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Life Cycle Assessment through BIM-based advanced Calculation Virtual Environment workflows

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Abstract. The current built stock in Europe is large and energetically inefficient due to material decay caused by lifelong use and lack of maintenance, combined. New buildings are commissioned and delivered everyday with an environmental cost, calculated using the Life Cycle Assessment methodology. The LCA is now widely requested for new assets, while existing ones are left for demolition and consequent carbon emissions released into the atmosphere, increasing the environmental crisis. In an effort to increase built stock's energy efficiency rates and decrease carbon emission, the recovery of these assets is depicted as the strategic next step for the construction sector. Both goals are achieved using data generated by dedicated construction software and processed in Calculation Virtual Environment, according to the specific needed data. The use of BIM for refurbishment design projects allows virtual construction separated by phases to simulate existing conditions of the envelope and its improvement with insulation material options. The use of one single file with clear phase definitions ensures data extraction and transference for all material options. The process is not entirely automated nevertheless it allows to save, use and share data whenever needed. The connection between data sources and databases in the cloud provides timesaving and regular updates. The research findings demonstrate the positive outcomes of modeling existing structures for energy simulation oriented to use in LCA, increasing the potential of BIM use in sensitive constructions while delivering appropriate results based on model and enriched geometry, with cost evaluation potential enabling scenario comparison for better decision making.

1. Introduction

The virtual building simulation supports the AEC sector and contributes with the European set of strategies towards decarbonisation known as European Green Deal [1] and its path towards carbon neutrality. It follows 2016 Paris Agreement main goal of preventing global temperatures to increase to dangerous levels.

According to IEA (International Energy Agency) the energy generation related to AEC sector was responsible for more than 40% of carbon emissions in 2018. This percentage is divided between building construction materials (known as embodied carbon) answering to 11% and building operations (known as operational carbon) answering to 28%.



Energy use is not only related to demand of electricity to daily tasks. It also relates to the amount of natural resources used and impact to manufacture everything and can be calculated using the LCA method. According to [2], **embodied energy** is the amount of energy consumed to manufacture a good, while **embodied CO₂e** is the amount of Greenhouse Gas related to the process of manufacture during its life cycle. Every material type has a different composition which demands energy to be manufactured and has an associated carbon emission rate.

According to [3] the buildings construction and operation has environmental impacts during their entire life cycle. The impacts are mitigated when recovering existing buildings, reducing construction waste, repurposing and extending their useful life.

The research focused in two strategies that immediately became protagonists of the European attempt for action applied to AEC sector:

(a) the Nearly Zero Energy Building (nZEB) concept implementation as an attempt to recovery existing inefficient buildings into high-energy efficient ones, powered them up with renewables, based on the argument of [4] and [5]. They also refers to these constructions as Energy Positive Buildings: when energy generation is higher than energy demand;

and (b) Greenhouse Gas (GHG) emissions rate reduction during their recovery works assessed by LCA calculation.

Both strategies related to the buildings envelope material composition - external walls, floors, roof, and outside openings. Improvements in these elements raises the envelope efficiency qualifying the building as an nZEB if powered up by renewable energy sources, according to [6]. The LCA calculation within this research was done by including materials data acquired from traditional construction materials for Phase 01 (Baseline) and through the use of EPDs, certified manufacturer documentation for Phase 02 (Insulation). The LCA calculation was performed using a dedicated software i.e. One Click LCA, interoperable with BIM.

1.1. The implementation in Italy

The research was conducted in Milano, in the Lombardy region (Climate Zone E), Italy. The country has an official nZEB definition stated in Law 90/2013 cited in [7] which defines nZEB as a building characterized by a very high energy performance, which the very low energy demand is significantly covered by renewable sources, produced within the building system boundaries.

Italy is a country with undeniable renovation potential, since 37,1% of total energy demand relates to AEC sector, according to [7]. Furthermore, the Country applies different requirements according to the level of intervention.

