Acta Polytechnica CTU Proceedings **38**:18–24, 2022
https://doi.org/10.14311/APP.2022.38.0018

ENVIRONMENTAL PERFORMANCES EVALUATION THROUGH BUILDING INFORMATION MODELS

Ambra Barbini[a,*], Giada Malacarne[b], Giovanna A. Massari[a], Carmen Marcher[b,c], Dominik T. Matt[b,c]

[a] *University of Trento, Department of Civil Environmental and Mechanical Engineering, Via Mesiano, 77, 38123 Trento TN, Italy*

[b] *Fraunhofer Italia Research, Via Alessandro Volta, 13 a, 39100 Bolzano BZ, Italy*

[c] *Free University of Bozen, Faculty of Science and Technology, Piazza Università, 5, 39100 Bolzano BZ, Italy*

[*] corresponding author: ambra.barbini@unitn.it

Abstract. The construction industry produces several negative environmental impacts. To promote solutions that reduce these negative impacts, it is crucial to increase awareness among all parties involved in the supply chain. Currently, certification protocols, environmental labels and declarations are the most common tools for promoting sustainability in the construction industry. However, these tools are generally non-mandatory and require specific competencies to thoroughly understand and interpret their outputs, especially for non-specialized users in sustainability assessment. This paper presents a tool for visualizing environmental impacts directly through a Building Information Model, by assigning different colours to model objects according to their environmental performances. Understanding environmental performances data is thus more accessible to non-expert users. Unlike several BIM-LCA integration studies that primarily focus on the needs of designers, this contribution considers the perspective of manufacturers. The developed tool focuses on building products and has been carried out with the Autodesk Revit BIM authoring platform and its VPL-based Dynamo plug-in. Through the combination of 3D models and histograms, the tool facilitates manufacturers to visualize with real-time updates which phase of a product life cycle requires sustainable innovation, which sub-components or process determine the major environmental impacts and calculate the environmental cost indicator of a product.

Keywords: BIM (Building Information Modeling), sustainability, environmental impacts, LCA (Life Cycle Assessment), ECI (Environmental Cost Indicator).

1. Introduction

According to international reports and statistics, the construction sector is responsible for about 36 % of waste generation in Europe [1], 36 % of world energy consumption [2] and 39 % of global carbon-dioxide emissions [3]. A conscious innovation of all the involved parties in the Architecture, Engineering and Construction (AEC) industry is a necessary step in limiting negative environmental impacts, such as non-renewable resources consumption and pollutant emissions. Interest in reducing environmental impacts is steadily increasing, as evidenced by the Sustainable Developments Goals (SDGs 2030), which encourage, among others, actions to combat climate change and to promote responsible production and consumption [4].

Within the construction industry there are different tools developed to increase consumer awareness of environmental impacts. These tools, such as certification protocols, labels and declarations, rate and certify the level of sustainability of buildings and their components. Building certification protocols are increasingly in demand and appreciated, as they are recognised to bring economic advantage, increasing rental and market value, and decreasing operating costs [5]. Similarly, labels and declarations highlight virtuous characteristics of a product, such as the possibility to disassembly it and recycle its sub-components or a low carbon footprint throughout its life cycle. Certification protocols are generally based on multicriteria analysis and based on the evaluation of an external committee, while labels and declarations can be self-declared (Type I), awarded by a third party after a qualitative (Type II) or a quantitative (Type III) assessment. This third type includes the Environmental Product Declaration (EPD), which is a certificate of the environmental performances of a product based on the results of a Life Cycle Assessment (LCA). LCA isa generally accepted methodology for assessing the sustainability of a product or process.

A Life-Cycle Assessment provides values that objectively quantify the impacts of a product on the environment, considering the consumption of energy and natural resources and the release of pollution and waste respectively as input and output flows of a process [6]. The analysis of LCA results provides access to important information on a production process and can support manufacturers in identifying the main factors that lead to negative environmental impacts. Despite the possibility to objectively quantify environmental impacts, LCA presents two main limits for common users:

(1.) it requires a large amount of input data, and

(2.) provides a detailed set of results, which are complex to understand and to compare.

Both limits can be overcome by taking advantage of Building Information Modelling (BIM).

