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IDENTIFYING THE POTENTIAL OF VISUAL PROGRAMMING FOR INTEGRATING BUILDING INFORMATION MODELING AND LIFE CYCLE ASSESSMENT

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Abstract
The significance of environmental sustainability and therefore its assessment, is gradually gaining recognition as an important factor in holistic building design. However, due to the high resulting demand for information, Building Information Modelling (BIM) is increasingly seen as an important data source for Life Cycle Assessment (LCA). The manual integration of BIM and LCA is a time-consuming process, which poses a challenge for many small and medium-sized companies that lack the financial resources to expend additional costs. Visual programming languages have the potential to enhance automation in the context of BIM and LCA integration and thereby enhance efficiency. Therefore, this research analyzes different use cases of visual programming languages, providing insight into existing approaches, their strengths and limitations. The objective is achieved by conducting a literature review, which aims to identify the most relevant use cases as well as their advantages and disadvantages. The potential of the three use cases parameterization, automatic assessment and hotspot visualization are then implemented and evaluated based on an exemplary case using Autodesk Revit and Dynamo. The findings provide a comprehensive understanding of how visual programming languages can streamline the integration of BIM and LCA, ultimately leading to more efficient workflows for sustainability assessments in building design.

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Keywords: Building Information Modeling (BIM)**,** Life Cycle Assessment (LCA), sustainability, visual programming

1. Introduction and Motivation

The construction industry is known to be one of the world's largest carbon emitting sectors [1]. In addition, with the European Commission aiming to achieve at least a 55% reduction in net greenhouse gas emissions by 2030 compared to 1990 levels, the construction sector is under immense pressure to identify the main sources of emissions and take appropriate measures [2]. A key tool for assessing the environmental impact of a product or system is the Life Cycle Assessment (LCA), as it is a standardized method [3]. In order to perform a building LCA, a lot of information about materials and their respective environmental impacts is needed. At the same time, Building Information Modeling (BIM) is proving to be a suitable method for providing semantic and geometric information about a building, offering the potential to become a reliable data source for LCA [4].

On the other hand, traditional LCA as well as the integration of BIM and LCA are typically associated with a high degree of manual effort, particularly when it comes to exporting Bills of Quantities (BoQ) to Excel or relying on other static workflows [5, 6]. Among the most laborious aspects is the manual mapping of materials to appropriate LCA data. This is not only time-consuming, but also error-prone. [4, 7, 8] LCA Plug-ins, parametric modeling approaches, and especially Visual Programming Languages (VPLs) address this problem by offering a more automated alternative [6]. VPLs can reduce the workload by streamlining repetitive tasks and enabling semi-automated workflows [9]. Moreover, VPLs provide

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the added benefit of real-time feedback and visualizations, which can significantly enhance the decision-making process during early design phases [7].

As different approaches for implementing VPLs in BIM and LCA integration are currently being widely researched, this work aims to identify the most promising use cases and their benefits for building LCA. While VPL can also support the calculation of the required operational energy of a building, the focus of this work is to automate the determination of the embodied energy. To achieve this goal, a literature review is conducted to identify the most relevant use cases and their potential. In addition, an exemplary implementation in Autodesk Revit and Dynamo is carried out to identify possible implementation challenges. The methodology is described in more detail in chapter 2, while the discussion of each use case is presented in chapter 3. Chapter 4 concludes with a discussion of which use cases are most relevant and the opportunities and challenges associated with their implementation.

2. Methodology

The objective of this work is to identify the potential and most relevant use cases of VPL in automating the calculation of embodied ecological impacts. For this purpose, a literature review is conducted with a focus on case studies that have implemented these use cases and demonstrate the potential. The review according to Webster and Watson [10] is performed by searching the databases Web of Science and Scopus, while the literature is filtered for open access publications between 2019 and 2025. This period is chosen because the intensity of research in this area has been at its highest since 2019, when BIM and LCA integration gained significant relevance. The keywords and initial number of results are shown in *Table 1*.

