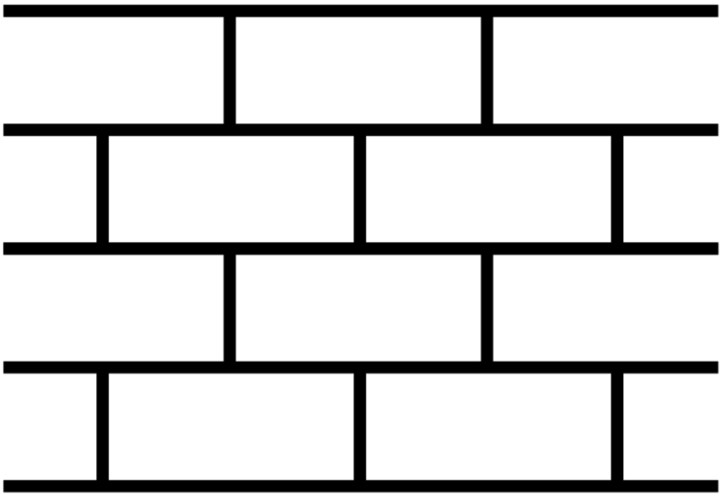

BIM

BASED

LCA

Workflow applied to a raw earth version of the bioclimatic greenhouse of Trompone

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Abstract

The e United Nations (UN)' aims to create synergy between all member countries to counter climate change, poverty, health and education. This initiative, part of a UN resolution called "the 2030 Agenda", is intended to be achieved by 2030.

The Architecture, Engineering and Construction (AEC) sector is the main sector in the world' efforts towards to increase sustainability. For this reason, the life cycle thinking is becoming more widespread. The introduction of Life Cycle Assessment (LCA) analysis in building sector and the BIM technologies seems to be a key solution to tackle these problems.

The goal of this research is to develop a workflow to integrate the LCA in the BIM environment and to create a tool able to monitor the environmental impacts of an architectural project, intercepting decision-making. To do this, we will study the model requirements to develop a BIM-based LCA workflow and, at the same time, to understand if the AEC industry is ready to welcome BIM-based LCA methodologies.

The case study we will carry out the analysis is the bioclimatic greenhouse of Trompone, in which we will create a raw earth version of the project. My passion for this material is the reason that led me to develop this thesis, so much that today I am working with a Swiss start up actively involved in the production of raw earth elements as bricks and panels, Terrabloc. Therefore, they also have contributed to the development of my thesis, sharing with me the LCA data of their products and experience in the AEC sector.

Through the creation of the tool and the test carried out on the case study, we managed to develop a workflow to analyse the environmental impacts of a project from the early stages. In this way, we managed to create understandable results for all stakeholders, including those with little technical knowledge, thus helping professionals to make decisions taking into account environmental impacts.

In conclusion, this work aims to take one step further for the integration of the LCA into the BIM environment, to intercept decision-making phases and improve sustainability.

Acknowledgements

First of all, I would like to thank my parents for their sacrifices, which made me possible to pursue all my studies.

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Abbreviations

AEC: Architecture, Engineering and Construction

AIA: American Institute of Architects

BIM: Building Information Modelling

BPS: Building Performance Simulation

BS: British Standard

CAD: Computer Aided Design

EN: Normazione Europea

EPD: Environmental Product Declarations

GHG: Green House Gas

GWP: Global Warming Potential

ID: Digital Identity

IFC: Industry Foundation Classes

ILCD: International Reference Life Cycle Data System

ISO: International Organization for Standardization

LCA: Life Cycle Assessment

LCI: Inventory analysis

LEED: Leadership in Energy and Environmental Design

LESBAT: Laboratory of Solar Energy and Physical Building

LoD: Level of Detail (America)

LoD: Level of Detail (Great Britain)

LoI: Level of Information

LoMD: Level of Model Definition

MEP: Mechanical, Electrical and Plumbing

PAS: Publicly Available Specification

PCR: Specific Product Category Rules

PEF: Product Environmental Footprint

RIBA: Royal Institute of British Architects

RSA: Residenza Sanitaria Assistenziale

SDG: Sustainable Development Goals

SODC: Silenziosi Operai della Croce

UBP: UmweltBelastungsPunkte

UNI: Ente Nazionale Italiano di Unificazione

VLP Visual Programming Language

1.Introduction

The building sector is the single largest consumer of energy and natural resources in the world and is therefore a key sector in the worlds efforts towards increased sustainability *(Nejat et al., 2015*). Only in Europe buildings are responsible for 38% of greenhouse gas emissions and 40% of energy consumption. (*United Nations Environment Program, 2020*)

The United Nations' 17 Sustainable Development Goals (SDGs), started in 2015, defines 17 interconnected objectives and aims to create synergy between all member countries to address issues such as climate change, poverty, health and education. This initiative, part of a UN resolution called the 2030 Agenda, is intended to be achieved by 2030.

The most important points for the construction sector are presented in Figure 1 and highlight the necessary factors for a radical change in the entire sector.

Fig. 1: SDGs related to sustainability in buildings (United Nations, 2015).

A year later, in 2016, the Paris Agreement was signed with the aim of strengthening the global response to the threat of climate change by keeping the global temperature rise for this century well below 2 degrees Celsius, above pre-industrial levels, and to pursue efforts to limit the temperature crease even further to 1.5 degrees Celsius (*Anders Lilleheim Vik, 2018)*.

"Half of the buildings standing in 2060 have not yet been built! The number of new buildings is likely to grow rapidly in the coming years, especially in Africa and Asia. This rapid growth will challenge the target of a 30% energy intensity improvement in buildings by 2030, needed to put the sector on track to meet the goals of the Paris Climate Change Agreement.

What we build today will be our emissions legacy, the buildings and construction sector need to lock in new norms of energy efficiency, green materials, and better practice in design and construction." (*GlobalABC, 2020*)

In this context, the life cycle approach has spread since it can be used to evaluate and compare building designs in function of greenhouse gas (GHG) emissions and other environmental impact categories. Thank to this approach, many manufacturers have started to compete on these parameters, putting on the market new materials or by making production processes less polluting.

Terrabloc, a Swiss start up, founded in 2011, actively involved in the production of raw earth elements as bricks and panels, in which I am actually working, is a virtuous example from this point of view, as they promote innovative material with low environmental impact and commit to produce LCA analysis for their products. Therefore, they also have contributed to the development of this work, sharing with me the LCA data of their products and experience in the Architecture, Engineering and Construction (AEC) sector.

However, the integration of life cycle assessment (LCA) in the designer's workflow as a tool for making decisions, is a difficult task, as it is a labour-intensive process that requires a huge amount of data and calculations. For these reasons, it is used only for the purpose of meeting the requirements of a certification or to calculate the impacts of a project, once all major decisions have been made, making it difficult changes to make or additions.

On the other hand, BIM is becoming more and more popular, thanks to the capacity of different software to store and manage data about graphical information, object properties and quantities related to a project. Therefore, BIM can be used to integrate LCA into the AEC sector to reduce time and efforts to manage data.

From a practical perspective, there is usually a gap of knowledge between these two techniques, so we need strategies in order to integrate new technologies, to improve communication between stakeholders and develop an overall vision of the complexity behind this kind of processes. In this regard, BIM should be considered a useful tool to develop this holistic vision.

2. Goal and scope definition

The goal of this research is to study the different methodologies and technologies useful to integrate LCA in the BIM environment and to create a tool able to monitor the environmental impacts of an architectural project, intercepting decision-making phases and stimulating communication between the different disciplines involved.

To achieve this goal, we will try answer to the following questions:

1. *What are the requirements of a model to develop a BIM-based LCA workflow?*
2. *Is the AEC industry ready to welcome BIM based LCA methodologies to improve sustainability?*

In order to answer these questions, we will present the state of the art and the existing research and methodologies in the first part of the thesis.

In the second part, we will calculate the environmental impact of a case study with a tool we developed. The project is a raw earth bricks variant of the bioclimatic greenhouse of Trompone.

To create the 3D model, we used Autodesk Revit 2020, a widespread BIM software. Whereas, for LCA we initially wanted to carry out the analysis with Tally, a Revit plug-in that allows to develop LCA analysis on a reference model. However, given the impossibility to integrate the Terrabloc products in their database, we decided to use Dynamo, a visual programming tool already incorporated in Revit, to create an interconnection between the data of the BIM model and those of a LCA database, thus creating a tool that can also host data from different sources.

This workflow aims to simplify LCA to help designers save time and resources to perform it and motivate them to integrate these methodologies as decision support, from the very early stages and not a task that has to be done at the end of the design process.

3. BIM - Building Information Modelling: state of the art and maturity

In the last 30 years, the AEC sector has exponentially implemented the IT toll use to manage the projects. Designers have gone from a 2D representation of the different views (Plants, Elevations and Sections) to the construction of intelligent 3D models.

Traditional CAD software represents objects based on geometric primitives (lines, points, etc.) keeping track of the different steps, but today we try to automate the most basic procedures by delegating them to the computer. "Here is where the technology has shifted to using object-based representation that is specific to the domain. In the case of the AEC sector, this translates to a representation schema that is modelled around project entities and their mutual relationships. For example, while defining a wall object, geometry is only one of the properties, among others, of these building elements. In this example, a room consisting of four walls, in addition to geometric information, has information such as connected walls and attached spaces" (*Marios Tsikos, 2016*). Therefore, BIM is a methodology that is applied, through different software, to create parametric models containing information about geometry, energy performance, physical properties, costs and maintenance.

Dynamic, interdisciplinary and shared models aim to stimulate collaboration between different professional figures and interoperability between different applications. Another added value of BIM is the ability to visualize the progress of activities over time by monitoring the relative quantities and costs. This allows to effectively manage the life cycle of the building by providing the information for facility management.

The question is about the real possibility of completing a turning point in the construction sector. In this regard, the UK has introduced the concept of maturity levels (Fig. 2) to define the transition to application and collaboration levels that are based on the use and sharing of files, thus going from an implementation of basic elements to a real involvement of all the elements of the process.

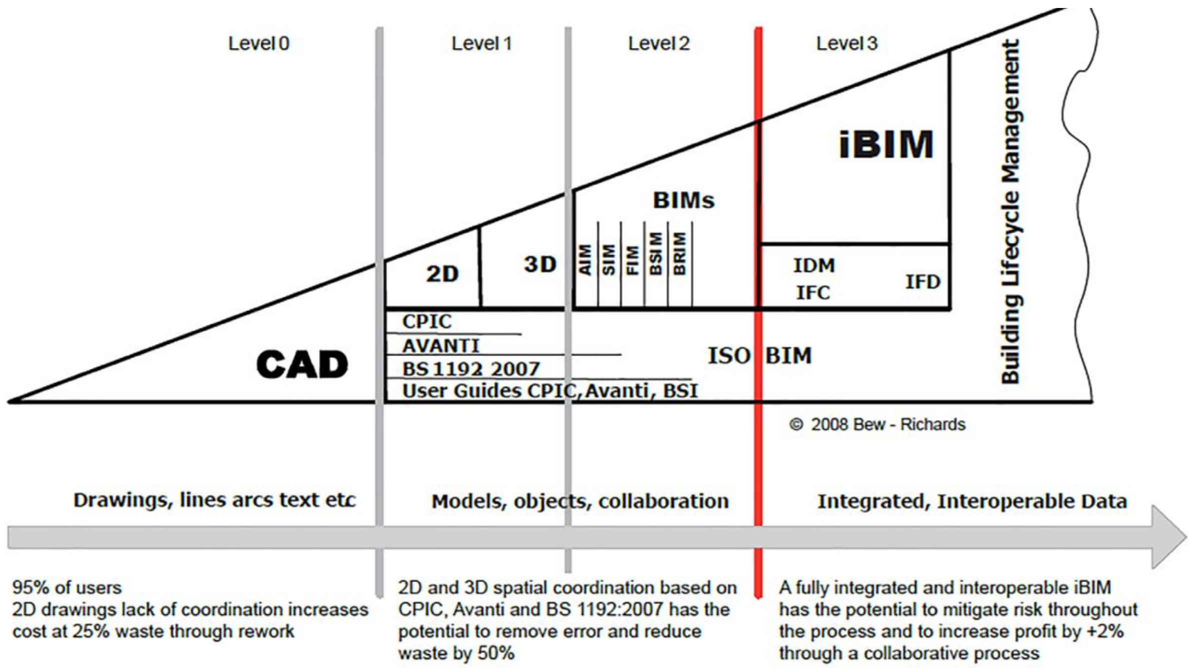


Fig. 2: Bew-Richards maturity model. (From International BIM implementation guide, 2014)

- At **level 0**, the implementation of projects is founded on paper-based information.
- In **level 1**, you move from a paper environment to a 2D and 3D environment, focusing on collaboration.
- **Level 2** is the first level in which you can talk about BIM. It is based on the concept of "Common Data Environment", in which the project implementation takes place on a common production environment where data are exchanged and stored. So, the group does not necessarily work on a single shared model, but the collaboration takes place with ways of exchanging information through common file formats.
- At **level 3** the process is fully integrated (iBIM) through a single centralized model accessible to all team members. In addition, it is considered an open level of maturity as it leaves room for further technological progress. (*Marios Tsikos, 2016*)

However, from the practical point of view, high costs and poor software interoperability are the main explanations from companies that do not implement BIM (*Ghaffarianhoseini et al., 2017*). Moreover, the lack of dissemination of these methodologies in the AEC sector nullifies the potential benefit that could be derived from it, making collaboration difficult.

