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Development of a Plug-In to Support Sustainability Assessment in the Decision-Making of a Building Envelope Refurbishment

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Abstract: Existing studies provide evidence that buildings and the construction sector are the largest consumers of natural resources and carry the greatest responsibility for greenhouse gas emissions. In order to reverse this situation, future challenges involve utilising the lowest amount of resources possible. To this end, building refurbishment has become a crucial strategy, given its potential to improve operational energy efficiency and to extend the life span of existing building stock, thereby reducing the environmental impact while also providing social and economic benefits to our cities. Life cycle sustainability assessment (LCSA) has become one of the scientific community's most widely recognised methodologies for the evaluation of the social, economic, and environmental dimensions (triple bottom line), as it assesses sustainability using quantitative metrics. However, the implementation of this methodology to support the refurbishment process at the project stage in building design tools, such as BIM, remains scarce. One of the main obstacles lies in the difficulties of accessing building information, given that the system boundaries only cover new materials and products. Hence, this study proposes a BIM plug-in developed to support multi-dimensional building material selection in the early design steps based on the LCSA of a building during the refurbishment stage and validates its application in a case study. The results show the viability of using this tool during the early design stages and demonstrate the consistency of the results for evaluating various material and product alternatives for the refurbishment of the envelope system of a multi-family residential building. This study contributes towards the integration of decision-making by providing real-time assessment of a building envelope.

Keywords: sustainability; life cycle sustainability assessment; building information modelling; tool development; building early design steps; building refurbishment; building envelope

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1. Introduction

Existing scientific studies provide clear evidence of the role played in the climatic crisis by the built environment, in that it emits 40% of greenhouse gas emissions worldwide [1]. Future tendencies indicate extreme climatic situations and a substantial decrease in biodiversity if no measures are implemented for their reduction [2]. Radical changes are, therefore, required to alter the ways of designing and conceiving our buildings and the built environment.

In the European context, strategies such as the Green Deal [3] and the Renovation wave [4] propose the progressive and absolute reduction of carbon emissions in order to achieve carbon neutrality by 2050, and suggest an increase in building renovation and rehabilitation, as well as an increase in data digitalisation throughout a building's life cycle. These ambitious objectives require the decarbonisation of all economic sectors, including the construction and building sector, for both the embodied and operational carbon footprints. The embodied carbon footprint is related to the materials and products that are installed in the building and includes processes such as manufacturing, construction, and transportation [5]. In the current context, in Spain, instruments such as the Climate Change Law [6] encourage the use of materials with the lowest embodied carbon footprint possible. However, these measures do not include a quantitative procedure, nor do they involve the calculation of the embodied carbon footprint. This calculation and its declaration are now being integrated into several European Countries, such as Sweden [7] and the Netherlands [8]. Its expansion across European countries has been planned for development in the next few years. Indeed, the new version of the Energy Performance of Buildings Directive, EPBD [9], proposes the calculation of the carbon emissions of the whole life cycle of buildings for both the embodied and operational carbon footprints.

In order to calculate the whole-life-cycle carbon emissions, the life cycle assessment (LCA) methodology is crucial, as the "carbon footprint is the sum of greenhouse gas emissions and greenhouse gas removals in a product system, expressed as CO_2 equivalent and based on this methodology (LCA) using climate change (CC) or global warming potential (GWP) as the only impact category" [10]. However, to implement effective measures for reducing carbon emissions from the building sector, it is also necessary to make these measures affordable (from an economic point of view) and positive for the community (from a social point of view). Hence, the scientific community [11,12] recognises the value of methodologies such as life cycle sustainability assessment (LCSA) in addressing the triple-dimension sustainability assessment. The LCSA methodology combines three methods based on impact quantification throughout a building's life cycle: life cycle assessment (LCA) (environmental dimension); life cycle costing (LCC) (economic impact); and social life cycle assessment (SLCA) (social dimension) [11]. Given the increasing necessity to address building sustainability from a holistic perspective (by integrating the environmental, economic, and social dimensions), the building design phase is crucial, as it is the phase in which it is the easiest and cheapest to incur design changes [13]. A study has demonstrated that the design phase has great potential to achieve accurate LCSA results during the early design stages in design tools such as Building Information Modelling (BIM) [14]. For instance, during this stage, it is possible to estimate more than 80% of the CO_2 emissions (environmental dimension), 60% of the costs (economic dimension), and 70% of the working hours (social dimension) of the total results for the product and construction impacts (A1–A3 and A5 information modules ISO 21931-1 [15]) in the detailed design stage.

In recent decades, multiple studies [16–24] have demonstrated the increasing development of life-cycle-based methods in the design process and in design tools, such as BIM. For example, Potrč Obrecht et al. [16], Soust-Verdaguer et al. [17], Mora et al. [19], and Santos et al. [22] reviewed existing studies in the field of LCA and BIM, and provided evidence of the growing tendencies. Llatas et al. [18] demonstrated the feasibility of LCSA implementation in BIM. Santos et al. [20] and Santos et al. [21] developed a plug-in to evaluate the environmental and economic dimensions in BIM. Hollberg et al. [24] investigated the application of BIM-LCA throughout the design process. These developments focused on simplifying the assessment process and workflows, and on integrating different life cycle information modules (system boundaries) for the assessment of new buildings and building refurbishment. However, the application of life-cycle-based methods to building refurbishment presents several particularities [25]. For example, not only must the life cycle inventory focus on the new materials and components [26], but it must also consider existing materials and components to correctly model the quantities of materials. This requires the control of building information in relation to new and refurbished elements. The number of existing studies [27–29] that focused on the application of the life cycle approach to building refurbishment in BIM remains limited and includes the assessment of the economic and/or environmental dimension(s), without considering the social dimension (S-LCA). For example, Dauletbek and Zhou [27] focused on the refurbishment of an existing residential building using BIM-enabled LCA and simplified LCC "considering environmental compatibility, energy efficiency, and profitability based on real construction and energy consumption data". Tushar et al. [29] developed a BIM and LCA workflow to compare different precast materials for a building retrofit. Kim [28] conducted LCA studies based on different energy standards and used BIM to formulate refurbishment alternatives through a case study. The study also showed the correlation between LCA and LCC. Moreover, it should be borne in mind that the level of automation in the application of BIM-LCA in these existing studies remains low. For instance, Dauletbek and Zhou [27] used WEBlca, a web application for LCA that has not been integrated into the BIM methodology. Tushar et al. [29] used a combination of tools, including Tally [30] for LCA calculation, FirstRate5 for regression analysis, and @RISK palisade for Monte Carlo simulation.

