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Modernization of Windows and Doors in Protected Buildings: Possibilities and Their Environmental Impacts

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During the renovation of protected buildings, strict regulations must be met. Buildings of different ages and protection categories require different structural solutions, including the modernization of windows and doors. In addition to heritage protection aspects, environmental awareness, sustainability, energy efficiency regulations, and the objectives of Fit for 55 and the Green Deal are given a prominent role. The research examines how the different categories of protection appear in Hungary in connection with the replacement of windows and doors and what regulations apply to their renovation. A case study of a historic building examines the effects of the interventions, with particular regard to the reduction of CO_2 emissions, with the help of life cycle assessment (LCA) based on a BIM model, using machine and manual calculations. The results show that it is worth staying with the original solid wood material because changing the material – for example, to modern PVC or aluminum triple-layer windows – involves a greater environmental impact. The methodology of the analysis can be used as an analogy for the renovation of other similar buildings and can serve as a basis for issuing different tenders.

1. Introduction

Energy reduction and efficiency are becoming increasingly important. The growing availability of better-quality, modern building materials and structural solutions allows for stricter energy regulations. Humanity has realized the need to manage resources—both material and immaterial—found in the environment, a key aspect of environmental protection. Modernizing existing buildings contributes to a more livable environment, and retaining windows in part or whole helps reduce environmental impacts. Resources are finite, and the built-in material is significant, which drives the tightening of energy regulations. The choice of materials and structural design of windows and doors should also take into account the environmental impacts, the input of natural resources, energy consumption and the environmental impacts associated with their manufacture (Asif et al., 2002). In the case of historic buildings, the historical value of the windows and doors must also be taken into account, and heritage protection may impose a number of restrictions depending on the possible protection or the environment. In the course of the research, windows and doors of different materials and glazing layers were tested in the same system and under different environmental conditions, so that the results obtained can be compared. It is important to consider the environmental impact of the materials installed in new structures before design and renovation, and to avoid the installation of structures that are more environmentally damaging or that emit significant greenhouse gases during the manufacturing and degradation process, when considering the life cycle of the replacement (Roncone et al., 2023). European Union directives are behind the stricter energy regulations. Hungarian regulations were created based on the directives, to which our buildings must comply. The introduction of the "Cost-optimized buildings" and "Near-zero energy buildings" regulations was a significant introduction. The EU Directive 2018/844 (2018) stipulates that by 2030, greenhouse gas emissions must be reduced by 55 % compared to 1990 levels. The name of this program is Fit for 55. As a result, the Hungarian regulations were changed and the ÉKM (2023) decree, which also applies regulations for the CO_2 equivalent, examining the carbon footprint of buildings during operation. Greenhouse gas emissions can be expressed in carbon dioxide equivalents (Kowalczyk et al., 2023). In the case study, the GWP values of different types of

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flush-mounted windows are presented and compared according to the strictness of the different monument construction regulations. GWP is an abbreviation for Global Warming Potential, which quantifies greenhouse gases in the atmosphere in CO_2 equivalents, the accepted unit being kg_{CO2eq} (Asdrubali et al., 2021).
The novelty of the research lies in the fact that there was no such task until now, it must be dealt with as a consequence of the new regulation. Thus, it is a new task to develop the GWP values for the components and alternatives of a window and door of a relatively unique design with the help of the Building Information Modelling (BIM) methodology and a manual manual calculation check. The basic task is to simulate values filled with environmental effects and material properties based on a high Level of details (LOD) BIM model. Using the BIM methodology, metadata can be assigned to structures to facilitate subsequent calculations. The LOD level shows how detailed the BIM model is. Typical levels are LOD100, LOD200, LOD300, LOD350, LOD400 and LOD500. Now LOD300 was used.

2. Problem formulation

The modernisation of windows and doors in historic buildings is limited due to the different protection categories. In Hungary, different standards apply to historical buildings, heritage buildings in the historic environment and locally protected buildings, which may vary from one municipality to another. The research was carried out on the windows and doors of a representative community building in Veszprém, in which case the standards applicable to buildings in Veszprém were taken into account. The different possible structural variations are detailed in the next chapter and presented in Table 1.