For the reasons discussed above, professionals, especially the smaller companies that for fear of not having sufficient revenue, often struggle to adapt. Instead, they prefer to use the old practices given the little experience and high risk.

To reach the third level of maturity it would be necessary to have web-enabled data integration, which means having a system that allows to work digitally with widespread broadband and Wi-Fi on construction sites. Because of this, it is clear that the individual will it is not enough. On the contrary, it is really a large-scale cultural change.

Despite these barriers, the digital revolution in the construction sector seems inevitable and today we are seeing a push towards industrialization of products and efficiency. In this perspective, the BIM has a great potential to transform the relationships between the partners of the supply chain to create new business models, reduce investment, management costs, speed up the implementation of new features and increase sustainability.

3.1 BIM Standards

The International Standard Organization (ISO) has developed regulations concerning BIM, but since it has not yet covered all areas of interest, countries have started to develop their own standards.

Currently, Europe refers to six BIM standards from the ISO as representative for the EU BIM standards:

- ISO 12006-2:2015 - Building construction - Organization of information about construction works - Part 2: Framework for classification
- ISO 12006-3:2007 - Building construction - Organization of information about
- Construction works - Part 3: Framework for object-oriented information
- ISO/TS 12911:2012 - Framework for building information modelling (BIM) guidance
- ISO 16739:2013 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries
- ISO 29481-1:2017 - Building information models - Information delivery manual – Part 1: Methodology and format

- ISO 29481-2:2016 - Building information models - Information delivery manual – Part 2: Interaction framework

(*European Commission, 2018b; European Committee for Standardization, 2018a*)

ISO standards related to BIM developed after 2018, or currently under development, include:

- ISO/AWI 23386:2020 - Building information modelling and other digital processes used in construction-Methodology to describe, author and maintain properties in interconnected dictionaries

- ISO/DIS 19650:2019 - Organization of information about construction works – Information management using building information modelling

- ISO/NP 22057 - Enabling use of Environmental Product Declarations (EPD) at construction works level using building information modelling (BIM)

Another important authority for the development of International Standards is BuildingSMART, which aims "to proactively facilitate the active use and dissemination of open data standards enabling infrastructure and building asset data and lifecycle processes to improving the value achieved from investments in built assets and enhance opportunities for growth. BuildingSMART's focus is on standardizing processes, workflows and procedures for openBIM enabling digital transformation" (*Building Smart, 2020*). The organization collaborates on standard development with several national and international organizations. BuildingSMART has made, for example, the Industry Foundation Classes (IFC) data model, an open standard which allow interoperability between different software from the AEC sector.

In Italy the BIM Decree (DM 560/2017), introduced the obligation to use electronic modelling methods and tools for public works starting in 2009, according to the following time frame:

- from 2019 for works over EUR 100 million.

- from 2020 for complex works exceeding EUR 50 million.

- from 2021 for complex works exceeding EUR 15 million.

- from 2022 for works over EUR 5,2 million.

- from 2023 for works over EUR 1 million.

- from 2025 for all new works.

In addition to the timing of progressive introduction, the decree provides the use of interoperable platforms through open formats (edilportale, 2020).

3.2 Level of detail (or development) in BIM

In the protocol of 2008, the American Institute of Architects (AIA) introduced the concept of LoD

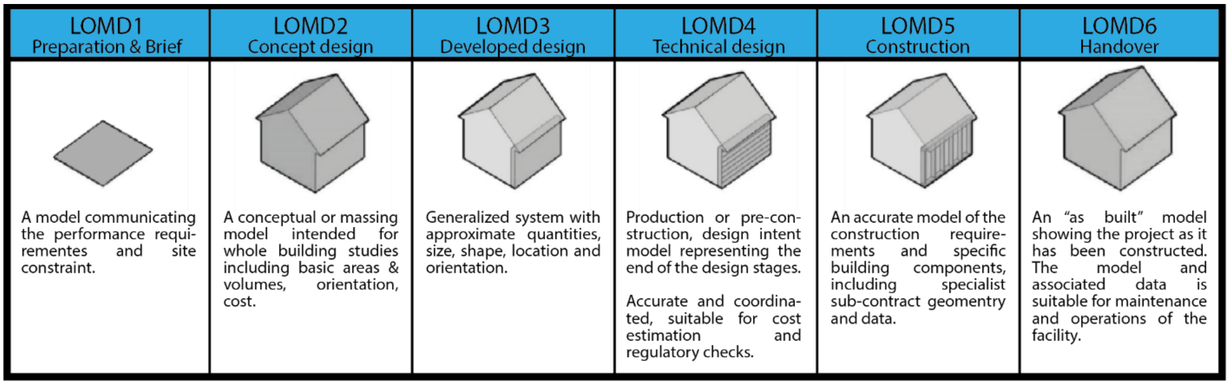


Fig. 3: LoD levels in American Institute of Architects

(Fig.3) referring to the development level necessary in relation to the model elements content. The choice to use the definition "level of development" instead of "level of detail" is motivated by the fact that an element, while being able to appear visually detailed, could be actually generic.

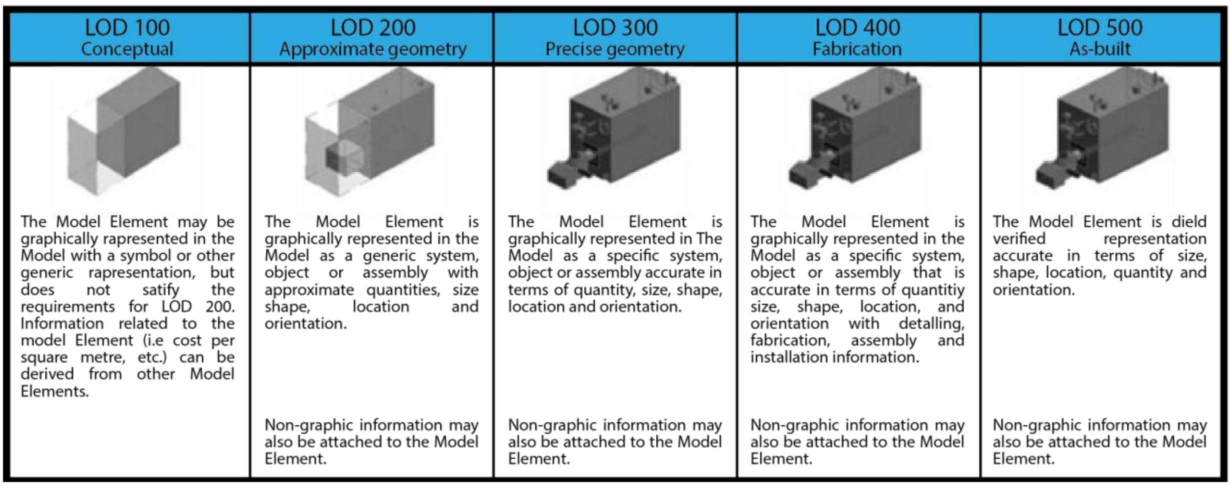


Fig. 4: UK convention of LOD

Another international reference is the British Legislation that makes the difference between level of Detail (LoD) relates to the model graphical content and Level of Information (LoI) relates to non-graphical content. These two components, together, define the Level of Model Definition (LoMD, fig 4).

In the UK, the RIBA (Royal Institute of British Architects), has a well-established project-based system on which contracts, fees, etc. are developed. For this, the PAS 1192-2 legislation of LoD are not referred to objects as in the US system but are referred to the model: "level of model definition". (*Pavan Alberto, 2017*)

The protocols provided by AIA, the British standard and the various guidelines developed in different countries of the world, seek to define the level of depth in which the model is to be developed; however, the issue is addressed and solved in different ways.

Therefore, there is no universally accepted system and Italy has decided to deal with the international scene, to define a national legislation, with particular reference to the US and UK. The first Italian legislation that refers to the LOD is the UNI 11337-4:2017, which makes it possible to use any of the existing LOD scales, without exclusions or priorities, depending on the specific needs of the condition where those specific references and objectives are defined at first glance in order to ensure maximum transparency for stakeholders.

In the Italian context there is also a terminological distinction between:

- LOG: Level of development of geometric attributes
- LOI: Level of development of information attributes
- LOD: Level of development level of digital objects

LOD A	LOD B	LOD C	LOD D	LOD E
				
Geometria. Elemento architettonico verticale o pseudoverticale rappresentato mediante un simbolo 2D.	Geometria. Solido generico per rappresentazione elemento architettonicco verticale o pseudoverticale con forma, spessore e posizione approssi-mata.	Geometria. Elemento architettonico (sistema e sottosistema) verticale o pseudoverticale rappresentato con ingombri calcolati secondo la normativa tecnica.	Geometria. Elemento architettonico verticale o pseudoverticale rappresentato mediante un solido avente dimensioni pari alle dimensio-ni reali. Sono modellate tutte le stratigrafie.	Geometria. Elemento architettonico verticale o pseudoverticale rappresentato mediante un solido avente dimensioni pari alle dimensio-ni reali. Sono incluse tutte le stratigra-fie, i dati specifici del fornitore e le finiture
Oggetto grafica 2D (linee e campiture 2D). Caratteristiche Posizionamento di massima.	Oggetto Solido 3D. Caratteristiche Semplici geometrie d'ingombro.	Oggetto solido 3D strutturato. Caratteristiche Definizione del sistema architetto-nico - Spessore - Lunghezza - Larghezza - Volume - Definizione materiali - Definizione stratigrafie princi-pali	Oggetto grafica 3D complesso. Caratteristiche Dettaglio dei componenti per gruppi e senza riferimenti a singoli prodotti - Definizione stratigrafie dettagliate - Spessori componenti - Struttura - Isolamento - Camera d'aria - Sottofondo supporto - Finitura - Dettagli costruttivi	Oggetto grafica 3D complesso. Caratteristiche Dettaglio dei componenti con singolo prodott, Informazioni di montaggio, materiale di supporto, schede tecniche singoli prodotti - Tipo finitura interna - Superfice finitura interna - Tipo finitura esterna - Composizione materia-le/com-ponente - Presenza certificazioni - Capacità strutturale - Trasmissione vapore - Valori per calcoli di temodina-micae acustica
Usi consentiti - semplici ingombri - Studio schemi compositivi	Usi consentiti - Studio preliminare - Computo metrico	Usi consentiti - Dimensioni esecutive - Utilizzo per computo	Usi consentiti - Previsioni di scheduling di cantiere	Usi consentiti - Cantierizzazione

Fig. 5: Italian's LOD classification according to UNI 11337-4:2017

A LOD scale defined according to a letters code: LOD A, B, C... (Fig.5) to avoid confusion with the US or British. The Italian LODs take their cue from the USA but integrate some UK aspects and suffer from other typically national prerogatives, not present in one or other Anglo-Saxon systems. *(Pavan Alberto, 2017*)

3.3 UNI EN 17412-1: 2021

The recent UNI EN 17412-1: 2021 about the Level of Information Need, differs from the traditional use of LOD because, thanks to a more specific definition of the information requirements, it is possible to:

- Improve the quality of information: automatic or semi-automatic comparison between requests and information produced;
- Support the contractual-legal framework: reduce the free interpretation of requirements and compliance control to contractual requests;
- Improve process flexibility and effectiveness: define and produce only the necessary information avoiding wastage (e.g. patterns with too much information) or lack of information (e.g. due to generic requests).