The level of intervention for the research development was defined as Second-level, where “refurbishment of at least 25% of the external surfaces of the building with or without renovation of the heating and/or cooling plant”, which can be seen in Table 1:

Table 1. U-Value limits for second-level Major and Minor Renovation (based on Energy Performance of Buildings Directive for 2021).

Components	Thermal Transmittance U W/(m ² K)	
	Validity period	Climate Zone E
Envelope Walls	From 2021	0,28
Envelope Roofs	From 2021	0,24
Envelope Floors	From 2021	0,29
Doors, Windows and rolling shutter boxes	From 2021	1,4

These requirements could be achieved by calculating the thermal properties of the envelope materials aiming upgrade, in this research by the addition on layers of insulation materials.

2. Methodology and Materials

The software Autodesk Revit Architecture 2021 was used to virtually build a test existing building (Figure 1) in order to perform the calculation of the current energy demand, and afterwards its embodied carbon. BIM promotes bi-directional workflow performing updates automatically whenever the model changes, updating any technical drawing, schedules, presentation graphical information within a file, and linked ones.

A proper BIM works as a data repository by adding data to geometry, which according to [8] can be used as an inventory. The way to do it is by creating parameters that can be grouped, scheduled, exported, complemented, and imported back to fill parameters gaps. Scheduling data also is used for management goals and be used on other platforms. The ability to retrieve data from the authoring tool and use them in management platforms saves time and avoid errors, and expand the boundaries of the communication by sharing these data, and getting updates almost instantly (Figure 1).

The thermal properties were calculated with a Microsoft Excel calculation model implementing thermal equations according to ISO 6946/2017 [9]. The thermal properties calculation needed the value of each envelope's material surface **Area**, and furthermore material's **Volume**, both quantities extracted from the BIM model.

The thermal properties calculated relates to the Heat Transfer capacity in Buildings and they were:

- heat conductivity λ [**W/mK**];
- resistance R-Value [**m²K/W**];
- Multilayered wall's heat transfer coefficient U-Value [**W/(m²K)**].

2.1. Computational design with Dynamo

The use of Computational Design while developing a BIM avoided repetitive work with the use of scripts. In this research, Dynamo was used to generate Schedules in Revit (Figure 1). The schedules could be exported for wide range of use and to be kept inside the model for consulting and data repository.

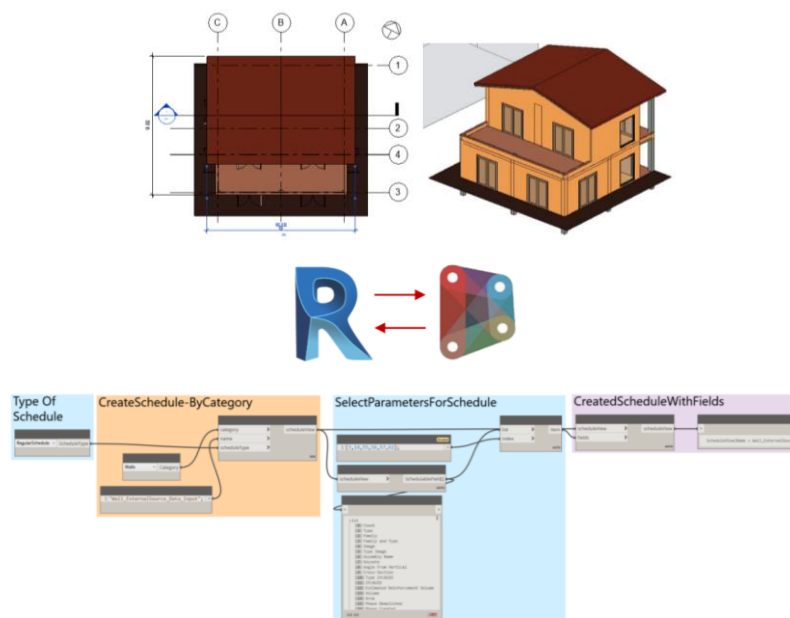


Figure 1. Case study building and Dynamo Script created to automatic generation of Schedule in Revit.

