition, MR can also enhance the construction inspection and monitoring process by allowing inspectors to visualize complex 3D models of hidden building elements and identify discrepancies between design and construction in real-time [11]. However, despite such benefits, the high cost of implementation and user acceptance are the main challenges for more widespread diffusions [9].

The integration of MR, DT, and CE technologies can be transformative in improving sustainability in construction. DT technology has increasingly been recognized as a key tool in the transition of the industry from linear to circular models, where the emphasis is on waste minimization and materials reuse for improved salvage value [12]. MR technologies introduce new ways of engaging stakeholders and building further awareness of the principles underlying CE in construction contexts [13]. The combination of MR and DT enhances real-time decision-making and visualization of the construction process, especially in tasks related to design optimization, life cycle analysis, and demolition planning. This integrated approach enables dynamic monitoring and immersive user interaction [14] [15] [16]. By embedding MR-based DT frameworks into building LCA, the construction sector can better align design and demolition phases with CE objectives, improving efficiency and sustainability throughout a building's lifecycle.

Conclusively, the main goal of this study is the development of an immersive Digital Twin Dashboard (DTD) of the circularity model of a building. This DTD helps to monitor and optimize every step of the entire life cycle of the building and contributes to sustainable construction. Then the DT is deployed into HoloLens, which is Mixed Reality (MR) hardware, for lab-scale testing. Immersive visualization and collaboration will enable stakeholders to make better decisions that improve building performance and sustainability.

2 Description of the case study

The single-family house building is located in Kelowna, British Columbia, Canada, which is designed to be a residential house, is comfortable for the family to stay in. The approximate area of this house is 4,465 square feet, having 5 bedrooms and 4 bathrooms, a spacious living area, a dining area, and a gourmet kitchen. It is situated in the Upper Mission area of Kelowna, featuring scenic views and a desirable residential environment. Kelowna has hot, dry summers and mild winters, and therefore is one of the best cities in terms of outdoor activities to enjoy throughout the year. The location and the size of the house allow the structure to be a representative example for the validation of circular economic principles in residential construction while integrating state-of-the-art technologies such as Digital Twin and Mixed Reality to optimize the life cycle performance. The detailed layout of the building is shown in **Figure 1**.

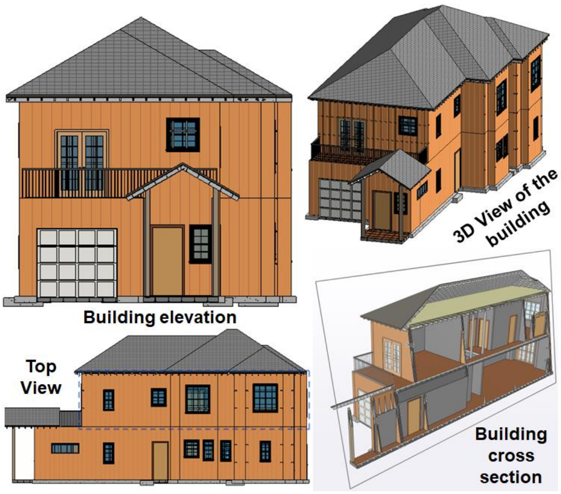

Figure 1: Plan Views of the House

This case study will go in-depth on the circularity of the building structure and the integration of LCA to analyze the environmental performances of the single-family house. OneClick LCA, an AI-powered sustainability software platform that helps construction and manufacturing industries calculate, manage, and reduce environmental impacts through automated life-cycle assessments, environmental product declarations, and circularity evaluations [17], is used to gain important insights into the key lifecycle costs, energy efficiencies, and embodied carbon related to the building. These insights include considerations on operational energy consumption, the choice of materials, and possible end-of-life scenarios.

Generic construction materials database – the default database from OneClick LCA – is used for the LCA process [18]. The LCA for this project is conducted following ISO 14040, ISO 14044, and EN 15804 standards, and the TRACI 2.1 method is applied to align with LEED Canada requirements [19] [20]. All Global Warming Potential (GWP) values are calculated using a 100-year time horizon, as required by EN 15804, ISO 21930, and TRACI 2.1 [19] [20]. The functional unit is m^2, and the assessment is performed from cradle to grave, covering all stages from raw material extraction and manufacturing to construction, use, and end-of-life disposal, in accordance with EN 15804 and ISO 14040/44.

The following section will discuss the implementation of the principles of the circular economy in the design and how the LCA model quantifies the environmental impact.