As a system able to collect and manage a variety of data related to building components at different levels of details and stages of their life cycle, BIM can support life-cycle analysis of buildings and their components. Indeed, LCA data can be easily integrated or linked to BIM objects, representing building components [7]. In addition, considering the ongoing digital implementation of the AEC industry, manufacturers and suppliers are also showing increasing interest in developing BIM object libraries of their products to use as digital catalogues or to support the optimization of design and production phases. Therefore, digital implementation and sustainable development strategies can support each other.

This paper presents the possibility of exploiting BIM objects of building components to improve the readability of LCA results and to support manufacturers in identifying possible opportunities for product innovation, towards the reduction of environmental impacts.

2. State of the art

The environmental impacts assessment of products is generally related to its whole life cycle and requires specific expertise to understand the results. By analysing the entire life cycle of a product, as well as, all possible environmental impacts and their aggregations, Life Cycle Assessment (LCA) is considered one of the most comprehensive procedures for the evaluation of environmental performances [8]. LCA results are generally presented as complex tables reporting the values of several impacts categories for each phase of a product life cycle, thus generally requiring the interpretation of an expert. To support manufacturers and suppliers in identifying and pursuing sustainable innovation strategies, not only motivated by marketing logics but with a real contribution to the SDGs, it is essential to improve the visualization and readability of these technical data.

Private and public organizations have developed digital tools to facilitate manufacturers in reading and visualizing the environmental performances of their products. Some of these tools [9, 10] do not refer to a specific product category (e.g. Ecoscan by Echochain), others are specifically addressed to the construction sector (e.g. TOTEM by OVAM). Within the AEC sector, several research groups worked on the integration of BIM and LCA, mainly adopting two approaches [11]: the first one involves the combination of a BIM platform with an LCA software (e.g. SimaPro, OpenLCA and GaBi) or plug-in (e.g. One Click LCA and Tally), whereas the second one requires the enrichment of the model with LCA data. Some of these research groups also considered the importance of results visualization through the model both at the building and infrastructure scale. For example, van Eldick et al. [12] developed a BIM-based system to assess environmental impacts of infrastructure, which includes report generation and model visualization for each phase of the project. Röck et al. [13] presented a solution to assess and visualise the impacts embedded in building elements, as a tool to support early stages of design. Therefore, BIM methods and tools can support not only the automatic and dynamic life cycle analysis of a building and its components but also the visualization of environmental impacts directly through a Building Information Model, making the results much more readable and accessible. However, most of the research, exploring the possibility of integrating LCA and BIM, consider the perspective of the designer or the client. This paper proposes a solution for the evaluation of building components environmental performances, considering the point of view of a building product manufacturer. The aim of the research is to support building products manufacturers to understand and interpret environmental impacts data of their products. To improve the readability and transparency of the environmental performances of the building component life cycle, three specific solutions for the results visualization have been implemented. Through 3D models and histograms, the developed solutions allow manufacturers to visualize:

- which phase of a product life cycle can benefit the most from a sustainable innovation,
- which factors are crucial to reduce environmental impacts,
- on which impact category a specific factor presents the highest influence.

3. Methods and tools

The research is based on a case study and tests the possibility to evaluate the environmental impacts of a building component through Building Information Models. The Fraunhofer Italia Research institute developed the case study in collaboration with the EcamRicert testing laboratory and with the support of the University of Trento, periodically discussing potential and limitations of the defined solutions with local stakeholders.

The case study is referred to a wooden window. Four stages of the window life cycle have been considered, according to EN 15978: product, construction process, use and end of life (Table 1). As an LCA of the considered window has not yet been performed, the EcamRicert laboratory selected from a database the LCA results of some components as similar as possible to those of the window and considered helpful for the research objectives. In this respect, it is important to note that the presented case study does not aim at

	Phase 1: *Product* stage	Phase 2: *Construction process* stage	Phase 3: *Use* stage	Phase 4: *End of life* stage
Factors	Wood [m^3] Glass [kg] Window handle [kg] Rubber seal [kg] Transport [tkm]	Silicon [kg] Nail [kg] Transport [tkm]	Rubber seal [kg] Window handle [kg] Transport [tkm]	Wood [kg] Glass [kg] Transport [tkm]

TABLE 1. Factors considered for each phase of the window life cycle and relative reference units according to EN 15978.