Table 1 Literature Review Keywords and Databases

Keywords	Database	Results
dynamo AND LCA OR Life Cycle Assessment AND BIM OR Building Information Modeling	Scopus	18
visual programming OR VPL AND LCA OR Life Cycle Assessment AND BIM OR Building Information Modeling	Scopus	13
("visual programming language" OR VPL) AND ("life cycle assessment" OR LCA) AND ("building information modeling" OR BIM)	Web of Science	3
("visual programming language" OR VPL OR "graphical programming") AND ("life cycle assessment" OR LCA OR "environmental impact") AND ("building information modeling" OR BIM OR "digital building model")	Web of Science	3

The results of the keyword search are then filtered by a title and consecutive abstract screening. After the first two keyword searches, mostly duplicates were found. Of the 37 initial results and further literature identified by the snowball method, 14 studies are identified as relevant, with 2023 being the year with the most publications.

To complement the literature review, the identified use cases are then implemented in Autodesk Revit and Dynamo to identify further potential benefits and barriers that arise when implementing.

3. Potentials of Visual Programming Languages in BIM and LCA integration

In visual programming, instead of text-based programming, a graphical interface, such as nodes and connectors are used for rule-based programming [11]. They have been developed to reduce the required programming knowledge, thereby increasing the ease of use for application in the construction industry. VPL in combination with BIM is most commonly used for parametric design, where the geometry of a building component is modeled automatically based on parameters and constraints. [12]

This potential for automation associated with VPL is also applicable for BIM and LCA integration, an area that is currently the subject of significant research. ZHENG ET AL. provide a classification of different BIM and LCA integration strategies and categorize the strategies based on the type of data extraction, data exchange, data flow, degree of automation and LCA application. Data extraction refers to how the data from the BIM model is linked to the LCA data and how the results are calculated. This process can be either conventional, static or dynamic. The data exchange category focuses on the data format in which the BIM model is linked to the LCA data and calculation. For example, exporting the Bill of Quantities to Excel or exporting the model to a non-proprietary data format and then connecting the materials to the LCA data are two of the different possible methods. The data flow category covers data processing in the sense that a distinction is made between third-party applications, plug-ins or APIs and open data exchange formats. The degree of automation can be categorized into a fully manual process, a semi-automated or a fully automated approach. Finally, the LCA application type determines the level of detail at which the LCA is performed (simplified or detailed LCA). [6] Within these categories, the application of VPL in BIM and LCA integration is a dynamic approach to extract data, while staying in the proprietary environment of a BIM authoring tool. Consequently, the application of VPL in BIM and LCA integration has the potential to increase the degree of automation, while providing real-time feedback and awareness during the design phase [7]. Semi-automating BIM and LCA integration offers a balance between efficiency and customizability [13].

As VPLs allow the implementation of many very individual approaches, there are many ways to use VPLs to automate the integration of BIM and LCA. The goal of this study is to identify the overarching potential and use cases to increase the level of automation in the determination of embodied energy and carbon in building structures. Based on the literature review, there are three use cases that receive the most attention in the literature: The enrichment of BIM objects by linking databases and BIM objects, automatic LCA calculation, and hotspot visualization. *Table 2* shows the number of case studies out of the 14 identified that have implemented each use case. Automatic LCA is the most implemented, followed by BIM object enrichment and hotspot visualization.

Table 2 Evaluation of identified use cases in literature

Case studies	Enrichment of BIM objects	Automatic LCA calculation	Hotspot visualization
CORNELY ET AL. 2024	X		
HAN AND RAJABIFARD 2024	X		
BARBINI ET AL. 2022	X	X	X
LLATAS ET AL. 2022	X	X	
GENOVA 2019	X	X	X
SOUST-VERDAGUER ET AL. 2021		X	
MOWAFY ET AL. 2023	X	X	X
KIAMILI ET AL. 2020	X	X	
CARVALHO ET AL. 2023		X	
WIBERG ET AL. 2019		X	X
ALZARA ET AL. 2023		X	
DEMPSEY ET AL. 2023	X	X	X
ALWAN ET AL. 2021		X	X
HOLLBERG ET AL. 2020	X	X	X
Total	9	12	7

The following chapters examine these use cases regarding their potential, exemplary implementation and challenges.

3.1. Enrichment of BIM objects

In the literature review, 9 out of 14 studies identify the use of VPL to enrich BIM objects as having the potential to further automate the integration of BIM and LCA. Performing building LCA and therefore the calculation of environmental indicators requires additional information beyond materials and volumes, such as corresponding LCA profiles in material databases [14]. Therefore, to reduce the manual effort involved in LCA calculations, the modeled objects can either contain relevant LCA information or link to the LCA profile [15]. The enrichment of BIM objects ties in here, as either the Unique Identifier of the corresponding database [16–18] or the values for environmental parameters [19–21] are assigned as parameters.

