A DIGITAL FRAMEWORK FOR GENERATING AND EVALUATING DIGITAL CIRCULAR TWINS

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Abstract

The Architecture, Engineering, and Construction industry is crucial in promoting circular economy principles to mitigate resource scarcity and negative environmental impacts. Taking the lead in the global extraction of raw materials and making significant waste contributions, the sector incorporates circular economy assessments into building design decisions. This paper introduces a concept using visual programming language for End-of-Life algorithms linked to Building Information Modelling Data. The goal is to create a decision-support tool for the early design stage using common architectural software coupled to visual programming. The results display a computational solution for implementing relevant parameters through utilised software.

Keywords: Circular economy, digital twins, generative design, virtual reality, digital ecosystem, end of life, material building passports, EU taxonomy

Introduction

The growing interest in the circular economy (CE) represents a paradigm shift from the prevailing linear economy, driven not only by the need for assessment for several certifications and EU regulations but also because of its significant advantages compared to the traditional linear model (United Nations Environment Programme, 2022). These benefits extend to environmental, social, and economic concerns, addressing crucial challenges such as resource scarcity and environmental degradation (Kovacic et al., 2020a; Ellen MacArthur Foundation, 2024; Gorgolewski, 2018; Korhonen et al., 2018; Cramer, 2022). Defining the basic concepts of circular economy and sustainability is essential to provide a framework for this research. The Brundtland Report (1987) offers a widely recognised definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland, 1987, p.37). Barbier (1987) was among the first to describe sustainability's three pillars: economic, environmental and social, with this paper concentrating on the environmental aspect (Barbier, 1987). Cramer (2022) introduces the 10 R's, which ranks circularity actions by their impact, placing reuse higher than recycling due to its more significant contribution to circularity (Cramer, 2022). Moreover, Geissdoerfer et al. (2017) define Circular Economy as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling." (Geissdoerfer et al., 2017, p.759), positioning it as essential for sustainability.

A transition to a circular system is particularly crucial in the construction industry, contributing to around 37% of global energy consumption and process-related CO2 emissions (United Nations Environment Programme, 2022). Furthermore, this industry's significant role in resource depletion, being the largest contributor to global raw material extraction (Almeida et al., 2016), highlights the need to transition to circular systems. However, this transition challenges existing design processes and policy frameworks, making revisiting and altering current approaches necessary (Korhonen et al., 2018). Therefore, there is a need for a framework to better include circular economy principles, such as reuse or reduce and especially guide cooperation between designers, fabricators and clients in the construction industry (Svilans et al., 2019; Çetin, 2023; Geissdoerfer et al., 2017; Çetin et al., 2021).

Digital tools are seen as critical enablers for efficient data sharing, monitoring, optimisation and enhanced communication between stakeholders throughout the design and construction process (Antikainen et al., 2018; Antova and Tanev, 2020; De Wolf et al., 2020; Martínez Rocamora et al., 2021; Çetin, 2023). Moreover, initiatives like Europe's Digital Decade (European Commission, 2021) and the 2020 EU CE Action Plan highlight the importance of digital tools in promoting sustainability and supporting the circular economy (European Commission, 2021; Çetin, 2023).

As a result, finding computational solutions to embrace a circular economy is among the most recent topics in the Architecture, Engineering and Construction (AEC) industry, as it can tackle today's pressing environmental problems (De Wolf et al., 2020; Kovacic et al., 2020a; Cramer, 2022). Building Information Modelling (BIM) and Material Passports, for example, promise to address sustainability barriers and facilitate the automatic inclusion of reliable datasets (Honic et al., 2019; Çetin, 2023; Martínez Rocamora et al., 2021; Santos et al., 2019). However, there are challenges in integrating these tools, particularly when considering one of the most commonly used methods, Life Cycle Assessment (LCA) (Santos et al., 2019). The reliability of LCA results is affected by uncertainties coming from assumptions, such as energy consumption and product lifespan. Additionally, challenges in integrating specific, local information from manufacturers and the lack of detailed data on material composition in the early design stages further affect the accuracy of LCA outcomes (Martínez Rocamora et al., 2021; Santos et al., 2019; Honic et al., 2019). This highlights the need for more flexible and comprehensive tools within the BIM environment to simplify the integration of environmental analysis in the design process (Martínez Rocamora et al., 2021; Çetin, 2023). Research into BIM-based LCA tools shows that most require a combination of BIM and other software to measure environmental impacts effectively. This process, while beneficial, often requires manual input and thus is time-consuming, contrary to the goal of automating these assessments (Martínez Rocamora et al., 2021; Honic et al., 2019). The need for a multidisciplinary approach comes with its hurdles, as the link between digital tools and circular economy principles requires skills spanning environmental science, architecture, engineering, and programming - raising another limitation: the interoperability issue between different software (Santos et al., 2019). Nevertheless, this collaborative effort is vital for developing tools that are both functional and beneficial (Martínez Rocamora et al., 2021; Ilhan and Yaman, 2016). Despite the identified potential of digital tools to integrate circular economy principles in the AEC industry, there remains a significant gap in creating user-friendly, integrated solutions that effectively bridge the gap between theoretical concepts and their practical application. This highlights the ongoing academic and practical need for research to develop accessible tools that enable sustainable construction practices within the circular economy framework(Ilhan and Yaman, 2016; Çetin, 2023; Martínez Rocamora et al., 2021).