On the other hand, the existing BIM-LCSA tools and advances [31–33] focus on new buildings. For instance, Figuereido et al. [32] developed a framework for sustainable material selection by integrating various software (such as Tally and Excel) and focused on a new building case study, which included all the building elements in the LCSA and was limited to the A1 to A4 information modules. In Soust-Verdaguer et al. [31], one of the main limitations was the control of the building elements that comprised the system boundaries. The plug-in neither allowed the identification of the existing and new building elements, nor that of the elements that belonged to the building element systems. The BIM objects library is limited to structural system elements and, therefore, fails to consider the recommended thermal transmittance values of the envelope to achieve the required operational energy performance.

The authors' previous studies are based on the development of assessment tools focused on new buildings [31]; hence, this present study proceeds with the improvement of the latter's development and explores its potential for the selection of building material in building envelope refurbishment.

To the best of our knowledge, no study has yet included the LCSA in the decision-making of the building refurbishment stage and supported results in BIM in real time. This study is, therefore, based on a plug-in developed to conduct LCSA in a BIM model to support decision-making in the refurbishment process. The plug-in's development aims to provide a solution to the existing limitations in the LCSA in BIM.

2. Materials and Methods

In order to achieve the aforementioned goals, this study proposes tool development following the steps described in Figure 1 and based on the methodological framework validated in several scientific publications [18,31,33].

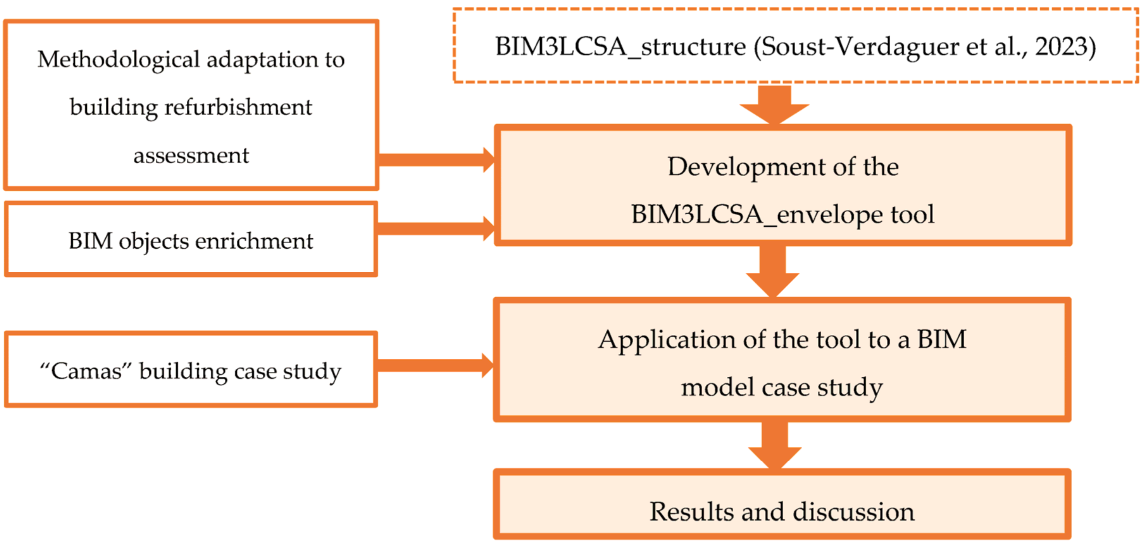

Figure 1. Graphical representation of the tool development strategy based on previous study Soust-Verdaguer et al. (2023) [31].

The tool's development took previous development [31] into consideration to conduct building structure evaluation based on the LCSA in BIM. The procedure to adapt the BIM3LCA_structure tool to the envelope building system consisted of a methodological adaptation of the LCSA to building refurbishment assessment and BIM-Object library enrichment. The methodological adaptation aimed to include the detected particularities to apply the LCSA to building refurbishment, as described in [26]. The BIM-LCSA implementation was based on the enrichment of the properties of the building elements that composed the BIM model (such as walls, windows, doors, etc.), using information extracted from a database (the so-called BIM-TBL database).

The BIM-TBL database is a BIM-Object library that includes alphanumeric information for the implementation of the LCSA methodology at the building element scale. The data referring to the environmental dimension (carbon footprint), the economic dimension (euros), and the social dimension (working hours) are organised according to the structure of the IFC Building Elements (IFC4) classes [34] and include the building elements that comprise the envelope system. The BIM model for the evaluation of a building includes information on the building's geometry and the quantification of the building's elements thereof at an intermediate level of development (LOD). The plug-in includes the LCSA calculation procedure in the BIM models and the visualisation of the results in real time developed in the native BIM modelling software: Autodesk Revit 2022 [35]. Lastly, the results and their discussion include the data extracted from the use of the plug-in to evaluate the BIM models and the building design alternatives. A brief discussion of the results in terms of operational and embedded aspects is also included.

2.1. Tool Adaptation to the Building Refurbishment Process

The plug-in's definition focuses on reducing effort by simplifying processes and increasing the level of automation in the LCSA calculation in the building envelope's refurbishment, thereby helping the designer to visualise the best design solution (while considering environmental, economic, and social dimensions).

The tool's development assumes that the definition of the BIM model's geometry to be employed for the evaluation presents a relatively low level of development (LOD) [36]. Therefore, in order to apply the LCSA to a building envelope system, the alphanumeric information on the BIM objects that make up the BIM model incorporates information of a more detailed nature regarding the materials and products.

This enables the rapid evaluation of construction alternatives so that the designer is aided in their definition of the best solution that would subsequently be incorporated into the BIM model. In order to minimise the effort invested in the identification of the elements and to facilitate the verification of the system boundaries, the plug-in includes a limited list of building elements that comprise the envelope system, including the façade, windows, doors, roofs, and floors (see Figure A1).