To implement this use case, the required new parameters must be defined and automatically created for each building element using VPL. In order to fill these parameters with relevant information, the selected database needs to be imported to the VPL environment. In this exemplary implementation, the German database Ökobaudat [22] is imported into Dynamo. In the Ökobaudat, every material has a Universally Unique Identifier (UUID) that is to be attached to the BIM objects. Filtering the Ökobaudat by the UUIDs of all walls extracts the data for, in this example, the Primary Energy Resource Total (PERT) per quantity unit of each material. These values for different life cycle stages can then be used for the calculation of the total environmental impact (see chapter 3.2) or can be assigned to the objects. Figure 1 shows demonstrates the structure of the developed Dynamo script.

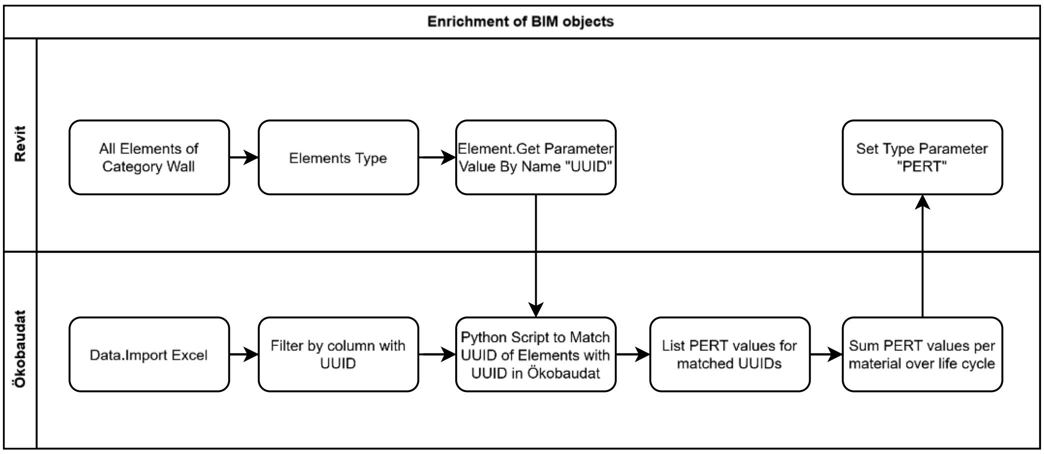

Figure 1 Structure of Dynamo script to add PERT values as parameters to all walls in 3D model

Since there is still some preliminary work to be done to match the identifier of the material, there is also a possibility to automate the creation of an extended material library in Revit. DEMPSEY AND MATHEWS for example implemented an Irish database and created a material library with all the necessary material information. The designer can then choose from the material library and thus enables a simple automatic calculation of the building LCA without additional effort for mapping the correct LCA profile. This enables generic LCA calculations in earlier phases and still offers the possibility to add specific manufaturer datasets later on. [16]

This use case offers many potentials when implemented in the design process. Not only can heterogeneous data sources and databases be integrated, the communication between these data scources and BIM is also more effective than in traditional processes. Hence, manual labor is reduced and erros can be avoided [9, 23]. Furthermore, the results of the LCA calculation can be fed back into the BIM objects to storage the information for the future [17, 18, 21]. In summary, this approach offers potential for increasing efficiency and is particularly advantageous when enriched libraries are used [18].

However, implementation challenges might arise as the data in many Environmental Product Declarations (EPDs) is not consistent. For example, in the implementation of the Dynamo script described above, the reference flow for the indicator PERT is different for each material. While the embodied energy of a concrete wall is given in megajoules (MJ) per square meter, the PERT of the bricks is given in MJ per cubic meter. Therefore, the required quantity unit of the environmental indicator always needs to be defined to avoid errors in the automatic calculation later on. This is typically done by adding a new parameter, which illustrates that the number of parameters to be implemented in BIM increases significantly when this approach is implemented. To give an example, CARVALHO ET AL. added 28 parameter per building element to evaluate 13 sustainability criteria [11]. Multiplied by the number of building elements, this procedure can quickly lead to very large models. Case studies also show that the availability of structured and pre-processed data is necessary to enable the automation of BIM object enrichment [16]. Since standardized material or component libraries are not yet state of the art, some type of manually assigned identifying element is required to enable machine-readable identification of materials. This is accompanied by an effort in terms of data maintenance, as the UUID is not updated automatically, and it has to be ensured that the data set is still up to date.