This gives a precise definition of the context and what you can achieve through more efficient digital processes. In fact, the ISO 19650 regulation on information management already stressed the necessity of defining the purpose before defining the information needed, thus avoiding the information wastage. The UNI EN 17412-1 provides details on how specify this Level of Information Need, thus completing the international standard ISO 19650. (*Bolpagni Marzia, 2021*)

3.4 Model requirements for a BIM based LCA

Each BIM software has a different data structure. In this thesis we decided to use Revit, a program that hierarchizes the different components of the model into Categories, Families, Types, and Instances (Fig. 6). An instance is an individual model element (with a unique ID) while a category defines a generic group (like "walls" or "floors").

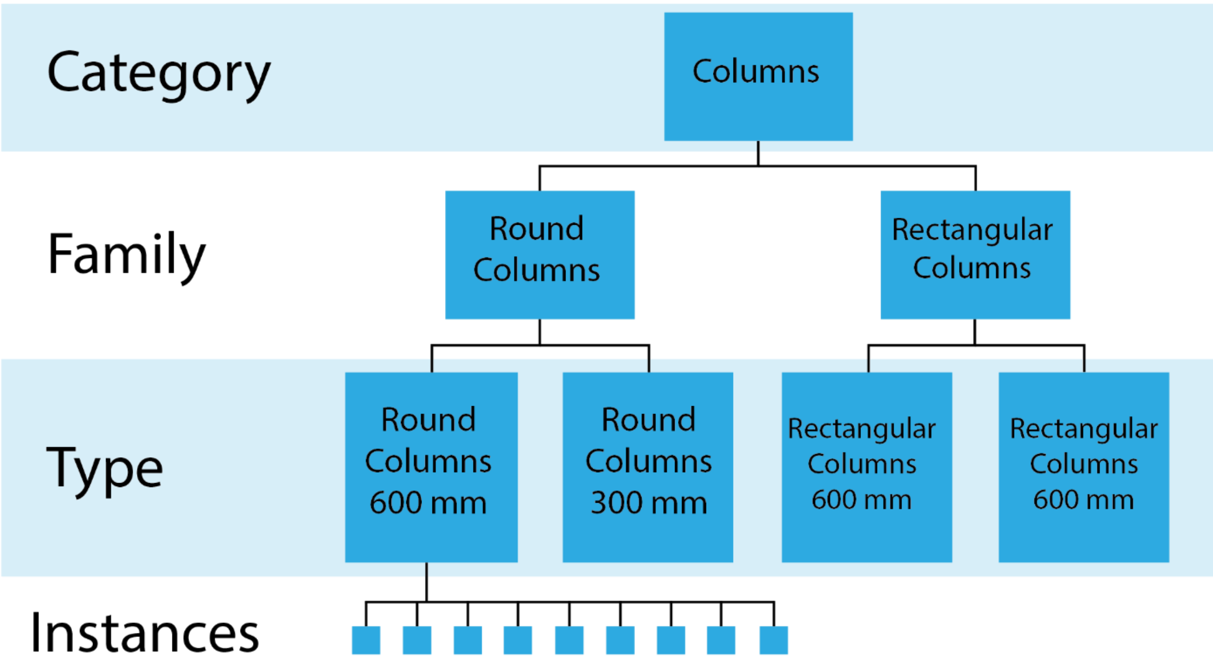


Fig. 6 : Revit Hierarchy

To make understandable LCA integration in a BIM model, the environmental information has to be overlapped with the native data structure of Revit. Every element in Revit model contains its ID, dimension and material composition together with its function. "If we would split the elements into its material components, we will reach material units which are also the third level of LCA information. A material can contain different Revit materials, and each material would have its area and volume information. However, Revit materials are usually generalized, simplified and most important combined version of real material components. For example, a brick material in a BIM software will represent the brick layer and will not contain its subcomponents like glue, light structure, mortar or printings. So, if the LCA databank, when giving the bricks' environmental impact information does not contain its sub material components, it has to be calculated separately. The material sub-unit would be then the deepest LCA information level in a BIM model. As material, sub-units are usually not modelled in BIM software and the composition percentage of each material has to be defined in the databank in order to make a more accurate environmental impact analysis." *(Gianluca Genova, 2018)*

Therefore, the concept of LOD and the quality of the model are fundamental for a good integration of the LCA in the BIM environment: the software capabilities to model the elements and information quality can condition or limit the input data (*Bernardette Soust-Verdaguer, 2016*).

Often, designers avoid having overdetailed objects, but they make sure to have the right size and a true representation of reality. Therefore, to develop a BIM-based LCA, it is important to have volumetric information as precise as possible and a clear division of its parts.

3.5 KBOB eco-bau Database

In this thesis I used the KBOB/eco-bau database, a Swiss source that today is a reference point in the European panorama.

The KBOB was established in 1968 as the coordinating body for the construction services of the Confederation. Initially, it dealt in particular with procurement issues, compensation for the increase in the price of building services and architects' and engineers' fees.

On 1 January 1999, the KBOB was reorganised and now represents the interests of its members, namely building contractors and property owners, in the construction industry. Together with its members, the KBOB aims to ensure the economic use of resources throughout the entire life cycle of buildings, considering the importance of the cultural and ecological aspects of construction. *(KBOB web site)*

Instead, Ecobau is an association focused on development and dissemination of planning tools for sustainable, ecological and healthy building. In the Ecobau association, the confederation building authorities, the cantons and the cities have joined with the aim of promoting ecological and healthy building. Members also include organisations such as KBOB, whit which have been developed the database that we will use in this thesis. We decided to use the Swiss database because it already considers the subunits of each material. For this we did not need to split the materials composition again to its sub-component.

Further details on the database and the categories of impacts are presented in the chapter 6.3.

4. Life Cycle Assessment (LCA): Guidelines and integration in the AEC sector

The Life Cycle Assessment is a methodology that considers the entire life cycle of a product or service by assessing the environmental impact, regulated by ISO 14040 and 14044 standards, where guidelines and framework are described and structured in 4 steps:

- Goal and scope definition: The phase in which the objective of the analysis is defined. Based on this, the breadth and depth of the study are established. In addition, the functional unit and the system boundaries are defined based on the quality and quantity of data available.

- Inventory analysis (LCI): In this phase the input/output flows of resources, material, energy, waste and emissions of the various passages are listed in relation to a reference unit. These data can be primary (directly collected) or secondary (usually taken from LCA database or EPD provided by manufacturers).

- Impact assessment: Estimation to identify and quantify environmental impacts.
- Interpretation: Technique which aims to identify and quantify information from the previous stages to discuss and evaluate them in relation to the objective.

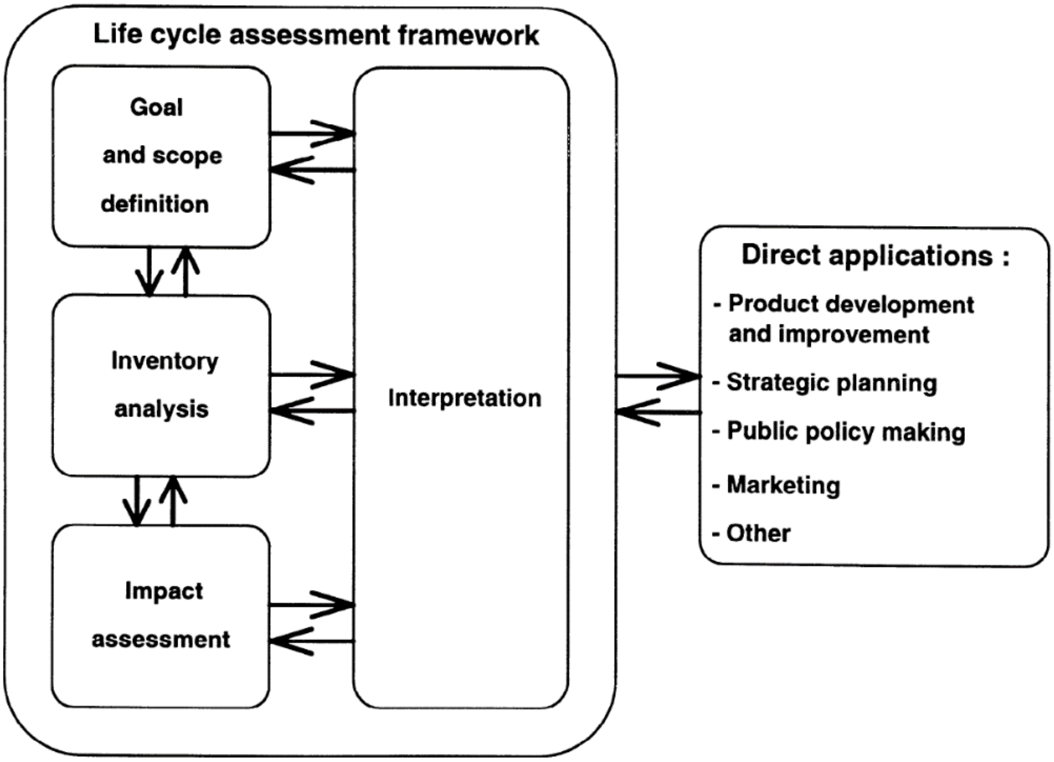


Fig. 7: Guidelines from ISO 14040

The following chart gives an overview of the EN 15804, a standard for LCAs in the construction sector, where all relevant impact categories are presented. Other impact assessment methods exist as well, which use slightly different categories.

Impact category / Indicator	Unit	Description
Global warming	kg CO_2-eq	Indicator of potential global warming due to emissions of greenhouse gases to air
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that cause the destruction of the stratospheric ozone layer
Acidification of soil and water	kg SO_2-eq	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides
Eutrophication	kg PO_4^{3-}-eq	indicator of the enrichment of the aquatic ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds
Photochemical ozone creation	kg ethene-eq	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
Depletion of abiotic resources – elements	kg Sb-eq	Indicator of the depletion of natural non-fossil resources
Depletion of abiotic resources – fossil fuels	MJ	Indicator of the depletion of natural fossil fuel resources
Human toxicity	1,4-DCB-eq	Impact on humans of toxic substances emitted to the environment (Dutch version of EN15804 only)
Fresh water aquatic ecotoxicity	1,4-DCB-eq	Impact on freshwater organisms of toxic substances emitted to the environment (Dutch version of EN15804 only)
Marine aquatic ecotoxicity	1,4-DCB-eq/sup>	Impact on sea water organisms of toxic substances emitted to the environment (Dutch version of EN15804 only)
Terrestrial ecotoxicity	1,4-DCB-eq	Impact on land organisms of toxic substances emitted to the environment (Dutch version of EN15804 only)
Water pollution	m^3	Indicator of the amount of water required to dilute toxic elements emitted into water or soil (french version of EN15804 only)
Air pollution	m^3	Indicator of the amount of air required to dilute toxic elements emitted into air (French version of EN15804 only)

Table 1: Environmental impacts categories from EN15804 standard

4.1 LCA: State of the art and maturity

There are many standards and labels developed both nationally and internationally that can be found in the market. This has created confusion among consumers, who are unable to compare two similar goods precisely, because such standards have often different characteristics and purposes that do not make them comparable. In the business-to-business relationship (company vs company) the information is clearer, but everything is related to the survey methodology that you go to perform.

In recent years, the most common methodology is the EPD, a label that has a certain degree of safety on the method adopted, because:

- It is always verified and validated by third-party bodies.
- It is based on the use of the LCA methodology required by ISO 14040, ensuring the objectivity of the information.

- It is applicable to a large number of products and services. Specific Product Category Rules (PCR) are available for different products. PCR must be followed scrupulously to obtain the certification, limiting the choices and assumptions those who manoeuvres and conducts the analysis.

EPDs declare the potential impacts of a product, without giving indications on its degree of sustainability (there are not benchmarked to be satisfied to obtain the EPD). Nevertheless, it is useful, to the distribution chain, which can evaluate the predisposition of a company to calculate the impact of its product trying to improve the critical points.

For fear of incurring unnecessary costs, companies consider certifications as a risk. Thus, the spread of a globally accepted Standard should help to transmit safety to the companies and to the consumers. *(European commission)*

Instead, another aspect that may question the scientific nature of the LCA method is the accessibility of initial data, since there are few companies that share data about the input/output flows of their productions. This can make it difficult the phase of Life Cycle Inventory, due to the absence of precise data, it is necessary to try to represent reality with data derived from averages and empirical evidence.