To enable quick and direct interaction of the user with the BIM model and the LCSA calculation, the plug-in includes a button for the manual selection ("Select Elements" button) of the building elements in the BIM model in a 3D view. Moreover, to adapt the plug-in's development to specific aspects of building refurbishment life-cycle techniques, the authors have included, apart from the building elements filter (see Figure A2, left-hand side) used to select the building elements that can potentially be included in the envelope, a field ("IsEnvelope") to confirm the specific elements that are to be included in the envelope, for example, if the slabs are not in contact with the ground or the doors are not exterior doors. Moreover, in order to adjust the system boundaries to the building refurbishment LCA's particularities [25], the plug-in displays the "Phase" of the construction process, which could be "Existing" or "Refurbish", to filter the existing and new elements.

In Spain, specific tools and methods are employed for the calculation of the operational energy and that for compliance with national regulations [37]. Building parameters are considered, such as the internal loads and operational conditions, climate zone, exterior conditions on inner and outer surfaces, building elements, thermal transmittance of materials, thermal bridges, the void factor, and transmission and radiation in opaque enclosures and the ground. From all these factors, the parameter that most influences the embodied impacts is that for the definition of the building elements and materials, especially regarding the thermal transmittance and opaque and transparent enclosures. Therefore, building design in BIM can be limited to utilising only recommended transmittance values and recommended proportions of openings and transparent enclosures. To simplify the integration of the operational energy calculation in BIM, the plug-in includes a library of predefined solutions for building refurbishment (including walls, doors, windows, and roofs) that comply with the recommended thermal transmittance values [38] for the climate zone of the case study.

2.2. Case Study Description

The case study is the energy rehabilitation of a multi-family building of 36 social housing dwellings located in Camas (Seville), which was conducted in 2020 and promoted by the Housing and Rehabilitation Agency of Andalusia [39]. The real total area of the building is 2686 m^2. As the case study is a building envelope refurbishment, the verification of the usefulness of the tool focuses on the analysis of several construction alternatives. For the evaluation of the model and verification of the methodology employed, only a portion of the building was selected, as shown in Figure 2. This portion of the building is representative, as it contains the same building elements (walls, exterior doors, windows, etc.) on which the rest of the building envelope is being refurbished. Moreover, the energy efficiency improvement operations on the façade, such as the replacement of carpentry and glazing, and the installation of thermal insulation, are the same as those in the rest of the building.

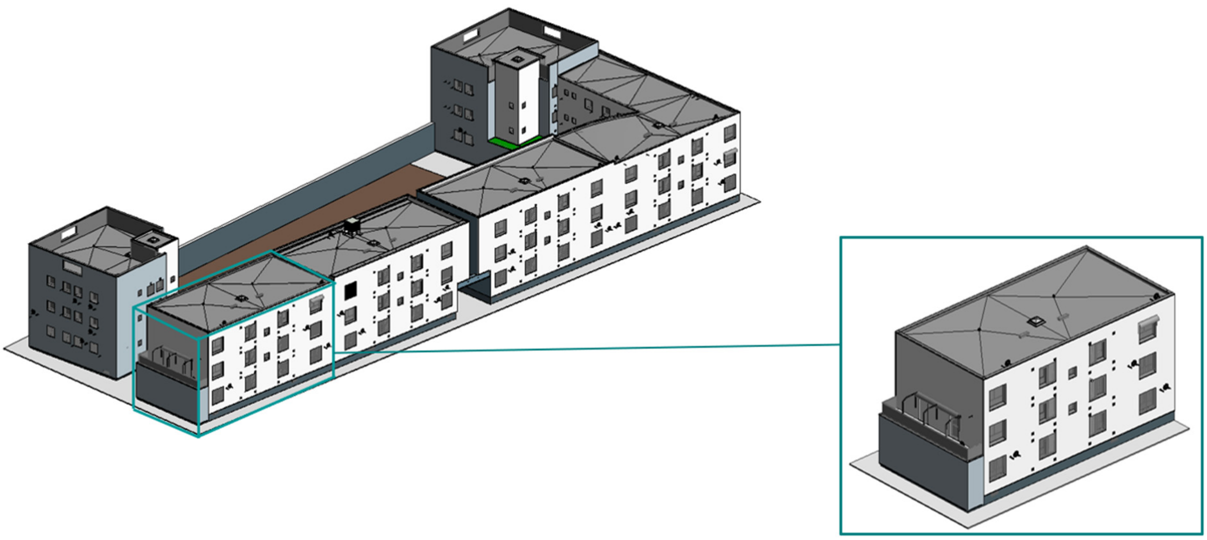

Figure 2. BIM model of the Camas Building (**left**-hand side: complete building; **right**-hand side: portion of the building included in the assessment).

The information to be included in the BIM model of the building was classified in accordance with the LOIN concept [40], wherein geometric information and alphanumeric information of the objects that comprise a BIM model are recognised.

2.3. Tool Application to the Case Study

The methodology used for the evaluation of the case study consists of the following steps (see Figure 3):