Environmental impact category	Equivalent unit	Weighting factor [€ / kg equivalent]
Depletion of abiotic raw materials (excluding fossil energy carriers) - ADP	Sb eq	€0.16
Depletion of fossil fuels - ADP	Sb eq8	€0.16
Climate change - GWP 100 y.	CO_2 eq	€0.05
Ozone layer depletion - ODP	CFC-11 eq	€30
Photochemical oxidation - POCP	C_2H_4 eq	€2
Acidification - AP	SO_2 eq	€4
Eutrophication - EP	PO_4 eq	€9
Human toxicity - HTP	1.4-DCB eq	€0.09
Freshwater aquatic ecotoxicity - FAETP	1.4-DCB eq	€0.03
Marine aquatic ecotoxicity - MAETP	1.4-DCB eq	€0.0001
Terrestrial ecotoxicity - TETP	1.4-DCB eq	€0.06

Raw materials

Emissions

1-point score

FIGURE 1. Conversion factors for calculating the environmental cost indicator (ECI).

defining real and precise LCA values for the selected window, but rather at testing the feasibility of the BIM-LCA integration process and different ways of displaying the results.

For the production stage, which includes the raw material supply and manufacturing, LCA results were collected for the wood of the frame, the window glass, the rubber seals, and the window handle. The construction process stage mainly refers to the products employed to fasten the window to the wall (nails and silicon). The use stage considers the possibility to replace and repair some components (e.g. window handle, rubber seals) and the end-of-life stage concerns the impacts connected to the dismission of the window components, including the possibility of recycling some of them (e.g. wood elements). For each phase the authors also considered the impact of transport assuming that the window was installed not far from (< 50 km) the production site and that the replacement components and disposal site are accessible within the same region (< 100 km).

The output of an LCA includes different environmental impacts categories (e.g. Ozone Depletion Potential) and each one has a different fictitious unit of measurement, known as equivalent unit (e.g. CFC-11 eq), used to quantify the possible effect of different factors on the environment. As evidenced by Cheng et al. [14], the difference in units prevents from a comprehensive assessment of all the embodied environmental impacts of a building. For this reason, the comparison among different products or among different phase of the life cycle, is only possible considering one environmental impact category at the time or adopting a system of conversion factors. In this research the authors adopted the conversion factors (Figure 1), that the Dutch government developed to determine the environmental cost indicator of a building product, by converting the values of impact categories into summable costs, expressed in euros [15].

The research workflow (Figure 2) includes three main steps:

(1.) the collection and organization of geometrical data within the BIM model and of environmental data within the spreadsheet;

(2.) the definition of the appropriate analysis for the evaluation of the environmental performances of the window;

(3.) the development of different progressively detailed options for results visualisation.

3.1. DATA COLLECTION AND ORGANIZATION

The geometry of the window is based on a prototype of a BIM object library. The University of Trento, in collaboration with a local manufacturer, developed the library with the BIM authoring software Autodesk Revit 2020, starting from the detail drawings and technical information of the product data sheet. The geometric model of the window is replicated four times and each one represents a different stage of the life

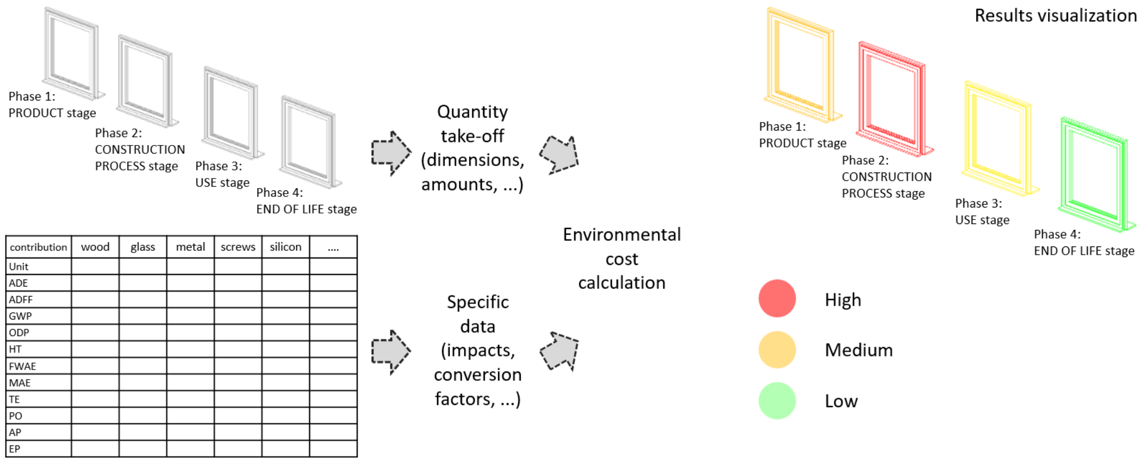

Figure 2. Workflow of the process.

cycle: product, construction process, use and end of life.