For these reasons, the European Commission launched a process of harmonisation between methods, models and tools through the International Reference Life Cycle Data System (ILCD) manuals and the development of Product Environmental Footprint (PEF), in order to find the most appropriate methodology, depending on the concerned sector, having compare results and ensuring more clarity and reliability on the evaluations performed.

4.2 LCA in the AEC sector: Methodologies

The LCA analysis was firstly introduced in the industrial field but it has been applied for many years also in the building sector, both at the product and building scale.

Due to the complexity and uncertainty related to building LCAs, the AEC sector cannot perform the analysis with the same level of detail as other product in other sectors (Eebguide Project, 2012). For this reason, the European standard BS EN 15978:2011 defined some specific frameworks for buildings LCAs split into life cycle stage (Fig. 8)

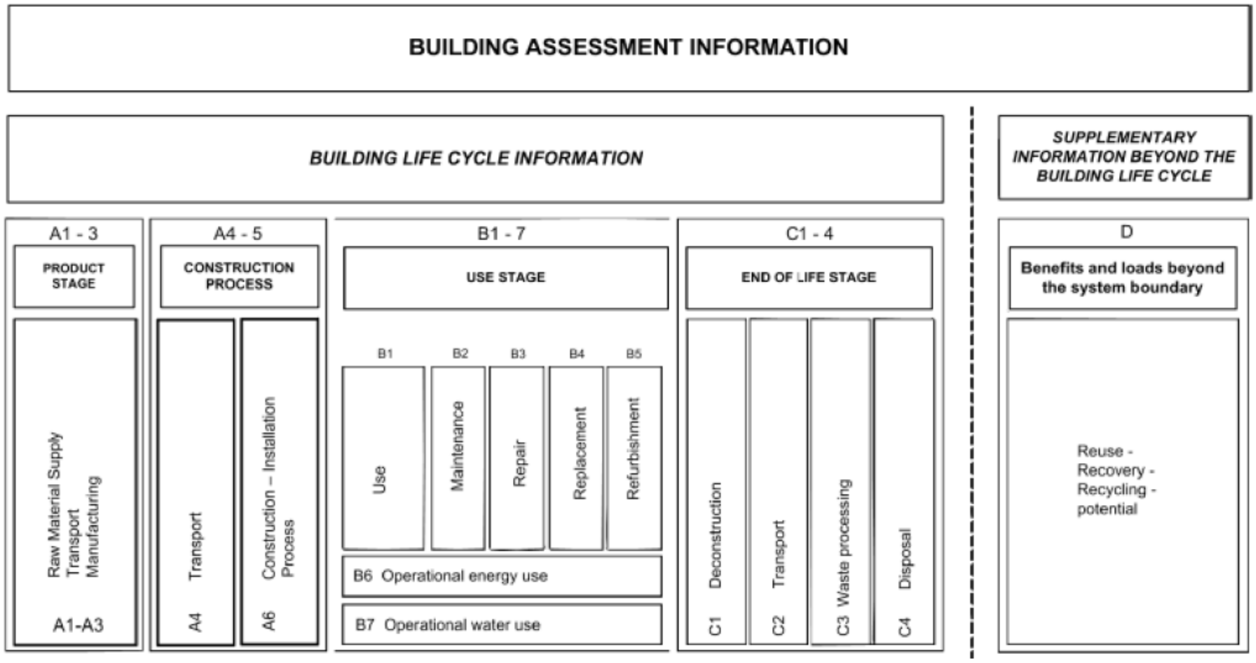


Fig. 8: Definition of information modules according to the standard Norge for LCA of buildings (From Standard Norge, 2001)

The building is not an industrialized product but, on the contrary, every building can be considered as unique and this makes the development of an LCA time consuming. Thus, the analysis can be based on a database containing environmental information on building materials. Once impacts for each material are calculated and multiplied by the related quantities, it is possible to find the impact of the entire project.

Many studies agree that LCA analysis would be more effective in the early stages of the project, but, since the level of detail for a specific project is based on knowledge which is progressively developed alongside the development of the building, a dynamic approach is indispensable to avoid long and repetitive steps at each change.

In this regard, a thesis carried out by Gianluca Genova at the ETH of Zürich with the collaboration of Basler & Hofmann AG, identifies all known LCA environmental assessments for the AEC sector and classifies the methods to develop a LCA in the following 3 categories:

- Conventional LCA
- Static BIM-LCA
- Dynamic BIM-LCA

4.2.1 Conventional LCA

This is the most common methodology in the AEC sector. Fig.9 shows a data source that can be a BIM model, any 3D model or even a 2D drawing.

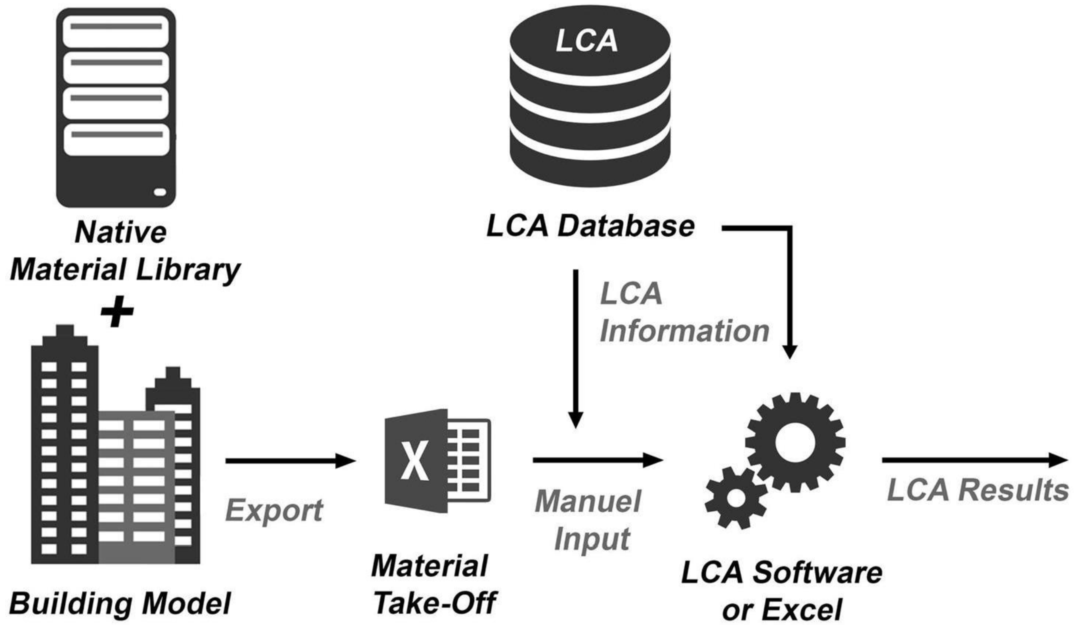


Fig. 9: Convectional LCA approach (Gianluca Genova, 2018)

In any case, there is a need for material take-off from the project that, at best, will be the output of a BIM model. This step can be automatic, otherwise the inventory can be compiled manually.

After the extraction of quantitative project data, the LCA data of individual materials should be searched in an LCA database or EPDs to perform impact calculations. Those calculations can be performed whit the aid of a software, where the data entry can be provided manually or through a spreadsheet tool (such as Excel) which could however require manual input.

4.2.2 Static BIM-LCA

In the second method, data are transferred from a BIM model using an interoperable format (such as the IFC format) and they are transferred to an LCA tool to make calculations.

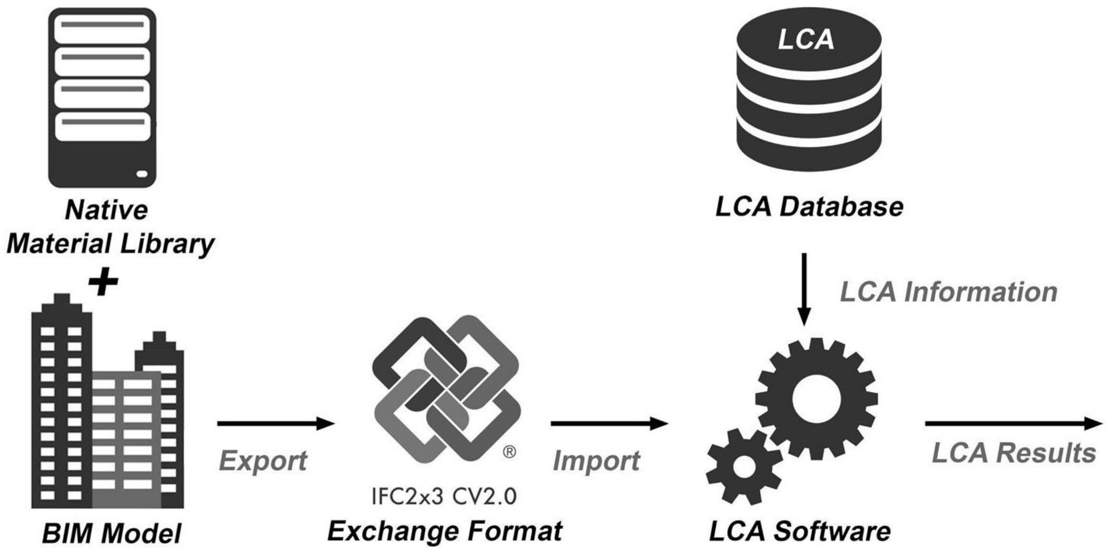


Fig. 10: Static BIM-LCA approach (Gianluca Genova, 2018)

The main advantage of this method is that it is not necessary to enter the project data manually, as these will be extracted directly from the BIM model and transferred to the LCA tool in a single format (IFC, gbXML etc.). Therefore, each extraction will represent the status of the project and will also allow to evaluate the alternatives much more easily than the conventional method.

Among the weaknesses of this method, there is the fact that "any changes in the BIM model can only be made by going back to the BIM software and re-importing the model into the LCA platform. Also, the interoperability between BIM models and LCA tools has not been fully developed yet [...]. The accuracy of the extracted BIM model in a standardized data format (IFC, gbXML, etc.) is limited and has a narrower range of environmental information. This makes the importing of the file into the software for LCA calculations also not sufficiently accurate. The challenge here is to avoid the loss of information during this workflow. Such software tools are standalone solutions which require specific LCA expertise for some manual settings that have to be done before the calculations." *(Gianluca Genova, 2018)*

4.2.3 Dynamic BIM-LCA

With this approach the environmental impact assessment is done in real-time and the whole process can be monitored. All information is collected in the BIM model "and the information flow it is allows a potential optimization and a feedback loop." *(Gianluca Genova, 2018).*

Fig.11 shows the approach just described in which a link is created between the BIM models and environmental information available in the LCA database

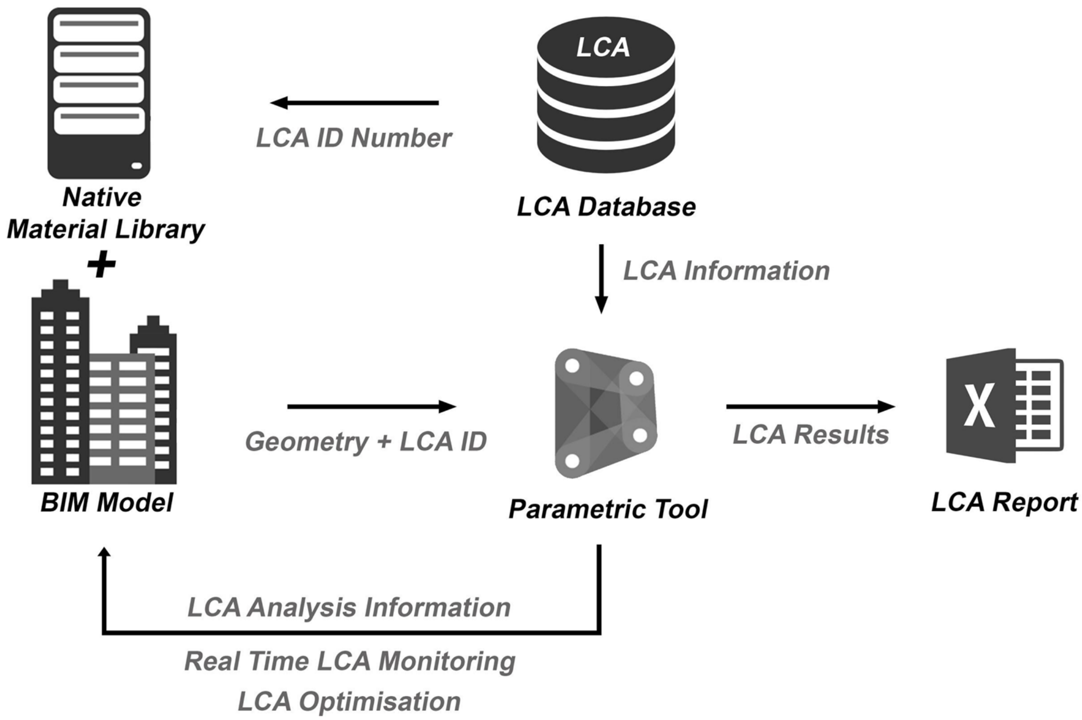


Fig. 11: Dynamic BIM-LCA Approach (Gianluca Genova, 2018)

This link is created through a parametric tool, that also in this research, will be Dynamo. In addition to allow a link between data, Dynamo allows you to calculate the environmental impact and to forward back the results to the BIM model, creating a feedback loop, thus helping the designer to monitor the process.