3 Circularity of the building structure and LCA model of case-study

3.1 Introduction to Circularity and LCA

The major objective of circularity in building construction is waste and resource consumption reduction by means of design for material reuse, recycling, and adaptability during its lifetime. This also meets the wider concept of the circular economy: principles of the circular economy support the closed-loop use of materials with limited environmental impacts [1]. LCA is the structured method for assessing the environmental footprint of a building throughout its whole life cycle, from material sourcing to construction, operation, and end-of-life. The following section demonstrates how such principles can be applied in practice to a single-family house by evaluating its environmental performance based on data provided by OneClick LCA.

3.2 Circularity of the Building Structure

The building was designed with circularity principles, using materials that at the end of their life will be either reusable or recyclable. The structure is designed to allow the dismantling and reputation of materials. Materials and finishes, as evidenced shows in the results from OneClick LCA, consume 55% of the embodied carbon; therefore, its thoughtful choice is extremely important to reduce the ecological footprint. Besides, for the sake of adaptation, the building design allowed partial deconstruction with recoverable elements. This flexibility will make components reusable or recyclable both in renovations or demolishing and extend their life span by fully meeting the goals of a circular economy.

3.3 LCA Model

The life cycle assessment of the single-family house involves environmental performance at every stage from material sourcing to end-of-life. Results from OneClick LCA show that a large part of the embodied carbon in the building arises during the production and construction phases. This, therefore, calls for a greater need to employ sustainable sourcing practices and energy-efficient construction techniques. It will also have substantial energy use during the operational phase, another big contributor to its environmental footprint.

The end-of-life phase of the building is designed to maximize recovery for reuse and recycling. A design for disassembly allows the structure to recover materials such as timber, steel, and concrete with high efficiency, reducing waste and conserving virgin resources. The LCA results quantify these strategies and prove that they are effective in reducing the overall environmental impact of the building.

3.4 Integration of Circularity and LCA

Merging circularity principles into an LCA model is one of the effective ways toward sustainability. The strategies under circular design – material reuse, adaptability, and efficient construction practices – reduce the embodied carbon and operational energy demands and hence contribute to improved LCA outcomes directly. OneClick LCA data also presented economic benefits by depicting possible cost savings resulting from material waste reduction, reduced energy usage, and minimized end-of-life disposal costs [21].

This project creates a holistic framework for the evaluation and enhancement of sustainability in residential construction by linking circularity with LCA. Such synergy not only reduced the environmental impact on the building but also proved to be a replicable model to integrate these principles into future projects, balancing functionality with economic efficiency and ecological responsibility. The OneClick LCA dashboard with results is shown in **Figure 2**. It presents the value of equivalent carbon dioxide emissions per square meter ($\mathrm{kg\ CO_2e/m^2}$) for the project is 733, and this falls in the

G rating level as per Canadian standards. In addition, the result of the tool Building Circularity v2 shows that 29.59% of the building materials can be reused, recycled, or repurposed after demolition [22].

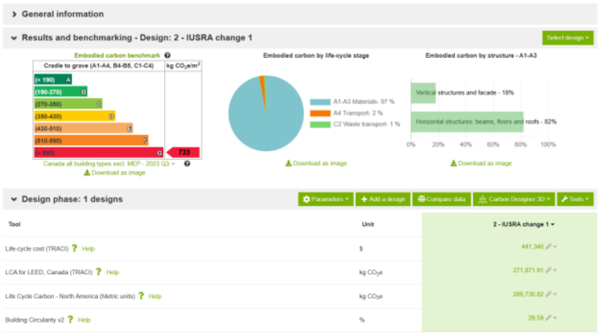

Figure 2: OneClick LCA Dashboard with Results and Benchmarking

4 Development of the immersive DT of the circularity model

The development of the immersive DT starts with the creation of the detailed 3D model (LoD 350 BIM model) using the Autodesk Revit environment. To effectively use this BIM model in the 3D game engine either the Industry Foundation Class (IFC) file or the FBX file can be imported from Revit to UNITY 3D. The only problem with using the IFC is that all the native properties of each structural element make the 3D model heavy and inefficient thus some extra manual work will be required to import all the design data of the building. Therefore, direct import using the FBX file format is preferred and recommended in such cases. Upon successful import of the BIM model to the UNITY platform, the DTD is created from scratch that works while switching to the game mode of the 3D model. The DTD workflow is based on the User Interface (UI) modules such as canvases that are used to mesh the 3D model (virtual counterpart of the DT model). These meshing elements enable the automation function of DTD and help to integrate with the physical model of the building. In the case of this research, the physical model is replicated with the online web platform (OneClick LCA) that accounts for the circularity of the building. In order to ensure the two-way communication between the DTD and OneClick LCA a C# code is embedded in the canvas of the DTD which calls upon the circularity model of the building in OneClick LCA once the game mode is switched on in the UNITY 3D.