3. Results

The material composition impacts the results of the energy consumption calculation due to its heat transfer resistance, providing the maintenance of internal temperatures.

3.1. Phase 01 – Baseline Thermal Properties calculation and Data inclusion within the model

The calculation was performed firstly for Phase 01-Existing Conditions (Baseline) and afterwards for Phase 02- Insulation (material types 01-05).

Table 2. Insulation material and % of recycled material in their composition informed in each EPD

	Main component	Functional Unit	% Recycled material
01. Rolan Rock Wool	Mineral Wool	1m ²	70
02. Mètisse Recyc. Cotton	Recycled Fabric Fiber	1m ²	85
03. Freudenberg Recyc. Plast.	Recycled Polystyrene PET	1m ²	100
04. Isol Confort EPS	EPS	1m ²	10
05. Stiferite EPS	EPS	1m ²	2,7

The thermal properties calculation results are exposed in Table 3:

Table 3. Wall Surface Thermal Properties values for Phase 01 (00) and Phase 02 (01-05)

	Width (mm)	λ (w/mK)	Wall R-value (m ² K/W)	Wall U-value (W/(m ² K))
Phase 01 - Baseline				
00. Existing Conditions	150	0,57	0,26	0,34
Phase 02 - Insulation				
01. Rolan Rock Wool	51	0,036	1,64	0,33
02. Mètisse Recycled Cotton	100	0,039	2,82	0,24
03. Freudenberg Recycled Plastic	100	0,033	3,29	0,21
04. Isol Confort EPS	100	0,031	3,48	0,20
05. Stiferite EPS	62,5	0,022	3,07	0,22

The calculated properties were transferred to the model as “Green Building Parameters” to be used by the Building Energy Modelling (BEM) and Calculation Virtual Environments (CVEs), selected for this research.

3.2. Bi-directional interoperability workflow

The parameters were created with DiRoots’s ParaManager add-in and added to specific Categories according to the BIM model. A second add-in - DiRoots’s Sheetlink allowed a level of interoperability between data and Microsoft Excel Spreadsheets in a bi-directional way: a table with category parameters was exported, filled in and imported back to the model, filling the Parameter values with external data.



Figure 2. Workflow for retrieving information from BIM and the calculation model.

The same process was implemented for Phase 02 – Insulation.

3.3. Phase 02 – Baseline Thermal Properties calculation and Data inclusion into the model

The data for the calculation of the five selected insulation types were provided by their EPDs, which are reports made available by manufacturers containing the materials thermal properties and their life cycle

environmental footprint. The chosen EPD database offered - for some specific materials, - Machine Readable EPDs to optimize digital processes due to its structure. None of the 5 selected insulation materials had it available and the process has been manually implemented.

Once the materials were selected in the One Click LCA database according to their thermal conductivity value (Table 1), the family types had their materials mapped with the same EPDs through Revit's add-in. The add-in allows to navigate One Click LCA material database inside thru Revit. Once the materials were selected the model is uploaded to the cloud based calculation tool of One Click LCA along with the material information.

3.4. Energy Demand CVE applied for both Phases 01 and 02

The tools for the Building Information Model Modelling (Autodesk Revit 2021) and Building Energy Modelling (Autodesk Green Building Studio) communicates between each other and a quickly calculated building Annual Energy Consumption and Life cycle Energy Consumption were defined. The Annual Energy Cost was obtained by multiplying Annual Energy Consumption with the cost of 1kWh (~ 0,24 €).