Each model representing a phase of the window life cycle is enriched with specific information useful for the evaluation of the environmental performances (Table 2). Most of this information represents the quantities of the window components (e.g. wood volume). These quantities are calculated through the parameter system of the BIM object and depend on both the technical data and the size of the window.

The flow of information is the following: the manufacturer supplies the technical data about the used material (e.g. specific weight) and the designer, according to the client wishes, defines the window dimensions. Other information related to the environmental impacts of each phase, comes out from the EPD, when available, otherwise environmental impacts values can be obtained from an LCA database, selecting products with similar characteristics or the average values peculiar of specific categories of materials and components. For this research, EcamRicert testing laboratory provided the environmental impacts values using the EcoInvent LCA database. Furthermore, data about the production site have been included, to consider the impact of transports during the window life cycle. Different stakeholders participate in the definition of this information according to the considered life cycle phase: the manufacturer contributes during the product stage; the construction company during the construction process stage; the building manager or the owner during the use stage; the demolition company for the end-of-life stage. As these data were not available for the case study, they were assumed.

To avoid modelling all these data within Autodesk Revit, they have been collected within a spreadsheet using Microsoft Excel and then linked to the BIM environment. The same spreadsheet also includes the conversion factors to calculate the Environmental Cost Indicator (ECI).

3.2. Analysis definition

To analyse the environmental performances of the selected window, the environmental impacts and the ECI of each phase have been calculated. To calculate the environmental impacts of each phase, all the values collected in the spreadsheet have been linked to the quantities and dimensions of the modelled window. The environmental impacts selected from the LCA database consider one cubic metre [m^3] as reference unit for wood, one tonne kilometre [tkm] for transports and one kilogram [kg] for all the other materials. The BIM software Autodesk Revit supports the extraction of information about the volume [m^3] of each modelled element. To get the mass of most of the window sub-components, the specific weight [kg/m^3] of each material needs to be multiplied for the corresponding volume [m^3]. The values of each factor, those contributing to the calculation of the window environmental impacts, have been saved in a new spreadsheet, where summed to obtain the environmental impacts of each LCA phase. At this point, using the conversion factors, the ECI can be easily obtained.

The development of a script supported the automation of all the steps of the analysis facilitating to automate and parametrically control different aspect of the Building Information Model. The script was developed with the Visual Programming Language (VPL) application Dynamo, an Autodesk Revit Plug-in. The link between the BIM environment and the spreadsheet has been also performed through Dynamo. It is important to note that when changing the dimensions of the BIM model while running the Dynamo script, the environmental impact values are updated to the new dimensions in real time.

3.3. Results visualization

Results are displayed both through 3D models and bar diagrams (Figure 3):

- to support the visualization of different information at different stage of the life cycle (3D model),

Parameter	Unit	Phase	Value origin
Window frame hight	m	1-2-3-4	Designer + Client
Window frame width	m	1-2-3-4	Designer + Client
Window volume	m^3	1-2-3-4	Model geometry
Wood specific weight	kg/m^3	4	Manufacturer
Wood mass	kg/m^3	1-4	Manufacturer
Glass specific weight	kg	1-3-4	Manufacturer
Glass mass	kg/m^3	1-3	Manufacturer
Window handle mass	kg	2-4	Manufacturer
Rubber seal specific weight	kg/m^3	2	Manufacturer
Nails mass	kg	2	Manufacturer
Silicon specific weight	kg/m^3	1-3	Manufacturer
Silicon mass	kg	1-3	Manufacturer
Distance (supply-manufacturing)	km	1	Manufacturer (assumption)
Distance (manufacturing-construction site)	km	2	Building company (assumption)
Distance (replacement-building)	km	3	Building manager/owner (assumption)
Distance (building-disposal site)	km	4	Demolition company (assumption)
ADE – Abiotic Depletion Elements	kg Sb eq	1-2-3-4	LCA Database/EPD
ADFF – Abiotic Depletion Fossil Fuel	MJ	1-2-3-4	LCA Database/EPD
GWP – Global Warming Potential	kg CO_2 eq	1-2-3-4	LCA Database/EPD
ODP – Ozone Depletion Potential	kg CFC-11 eq	1-2-3-4	LCA Database/EPD
HT – Human Toxicity	CTUh	1-2-3-4	LCA Database/EPD
FWAE – Fresh Water Abiotic Ecotoxicity	CTUh	1-2-3-4	LCA Database/EPD
MAE – Marine Abiotic Ecotoxicity	CTUe	1-2-3-4	LCA Database/EPD
TE – Terrestrial Ecotoxicity	kg 1,4-DB eq	1-2-3-4	LCA Database/EPD
PO – Photochemical Ozone	kg 1,4-DB eq	1-2-3-4	LCA Database/EPD
AP – Acidification Potential	kg C_2H_4 eq	1-2-3-4	LCA Database/EPD
EP – Eutrophication Potential	kg SO_2 eq	1-2-3-4	LCA Database/EPD