The calculation of the circularity parameters i.e., Embodied carbon benchmark, Embodied carbon by life-cycle stage, and Embodied carbon by structure are automatically linked to the DTD directly from the OneClick LCA interface. This way the DTD performs the LCA of the building while ensuring the basic principle of circular design such as material reuse, adaptability, and efficient construction practices resultantly reducing the embodied carbon and operational energy demands while contributing to improved LCA outcomes automatically. The DTD with the LCA data is shown in **Figure 3**.

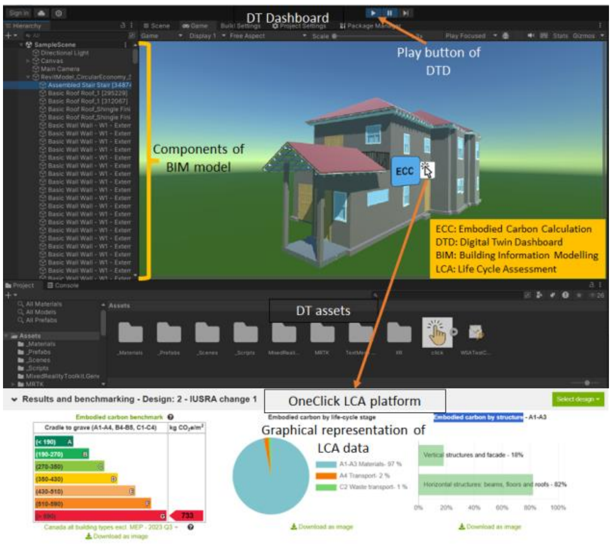

Figure 3: Digital Twin Dashboard of Integrated BIM-LCA system in 3D game engine

5 Deployment of DT to MR hardware and lab-scale testing of the DT-based circularity model

To enhance collaboration between the stakeholders and enable better visualization, the DT model, along with the LCA system, is deployed into Microsoft HoloLens – an MR hardware. This includes embedding the LCA system into the DT model, adjusting the direction and location of the model to better fit the camera, building the application in Unity, and finally deploying the application into HoloLens via Visual Studio.

For starters, the LCA system of the building is added to the DT model by attaching a button with a web link to the wall of the building, so that the user can click on the button and access the OneClick LCA webpage to see the LCA results of the building. Detailed result components will be discussed in the next section.

To deploy the app to HoloLens, the Mixed Reality Tool Kit (MRTK) is used for this project. The main camera of the Mixed Reality Play Space is adjusted to the right location to provide a better view of the building and the LCA button. It is expected that once the users open the app in HoloLens, they can see the whole building in a proper size, and can see the LCA button clearly, guiding them to click on the button to see the LCA results.

As for building the application, the Universal Windows Platform (UWP) in Unity is used for the purpose of developing and running the application on a wide range of Windows devices, including HoloLens, PCs, etc. In this way, the application can be tested not only in HoloLens but also on PCs.

The application is built on the Remote Device (Via Windows Device Portal). HoloLens is connected to the same Wi-Fi network as the PC, so the PC can be paired with HoloLens via Windows Device Portal. The application is built in Unity and then deployed to HoloLens in Visual Studio using the IP address HoloLens connected to, the username and password of the Portal. After deploying, the application can run on HoloLens.

While running the application, the users can see the entire building DT model and the LCA button attached to it. By clicking the button, that embeds the web link, the users can see a webpage jumping out, as shown in **Figure 4**. The webpage shows the LCA results, including graphs and diagrams of Embodied Carbon, Life Cycle Cost, etc.

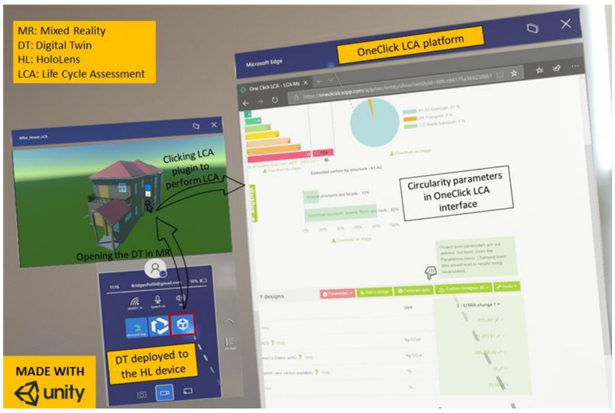

Figure 4: Immersive DT of the building circularity system

6 Discussion

The LCA results in OneClick LCA mainly explain embodied carbon, life cycle costs, and building circularity. Following is the breakdown of each part.

6.1 Embodied Carbon Results

The analysis provides very important insights into the embodied carbon of the design. Almost all emissions lie within A1-A3 (Materials), and only a small amount lies within A4 (Transport) and C2 (Waste Transport). Those materials comprise almost the entirety of the total carbon footprint in the building project. Horizontal structures such as beams, floors, and roofs contribute the most. The results have shown strong evidence for the consideration of material alternatives in the design stage so as to reduce environmental impact.