The ongoing research presented in this paper addresses these challenges by aiming to optimise architectural designs in terms of circularity and sustainability in the early design stage, as it promises fundamental advantages, representing a vital phase where materials can enter (or re-enter) a new life cycle, and design concepts are still in their initial adjustable stage, thus more flexible to adapt (Gorgolewski, 2018; Honic et al., 2019; Çetin, 2023; Çetin et al., 2021). This paper emphasises the need to flexibly document, validate and benchmark environmental impacts to ensure current activities support a sustainable future and bridge the gap between abstract principles and practical implications (Çetin, 2023; Geissdoerfer et al., 2017). Therefore, this paper considers key indicators, including the building's overall mass, Global Warming Potential (GWP-total), Acidification Potential (AP), and Primary Energy Non-Renewable, Total (PENRT). These indicators were chosen because they are used in the Austrian klimaaktiv OI3 Eco Index calculation to assess the environmental impact of materials (IBO – Österreichisches Institut für Bauen und Ökologie, 2023), and are also relevant for compliance with the EU Taxonomy classification system (European Commission, 2024).

The concept of this research merges Algorithm Aided Design (AAD), Building Information Modeling (BIM) (Pibal et al., 2022), and Virtual Reality (VR). It supports sustainable architectural planning by automating variant generation, conducting circularity assessments, and using a VR platform interface to facilitate decision-making in the early design stage, aligning with Circular Economy (CE) principles and objectives. The framework of the project is based on:

1. a BIM-based architectural model (in software ArchiCAD)
2. an End-of-Life (EoL) design algorithm to conduct the variant study generating an assessable geometric twin, an identical digital illustration of the variant in the VR platform
3. an EoL- assessment algorithm for attributing and evaluating different building variants
4. VR platform with included Virtual Agent for planning support
5. An enriched spreadsheet-based object catalogue containing relevant data from material databases such as the Austrian database "baubook" (baubook, 2024), essential for conducting defined assessments

This research builds on the previous publication, Wohnen 4.0 (Pibal et al., 2023), Digital Ecosystem to enable Circular Buildings – The Circular Twin Framework Proposal (Schützenhofer et al., 2024) and Digital Platform for Affordable Housing - a Framework Proposal (Kovacic et al., 2020b). The overall context established is visualised in Figure 1, which provides an overview of the proposed framework. This paper focuses on Module 2 and Module 3, shown in Figure 1. These EoL algorithms are implemented in the visual programming environment Grasshopper 3D within Rhinoceros 3D and their connection to the architectural design model in ArchiCAD. It discusses the challenges of incorporating these EoL algorithms to enhance the effectiveness of circular design approaches to incorporate crucial data regarding building materials and their reuse potential, as well as Life Cycle Assessment (LCA) and EU taxonomy compliance (European Commission, 2024).

The paper is structured as follows: First, the methodology section reviews the different digital tools used and outlines the intended workflow between Grasshopper and ArchiCAD. Followed by illustrating in more detail the steps created in the EoL algorithms to generate the needed data flow between the programs. Finally, the paper discusses findings and suggests ways for further improvement in integrating these algorithms effectively.

Methodology - Data Integration for EoL- Algorithms

The method is an interdisciplinary research approach. A specific set of digital tools has been selected to facilitate the research objectives. ArchiCAD, employed as a BIM-model and digital planning tool (IFC data/OpenBIM), was selected not only because it is one of the most used digital tools in the AEC industry but also for its ability for efficient data storage and its inclusion of essential data required