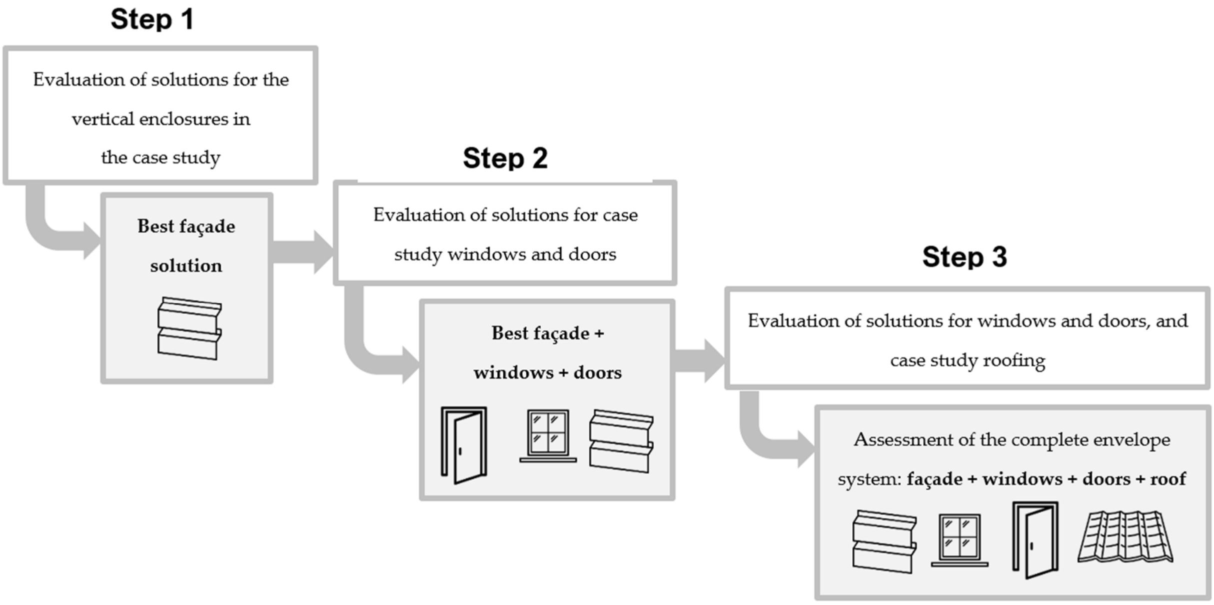

Figure 3. Diagram of the methodology followed for the evaluation of the case study.

Step 1: Evaluation of solutions for the walls: the study compares three alternatives to determine the best solution for this type of building element and adopts this solution before continuing on to the following step.

The three alternative construction solutions that were selected for the rehabilitation of the façade were the following: the exterior thermal insulation system (ETICS), ventilated façade, and interior insulation (see Table 1). The selection of these options focuses on the most frequent ones for façade rehabilitation [41]. The ETICS solution was the constructive solution implemented in the real building. On the other hand, each of these solutions was evaluated using two alternative materials for the insulation layer: expanded polystyrene (EPS) foam and mineral wool, the most frequent for this type of building refurbishment [41]. The thermal transmittance (U) values for the three solutions were all the same (0.30 W/(m^{2}K)). This value was used in the operational energy simulation to comply with the energy regulations [38] and was lower than the oriented values for this climate zone and type of element (climate zone B4, element wall U value = 0.38 W/(m^{2}K)).

Table 1. Description of the solutions for exterior walls included in the case study.

	Solution 1	**Solution 2**	**Solution 3**
Type of solution	ETICS	Ventilated façade	Interior insulation
U-value	0.30 W/(m^{2}K)	0.30 W/(m^{2}K)	0.30 W/(m^{2}K)
Materials for insulation	EPS	EPS	EPS
	Mineral wool	Mineral wool	Mineral wool

Construction solutions were designed in accordance with the Technical Guidelines for Façade Rehabilitation in Spain [42]. For example, the ETICS system included a finishing layer, which must comply with the degree of waterproofing required for the facade according to the Technical Building Code (CTE) in Spain [38]. Its thickness may vary depending on the rainfall of the climatic zone. In Seville, a 6 mm layer can be sufficient. The ventilated facade used a system based on cellulose panels. To improve its waterproofing conditions, a finishing coat was considered, providing openings in the joints for the ventilation of the chamber. In the case of EPS, located in the ventilated chamber, a gypsum board was used for fire protection. In the case of mineral wool, as it is non-combustible, this panel was not necessary.

Finally, the interior thermal insulation solution used a gypsum board system with adhered thermal insulation. This panel was coated to hide the joints between the panels and improve its appearance. Appendix A includes a detailed description of the materials and thicknesses (see Tables A1 and A2). The load-bearing structures were not included in the calculation because they were common to all the solutions analysed. Other minor elements, such as screws and pieces of connecting meshes, were excluded from the evaluation due to their small contribution to the total bill of materials.

Step 2: Comparison of solutions for windows and doors in the case study, whereby the best solution is determined and adopted for the evaluation of the last element. For this purpose, three types of carpentry were considered for the windows, two solutions for the exterior doors (steel and aluminium), and a combination of both solutions (see Tables 2 and 3).

Table 2. Description of the solutions for windows included in the case study.

Solution and Material 1	Solution and Material 2	Solution and Material 3
Double glazing	Double glazing	Double glazing
Wood	PCV	Coated Aluminium

Table 3. Description of the solutions for exterior doors included in the case study.

Solution and Material 1	Solution and Material 2	Solution and Material 3
Steel	Aluminium	Steel and Aluminium

Step 3: Incorporation of the roof into the evaluation of the sustainability of the envelope to obtain the results of the complete envelope system. Finally, Table 4 shows the horizontal envelope taken into account for the roof.

Table 4. Description of the solutions for the roof included in the case study.

Solution and Material 1
Non-trafficable roof finished in gravel with XPS (thermal insulation) and trafficable roof finished with ceramic tiles and XPS (thermal insulation) for the terrace.

The feasibility of this tool for the evaluation of the case study was largely due to the speed and simplicity of the procedure, which only required the assignment of the codes corresponding to the BIM objects to be evaluated according to the characteristics specified in the BIM-TBL library [31,33], which were integrated into the plug-in.

2.3.1. Life Cycle Sustainability Assessment Applied to the Case Study

The scope of the building sustainability assessment is defined, in the first instance, by the type of assessment of the three main dimensions: environmental, economic, and social. Moreover, by considering the methodological aspects and assumptions in order to conduct the LCSA applied to the design phase of buildings in BIM, as previously addressed in [14,18,33], the scope of this assessment covered the following aspects: the definition of elements to be included in the assessment, the definition of the building life cycle phases to be included in the assessment, and the definition of the impact categories and indicators to be used for the sustainability assessment (Section 3.1).

2.3.2. Definition of Building Information Included in the Assessment

Figure 4 shows the information modules included in this study following the criteria defined in previous work [14,18,33], together with the data availability and the relevance of the information modules [14]. As the case study was a refurbishment and followed the criteria established in previous work [26], the sustainability assessment focused on the new materials and processes incorporated in this phase and excluded those existing in the building. For the evaluation, the building elements employed were those detailed in the previous section that were included in the BIM model in the refurbished/rehabilitated phase. This study compared the embodied aspects of each solution, including the information modules A1–A3, A5, B2, B3, B4, and C1 for the new materials, products, and components incorporated in the building envelope's refurbishment.