The procedure was performed for the baseline and each insulation material and the results are exposed in Table 4:

Table 4. Consumption and cost - Phase and Materials

	Annual Energy Consumption (kWh)	Annual Energy Cost (€)	Life cycle energy consumption (kW)
Phase 01 - Baseline			
00. Existing Conditions	43.605	10.406	1.308.140
Phase 02 - Insulation			
01. Rolan Rock Wool	21.480	5.155	644.414
02. Mètisse Recyc. Cotton	19.923	4.781	597.698
03. Freudenberg Recyc. Plast.	19.657	4.717	589.718
04. Isol Confort EPS	19.571	4.697	587.122
05. Stiferite EPS	19.836	4.760	595.095

3.5. Photovoltaic Energy Generation CVE

An additional value needed for LCA options for Phase 02 calculation was the potential of photovoltaic system energy generation and the Photovoltaic Geographical Information System (PVGIS) provided by European Commission was used as Calculation Virtual Environment.

The tool allowed to manually input panel data provided by manufacturers along with building's geographic data to perform the calculation of PV generation. The CVE provided PV generation data needed to LCA, such as the "Energy Supply" value. The CVE allows data files to be exported such as .csv and .json files for further use. The value included in the LCA CVE was not the result provided by the PVGIS CVE, it was the result of the subtraction between "Energy Supply" and "Energy Demand" called "Exported Energy", and the calculation was performed in the Microsoft Excel calculation model.

One of the goals of the research was to simulate the energy production by renewable sources within the system-boundary by installing a PV system on the roof. The model allowed to schedule PV area and the value was included in the PVGIS CVE, as well as technical data provided by the PV manufacturer. The PVGIS CVE was used to perform the simulation once the building's energy demand was calculated, during Phase 01. The results of energy supply, energy demand and exported energy are listed in Table 5.

Table 5. Exported Energy Calculation results

	Energy Supply (kWh)	Energy Demand (kWh)	Energy Demand (%)	Exported Energy (kW/h)	Exported Energy (%)
Phase 01 - Baseline					
00. Existing Conditions	0,00	43.605	--	--	--
Phase 02 - Insulation					
01. Rolan Rock Wool	451.696	21.480	4,76	430.216	95,5
02. Mètisse Recyc. Cotton	451.696	19.923	4,41	431.773	95,6
03. Freudenberg Recyc. Plast.	451.696	19.657	4,35	432.039	95,6
04. Isol Confort EPS	451.696	19.571	4,33	432.125	95,6
05. Stiferite EPS	451.696	19.836	4,39	431.860	95,2

The addition of Mechanical, Electrical and Plumbing (MEP) systems and devices into the model is most likely to increase energy demand and proportionally decrease the exported energy value for each material in any case.

3.6. Life Cycle Assessment CVE

One Click LCA is a cloud-based SaaS designed for carbon emission calculation. A SaaS is the acronym for Software as a Service, allows a user to rent/buy/enroll in a service that provides remote digital and high processing capability, hosting results in the web to be consulted and shared easily.

One Click LCA calculates the environmental footprint of construction materials using several databases of materials environmental footprint reports provided by manufacturers, called Environmental Product Declaration (EPDs).

A Life Cycle Assessment calculates the environmental impact by the means of indicators, following [10]. The material's manufacture process releases gases into the environment and their impacts are listed the follow:

- *Global Warming Potential*: measures the increase of the concentration of greenhouse gas in the atmosphere;
- *Acidification*: measures the rate of water acidification, increasing the occurrence of "acid rain"
- *Eutrophication*: increase of plants in delicate ecosystems caused by unbalanced amount of nutrients;
- *Ozone Depletion Potential*: depletion of stratospheric ozone layer increasing sun's UV-A and UV-B radiation, impacting fauna and flora.
- *Formation of Ozone Lower Atmosphere*: impact the generation of toxic smog and causing damage to the respiratory system.

The total amount of carbon emissions is calculated through the whole buildings life cycle and considers carbon emissions from:

- construction material quantification input (BIM connected by add-in) **Mandatory data input**;
- annual energy consumption (calculated by GBS) **Mandatory data input**;
- water consumption (calculated by GBS);
- constructions site operations (provided by documentation related to the building, if any);
- building area (retrieved by the Authoring tool, such as Revit) **Mandatory data input**;
- Calculation period (in years) **Mandatory data input**.