"In dynamic approach, BIM objects have continuously updated environmental properties based on LCA calculations in their properties. In this way, it would be possible in the pre-design and design phases to include environmental criteria in the decision-making process regarding the selection of materials and building elements. This can also allow the designer to make an LCA optimization at any given time directly in design software." *(Gianluca Genova, 2018)*

This is the beginning of the full integration of the LCA into the BIM environment. The biggest benefit is that all data are within the same program and the calculations are done automatically. Though, "it is still necessary to improve the availability of information on construction materials as there are unsolved issues regarding automatically inclusion of information related to transportation, location and regional characteristics of the project." *(Diaz, 2014)*

In the dynamic approach, the operator who creates the Dynamo script will have to choose the calculation methodology and will be free to extract data from any database. This manoeuvre freedom can lead to excessive simplifications or even compromise the analysis. Therefore, at least, in the phase of script construction, an LCA expert could be important.

One of the reasons that pushed me to develop this research, was to find a methodology that would allow me to include the environmental impact of Terrabloc bricks in a BIM based LCA. I studied a methodology able to give flexibility to the data collection and calculation methodologies, and at the same time, able to support decisions at the early stages of the project and to generate outputs as soon as the project progresses. In other words, a tool that can work as a support for stakeholders' decisions while also being understandable for those who do not have experience with LCA.

5 Integration BIM – LCA, state of the art

As mentioned above, LCA tool is getting more and more employed in the AEC sector and many professionals are trying to incorporate this methodology into their design processes.

If on the one hand, thanks to BIM software, you can manage part of the huge amount of data, on the other hand, the level of automation is still low. A BIM based LCA workflow has the advantage of facilitating the compilation of the inventory since of the possibility of querying the software on the quantities involved, but many steps still require a lot of manual work to manage the data between the different software systems.

In Table 1 it is possible to note that LCA software are mostly stand-alone solutions, where project information is extracted from a CAD or BIM program and the impact calculations are performed in the LCA tool. Thus, the process is strongly influenced by software integration and the data exchange between them.

Existing Computer Supported sLCA-Tools									
Type	Name	3D Model	Energy Demand	LCA	Optimisation	Online/Offline	Country	Website	LCA Approach
Generic	Gabi			●		Off	Germany	www.gabi-software.com	Conventional
	SimaPro			●		Off	Netherlands	network.simapro.com	Conventional
	OpenLCA			●		Off	Germany	www.openlca.org	Conventional
	Umberto			●		Off	Germany	www.ifu.com/umberto/	Conventional
Table Based Calculation	Envest			●	○	On	UK	envest2.bre.co.uk/detailsLCA.jsp	Conventional
	SBS Building Sustainability		○	●		On	Germany	www.sbs-onlinetool.com	Conventional
	Ökobilanz Bau		○	●		Off	Germany	www.oekobilanz-bau.de	Conventional
	eToolLCD		○	●		Off	Austria	/etoolglobal.com/	Conventional
	Athena Impact Estimator		○	●		Off	Canada	www.athenasmi.org	Conventional
	EcoBat		○	●		Off	Swiss	www.eco-bat.ch	Conventional
	Legep		●	●	○	Off	Germany	legep.de	Conventional
	novaEquer		○	●		Off	France	www.izuba.fr	Conventional
	Elodie		●	●		Off	France	www.elodie-cstb.fr	Conventional
	SIA 2040			●		Off	Switzerland	http://www.sia.ch/	Conventional
	GreenCalc+			●		Off	Netherlands	www.greecalc.com	Conventional
Component catalogue	Eco2soft			●		Off	Austria	www.baubook.info	Conventional
	Bauteilkatalog			●			Swiss	www.bauteilkatalog.ch	Conventional
	eLCA		○	●		Off	Germany	www.bauteileditor.de	Conventional
	CAALA	○	●	●	●	Off	Germany	www.caala.de	Conventional
	BEES			●		Off	USA	www.nist.gov	Conventional
BIM Integrated	Green Building Assesment Tool (GBAT)	●		●			Turkey	no link for the tool	Static
	Green Building Studio	○	●	●			USA	https://gbs.autodesk.com/GBS/	Static
	Impact Compliant Suit	●	○	●		Off	UK	www.impactwba.com	Static
	Cocon-BIM	○	●	●		Off	France	www.cocon-bim.fr	Static
	Lesosai	○	●	●		Off	Swiss	www.lesosai.com	Static
	360optimi /OneClickLCA	●	●	●		Off	Finnland	www.oneclicklca.com	Static
	Tally	●	○	●		Off	USA	www.choosetally.com	Static / Dynamic
●	fully functional								
○	partly functioning / needs additional software / extern calculation								

Table 2: *Existing Computer supported LCA Tools (Hollberg, 2016) and input from existing BIM – LCA Tools (Cristine Bueno, 2016) - Table edited by Gianluca Genova, 2018*

Also, Table 1 presents the tools categorization in 4 groups:

- Generic: Programs that do not allow data transmission from the model to the LCA tool automatically, so a lot of manual work is required.

- Table based calculation: Tables that calculate the environmental impacts, requiring a lot of manual work to insert the dimensional values from the project.

- Component catalogue: Several countries have their own catalogues to structure the data during an LCA but also here, to calculate the impact, a lot of manual work is required

- BIM integrated: Programs that allow to collect data from BIM software, facilitating the collection of some data and making the analysis less time consuming.

Most of these have a conventional or static approach thus highlighting the need for process optimization to achieve successful integration.

6 CASE STUDY – Trompone di Moncrivello

Fig. 12: Top view of the RSA Virgo

The case study for this thesis is a bioclimatic greenhouse of the hospital district of Trompone (Fig.12) located in Moncrivello, in Vercelli province (Fig. 13), a rehabilitation facility active since 1970 and managed by the "Silenziosi Operai della Croce" (SODC). The health facility is built around the Trompone sanctuary, dating back to the end of ‘500.

The complex is divided into several poles with different uses: in the North part there is a health resort called RSA Virgo Potens that is dedicated to patients with neurological diseases and muscular dystrophy. While, in the South part, there is a nursing home which takes care of motor rehabilitation, physiotherapy and cardiac rehabilitation

Fig. 13: Distance from Turin

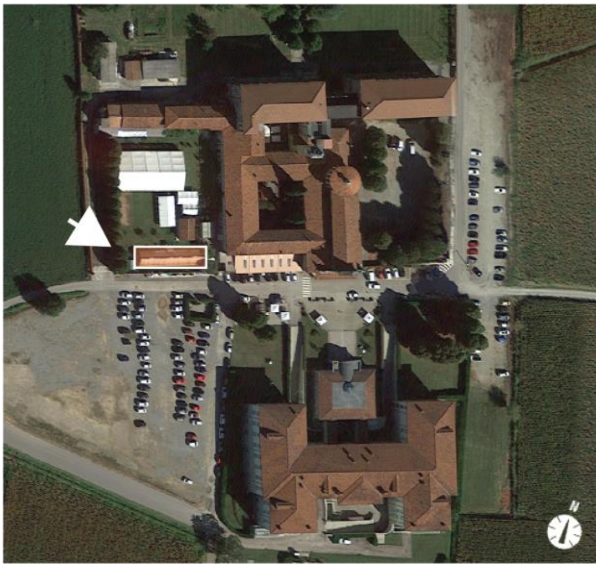


Fig. 14: Top view of the Complex

This collaboration between the Polytechnic of Turin and the RSA of Moncrivello allowed to insert several students that, through different thesis, has contributed to the design development and data management in different fields (Fig. 14).

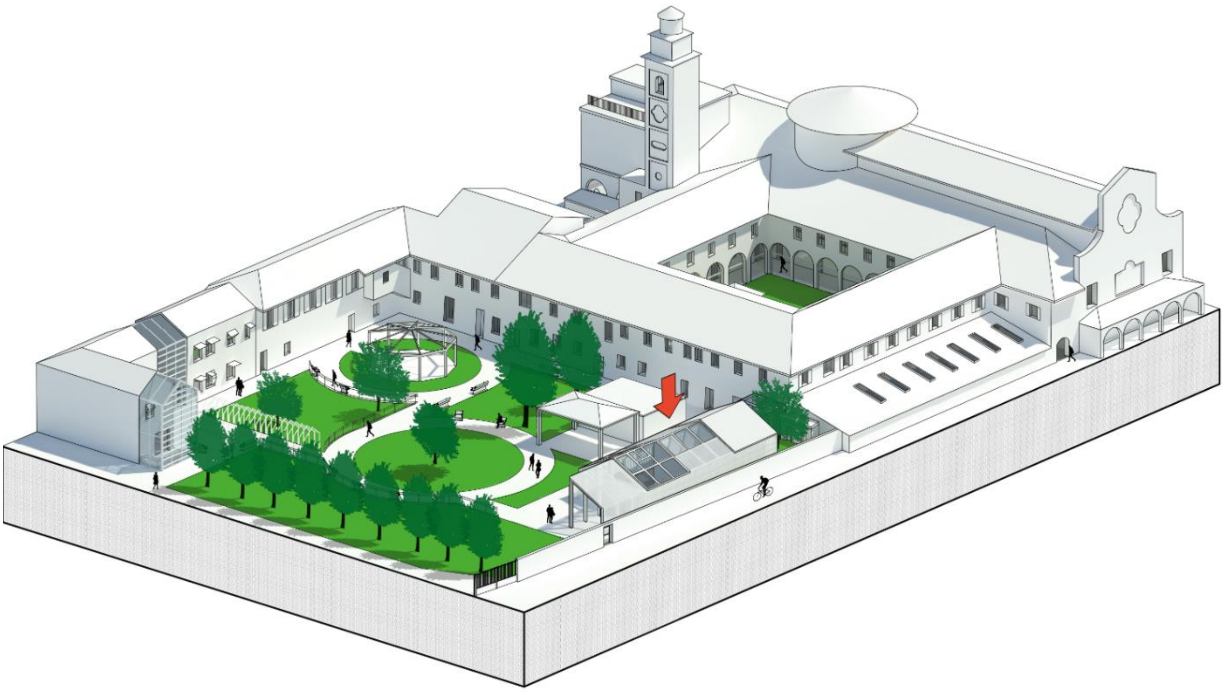


Fig. 15: Design development and data management of the Tormpone by the Polytechnic' students

In my specific case I decided to refer to Sara Rosato's thesis, "*BIM per il Construction Management - Metodologia applicata al progetto di una serra Bioclimatica al complesso Trompone*" where, after the elaboration of a project proposal for the bioclimatic greenhouse, Sara created parametric and interoperable models on different disciplines: architectural, structural and MEP, to experiment data sharing and collaboration.

The existing building develops in length on the East-west axis and overlooks the courtyard on the North side. The greenhouse is used to organize cultural initiatives, dinners or seasonal events, and is composed of a steel skeleton closed with glass panels. As there are no adequate shielding, direct solar radiation makes it difficult to use the greenhouse in the warmer seasons. Moreover, to reach the greenhouse, there is not an indoor passage. Therefore, cause of this weaknesses, the building is unused for most of the year.