Benchmarking also puts the performance of the design in a wider context, such as building types in Canada or the MEP benchmarks. By doing so, one gains the ability to perform a relative comparison, showing areas that are excellent or fall behind in the design. These indeed are valuable insights from where the design team can thereafter work towards making targeted improvements to meet and hopefully even better the benchmarked targets in sustainability.

6.2 Building Circularity

Circularity is important because it reduces waste, saves resources, and supports the closed-loop system for long-term sustainability [1]. The report shows that the Building Circularity is around 29.59%. This means that although there is a considerable portion of materials that can be recycled or renewed at the end of the building's life cycle, most materials may still be linear and would be disposed of in the end. To improve circularity, we changed these materials to recyclable materials, and the LCA results are shown in **Figure 5**. In this case, the Building Circularity is 100%, which means all the materials we use in this building can be reused at the end of the building's life cycle, and therefore the embodied carbon intensity is decreased from 733 kg CO_2 e/m^2 to 229 kg CO_2 e/m^2 .

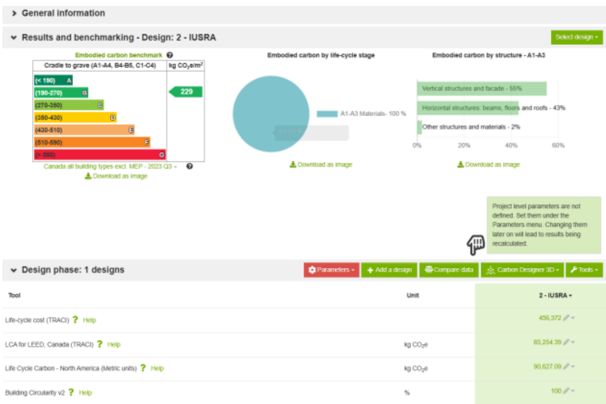

Figure 5: LCA Results after Changing Materials

6.3 Life Cycle Cost Analysis

The LCC results show a detailed breakdown of the financial impacts across various building elements and life-cycle stages. Construction costs between A0 to A5 come out as the largest cost contributor. These are primarily determined by material and labor costs. The design team may reduce the initial cost through such cost-effective and sustainable methods as pre-fabrication or sourcing materials locally.

The costs of operational energy use B6 are also high, indicating that energy efficiency will be very important for the reduction of long-term expenses. The end-of-life costs, C1 to C4, are relatively low but can be further reduced by specifying the materials and systems for reuse or recycling, thereby avoiding demolition and waste management costs.

6.4 Combined Analysis of Life-Cycle Stages and Elements

An integrated view of life cycle stages and elements gives an insightful understanding of how the costs evolve over the life of the building. The analysis will enable stakeholders to prioritize interventions based on their life-cycle stage and element-specific impact. For example, it would have immediate cost and environmental benefits if high-impact materials were focused on during the construction phase.

7 Conclusions

The integration ofDT and MR technology with the CE framework is a great improvement in the building sustainability analysis. This study has developed a novel DTD which is further deployed to MR headset and allows for immersive monitoring and optimization of the whole life cycle of the building. It enhances the efficiency of resource management and allows for the potential of collaborations between stakeholders.

The case study of the Kelowna single-family house is considered in this research. LCA of the building is performed by incorporating circularity principles – such as using reusable materials – that significantly reduce embodied carbon emission and improve building sustainability performance. After changing to more eco-friendly materials, the embodied carbon intensity decreased from 733 kg $\mathrm{CO_2\ e/m^2}$ to 229 kg $\mathrm{CO_2\ e/m^2}$, and the building circularity ratio is increased from 29.59% to 100%.

This study emphasizes the importance of embedding LCA and CE principles early in the design process to mitigate environmental impacts effectively and by integrating cutting-edge technologies such as DT and MR, this analysis process can be improved significantly.

However, there are also limitations and challenges for the integration of MR, DT, and LCA. Construction workers and project teams may need targeted training to develop the skills required to use these tools effectively, which could delay widespread implementation. Furthermore, how well these technologies perform could differ depending on project size and building type. While they may be suitable for straightforward projects, more extensive or highly complex developments could experience challenges related to data integration, system compatibility, and overall performance, which would benefit from further investigation. Future work can focus on how to implement this framework in different construction types, reducing costs and increasing user acceptance to promote wider sustainable practices. In addition, conducting a cost-benefit analysis that compares advanced tools, such as OneClick LCA software, with traditional LCA methods could provide valuable insights. This analysis would help stakeholders make more informed decisions by evaluating both the financial investment required and the potential benefits, such as improved accuracy, time savings, and enhanced sustainability outcomes.

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