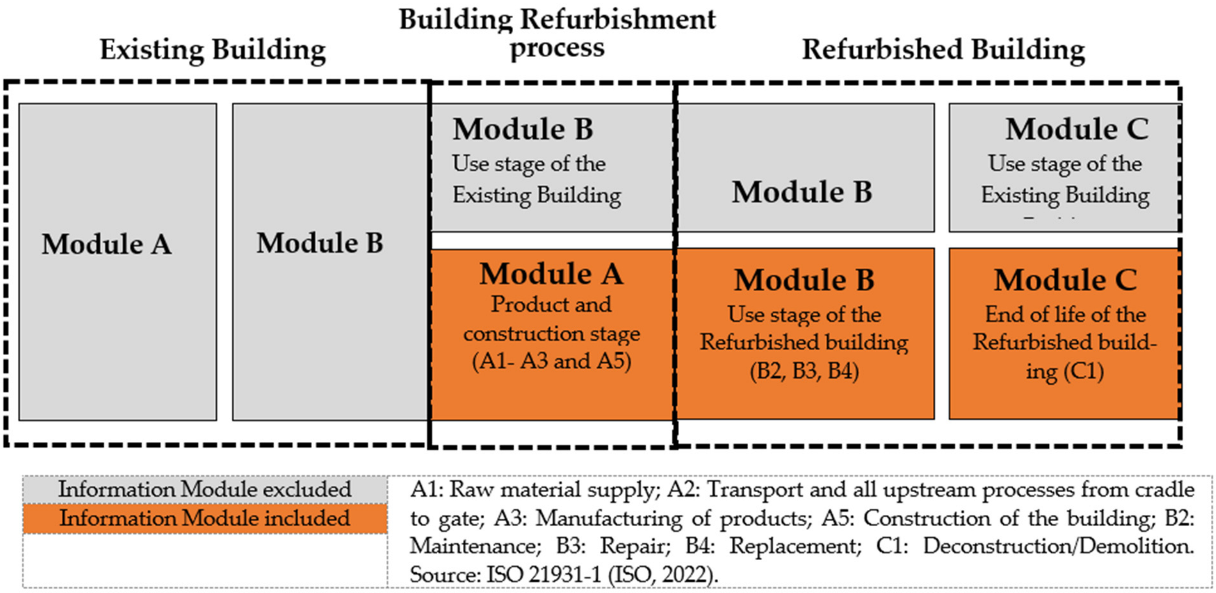

Figure 4. LCSA information modules based on ISO 21931-1 [15] included in this study.

2.3.3. Definition of Building Elements Included in the Assessment

The building assessment was based on the building envelope system and included the IFC element classes listed in Table 5. The definition of the BIM objects that comprised the building corresponded to an LOD of approximately 200–300 [36]. This means that the elements included in the evaluation were modelled following the criteria detailed in Table 5, including the geometric information of the BIM model.

Table 5. Main specifications of the elements integrated into the BIM model according to BIM Forum [36].

IFC Building Element	BIM Forum Specifications
IfcDoor	LOD 200: Doors are either modelled as a single component or represented with a single frame and panel. Approximate unit size, location, and type are provided.
IfcRoof	LOD 200: These are defined as generic objects separated by material type with an approximate total thickness represented by a single layer. Designs and locations are still flexible.
IfcWall	LOD 200: These include the size, shape, location, and orientation of the element. They are defined as generic objects separated by material type with an approximate total thickness represented by a single layer. Designs and locations are still flexible.
IfcWindow	LOD 200: Windows approximated in terms of location, size, count, and type. Units are either modelled as a single monolithic component or depicted with a single frame and glazing.

2.3.4. Definition of Impact Categories and Indicators

Considering the three dimensions (environmental, economic, and social), the assessment included the following impact categories and indicators: global warming potential (GWP) in CO_2-equivalent emissions, costs (euros), and working hours (hours).

One of the contributions of the methodological development of the LCSA [18] and the BIM-TBL database is the harmonisation of the structure of environmental, economic, and social data provided by the BCCA [43]. This database uses a systematic structure [44] to organise the information of the building and its elements, as well as the materials and processes that are necessary from the product phase, construction, and use, to the end-of-life phase.

For the evaluation of the case study, generic BIM objects were used. These BIM objects included information on environmental, economic, and social impacts of general BIM elements from the BIM-TBL library and included generic data on environmental impacts (kg CO_2 eq.) extracted from the ecoinvent v3.7.1 database [45] and systematically organised through the BCCA [43]. Economic (euros) and social (working hours) data were extracted from the BCCA [43].

3. Results and Discussion

3.1. Case Study LCSA Results

After applying the evaluation procedure to all the technical solutions detailed in Section 2.3, the best solution was that which included ETICS-EPS in the façade, wooden windows, and aluminium for the main door and exterior doors (see Figure 5).

Figure 5. Results obtained from the evaluation of the ETICS-EPS façade solution, wooden windows, aluminium doors, and non-transitable roof.

From the results obtained, the EPS solution for the exterior walls was indicated as the best-performing option in the environmental dimension. However, when analysing the material variation between the EPS and mineral wool ETICS solutions, it can be seen that the impacts per kilogram of mineral wool for the manufacturing process were lower than those of EPS. The results extracted from the ecoinvent v3.7.1 database [45] for the GWP impact category (IPCC 2013) showed that the impact per functional unit (kg) of EPS was 3.541593 kg CO_2 eq. and of mineral wool was 1.306912 kg CO_2 eq. Due to the differences in the density of the two materials, the results of the environmental assessment turned in favour of EPS when similar thicknesses (similar thermal conductivity) were installed as thermal insulation in the building to obtain equivalent thermal transmittance values. Moreover, the ETICS solution and the ventilated façade may have been better solutions than the interior insulated façade, which may have been the cheapest, but not the best, solution to reduce thermal bridges [41].

This demonstrates the importance of using assessment tools and methods that are close to the real materials and quantities installed in the building. Other types of comparisons that simply compare impacts (e.g., per kg) without considering the totality of the characteristics of the materials installed in the building could lead to erroneous decisions. On the other hand, it should be borne in mind that the results of this assessment were limited to the inclusion of one impact category (GWP), which was mainly focused on the product and construction phase (A1–A3 and A5). In this respect, it is understood that the order of the alternatives evaluated could be modified if, for example, another life cycle phase is included or the results of the benefits of recycling or reuse of the materials and products utilised (module D) are communicated.