Table 1: The possible structural solutions examined in the research (variables)

	modernization level	frame type	1+1-layer glazing	1+2-layer glazing	2+2-layer glazing	3-layer glazing
box type window, wooden frame and wings on external and internal side	initial condition	box	x			
a) replacement of inner wings only, new wooden wings	partial	box		x		
b) replacement of inner and outer wings, new wooden wings	partial	box		x		
c) the whole window is rebuilt, new wooden frame and sashes	complete	box			x	
d) modern new wooden window	complete	block				x
e) modern new plastic window	complete	block				x
f) modern new aluminium window	complete	block				x

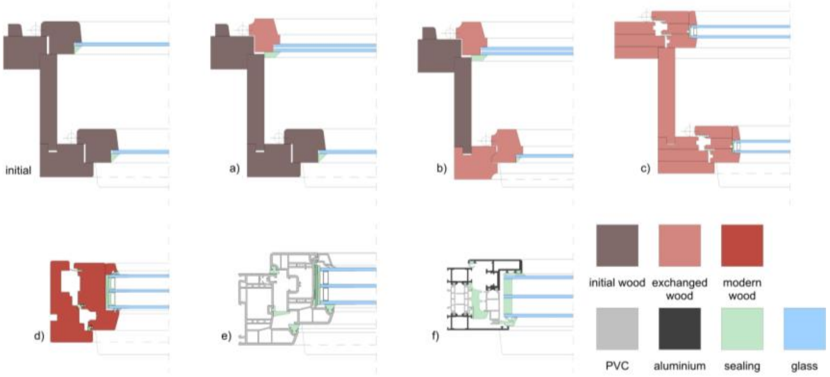

Figure 1: Structural variations of windows and doors. Initial: initial condition, wooden frames and sashes (Horváth, 2022), a) replacement of the inner sash only (Bársony, 2019), b) replacement of both sashes (Bársony, 2019), c) replacement of the whole window (Resch, 2023), d) modern wooden window (Norrsken P41T), e) modern plastic (REHAU GENEO), f) modern aluminum window (WICONA WICLINE 75)

3. Case study

Figure 2 shows the building chosen as a case study, the Eötvös Károly County Library in Veszprém, which is a historical building. The first step in the study was to survey the County Library, followed by the creation of a BIM model using ArchiCAD 26 software. The facade was surveyed using laser scanning and photogrammetry, while the internal geometries were surveyed using LiDAR and various mobile phone applications. The point cloud processing consisted of several steps. First, the laser scanner point clouds were merged in a software called ReCap, and then automatically generated lines were fitted to the point clouds in a software called PointCab. The lines could be imported into Rhino 7, where Grasshopper was used to fit the reference lines of the ArchiCAD walls onto the lines and then transferred to ArchiCAD using a live connection (Ördög et al., 2023).