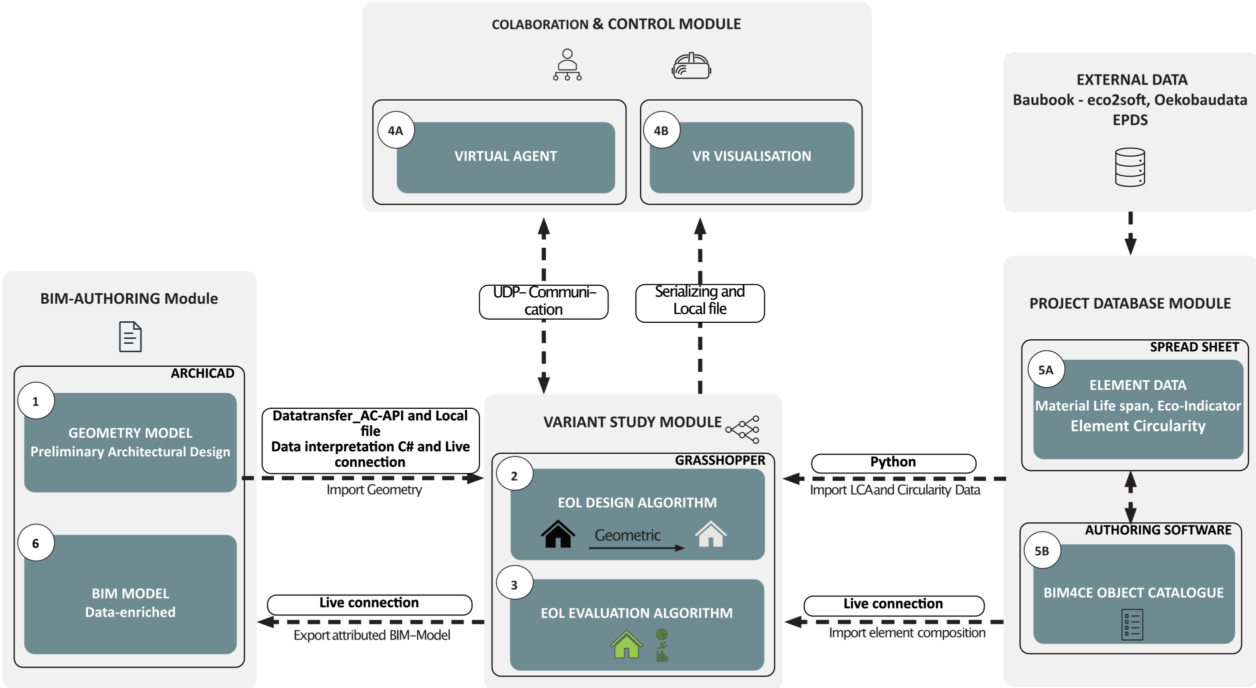

Figure 1: Overview of the proposed framework and software interfaces

for diverse Life Cycle Assessment calculations. Additionally, Grasshopper as a visual programming tool, with an established Live Connection to ArchiCAD (Graphisoft Deutschland, 2024), handling spreadsheet-based documents and including Python/C# script, has been incorporated because of its multifaceted benefits. Furthermore, Grasshopper enables the Virtual Agent in the VR platform to access and modify various components, a crucial requirement for this project. This selection of tools was analysed, leading to the development of an initial prototype of End-of-Life (EoL) algorithms by utilising these diverse interfaces. The conducted literature review led to assessment collection (LCA), which defined the necessary data and basic information and connections required to create the Grasshopper script obtained from the BIM model, are shown in Figure 2 and described below.

Data Input and Model Reconstruction

- Extracted from the architectural design model: Basic geometric data, the quantity of elements essential for subsequent calculations, and spatial reference line accurately generating the geometric twin in Grasshopper for access by the Virtual Agent in the VR platform.
- From ArchiCAD composites (products): The composite name, crucial for efficient product search within the spreadsheet-based object catalogue and the retrieval of accurate data for LCA calculations, and the dimensions of the (new) elements, necessary for precise volume calculations used in mass determination.

Using basic geometric data, the visual geometric twin of the preliminary architectural design is established within the Rhino/Grasshopper environment. This is achieved through the Grasshopper – ArchiCAD Live Connection (Graphisoft Deutschland, 2024) and direct model integration. Recreating the architectural design in Grasshopper is crucial because it cannot perform basic operations with ArchiCAD components. As a result, the geometric information must be filtered, and the model reconstructed accordingly in the Grasshopper environment.

Algorithm Development

a) EoL- design algorithm
After successfully incorporating the geometric form of the case study and the subsequent visualisation of the 'circular twin', the process continues with the extraction of design parameters derived from the data imported from the case study and the BIM-based object database created in ArchiCAD. This process uses several components from the ArchiCAD Plug-in within the Grasshopper environment while maintaining a live connection to ArchiCAD. This allows users to select different materials and compositions from the BIM object database to visualise and generate different variants of the initial case study.
b) EoL- assessment algorithm
In the following part, connecting the user-selected data from the EoL- design algorithm and assessment information, such as the Key Performance Indicator GWP(total) for an LCA calculation through an EoL- assessment algorithm, is essential.