The evaluation of the window solutions (Table 6) shows that the wooden solution yielded the best results for all three dimensions (environmental, economic, and social), as it presented the lowest CO_2 emissions and costs, and generated the most local working hours. Given that demolition works of the new materials and product were manually developed the C1 values for the environmental impacts did not consume fuel or electricity, thus the values obtained are zero (see Figure 5).

Table 6. Results of the window solutions and the best solution for walls.

	Main Material Solution	Environmental kg. CO_2 eq.	Economic €	Social h Working Hours
1	Façade: ETICS-EPS, Windows: wood	5790.01	45,274.93	4263.44
2	Façade: ETICS-EPS, Windows: coated aluminium	6094.88	59,353.22	4258.11
3	Façade: ETICS-EPS, Windows: PVC	6743.41	57,349.72	4256.71
		Best value	Intermediate value	Worst value

Finally, the results were calculated for the three dimensions, including the best solutions for the façade, windows, external doors, and roof. The multidimensional (environmental, economic, and social) assessment gave equal weight (33.3%) to all dimensions. Table 7 shows the three best solutions for the façade, windows, and doors. In Tables 6 and 7 the colour code green indicates the best values, the yellow ones the intermediate and the red ones the worst values.

Table 7. Normalised results for the multi-dimensional assessment of the three best solutions for the envelope system.

	Combination of Material Solution	Environmental	Economic	Social	Total
1	Façade: ETICS-EPS, Windows: wood, Main exterior door: steel, Exterior doors: aluminium	0	0	0	0
2	Façade: ETICS-EPS, Windows: wood, Main exterior door: steel, Exterior doors: Steel	0.88282628	−0.8828047ε	0.8825072	0.882529
3	Façade: ETICS-EPS, Windows: wood, Main exterior door: aluminium, Exterior doors: aluminium	−1.11276295	1.11278286	−1.11305839	−1.113038
	Best value		Intermediate value		Worst value

3.2. Advantages of the Tool Developed

The results show that the triple-dimension assessment (environmental, economic, and social) of the building envelope refurbishment could be conducted in real-time using a BIM model. The tool enabled the comparison of various materials and technical solutions in real-time, enabling the logical and orderly organisation of the evaluation of the elements that comprised the building envelope, thereby facilitating the calculation of the LCSA. However, the normalisation of the results and the weighting of the three dimensions (environmental, economic, and social) was manually implemented.

It was possible to perform the assessment and attain coherent values for the information modules included. For instance, the values obtained for the environmental dimension were consistent when compared with those in similar work [46]. In Hollberg et al. [46], the reference values obtained for the case of external walls varied between 0.82 and 3.82 kg CO_2 eq. per square metre per year. In this study, these values were lower (0.38 kg CO_2 eq. per square metre per year) due to the fact that it was a building refurbishment; hence, the structure system and other building systems were excluded from the system boundaries. Other studies [27] that focused on comparing two scenarios for the refurbishment of multi-residential buildings assumed different U-values for the external walls: 0.23 W/m^{2}k and 0.62 W/m^{2}k. The results for that study varied from 5.74 to 3.79 kg CO_{2-} eq. per kg of building material per square metre per year, considering all the building systems that comprised the building envelope.

This study demonstrates the adjustability in the definition of the system boundaries of the building for a building refurbishment LCSA and its correlation with the 3D-view BIM model. The tool focused on the envelope design at the material and geometry level, which could help to optimise the building's performance. Therefore, by focusing the building envelope's design on the material's thermal transmittance parameters, a reduction was facilitated in the effort required in the operational energy calculation. This could help towards optimising the embodied impacts, while leaving other variables that affect the calculation of operational energy (such as form factor and occupancy) at fixed values.

3.3. Limitations and Future Developments

Limitations in the scope of the assessment and of the information modules included were detected. For example, several information modules, such as C3, C4, and D, were not included in the case study validation. Although the integration of the building elements was limited to the building elements implemented in the real building, the authors aimed to maintain the scope of the study close to the expected theoretical values for operational energy demand (33.07 kWh/m^2 yr.) and to provide a fair comparison of the solutions.

The results demonstrate that the EPS solution is better than that of mineral wool if solely the product, construction, and deconstruction processes (C1 module) were considered, which was also aligned with other studies, such as [47–49]. However, waste processing and benefits beyond the building system were not included. Other studies [50] that focused on material circularity analysis provided evidence that the flame-retardants in polystyrene materials in the existing stock made polystyrene-based materials less suitable for recycling than mineral-based insulation.

This study focused on the use of predefined combinations of materials and precalculated thermal transmittances in accordance with the recommended values for the climate zone of the case study (Seville, B4 according to the CTE [38]). Future studies could include dynamic calculation to verify a wide range of options for the building envelope, or could include a more comprehensive number of values for the various climate zones in Spain [38]. Future research could, therefore, be focused on its automatic integration into plug-in development. For example, as highlighted in Soust-Verdaguer et al. [31], multi-criteria decision methods, such as the TOPSIS (technique for order of preference by similarity to ideal solution) [51] and AHP (analytic hierarchy process) [52] could support automatic weighting and the performance of multi-criteria assessment in the plug-in.

4. Conclusions

The application of the plug-in and the methodology developed to carry out the quantitative evaluation of sustainability during the design phase of buildings enabled the identification of the best construction solutions, materials, products, and processes to be used in building refurbishment without the necessity of attaining high levels of detail in BIM models. The results presented herein provide evidence of the special consideration that should be taken into account in the application of building refurbishment LCSA in BIM.

The main contribution of the tool lies in the flexibility in the use of data regarding the BIM model to conduct the LCSA in order to comply with the requirements of the application of the LCSA for building refurbishment.

Moreover, the study proposes a design methodology to not only reduce the GWP of buildings and building life cycle costs (e.g., materials that help to minimise maintenance costs and require the lowest number of replacements over the life cycle of the building), but also to increase the social benefits following element optimisation based on its relevance in building geometry design. From the results attained herein, the integration of various dimensions (economic, environmental, and social) in building design demand special attention, especially in building refurbishment, where the return on the investment needs to be assessed not only from the economic dimension (savings in energy consumption), but also from the environmental (embodied and operational impact optimisation) and social dimensions.