Table 2. List of parameters included within the BIM object according to their phase.

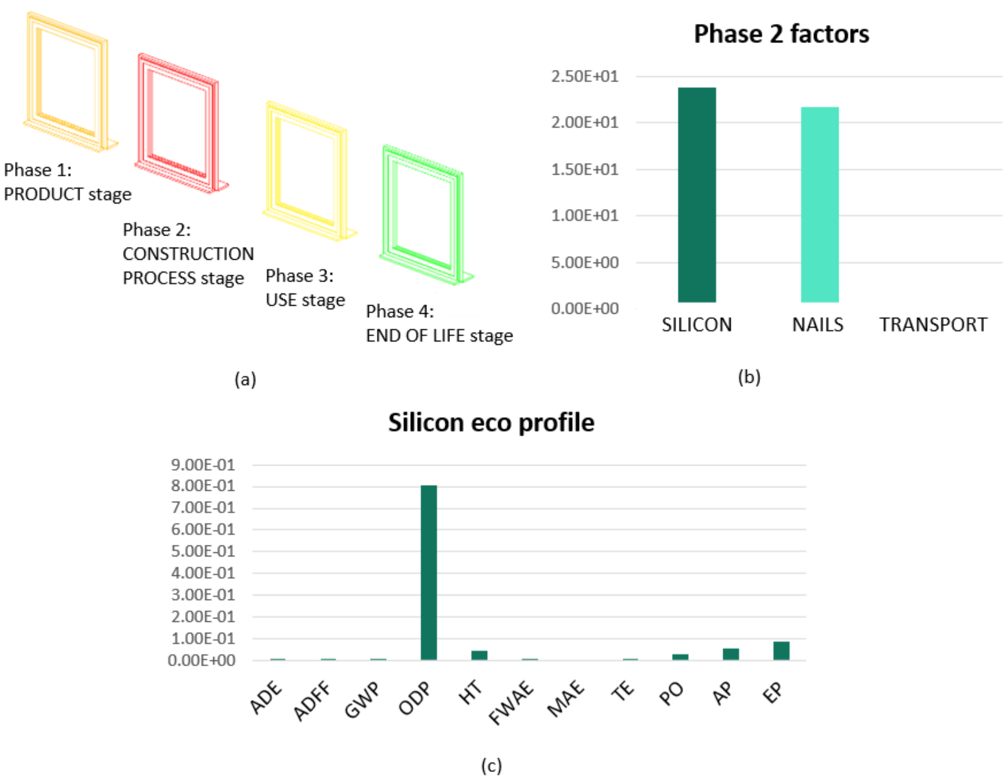

Figure 3. Results visualization options: (a) colour variation of the four life cycle phases, considering the impact category "Human Toxicity" (HT), (b) bar diagram of the environmental impacts factor of the installation phase and (c) bar diagram of the silicon eco-profile.