Fig. 16: West view of the greenhouse

Fig. 17: Internal view of the greenhouse

Fig. 18: North view of the greenhouse

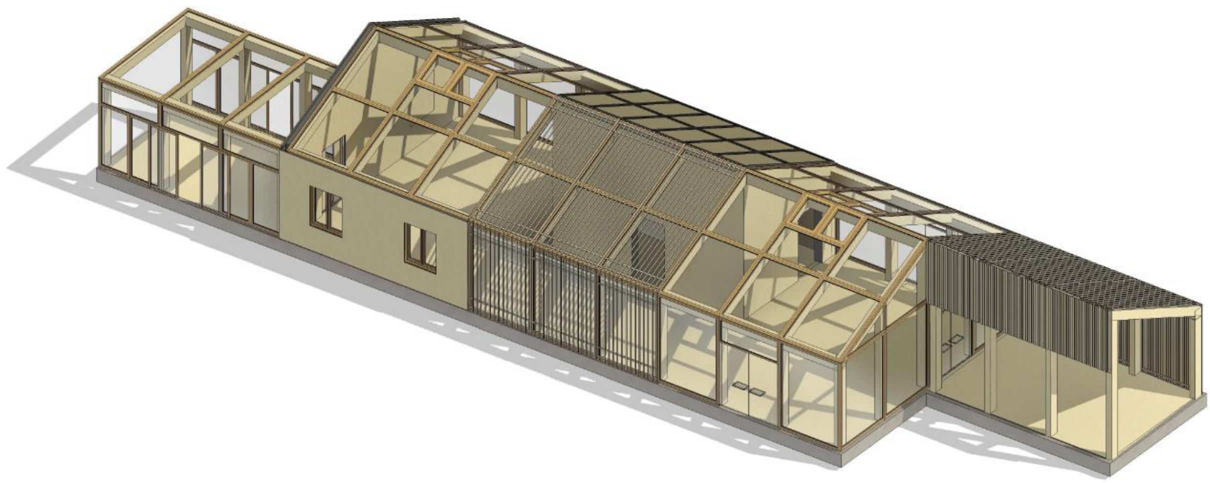


Fig. 19: Greenhouse project by Sara Rosato

Sara Rosato opted for the construction of a greenhouse with structure of beams and wooden pillars with glass closures alternating with load-bearing wooden walls with frame construction.

Starting from his work, two variants of the project are developed: one with bricks in raw earth and the other one with normal fire bricks, to assess the ability of the tool to compare the results after carrying out environmental impact calculations in any design phase.

6.1 Architectural and construction features

For the design choices, the previous student used the interviews as an instrument of investigation, developing a questionnaire that was submitted to doctors, health workers, the staff of the SODC association, the families of patients and patients with cognitive capacity with the help, where necessary, of communication machinery.

This work has built a meaningful sample useful to create a design process that would involve the users to understand the needs and to compare opinions. Investigations have revealed the will of majority of interviewed to have indoor areas for visits usable all year-round, that do not suggest that you are in a hospital. In addition, the staff asked for recreation environments where they could spend breaks and covered passage that connected the greenhouse to the rest of the complex.

In the light of the results obtained from the interviews, Sara Rosato decided to create, from scratch, a bioclimatic greenhouse habitable, able to take advantage from the southern exposure to create a building that exploits solar contributions. The new building is composed by a wooden supporting structure shaped by a system of beams and pillars in laminated wood interspersed with load-bearing walls in wood or large windows. The glazed surfaces cover most of the surfaces; some parts have been created with a light shielding made of wood brise soleil to create some opaque shaded areas.

The interior is composed of a main room that give continuity to the historic building, characterized by a large open space for multipurpose use. In the middle, there is a central body which makes up the inside, bathrooms, a storage room and a technical room.

This projecting body determines two niches that create a couple of semi-private spaces to make available to everyone.

Additionally, there is a shelter outside which takes up the system of brise soleil; external floor does not present obstacles for those who have to cross it. The intention was to characterize the project with a strong presence of wood in order to create a welcoming space that does not give the feeling of being in a health facility. For the same reason, the central compartment presents a hidden storage room, since interviews have shown the desire to have emergency medical equipment.

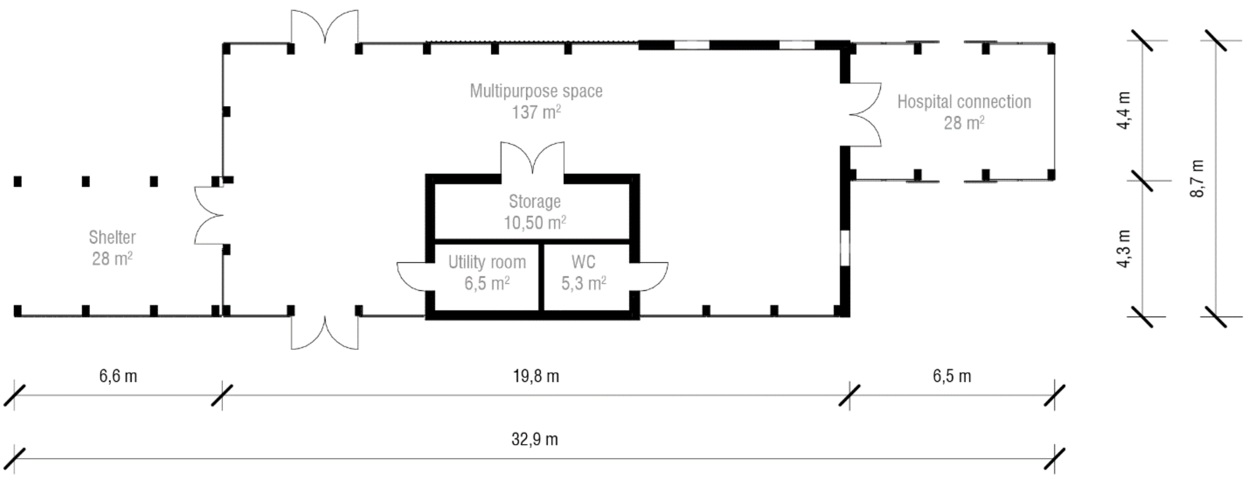
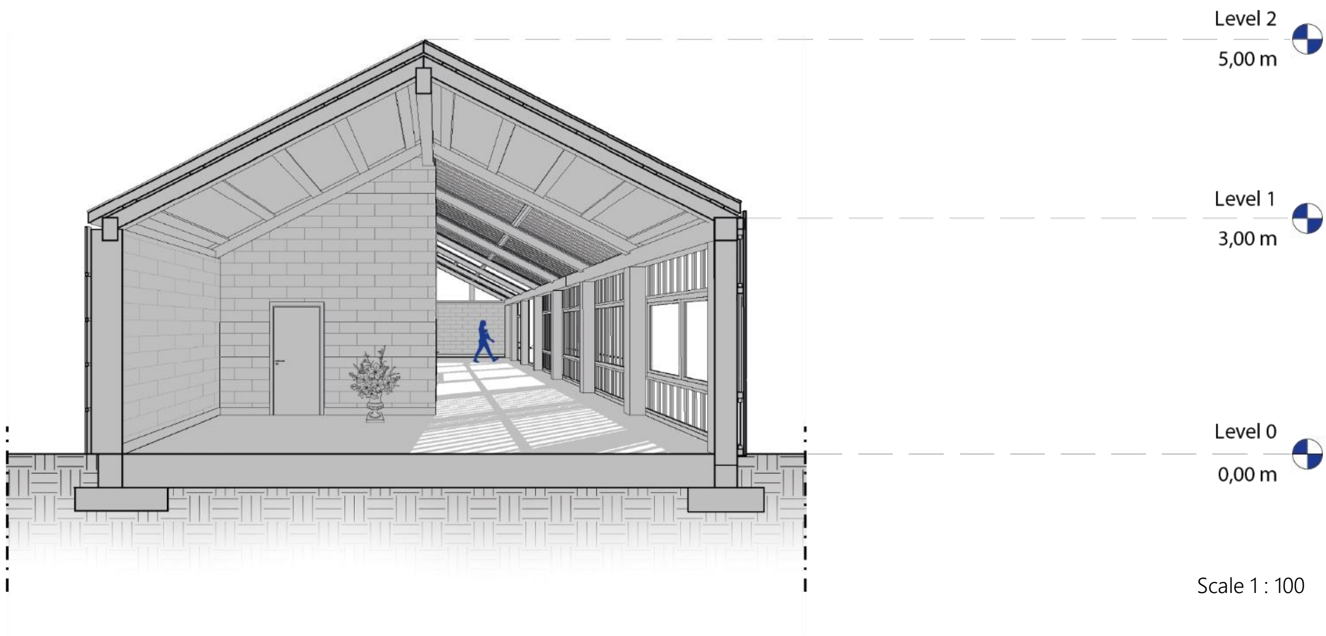


Fig. 20: Plan form the project by Sara Rosato

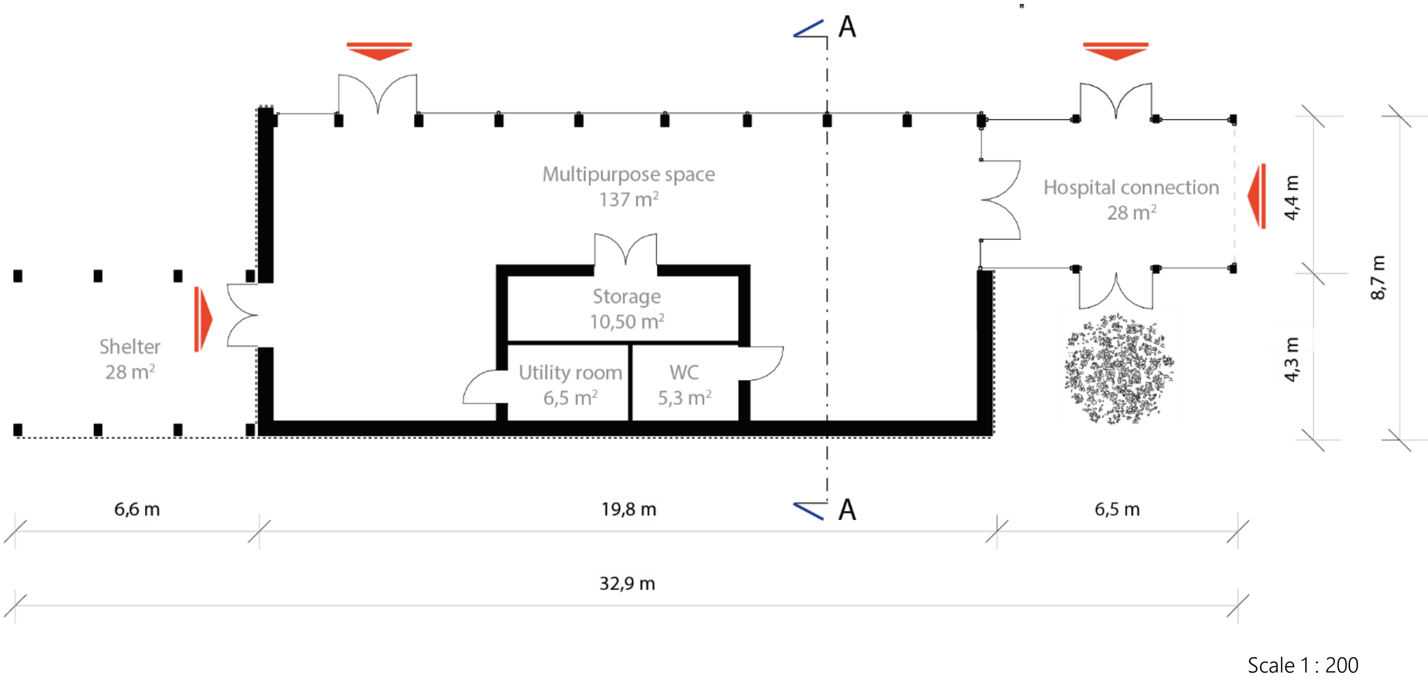
For this thesis we did not want to upset the initial project. Therefore, the same configuration of the previous project was maintained, with the difference that the load-bearing structure will not be a wooden frame system, but a structural earth masonry will be integrated instead. We also decided to replace the window on the side of the road with a masonry and keep a large glass wall on the side of the garden.