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Data Availability Statement: The data is available in a public access repository that does not issue DOIs. Publicly available datasets were analysed in this study. This data can be found here: https://www.juntadeandalucia.es/haciendayadministracionpublica/apl/pdc_sirec/perfiles-licitaciones/detalle-licitacion.jsf?idExpediente=000000222870. All other supplementary data were provided in Appendix A.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

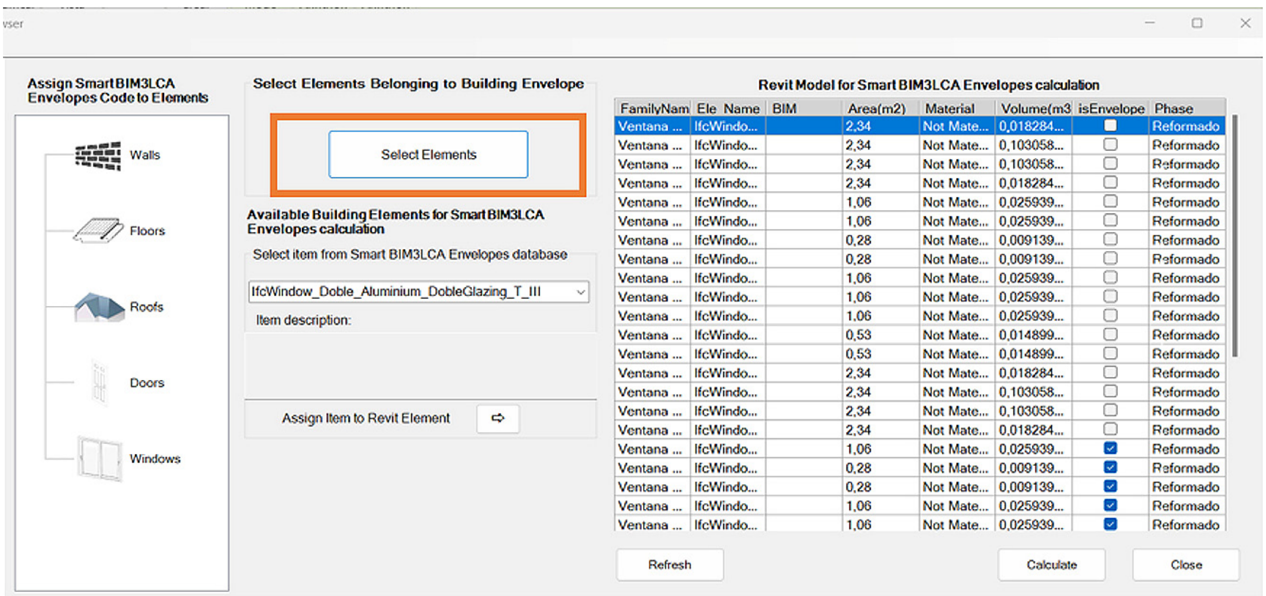


Figure A1. Screenshot of the plug-in user interface showing the "Select Elements" button.

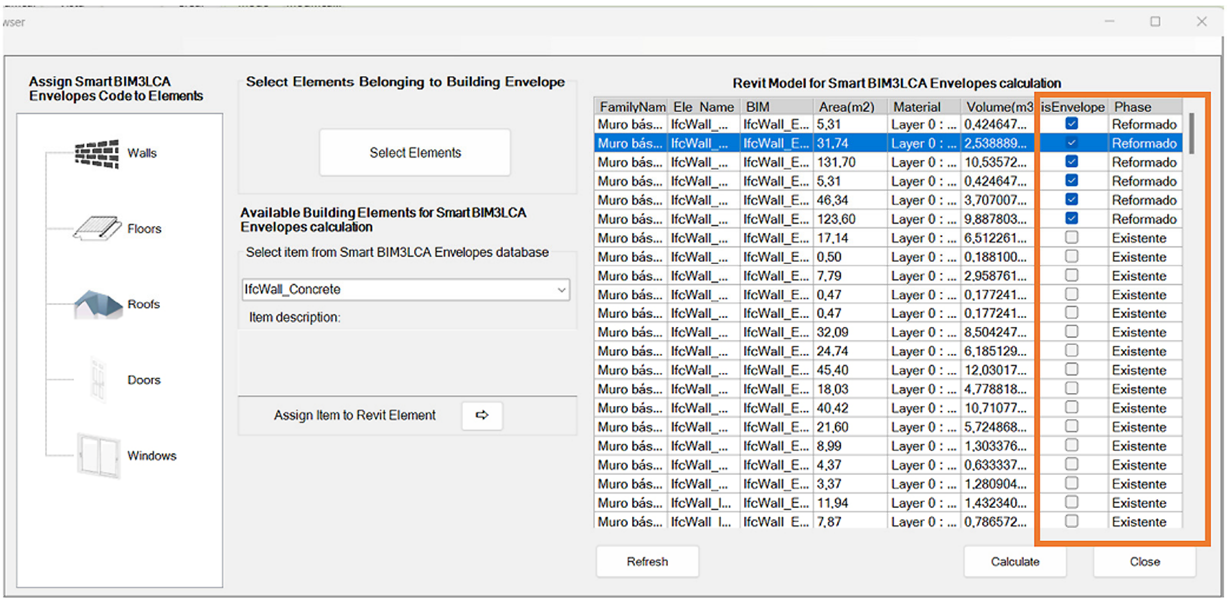


Figure A2. Screenshot of the plug-in user interface showing the "IsEnvelope" field and "Phase" display.

Table A1. Description of the façade solutions.