Visualisation - Virtual Reality Integration

The visualisation aspect of the conducted research is not the main focus of this paper. However, it is essential to emphasise that during the development of the algorithm, we needed to consistently consider that the Agent within the VR platform, who interacts with the user, must be able to access and control changeable parameters in Grasshopper.

Framework

To better understand the implementation within the visual programming environment Grasshopper, Figure 3 displays a simplified version of the Grasshopper script and its structure, focusing on wall elements within a test building. Achieving a seamless intersection with the BIM model data required the utilisation of a custom Plug-in within Grasshopper, tailored to receive and process data from ArchiCAD dynamically via the bi-directional Grasshopper-ArchiCAD Live connection was necessary (Graphisoft, 2023).

The framework described will be further validated through its application to a specific use case, showcasing its practical utility and effectiveness in a real-world scenario. This use case involves an architectural design project where the integration of circular economy principles is paramount. By implementing the digital framework within this context, the seamless interaction between Grasshopper and ArchiCAD facilitates a comprehensive analysis and reconfiguration of wall elements, demonstrating the framework's capacity to adapt and optimise based on circular design criteria. This application not only highlighted the robustness of the custom Plug-in and bi-directional live connection but also underscored the potential of the developed EoL algorithms to significantly enhance the sustainability of architectural projects through informed decision-making and design optimisation. The following section describes parameter mapping, variant and assessment generation of our status quo.

Concept of Parameter Mapping

In order to integrate ArchiCAD element types, such as walls, facades, or columns, from the BIM model, it is necessary to manually select each architectural design element per type for every floor within ArchiCAD, done by right-clicking on the parameters used for including a collection of ArchiCAD element types. This method enables the user to subsequently change each element type on each floor separately. However, this initial step cannot be achieved using the Agent in the VR platform, as it cannot access components through right-clicks.

After successfully incorporating all elements, the subsequent phase involves extracting crucial information. The custom components within the "Deconstruct" group of the Live Connection Plug-in were required to achieve this. Each element type parameter was linked to its corresponding "Deconstruct" component to obtain further details, including Brep (Polysurfaces) and reference lines. The obtained information is used to generate new variants at the exact location and assemble the visual digital geometric twin of the architectural design by merging all "Brep" outputs, which can be accessed by the Agent and displayed in the VR platform.

However, it turned out that retrieving the net volume, crucial for assessment methods, was not achievable using this method. Thus, a custom property set (CPset) had to be included within ArchiCAD to automatically retrieve the net volume for every element via the "Get Property Settings" component in Grasshopper. This workaround enabled the inclusion of the missing geometrical data in the script to calculate the overall mass of the building design.

Notably, during the development of the Grasshopper script, to ensure the accurate functionality of new connections, minimise dataflow time, and maintain proper data structuring. Initially, the focus was on a single ArchiCAD element type (wall) and one floor. Later, the other ArchiCAD element types were integrated for each floor.

Concept of Variant Generation

The tailored Grasshopper component "Composite" represents products from the current ArchiCAD project and is used to include a selection of products from the object catalogue in the algorithm, for which information is available for the evaluation calculation. In order to make it accessible to the Virtual Agent, it was essential to link components that the Agent could modify to the customisable information in the script. In this case, the Virtual Agent could use the "Number Slider" to run through predefined products to select from a list, facilitated by the Grasshopper "List Item" component.

Once all the required information had been imported and retrieved, it was used to generate new ArchiCAD type elements using the 'Design' group components to create new ArchiCAD elements, such as Walls or Columns along the acquired reference data, creating new design variations. Figure 3 shows a simplified representation of a variant in the Grasshopper environment.

Concept of Assessment Generation

The final segment of the Grasshopper script involved incorporating crucial data to evaluate the circularity potential and environmental impacts of the user-generated variants, such as environmental product declarations (EPDs) and material densities, which could not be retrieved through BIM (Honic and Wolf, 2023). The spreadsheet-based object catalogue based on material databases was incorporated through a Python script developed for the EoL- assessment algorithm. This script imports the density required for calculating the overall mass of the building, along with the net volume of the products obtained through the customised CPset in ArchiCAD. Additionally, it provides the necessary data for evaluating the designs in terms of the circular economy. The Python script contains the following inputs:

- The names of the new products of all the elements modified or not modified as a list.
- The location and name of the external spreadsheet-based database