The roof will be partly opaque and partly glazed, so as not to subject the building to excessive overheating during the summer and, at the same time, ensure a good solar intake in the colder months. For this purpose, the masonry in raw earth will play an important role in regulating the internal temperature, given its ability to accumulate and retain heat from the sun rays in the hottest hours (maintaining a comfort temperature inside the building) and release it slowly during the coldest hours. In addition to thermal inertia, the earth also has excellent hygrometric adjustment capacities, thus ensuring a relative humidity that is optimal for internal comfort (between 40 and 60%). Lastly, we kept the system of wooden slating on the facade as brise soleil to create areas of shade.

SECTION A-A



FLOOR PLAN



6.2 Elements analysed

We decided a masonry in raw earth to be able to use the values derived from an LCA analysis that Terrabloc has carried out with the collaboration of the Laboratory of Solar Energetic and Building Physics (LESBAT) at the Haute Ecole of engineering of the canton of Vaud in 2017. These data are also published in the KBOB database, but they do not reflect the current production system, as the processes have been improved and a new product has been created. Therefore, since we did not have the new results, we used those of the old process.

It is essential that manufacturers of construction materials realise the value of data on the environmental impacts of their processes and products. Therefore, the AEC sector need a collective will to produce and disseminate this type of data to be able to obtain much more realistic results from this type of investigation. Data are often missing, and to compensate these shortcomings, similar material values or data obtained from averages are used, which do not always reflect those of the real ones.

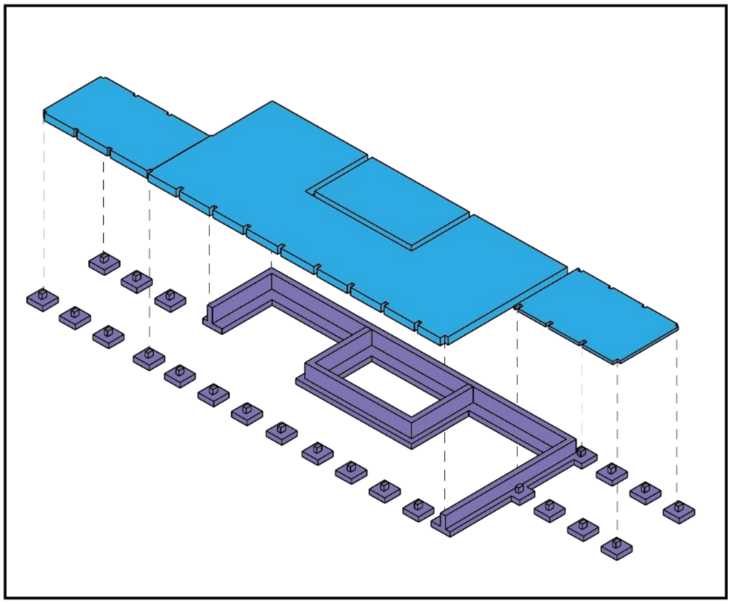
We decided to analyse the environmental impact of the architectural and structural part of this project, omitting the MEP part since Dynamo cannot directly access the volumetric information of these elements. Therefore, we did not immediately have the necessary data. We also did not have enough time to develop an MEP model for this thesis.

This analysis will form an attributional LCA, an analysis aimed to "provide information about the impacts of the processes used to produce (and consume) a product but does not consider indirect effects arising from changes in the output of a product." (Brander, 2008)

Then, we decided to make a focus on the walls by evaluating two variants, one with a load-bearing structure in the raw earth and the other with the classic fired bricks thus creating a comparative LCA with the aim of identifying variations in environmental impacts from changing a system or replacing a product with another. Obviously, with the same process, it can be possible to compare other parts of the project or even two different projects

In the following show the subdivision of the elements analysed, in the raw earth version of the case study.

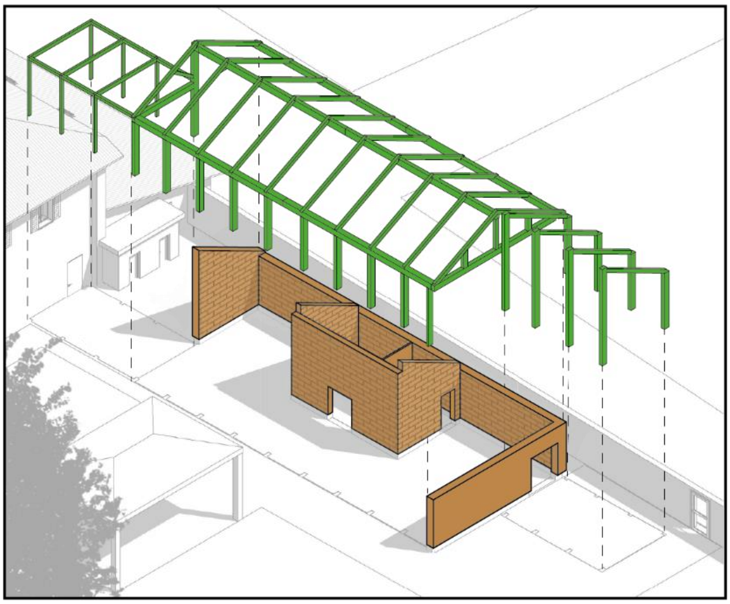
FUNCTIONAL UNIT [Kg]



Floors: All elements coloured blue have been calculated by subdividing the stratigraphy, to be able to consider every single layer modelled and not the whole category as a single volume. Alternatively, you could study the entire volume and get the results of the different layers considering them as a percentage of the total volume.

Foundations: We have isolated spread footing for the pillars and a strip footing for the walls; the set of these elements will form a foundation system in reinforced concrete. To include the information of the reinforcement, we considered 100 kg of steels for every m3 of concrete. concrete. To also include the information of the reinforcement, we considered 100 kg of steels for every m3 of concrete.

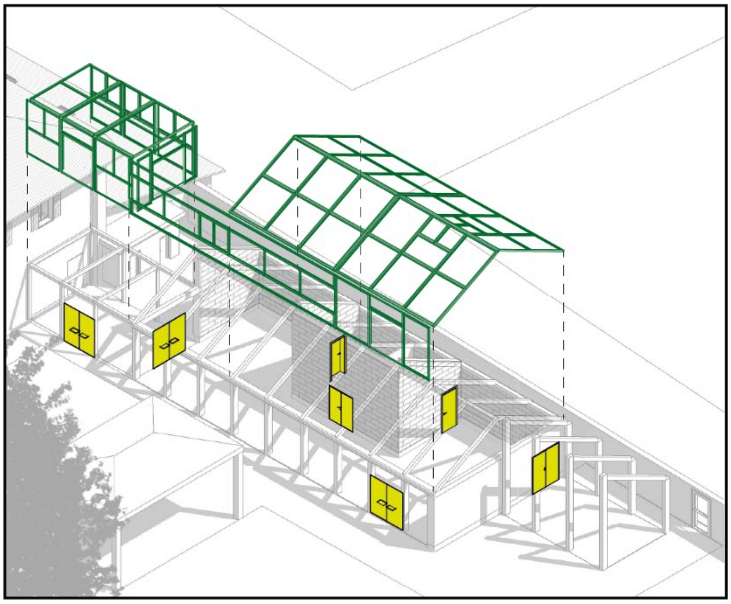
FUNCTIONAL UNIT [Kg]



Wooden skeleton: System of beams and pillars in lamellar wood that on the one hand support the roof in the northern part of the building, but on the other constitute the supporting system for the roof. Here, starting from the volumes obtained by the BIM model, we calculated the impacts assuming that the structure was made of laminated wood.

Walls: The structural walls will be composed of Terrapads, a masonry composed by blocks of 80x30x15cm, designed to offer an alternative to the rammed earth (Table 7C). While, the non-bearing walls will be built with the Terraplac (Table 7C), non-structural elements consisting of 60% earth and 40% expanded clay. In addition, we also considered the quantity of mortar on the calculation to enhance the precision

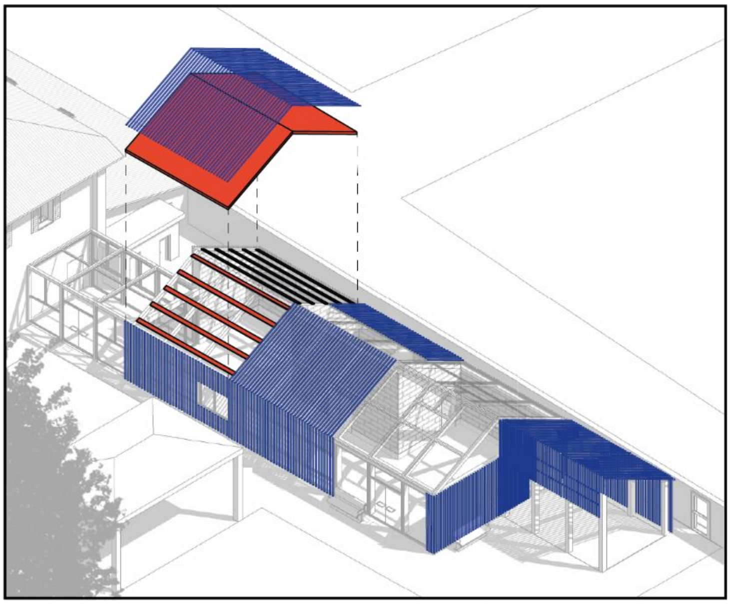
FUNCTIONAL UNIT [m²]



Curtain walls elements: all the elements that composed the vertical and roof glazing, are made of double glazing and aluminium-wood frames. These elements were calculated using the m2 as functional unit cause the KBOB database gave environmental impact of these materials in function of surface and not in mass as the majority of the other categories.

Doors: Internal and external doors made of wo- od or glass with aluminium frame. Also, for this category, we used the m² as functional units for the same reasons of the curtains walls.

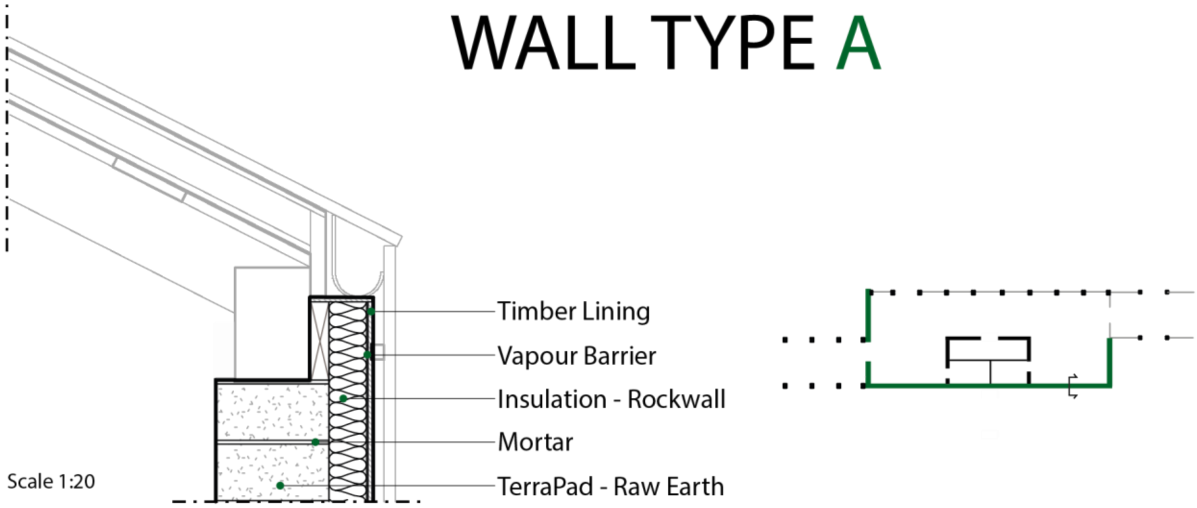
FUNCTIONAL UNIT [Kg]



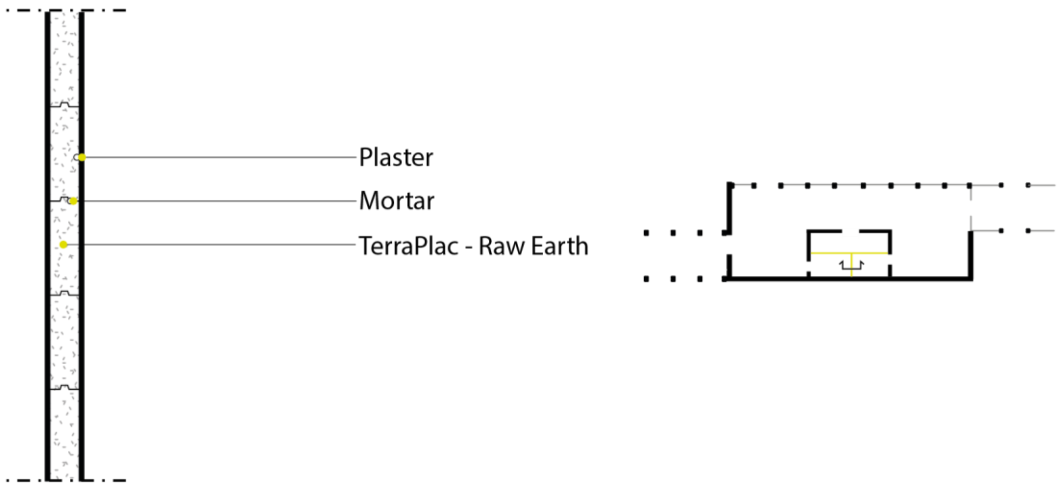
Wooden slats: Wooden slats that co- ver the building creating a protective layer in opaque parts or shadow areas in glazed areas as brise soleil. These elements also cover the external shelter thus creating continuity with the main body.