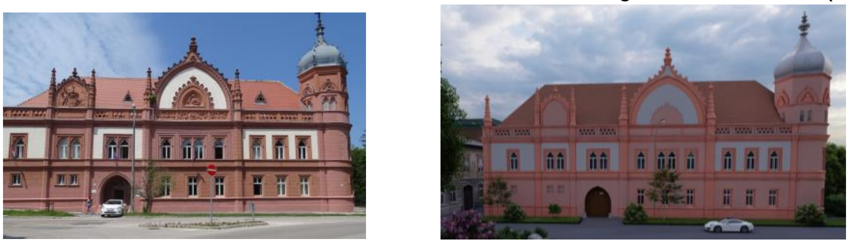

Figure 2: Photo (left) and BIM model (right) of the Eötvös Károly County Library

It is important to note that the historic nature of the building meant that the windows also required individual modelling. Six different versions will be considered for the upgrading of the windows, summarised in Table 1 and Figure 1. In certain cases, the legislation (68/2018. (IV. 9.) Gov. Decree 56. § (1) and (2) article) stipulates that the material of the opening cannot be changed in a historical building. In this case, only the glazing may be replaced, sometimes including the inner sash. In such cases, the minimum change permitted is the replacement of the inner sash with a double glazed sash. This solution is included in case (a).
There are some categories of protection where the legislation only requires the use of the same material as the original. These are variations (b), (c) and (d). In the case of the Veszprém case study, 23/2017 (IX.28.) Municipal Decree 8. § (3) article regulates the material that can be used for the installation of the opening. According to the Municipal Decree, in the castle area and in the historic built-up area of the town centre, 'the external sashes of new or replacement windows and doors on the facade may only be of traditional wood materials, in the case of existing buildings, with elements of the same division, material and structure as the building. Plastic or plastic-finished external casement windows shall not be used'. Cases (e) and (f) refer to situations where the requirements are most flexible for locally historical buildings and unhistorical buildings in the historic environment. Pursuant to 68/2018. (IV. 9.) Gov. Decree 74. § (2) article b) point, it is possible to replace the original opening with an opening of the same colour but of a different material, which has better energy performance. The replacement of the glazing by plastic or aluminium also allows for a change in the number of layers of glazing, so that 3 layers are possible.

4. The investigation

During the research, the replacement of windows and doors in different structural solutions was carried out and examined in accordance with the permitted standards. The extent to which the GWP values change with changes in the material and the number of glazing layers compared to the original single-layer glazing with wood was demonstrated. In addition to the energy impacts, the change in material includes environmental and manufacturing impacts from different materials and end-of-life pollutants from waste generation and disposal. The study has been carried out using the LCA (Life Cycle Assessment) method, a standardised assessment method used to evaluate the different environmental impacts throughout the life cycle of a building. The two standards for LCA are ISO 14040:2008 and ISO 14044:2008, which, among other things, regulate the transparency of baseline data, lay down the principles and are used as a guide for the implementation of LCA. The LCA method provides environmental data for the whole building life cycle. All phases, from the delivery of the material to the site to the formation of the blue body, have to be taken into account. Each material has a value for each phase (Birgisdottir and Rasmussen, 2016).
In this research, the calculation was carried out using a BIM-based digital software, which was also checked manually. The manual calculation method was used to verify the accuracy of the values calculated by the software in terms of magnitude and also helped to better understand the life cycle processes in the research.

4.1 BIM-based calculation method

During the research the Danish ArchiCAD plug-in DesignLCA 4.1 was used which is able to calculate the carbon footprint of the project for the set period using the LCA standard based on the data from the ArchiCAD BIM model. The plug-in calculates the GWP data of the BIM model. The software recognises each modelled structure, records the geometries and material quantities, and then the different environmental impact values can be assigned to the materials carefully set and used in the modelling, which are used to calculate the GWP value of the project under consideration. Figure 3 shows that a DesignLCA tab (1) appears in the upper toolbar of ArchiCAD, which can be opened to set the LCI data for each material. The setup process is shown in Figure 3. During the use of the plug-in, it is necessary to determine which life cycle phases (2) the software should calculate and which calculation should be aimed at. During the research, the environmental impact of the entire life cycle was taken into account. The appropriate setting of the life cycle data of the building materials used during the research is possible using the "Building Materials LCA Settings" (3) menu item (GRAPHISOFT, 2023). The data used for the research mostly come from the Ökobaudat database. The obtained results can be viewed in the "Show palette" menu item marked with the number 4.