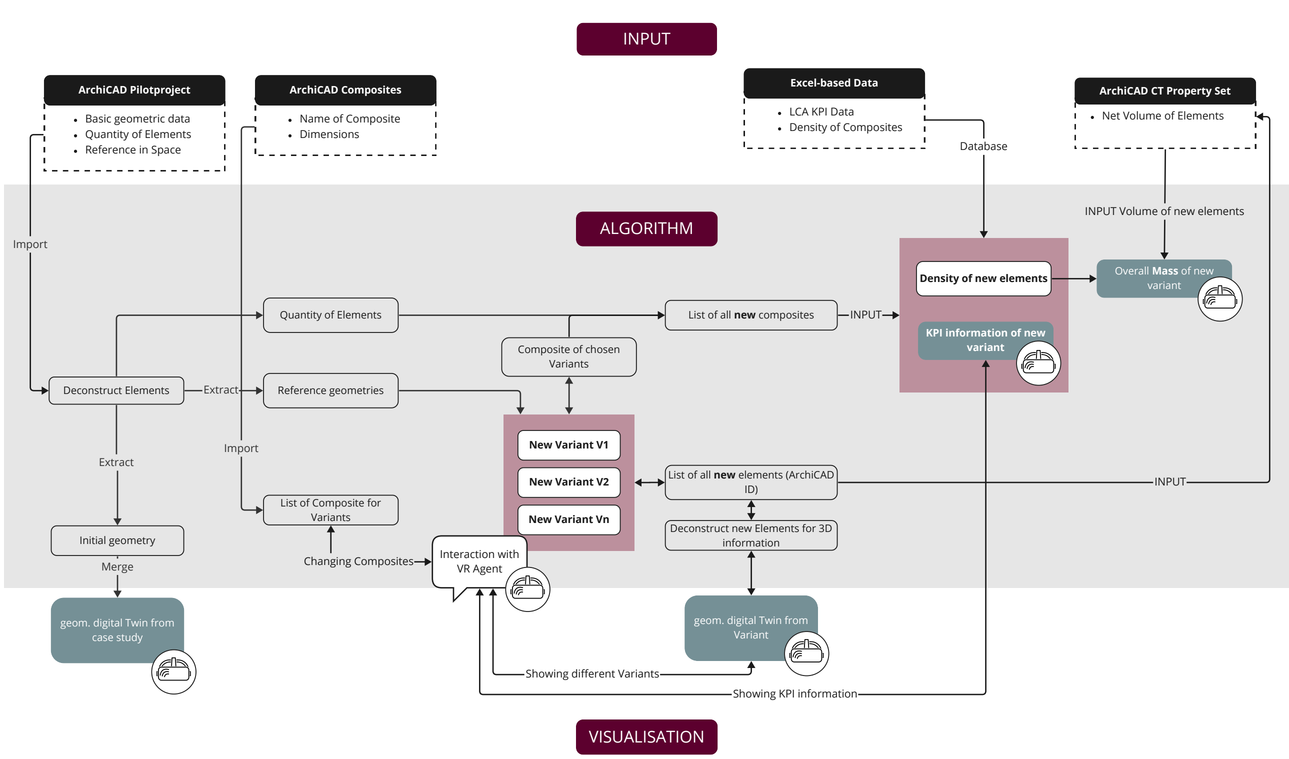

Figure 2: The process and data requirements to develop the EoL algorithms

- The Key Performance Indicator (KPI) the script should search for, e.g., Total Global Warming Potential (GWP - total) and the Material Density

Given the constant requirement for material density, the Python script has been duplicated. This allows the Virtual Agent to use a ”Number Slider” to modify the search input for the calculations in the first Python script while providing a stable estimate of the total mass in the second. However, the outputs of both scripts consist of lists outlining the requisite values for each product. Consequently, these lists must first be aggregated using the Grasshopper ”Mass addition” script before being made accessible to the Agent, enabling user visualisation in the VR platform.

Discussion

Throughout the development of the EoL- assessment algorithm, a consistent pattern emerged: the need for practical solutions to overcome various challenges concerning the interaction between the software used. These challenges primarily revolved around accessing and managing diverse data formats and flows.

One notable solution involved integrating spreadsheet-based circular economy assessment data and material density values using a Python script. This approach was necessary because of the inherent limitations of extracting such information directly from the BIM file (Honic and Wolf, 2023) using the Live connection and its ArchiCAD Grasshopper Toolset components or the customised CPset. Nevertheless, while effective, this solution revealed a vulnerability: the dependence on the spreadsheet-based file's location. However, having an external database for updates can be beneficial as more and more products on the market are expected to receive environmental information (baubook, 2024). This allows easy access to the latest data for design decisions and variant generation with the EoL algorithms.

To address the challenges associated with the extended processing time of the script, which arises from heavy data flow, including constant API interaction, visualisation of 3D elements, and execution of Python scripts for accessing and searching external data, the generation of variants becomes excessively time-consuming. To tackle this issue, exploring innovative approaches becomes imperative. One option worth considering is integrating the ” API - Grasshopper Plug-in” from (Wilk et al., 2023), which promises faster integration of the architectural design model and its data. However, as it relies primarily on textual input and output, it will require a hybrid script to ensure 3D visualisation in the VR platform.