In summary, the enrichment of BIM objects with VPLs offers potential for the automation of LCA calculations. Currently, there is a significant amount of preliminary work to be done in order to efficiently implement this approach, but with the standardization of material libraries and the further development of EPD in the construction sector, the potential can be increasingly exploited.

3.2. Automatic LCA calculation

Based on the enrichment of BIM objects, an automatic LCA calculation can be performed using VPL. This use case is applied in 12 out of the 14 studies analyzed. By implementing automatic LCA calculation, the mass, volume or area of the materials are first extracted and then multiplied by their corresponding indicator values. The results can be either exported to Excel [17], visualized as bar charts [16] or attributed to the BIM objects [21].

The automatic calculation of the embodied energy of different walls is implemented in a Dynamo script, the structure and result of which is shown in Figure 2. To calculate the total PERT in MJ of all walls of the building, the values for each life cycle phase are added and multiplied by their respective quantity unit. The results are then shown in a bar chart. This is done exemplary for one indicator but can be done for all LCA indicators.

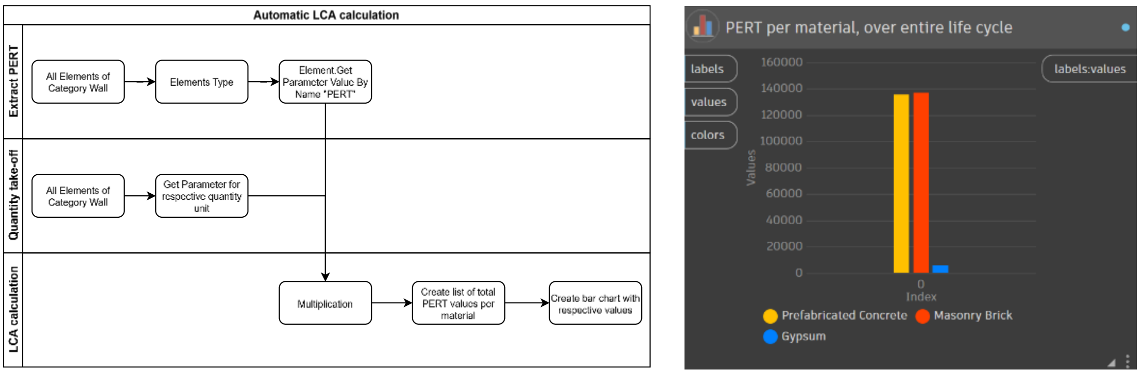

Figure 2 a) Structure of Dynamo script for automating calculation b) Exemplary bar chart to visualize the result

In analogy to the enrichment of BIM objects, the automatic LCA calculation offers higher efficiency and reduced errors [9]. Moreover, real-time feedback is enabled, which can help the planner make more sustainable decisions and being aware of the consequences of design choices [7, 17, 24].

Nevertheless, there are inherent challenges to automating the LCA calculation. As already indicated in the previous use case, the reference flows for the materials differ, which leads to different quantity units being required to calculate the results for each indicator. Additionally, for technical building equipment, the determination of volume involves additional data and calculation steps, as the volume is not automatically provided by Revit [23]. Regarding LCA in general, there are not always data points for each indicator for each life cycle phase. These inconsistencies can be easily overlooked when the process is automated.

To summarize, automated LCA based on a VPL script offers significant benefits such as reduced effort and real-time feedback for planners, but the actual degree of automation achieved in implementation can be hindered by inconsistencies in the data sets.

3.3. Hotspot Visualization

Once the LCA is calculated, the results can be visualized directly in the model view by applying color variation for different ranges of values, which is a use case applied by 7 out of 14 studies. Building components that have less environmental impacts, for instance, can be colored red, while more sustainable material choices can be visualized in green [24]. This requires either normalizing the values of the indicators or defining ranges and thresholds for different colors, which necessitates an absolute assessment of sustainability. When combined with certification systems, criteria for different certification levels can be checked and visualized accordingly [25].