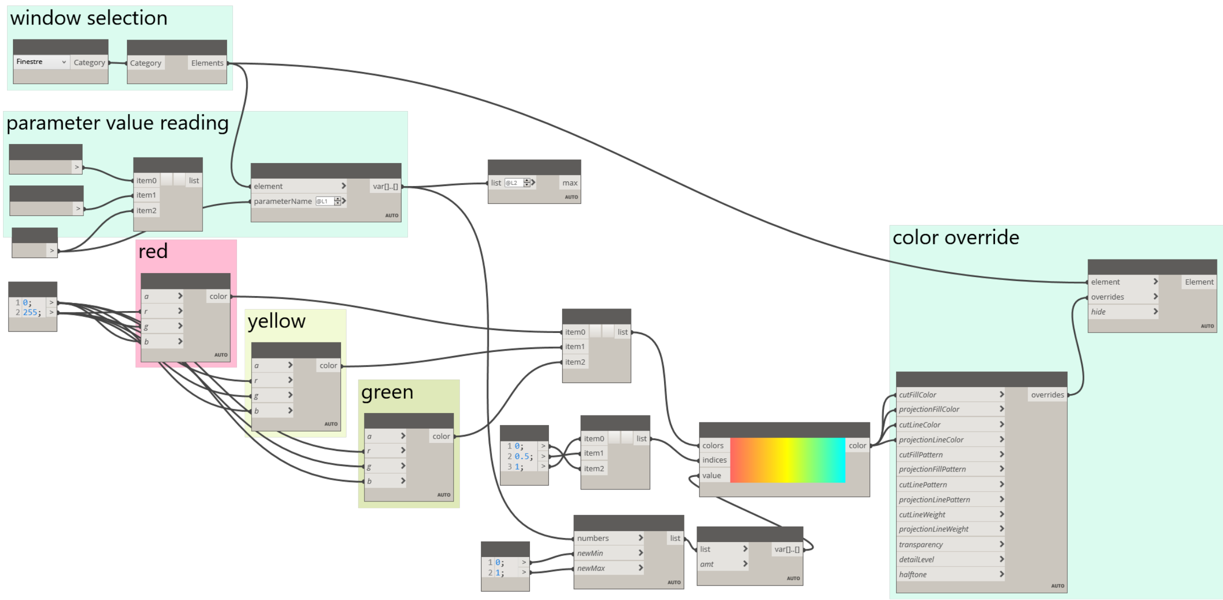

Figure 4. Dynamo script to automate the colour variation of the four life cycle phases.

- to allow the comparison of the environmental impacts of different components of the same stage and the visualization of the eco profile of a single component (bar diagrams).

The environmental impacts of each factor and of each phase and the ECI of each phase are stored within the spreadsheet collecting all the results. The ECI of each phase is also integrated in the models as parameter value. Furthermore, a colour variation of the models has been developed to enhance the readability of the environmental data. The colour variation can be applied both on the values of the impacts of individual categories or on their ECI and displays the geometric models of the window according to a colour scale, indicating respectively high, medium or low environmental impacts. The environmental impact values or their ECI in each phase are normalized and automatically associated to a colour range that varies from green, for lowest values, to red, for highest values, going through shades of orange and yellow for intermediate value. All the intermediate results stored into the spreadsheet are used to display impact categories for single factors and the environmental profile of each factor through bar diagrams. By changing the window dimensions in the BIM environment, both the colour comparison and the diagrams display are automatically updated according to the effective volumes of sub-components.

4. Results

The developed case study tested the possibility to visualise environmental data through a Building Information Model through the thematic colour variation of the model. Furthermore, an automated process has been developed, allowing:

- the correct matching of corresponding values between the spreadsheet and the BIM object data,
- the automatic calculation of environmental performances referred to the window dimension,
- the visual comparisons of the analysis results though the colour variation of the geometric model,
- the creation of bar diagrams with detailed information on the component environmental performances,
- the real time update of the results changing the dimensions of the model in the BIM environment.

The automatic calculation of environmental performances regards:

- the impact categories of each factor (material and transport impacts),
- the impact categories of each life cycle phase,
- the ECI of each life cycle phase according to the Dutch conversion factors.

For the visual comparison through colour variation, the user can choose to compare a single impact category (e.g. Global Worming Potential) or the Environmental Cost Indicator (Figure 4).

5. Discussion and conclusion

The tool developed aims to support manufacturers and suppliers in increasing their awareness on the environmental impacts of the products they place on the construction market. Ideally, the starting points of this solution are the EPD and the BIM object of the product which has to be evaluated. Therefore, this solution is mainly thought for those manufacturers and suppliers interested both in sustainable innovation and in digital implementation. Moreover, BIM objects containing environmental performances data of products can facilitate the design phase to perform sustainability simulations and analysis and to support decision making processes.