Another challenge is the need for manual selection of ArchiCAD elements, as explained in the section ”Grasshopper Customisation - Parameter Mapping”. This requirement places a disadvantage on the user, requiring access to the Grasshopper script and understanding the basic concept and workflow of the EoL algorithms. However, one method currently under development involves a C# script in Grasshopper, connected via an Add-On in ArchiCAD, to collect and export the required data from ArchiCAD, which must be integrated into the developed algorithms structured according to the Grasshopper-script requirements. This approach would make the steps of

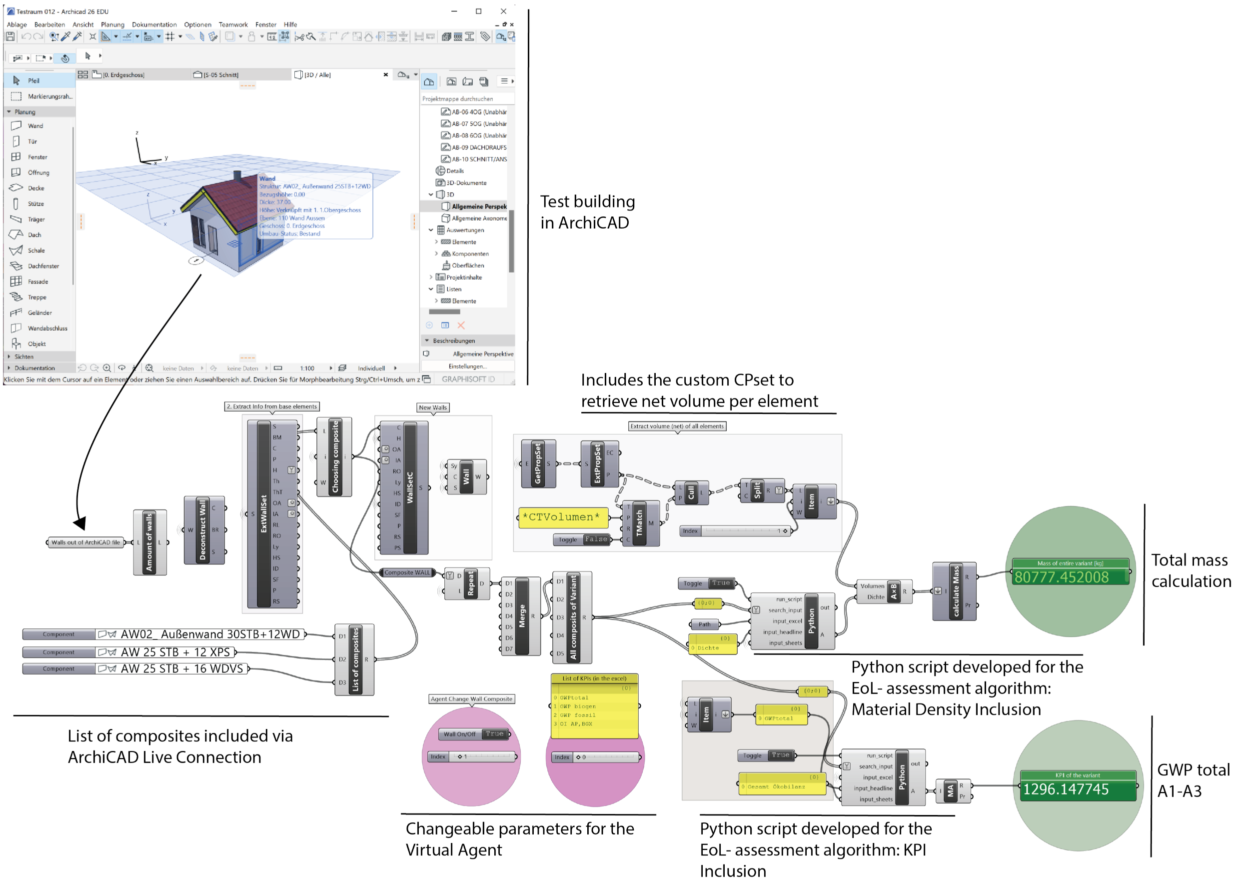

Figure 3: Simplified representation of the Grasshopper script using a test building focusing on four existing walls, showing how the mass [kg] and, in this example, the embodied carbon (GWP-total) for phases A1-A3 (product stage) [kg CO2e] are calculated

picking ArchiCAD elements manually per floor obsolete, enhance the script processing, and mitigate the risk of overlooking elements in ArchiCAD. It may improve user-friendliness, and other initial architectural designs can used.