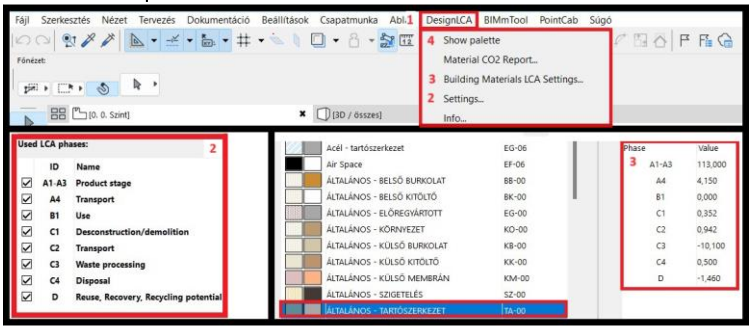

Figure 3: A DesingLCA plug-in palette in ArchiCAD 26 (top), DesingLCA plug-in settings (bottom left) and material lifecycle data settings (bottom right)

4.2 Presentation of variables

Chapter 2 Different materials had to be set for the different components of the windows, so later the values for each material could be modified separately. Within the settings of the DesignLCA plug-in, as shown in Figure 3 (3), the structural variations included in Table 1 became adjustable with the GWP data in Table 2. After performing the calculation for the original door and window, the values necessary for the other cases were rewritten. GWP values were then calculated in these cases as well. The BIM model of the doors and windows was created at the LOG300 level.

Table 2: GWP data obtained from the database

	unit	A1-A3	C2	C3	C4	D
		production	transport	waste processing	disposal	recycling potential
1-layer glazing	m^2	13.35	0.04307	-	0.176	-
2-layer glazing	m^2	36.64	0.08971	1.52	0.352	-0.4441
3-layer glazing	m^2	57.14	0.1355	3.039	0.528	-0.8882
red pine (original)	m^3	-902.8	2.151	1207	-	-369.5
replaced wood	m^3	-632.1	0.537	771	-	-394
modern wood	m^3	-639.34	0.536	749	-	-395
PVC	m^2	191	1.06	10.43	0.26	-73.88
aluminium	m^2	1.03	0.00302	-	0.00242	-0.0316

4.3 Parallel manual analysis

In order to validate the software calculations based on the BIM model, manual calculations were also performed so that the accuracy of the machine results could be verified with the results. In addition to verification, manual calculations also helped to better understand the process. The door and window structures shown in Figure 1 were also used as a basis during the manual calculation. The calculations could be started from their cross-sections and then from the volumes calculated from them. The manual calculation required the same data as the machine calculation. The values of the cross-section of the doors and windows drawn on the machine had to be multiplied by the length of the structure and then added by the corresponding GWP values, if the GWP value was given in m^3. When the GWP values given in m^2 had to be multiplied by the surface of the material expressed in m^2, because in that case the thickness of the structure was already included in the GWP value.

5. Comparison of results

In the machine calculation, the cross sections were modelled at the LOD300 level. A higher LOD level results in the determination of the exact amount of substances. The results are adequate in the present context as well. With the help of the plug-in, it was easy to assign the values necessary for the calculation of the GWP of the various materials to the windows of different sizes, as shown in subsection 4.1, with which the GWP value applied to the windows of the entire building could be calculated. The values are given in Table 3.

Table 3: GWP results of the investigated structural variations with BIM-based and manual calculation

GWP [kg_{CO2eq}]	manual		machine calculation		% of its original volume	whole building	
box type window, wooden frame and wings on external and internal side	34.75		31.91		100	1,742.28	
a) replacement of inner wings only, new wooden wings	67.60	3.	47.03	2.	93.7	2,687.39	3.
b) replacement of inner and outer wings, new wooden wings	62.96	1.	20.68	1.	108.7	1,410.36	2.
c) the whole window is rebuilt, new wooden frame and sashes	89.74	4.	62.15	3.	127.78	1,013.57	1.
d) modern new wooden window	67.036	2.	65.43	4.	112.2	3,523.42	4.
e) modern new plastic window	760.29	6.	668.74	6.	34.07	7,384.28	6.
f) modern new aluminium window	109.85	5.	109.66	5.	17.46	5,430.17	5.