It is important to note that in this case the wooden window frame is a solid material in cross-section. This way, the volume of the 3D model corresponds to the real volume of the frame. In case of aluminium or PCV frames there are air chambers, which are usually not in the model due to hight performance demand on the computer, the volume of the 3D model should be adjusted through a formula to obtain the real volume of the frame and avoid small errors that could have high impact on the whole assessment. A similar issue is related to window glazing systems, that are not necessarily three layers of glass.

A further development of this study concerns the use of BIM data in IFC (Industry Foundation Classes) open format to visualize the results. Many building components manufacturers and suppliers do not have a licence for a BIM authoring software and therefore the neutral environment of an IFC viewer could be much more accessible [16]. Future implementations of the tested prototype could concern the comparison of the window components directly through the 3D model, changing the colour of the exact component of the window to show hot spots. Moreover, the prototype could be extended to larger elements, such as systems of components, functional units or entire buildings and considering different points of view. This case of study privileged the point of view of a building component manufacturer, but environmental performances visualization could also support clients, both private and public, as well as designers and construction companies in monitoring and improving project sustainability.

References

[1] Global Alliance for Building and Constructions. 2018 global status report for buildings and construction, 2018. [2021-08-26], `https://wedocs.unep.org/bitstream/handle/20.500.11822/27140/Global_Status_2018.pdf`.

[2] Eurostat. Waste gerenation by economic activities and households. [2021-08-26], `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Waste_generation_by_economic_activities_and_households,_EU-28,_2016_(%25).png&oldid=413561`.

[3] Global Alliance for Building and Constructions. 2019 global status report for buildings and construction, 2019. [2021-08-26], `https://globalabc.org/sites/default/files/2020-03/GSR2019.pdf`.

[4] United Nations. Sustainable development goals. [2021-08-26], `https://sdgs.un.org/goals`.

[5] N. Leskinen, J. Vimpari, S. Junnila. A review of the impact of green building certification on the cash flows and values of commercial properties. *Sustainability* **12**(7):2729, 2020. `https://doi.org/10.3390/su12072729`.

[6] National Italian Unification Body. UNI EN ISO 14040: 2021 Environmental management – Life cycle assessment – Requirements and guidelines.

[7] A. Barbini, G. Malacarne, K. Romagnoli, et al. Integration of life cycle data in a BIM object library to support green and digital public procurements. *International Journal of Sustainable Development and Planning* **15**(7):983–990, 2020. `https://doi.org/10.18280/ijsdp.150702`.

[8] F. Asdrubali, C. Baldassarri, V. Fthenakis. Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings. *Energy and Buildings* **64**:73–89, 2013. `https://doi.org/10.1016/j.enbuild.2013.04.018`.

[9] Ecoscan. Website echochain. [2021-10-12], `https://ecochain.com/ecoscan/`.

[10] TOTEM. Website OVAM (Flanders Public Waste Agency). [2021-10-12], `https://www.ovam.be/materiaalprestatie-gebouwen-0`.

[11] L. Álvarez Antón, J. Díaz. Integration of life cycle assessment in a BIM environment. *Procedia Engineering* **85**:26–32, 2014. `https://doi.org/10.1016/j.proeng.2014.10.525`.

[12] M. A. van Eldik, F. Vahdatikhaki, J. M. O. dos Santos, et al. BIM-based environmental impact assessment for infrastructure design projects. *Automation in Construction* **120**:103379, 2020. `https://doi.org/10.1016/j.autcon.2020.103379`.

[13] M. Röck, A. Hollberg, G. Habert, A. Passer. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Building and Environment* **140**:153–161, 2018. `https://doi.org/10.1016/j.buildenv.2018.05.006`.

[14] B. Cheng, K. Lu, J. Li, et al. Comprehensive assessment of embodied environmental impacts of buildings using normalized environmental impact factors. *Journal of Cleaner Production* **334**:130083, 2022. `https://doi.org/10.1016/j.jclepro.2021.130083`.

[15] Stichting Bouwkwaliteit (Foundation for Building Quality). Determination method. Environmental performance. Buildings and civil engineering works [update 2017], 2019. [2021-10-12], `https://milieudatabase.nl/wp-content/uploads/2020/02/05-Determination-Method-v3.0-JAN2019-EN.pdf`.

[16] A. Barbini, G. Malacarne, G. A. Massari, D. T. Matt. Environmental impacts visualization through open BIM procedures. *TECHNE – Journal of Technology for Architecture and Environment* (23):240–249, 2022. `https://doi.org/10.36253/techne-12143`.