Moreover, to increase the efficiency and versatility of the presented framework's application, the architecture model must be created following certain rules and structures. This involves the creation of specific ArchiCAD layers to more clearly distinguish between element types, such as internal and external walls. This step is essential due to the different structural functions of these elements and, therefore, different dimensions and product specifications. In addition, an ArchiCAD template should facilitate the seamless integration of the EoL algorithms into other architectural designs. However, it is important to note that doors and windows have been excluded from the EoL- design algorithm for this paper. This decision is due to the fact that the door/window ArchiCAD library part can only be accessed and modified by right-clicking on the "Window Settings" component in Grasshopper, which is inaccessible to the Agent.

The complexity is additionally increased by successfully storing selected variants to ensure the comparability of generated design decisions. Whenever the Agent modifies the algorithm, the previously selected variant is replaced with the new one. In an initial attempt to address this issue and preserve the variants, a Python script was developed to save generated information through a repetitive loop. However, as the results of the loop were insufficient, either the Python script needs adjustment or an alternative solution must be pursued.

Table 1 outlines each limitation with its respective description and proposed future steps to address challenges that occurred during framework conceptualisation.

Conclusion

This paper outlines the possibility of automated decision support through EoL algorithms via a VR platform for design optimisation in terms of circularity and sustainability. It successfully implemented a case study and its building elements and obtained outcomes related to circular economy. While modifying the elements and generating a variant were successful, numerous technical and design challenges remain. However, assuming the intended changes and workarounds are well implemented, the potential for success is promising. It can provide a basis for further research to combine digital tools to better determine the feasibility of the respective interdisciplinary methods. This way, a computational approach and strategy for continuous environmental impact assessment in the construction industry can be developed. By addressing challenges head-

Table 1: Outline of limitations with descriptions and proposed future steps

Limitation	Description of Limitation	Future Steps
Integration Challenges with Diverse Data Formats and Flows	Managing and accessing various data formats between software tools presents significant challenges	Develop and implement middleware or APIs that can automatically translate and integrate data across platforms
Dependence on External spreadsheet-based File Locations	Utilising spreadsheet-based data for assessment data introduces a dependency on the file's location	Transition to cloud-based databases for dynamic access and updates, reducing reliance on static spreadsheet-based files
Extended Processing Time Due to Heavy Data Flow	The extensive data flow leads to time-consuming variant generation processes	Optimise algorithms for efficiency and explore parallel processing to manage and process data more quickly
Manual Selection of ArchiCAD Elements	Manual selection of elements in ArchiCAD for every floor adds complexity and time to the design process	Automate the selection process with AI or develop intuitive UIs that simplify and expedite the selection process
Structural Requirements for Architectural Models	Specific rules and structures must be followed for effective integration of EoL algorithms	Create templates and guidelines that standardise model structures, facilitating smoother integration
Exclusion of Doors and Windows from the EoL-Design Algorithm	Doors and windows are excluded due to limitations in accessing and modifying ArchiCAD library parts	Develop enhancements or Plugins for the VR platform to allow direct manipulation of doors and windows
Difficulty in Preserving Selected Variants for Comparison	Storing selected variants becomes complex when the Agent modifies the algorithm, leading to loss of previously selected variants	Implement a versioning system within the software that automatically archives and tracks changes to design variants

on and continuously iterating on the process, the EoL algorithms move closer to facilitating decision-making in the early design process, enabling circular building structures and integrating End-of-Life concepts.

Acknowledgment

The research described in this paper was carried out as part of the project "Circular Twin - Ein digitales Ökosystem zur Generierung und Bewertung kreislauffähiger Digitaler Zwillinge", funded by the Austrian Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology through the Austrian funding agency (FFG), grant number 899167, which facilitated the conduct of this research.

References

Almeida, P., Solas, M., Renz, A., Bühler, M., Gerbert, P., Castagnino, S., and Rothballer, C. (2016). Shaping the future of construction: A breakthrough in mindset and technology.

Antikainen, M., Uusitalo, T., and Kivikytö-Reponen, P. (2018). Digitalisation as an enabler of circular economy. Procedia CIRP, 73:45 – 49. 10th CIRP Conference on Industrial Product-Service Systems, IPS2 2018, 29-31 May 2018, Linköping, Sweden.

Antova, G. and Tanev, V. (2020). Creation of 3d geometry in scan-to-cad/bim environment. IOP Conference Series: Earth and Environmental Science, 609.

Barbier, E. B. (1987). The concept of sustainable economic development. Environmental Conservation, 14(2):101–110.

baubook (2024). Web-portal für bauprodukte, bauteile und tools, das ökologisches und gesundes bauen vereinfacht. `https://www.baubook.info/de` [Accessed: 2024-02-11].