The LCA calculation was performed for the six scenarios initially for Phase 01-Existing Conditions (Baseline) and afterwards for Phase 02- Insulation (material types 01-05).

Ideally, dealing with data inclusion and connected software allows a level automation on data transference, avoiding errors and fastening procedures. The method for data input and transference into One Click LCA mandatory fields are exposed in the Table 6:

Table 6. Data input by Software in One Click LCA / Input Model and results

Software / Documents	Data	Input mode	Destination One Click LCA	Status of data input
Revit (By Phase)	Material quantities m ² ,m ³ ,pieces)	Add-in to the cloud	Building Materials	Correct input, following mapping and classification system
Green Building Studio (By Run)	Annual Electricity Energy	Manual	Energy Consumption	Correct, updated manually
Green Building Studio (By Run)	Annual water use (Annual, L/year)	Manual	Water Consumption Annual	Correct, updated manually
Non calculated	Construction Site Operations	Manual	Construction Site Operations	No input
Revit	Gross Building area plan (121m ²)	Manual	Building Area	Correct, updated manually
Expected life of the building	Number (60y)	manual	Calculation Period	Correct, updated manually

In order to calculate LCA of Phase 01, material data was transferred from Revit model into the SaaS using an add-in provided by the company and accessed through Autodesk Revit to map the used materials with One Click LCA database options. One challenge was to map a potentially degraded existing material using a database which offered high performance ones. The solution was to map the most basic and traditional ones along the database to create a baseline for comparison. The simulation of refurbishing didn't consider demolition, in a way that all materials included in the baseline were maintained for Phase 2 calculation, however accounted differently using a reusable option in the cloud system calculation setup. The LCA results follows in the Table 7 and Table 8.

Table 7. Material Cost and LCA results by Material and LCA Calculation according to EN 15978 (a)

	Total Material Cost (€)	GWP (%)	AP (%)	EP (%)	ODP (%)	POCP (%)
Phase 01 - Baseline						
00. Existing Conditions	Non considered	100	100	100	100	100
Phase 02 - Insulation						
01. Rolan Rock Wool	732,6	48,2	48,8	48,8	48,5	47,3
02. Mètisse Recyc. Cotton	435,9	44,5	45,0	45,1	44,9	43,2
03. Freudenberg Recyc. Plast.	818,6	44,2	44,7	44,8	44,7	43,0
04. Isol Confort EPS	1.539,8	43,8	44,2	44,2	44,0	42,4
05. Stiferite EPS	922,1	46,0	45,4	45,8	48,4	44,7

Table 8. Material Cost and LCA results by Material and LCA Calculation according to EN 15978 (b)

	Total use of primary energy (%)	Bio-CO2 storage (%)	LCA (kg CO ² e)	LCA (%)
Phase 01 - Baseline				
00. Existing Conditions	100	100	137.003	100
Phase 02 - Insulation				
01. Rolan Rock Wool	49,0	30,2	660.574	48,2
02. Mètisse Recyc. Cotton	45,1	11,8	610.099	44,5
03. Freudenberg Recyc. Plast.	45,1	2,1	605.709	44,2
04. Isol Confort EPS	44,4	2,1	601.029	43,8
05. Stiferite EPS	45,9	36,2	630.966	46,0

The CVE environment of One Click LCA provides data visualization in the shape of many different options according to the user's needs. The following image compares all chosen materials, by LCA impact Categories, and displays the specific results in an interactive way. The results can be updated and the values recalculated.

**Figure 3.** LCA, EN-15978 - All impact categories

The results of the LCA demonstrates the environmental impact of chosen materials. It depicts the difference between used material types and, in a moment where recycling and circularity, oriented by [11] are requested as Lean construction goals, evaluating the effectiveness and impact altogether makes the LCA a needed step in construction works planning. Choosing the materials to perform Life Cycle Assessment for the refurbishment phase had a purpose, to assign high-performance ones based on thermal transmittance information provided by EPDs.

The materials were selected based on their composition in an attempt to evaluate the impact of choosing materials with diverse composition and how well they perform.