There are small differences between the values of the manual and machine calculations. The reason for the differences can be found in the issue of accuracy, the machine calculation was done with a LOD300 level cross-section, while the manual calculation was done with the exact values, and the calculation for the entire building was also done with the help of the software as detailed above. The minimal deviation of the results of the manual and machine calculation of individual windows confirms that the machine calculation is also accurate and reliable. In the following, the results will be discussed in relation to the calculation of the entire building.
The Table 3. shows that in the construction of the entire building (in which all sizes and types of windows were included) it is most favourable from the point of view of environmental impact when windows manufactured from modern materials with 2+2 layer glazing are installed. It came second, when the case is not replaced, only the wings are replaced from high-quality solid wood. The third change was the replacement of only the inner wing and its double glazing. The installation of a modern, single-wing, triple-glazed wooden window results in significantly more carbon dioxide emissions, and sixth, the installation of an aluminium window increased this value by two-thirds. Finally, the highest GWP value was calculated for the installation of the PVC window.
The obtained values are determined by the invested input and output quantities. By using double glazing, it becomes necessary to use more materials, so more CO_2 is released during production, decomposition, etc. Regarding the use of materials, it can be stated that produced plastic emits a large amount of greenhouse gases during its production and decomposition (Stachowiak-Wencek et al., 2013). Aluminium has a less polluting effect on the environment, and the recycling of aluminum is becoming more and more common these days (Kumai, 2023). Regarding the obtained results, a significant jump in quantity can be observed in the case of variation d), then f) and finally e). From all of this, we can conclude that improving the quality of the wood and doubling the glazing does not entail as much environmental impact as the use of PVC or aluminium casement and frame doors and windows. The last three most environmentally damaging cases were ranked 4th, 5th and 6th in each calculation. As can be seen in Table 3, increasingly modern materials have increasingly significant environmental footprints. Better-quality wooden windows, or replacing them with plastic or aluminium case and frame structures, modify and increase the amount of greenhouse gas emissions. In the case of historical buildings, you cannot rely on standards, they are built from site-specific materials and the geometry of the windows is also different. As an analogy, the research can be applied to other buildings of a similar age.

6. Conclusions

The research examined the environmental effects of window replacements belonging to different monument protection categories in relation to the CO_2 equivalent, which is significant nowadays due to energy regulations. The calculations were carried out using both software and manual methods, and then the data were compared. According to the results, the production and degradation of windows and doors with better thermal insulation can emit more greenhouse gases than those with worse thermal insulation. In the case study, the GWP value

of the building is 1,013.57 kg_{CO2eq}, if a modern solid wood window with 2+2 layer glazing is installed, but if it is replaced with a PVC window, the value increases by almost seven times (7,384.28 kg_{CO2eq}).
Another potential research question whether the carbon footprint of the energy savings covers the amount of CO_2 resulting from the structural change. The lessons learned from the tests presented above help during the window renovation, we can show the environmental impact of replacing the windows. If we are looking to renovate a similar building, the values experienced here will help us in how to deal with it and how to approach our buildings. The results are partly generalizable to other buildings of similar age and construction, but historic buildings have different geometries of openings, so it may be rare that the best condition will be different. If a more detailed LOD-level model had been created, the values of the two types of calculation methods would indeed be closer to each other. It is only worth increasing the LOD level to a certain degree of detail, because after a level it becomes unnecessarily detailed, which requires calculations and a lot of time.
As mentioned above, within the framework of Fit for 55, it is important to significantly reduce CO_2, which can be investigated using the research methodology. In addition, the EU Green Deal sets significant targets for the continent to become climate neutral. Based on these calculations, it is possible to reproduce which type of window in renovation projects produces the lowest CO_2 emissions and responsibly protects the environment. The developed methodology can serve as a basis for European Union or government tenders. Applicants can prove how much the CO_2 emissions of buildings can be reduced during the renovation of windows and doors. The research draws attention to the fact that it is worth considering the use of materials, the position of the wings and the number of glazing layers used. With conscious planning and careful consideration, the state of our built environment can not only be improved, but also sustainable.

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