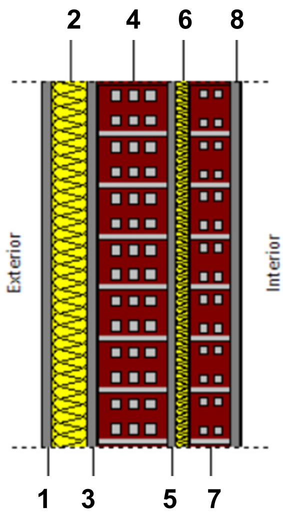
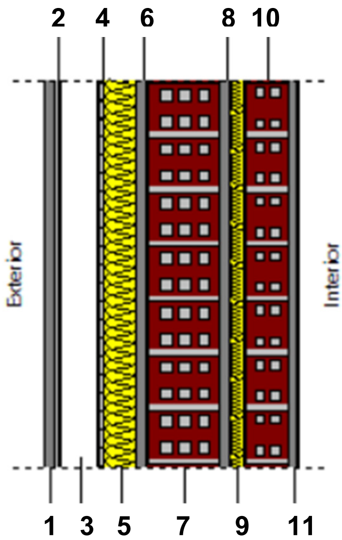
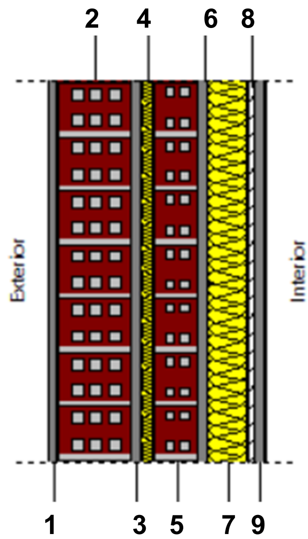
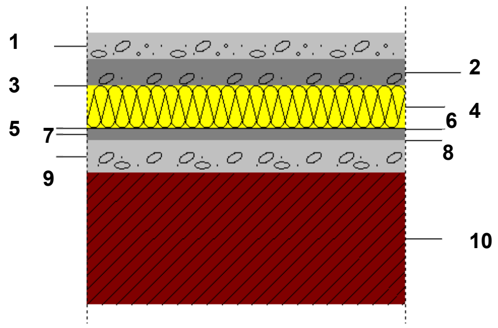
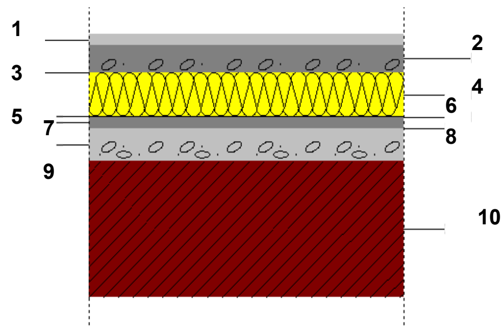
Solution 1	Solution 2	Solution 3
ETICS	Ventilated façade	Interior insulation
		
New materials	New materials	New materials
1. Lime paint on cement or lime mortar for finishing 1000 < d < 1250: 0.60 cm 2. EPS expanded polystyrene or mineral wool (0.029 W/m.k): 6.00 cm	1. Lime paint on cement or lime mortar for finishing 1000 < d < 1250: 0.60 cm 2. Cellulose cement board: 0.80 cm 3. Air chamber: 6.00 cm 4. Gypsum plasterboard, water-resistant (PYL) 750 < d < 900: 1.00 cm 5. EPS expanded [olystyrene or mineral wool (0.029 W/m.k): 6.00 cm	7. EPS expanded polystyrene or mineral wool (0.029 W/m.k): 6.00 cm 8. Gypsum plasterboard 750 < d < 900: 1.30 cm 9. Lime paint on gypsum mortar to hide the joints between panels: 0.50 cm

Table A1. *Cont.*

Solution 1	**Solution 2**	**Solution 3**
Existing materials	Existing materials	Existing materials
3. Cement or lime mortar for masonry and rendering/plastering 1000 < d < 1250: 1.50 cm 4. $\frac{1}{2}$ foot perforated brick metric or Catalan 40 mm < G < 60 mm: 11.50 cm 5. Cement or lime mortar for masonry and plastering 1000 < d < 1250: 1.50 cm 6. PUR hydroflurocarbide HFC projection (0.028 W/m.k): 2.00 com 7. Double hollow brick board (60 mm < E < 90 mm): 7.00 cm 8. Lime paint on gypsum mortar: 1.50 cm	6. Cement or lime mortar for masonry and rendering/plastering 1000 < d < 1250: 1.50 cm 7. $\frac{1}{2}$ foot perforated brick metric or Catalan 40 mm < G < 60 mm: 11.50 cm 8. Cement or lime mortar for masonry and plastering 1000 < d < 1250: 1.50 cm 9. PUR hydroflurocarbide HFC projection (0.028 W/m.k): 2.00 com 10. Double hollow brick board (60 mm < E < 90 mm): 7.00 cm 11. Lime paint on gypsum mortar: 1.50 cm	1. Cement or lime mortar for masonry and plastering/rendering 1000 < d < 1250: 1.50 cm 2. $\frac{1}{2}$ foot perforated brick metric or Catalan 40 mm < G < 60 mm: 11.50 cm 3. Cement or lime mortar for masonry and plastering 1000 < d < 1250: 1.50 cm 4. PUR hydroflurocarbide HFC projection (0.028 W/m.k): 2.00 com 5. Double hollow brick board (60 mm < E < 90 mm): 7.00 cm 6. Lime paint on gypsum mortar: 1.50 cm

Table A2. Description of the roof solution.

Solution 1	
Non-Trafficable Roof	**Trafficable Roof**
	
Existing materials	Existing materials
1. 5 cm gravel layer with aggregate between 16 and 32 mm diameter: 5.00 cm 2. 2.5 cm mortar layer reinforced with fiberglass mesh: 2.50 cm 3. Geotextile anti-zonation separator filter 0.10 cm 4. 80 mm extruded polystyrene insulation panel (XPS): 8.00 cm 5. Geotextile anti-zonation separator filter: 0.10 cm 6. Waterproofing sheet IBM-4.8: 0.10 cm 7. Separation sheet IBM-4.8: 0.10 cm 8. 2.5 cm regularization mortar layer 9. Existing slope formation cleaned and resurfaced: 6.00 cm 10. Exsiting concrete slab: 30 cm approx.	1. Ceramic tiles 14 × 28 cm: 1.50 cm 2. 2.5 cm tile bonding mortar: 2.50 cm 3. Geotextile anti-zonation separator filter 0.10 cm 4. 80 mm extruded polystyrene insulation panel (XPS): 8.00 cm 5. Geotextile anti-zonation separator filter: 0.10 cm 6. Waterproofing sheet IBM-4.8: 0.10 cm 7. Separation sheet IBM-4.8: 0.10 cm 8. 2.5 cm regularization mortar layer 9. Existing slope formation cleaned and resurfaced: 6.00 cm 10. Exsiting concrete slab: 30 cm approx.

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