The same composition impacts the environmental footprint of the selected material since the inclusion of recycled and natural components decrease the carbon emission during their manufacture process. The result demonstrated by the LCA Indicator Bio-CO₂ storage shows the amount of carbon that shall be released at the end-of-life phase of that material, being the recycled plastic based the best option to achieve the lower emissions.

The high-performance materials shown to contribute to a lower energy consumption, which decreases the carbon emissions related to energy use (B6). Recycled materials didn't perform so well in energy use (stage B6) but decrease radically the carbon emissions related to stage A1-A5. Commonly used high performance expanded insulation material also contributed to decrease stage B6 carbon emission rate but it has high emissive impact related to material emissions shown in stage A1-A3, and the emissions related to the end-of-life on stage C1-C4 are also high, due to their composition and method of discard.

4. Discussion:

The process of a virtual model developed with BIM methodology can be performed in many ways. The authoring tool used allowed to create the Phase 01 envelope components (i.e. walls, floors and roofs) both as one multilayered element and with attached independent layers. The problem related to modelling focused on the calculation method of thermal properties with independent layers, when, in a real survey the entire existing composition would be evaluated.

The best way to acquire thermal calculations from an existing building would be to consider the multi layered component, since the thermal value added was a type parameter. For Phase 02, an existing component and the added insulation type would have the thermal values summed up, increasing thermal resistance.

The PVGIS retrieved PV generation data was included in the LCA SaaS manually. None of the exported data files (.json nor .csv files) could be uploaded in the LCA CVE. The solution was to add them manually for every design option.

The research was performed with tools provided by public and private suppliers, which means they are constantly being updated. These improvements have the potential to slightly change the workflow. For example, One Click LCA version used during the research calculation phase (v2.2.0) didn't allow to save material mapping. The material's EPD data could be included using the authoring tool Revit Architecture, however it didn't allow saving mapped materials. Once the model file was closed the mapping was lost.

After calculation phase, the add-in was updated to (v.4.0.2) and it was possible to enable the material mapping to be saved.

5. Conclusion.

Developing a BIM for refurbishment intervention depends highly on the quality of the existing acquired data, preferably by site surveys. The acquired data becomes useful when it is easy to reach and extract them, both tasks are provided by modelling with BIM methodology. Moreover, the implementation of Phases made data extraction more assertive and easily checked.

The material thermal properties calculation was a challenge and demonstrated the need of a multi-skilled team to manage data, accurately. The inclusion of data into Cloud services proved essential and enabled to quickly check and correct them, when needed.

Also, adding paths to results locations locally or online eased their usability. Nevertheless, they rely in service availability and access if data are to be kept online.

The BIM methodology offers solutions that involves many providers, who update their tools regularly. There's always the possibility to include programming skills to connect massive amounts of data generated by computational calculation nonetheless it also needs specific knowledge to provide smooth solutions for complex and constantly updated services.

The use of One Click LCA to calculate environmental footprint of Phase 01 – Existing Conditions raised doubts about mapped materials considered as degraded with high performance database options. For Phase 02 – Insulation, it performed well and the results visualization followed the expectation where the differences between their impacts were clear according to the materials composition.

The LCA CVE delivered interactive and intuitive method of explaining the calculation's results. The tools exposed results associated to the material quantity in many interactive ways, giving insight into GHG Indicator and offered alternatives to decrease the impact.

The use of CVE and BIM combined methodology turned to be a dynamic and ever evolving process. It is essential that updates are constant to improve results seeking trustworthy simulation.

Finally, the proposed sequence demonstrated usability and achieved the proposed research goals.

The proposed methodology involved a level of automation started by the authoring tool and finished after energy calculation, done with the chosen tools (Revit and Green Building Studio). Dealing with several data sources required an organized and systematic sequence for the allocation of results towards comparative goals.

The virtual building required fair development based on industry best practices results from LCA tool would be considered reliable. Data manipulation skills are essential for data comparison.

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