The visualization of particularly high and medium values for environmental indicators is then implemented in Dynamo and the result is illustrated in Figure 3. In this exemplary implementation, the cradle-to-grave Global Warming Potential (GWP) per kilogram is visualized in a dedicated 3D view, so that the focus is on material selection rather than the amount of material used. A challenge is to define which indicator values are considered high impact. In this case, different color ranges are defined from the value range that occurs in this model, meaning that higher values are visualized in red and lower values are visualized in orange or yellow.

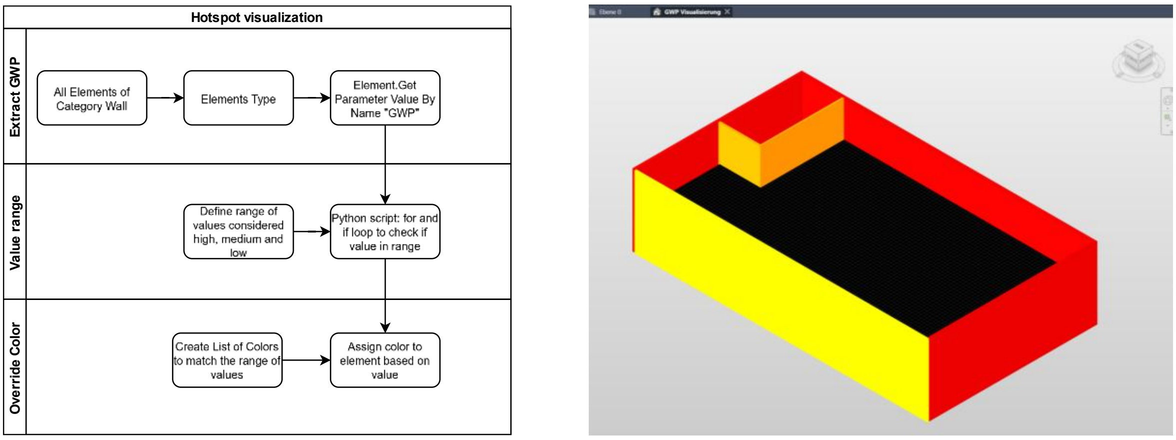

Figure 3 a) Structure of Dynamo script b)Visualization of GWP per kg hotspots in 3D model

This example shows how visual programming can support intuitive, model-based interpretation of environmental data. However, the success of implementing this use case of VPL is highly dependent on the required previous steps and inherent challenges, as described in chapter 3.1 and 3.2.

4. Conclusion

The use of VPLs to automate BIM-based LCA in building construction has increased in recent years, as it offers great potential for reducing the effort required to perform building LCA. A literature review is conducted to identify the most relevant use cases for VPL implementation in BIM and LCA integration. Out of 14 case studies, 9 implemented the enrichment of BIM objects, 12 used VPL to calculate LCA results automatically, and 7 studies examined hotspot visualization.

By enriching BIM objects with LCA data semi-automatically, VPL enables the systematic enrichment of BIM objects by assigning environmental data, such as UUIDs from LCA databases like Ökobaudat, directly to building components. This facilitates the linkage of geometric and environmental data and provides the basis for automation. The second use case, automatic LCA calculation, leverages these enriched objects to calculate environmental indicators based on extracted quantities and mapped LCA profiles. The results can then be exported, stored in the model, or visualized directly. The third use case focuses on hotspot visualization, where calculated LCA results are displayed in the model through color schemes, providing intuitive feedback that supports sustainable decision making.

Across all use cases, the benefits of using VPL include reduced manual effort, increased data consistency, and the ability to provide real-time feedback during early design phases. These capabilities enable designers to quickly identify environmental impacts and adjust design decisions accordingly. Furthermore, the integration of heterogeneous data sources becomes more practical through easily customizable workflows.

However, there are inherent challenges to these use cases. These include inconsistent data and reference flows across LCA databases and the risk of creating overly large and complex models. In addition, a lack of standardized material libraries and the need for manual pre-processing hinder full automation. Despite these barriers, the potential for VPL to improve the efficiency, transparency, and impact of BIM and LCA integration is significant, especially as data quality and standardization in the building industry continues to improve.

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