Brundtland, G. H. (1987). Report of the world commission on environment and development: Our common future. Technical report, the World Commission on Environment and Development (WCED).

Cramer, J. (2022). Building a Circular Future - Ten Takeaways for Global Changemakers. Amsterdam Economic Board.

De Wolf, C., Hoxha, E., and Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. Sustainable Cities and Society, 61:102322.

Ellen MacArthur Foundation (2024). What is the circular economy? https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy[Accessed: 2024-02-11].

European Commission (2021). Europe's digital decade: Commission sets the course towards a digitally empowered europe by 2030. https://ec.europa.eu/commission/presscorner/detail/en/IP_21_983 [Accessed: 2024-04-02].

European Commission (2024). Eu taxonomy for sustainable activities. https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en#related-links [Accessed: 2024-02-11].

Geissdoerfer, M., Savaget, P., Bocken, N., and Hultink, E. (2017). The circular economy – a new sustainability paradigm? Journal of Cleaner Production, 143:757–768.

Gorgolewski, M. (2018). Resource Salvation: The Architecture of Reuse. John Wiley & Sons, Ltd.

Graphisoft (2023). Grasshopper-archicad live connection user guide for archicad 27. https://help.graphisoft.com/AC/27/INT/GC.pdf[Accessed: 2024-02-11].

Graphisoft Deutschland (2024). Rhino – grasshopper – archicad toolset. https://graphisoft.com/at/downloads/addons/interoperability/rhino[Accessed: 2024-02-11].

Honic, M., Kovacic, I., and Rechberger, H. (2019). Improving the recycling potential of buildings through material passports (mp): An austrian case study. Journal of Cleaner Production, 217:787 – 797.

Honic, M. and Wolf, C. D. (2023). Applying eu level(s) framework indicators to improve circularity: A case study. IOP Conference Series: Earth and Environmental Science, 1196(1):012041.

IBO – Österreichisches Institut für Bauen und Ökologie (2023). Oekoindex oi3. https://www.ibo.at/materialoekologie/lebenszyklusanalysen/oekoindex-oi3[Accessed: 2024-04-02].

Ilhan, B. and Yaman, H. (2016). Green building assessment tool (gbat) for integrated bim-based design decisions. Automation in Construction, 70:26–37.

Korhonen, J., Honkasalo, A., and Seppälä, J. (2018). Circular economy: The concept and its limitations. Ecological Economics, 143:37 – 46.

Kovacic, I., Honic, M., and Sreckovic, M. (2020a). Digital platform for circular economy in aec industry. Engineering Project Organization Journal, 9.

Kovacic, I., Pibal, S., Reisinger, J., and Lorbek, M. (2020b). Digital platform for affordable housing - a framework proposal. In Working Paper Proceedings (EPOC 2020), page 1–16).

Martínez Rocamora, A., Rivera-Gómez, C., Galán-Marín, C., and Marrero, M. (2021). Environmental benchmarking of building typologies through bim-based combinatorial case studies. Automation in Construction, 132:103980.

Pibal, S., Kovacic, I., Lorbek, M., Jakoubek, R., Reisinger, J., Temel, R., Ilcik, M., Wimmer, M., Kerbl, B., Travas, D., Bajric, A., Hagmann, E., and Hödl, C. (2023). Wohnen 4.0 - digitale plattform für leistbares wohnen.

Pibal, S. S., Khoss, K., and Kovacic, I. (2022). Framework of an algorithm-aided bim approach for modular residential building information models. International journal of architectural computing, 20(4):777–800.

Santos, R., Aguiar Costa, A., Silvestre, J., and Pyl, L. (2019). Integration of lca and lcc analysis within a bim-based environment. Automation in Construction, 103:127–149.

Schützenhofer, S., Pibal, S., Wieser, A., Bosco, M., Fellner, M., Petrinas, V., and Kovacic, I. (2024). Digital ecosystem to enable circular buildings – the circular twin framework proposal. J.sustain. dev. energy water environ. syst., 12(2),1120500.

Svilans, T., Tamke, M., Thomsen, M. R., Runberger, J., Strehlke, K., and Antemann, M. (2019). New Workflows for Digital Timber, pages 93–134. Springer International Publishing, Cham.

United Nations Environment Programme (2022). 2022 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector.

Wilk, G., Beneitez, J., and Enzyme APD (2023). Archicad api - grasshopper plugin. https://www.archicad-api.com [Accessed: 2024-02-11].

Çetin, S. (2023). Towards a circular building industry through digitalisation: Exploring how digital technologies can help narrow, slow, close, and regenerate the loops in social housing practice. A+BE | Architecture and the Built Environment, 13(22):236.

Çetin, S., De Wolf, C., and Bocken, N. (2021). Circular digital built environment: An emerging framework. Sustainability, 13.