Roof: This category does not include glazed roofing, but only the opaque roof composed by different layers of materials and its structure. As for the walls and floors the stratigraphies are illustrated in detail in the following pages.

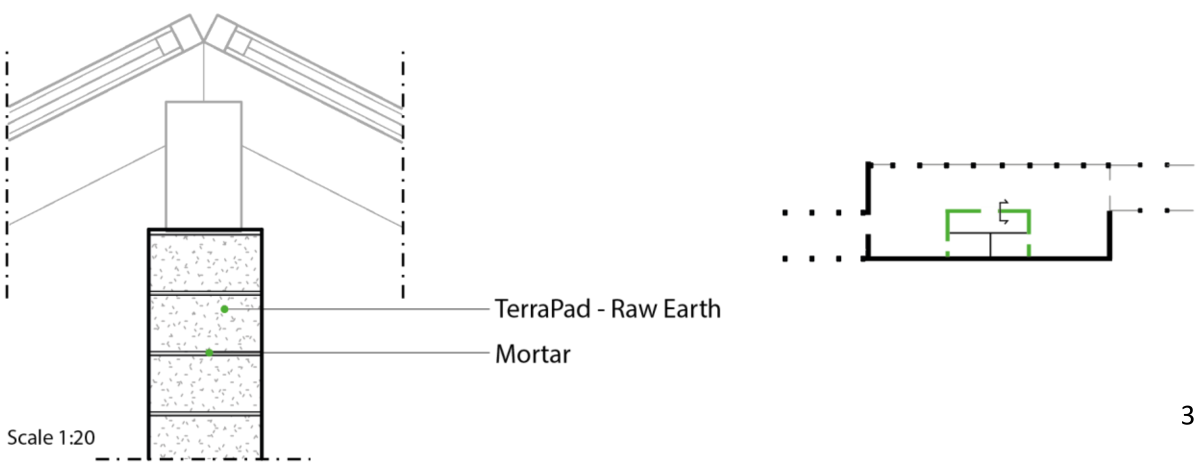
WALL TYPE A



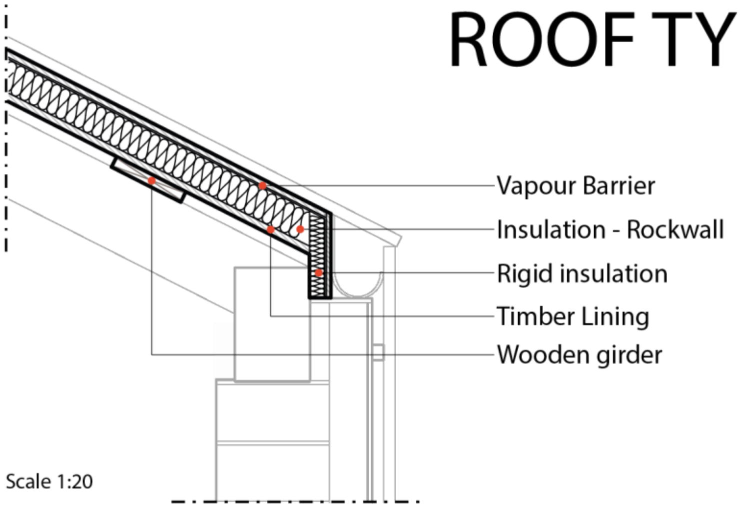
WALL TYPE B

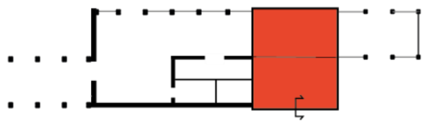


WALL TYPE C

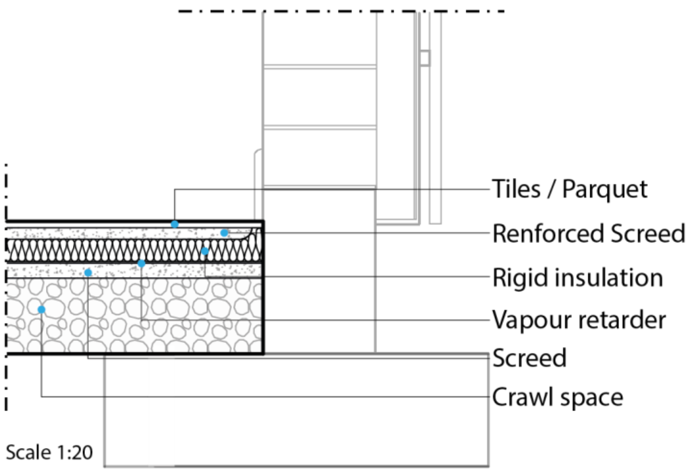


ROOF TYPE A

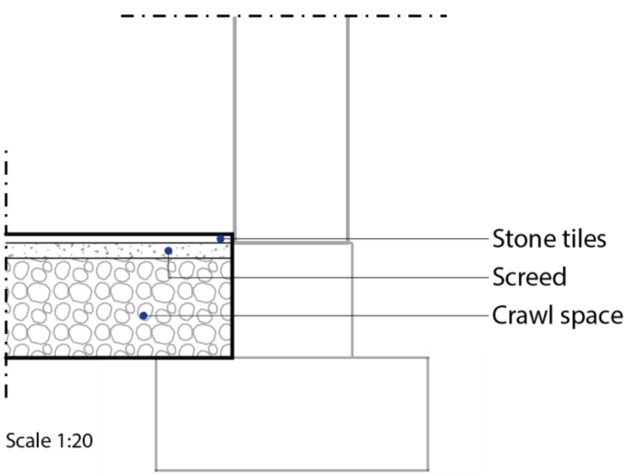


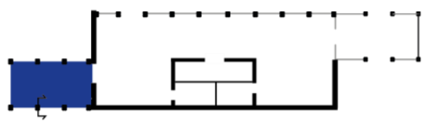


FLOOR TYPE A



FLOOR TYPE B





FOCUS: RAW EARTH

At the end of my bachelor's degree, I made a thesis about the raw earth as a construction material. Starting from a historical analysis of this vernacular material, I analysed the physical, chemical, economic and environmental property. With this work I would like to take a further step by going to study the means and the real possibilities of implementing a sustainable project, minimizing costs without sacrificing good performance.

Fig. 21: Kasbah of Ait Benhaddou, Ouarzazate, Morocco

I had the good fortune to admire the Kasbahs (Fig.21) in the south of Morocco since I was a child: huge cores of dwellings built with the Pisé technique and scattered in small villages close to the desert. Driven by the desire to study the material, I realized that often the knowledge was linked to vernacular traditions of different cultures and there was a need of divulgation to move from experimentation to the dissemination possessed in the past. For this, after the end of my first cycle of studies, I got in touch with a Swiss start-up, Terrabloc, which deals with the production of blocks in compressed earth and consulting on works in raw earth. The founders, the Eng. Rodrigo Fernandez and the architect Laurent de Wurstemberger got me in contact with various actors of this niche market at the European level. For a long time underestimated, this material has been revalued by different research groups and companies that have reproposed the recovery of the existing and the actualization of the techniques; a mixture of earth, water, gravel and/or inert fibres, shaped and dried. In addition to the advantages related to the internal microclimate, availability, versatility, economy and ease of installation, raw earth has considerable environmental benefits, which highlight its potential in the current "ecological alarm": low emissions, minimum consumption and a rapid recycling lead to a very efficient LCA.

Composition and properties

The earth comes from the disintegration of primary rocks whose debris, moved by physical phenomena, undergo chemical and granulometric changes. Once sedimented, the grains are distributed and continue their evolution by means of climatic, biological and anthropic activities.

In relation to their nature the lands are different (sandy, tuffaceous, calcareous or other...) but thanks to the secular processes of sedimentation, a stable and heterogeneous material is obtained.

To use it, it is necessary extract it under 40 cm, avoiding organic residues that are not suitable for construction.

The granulometric classification identifies:

- **Clays** (< 0.002 mm), sediments belonging to the class of phylloxylicates which give plasticity to the mixture, fundamental properties when the material is fresh (in terms of cohesion and malleability) and start to dry (acting as a binder);

- **Silt** (from 0.06 to 0.002 mm) fine inert which confers malleability; if in excess, the cohesion decreases;

- **Sand** (from 2 to 0.06 mm) and **gravel** (from 60 to 2 mm) form the skeleton stabilizing the dough and reducing its shrinkage during drying.

The earth has excellent hygrometric regulation properties: it maintains an internal relative humidity from 50 to 70%.

A lean dough (low in clay) is characterized by high specific weight (up to 2000 kg/m^3), low porosity and low water content. This optimizes the capacity to accumulate heat, thermal inertia (coefficient of thermal lag =10-12h, CRAterre, 1989, p.155), mechanical resistance and flammability (German regulations DIN 18952 consider mixtures with density >1700 kg/m^3 fireproof); instead, a fat dough, requires more water and additives are sometimes required to stabilize the mass and avoid cracking during withdrawal.

The low specific weight (1200/ 1300 kg/m^3) and the presence of micropores give thermal insulation capacity, from 0.47 to 0.09 W/mk (Sia, 1994)

Main techniques

There are several techniques to build in raw earth. The following six summarize the main ones:

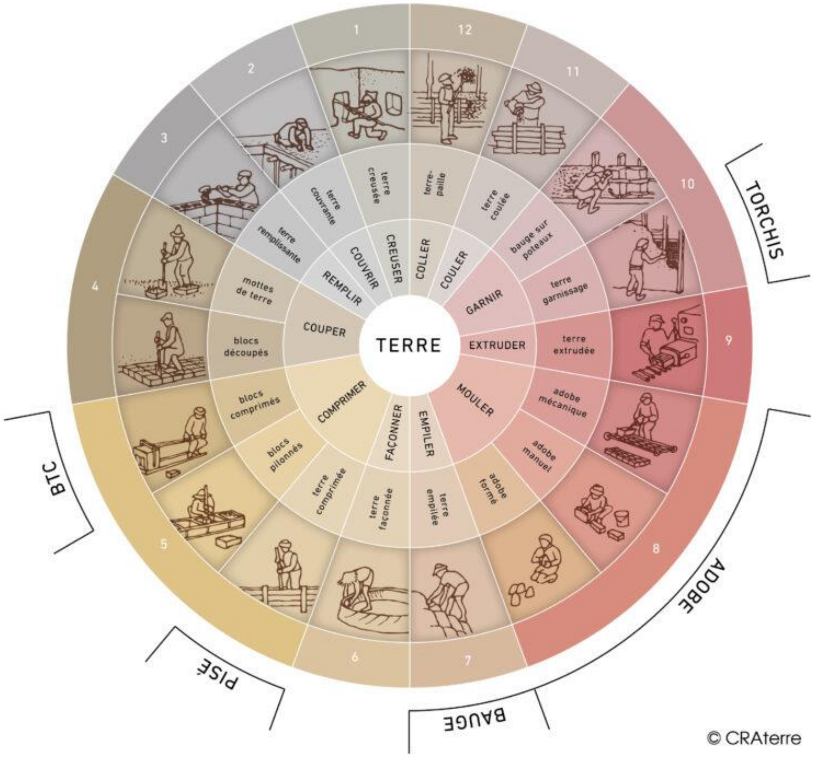


Fig.22 La roue des techniques CRATerre, 1994

Adobe: Bricks formed with moulds, left to dry naturally and then laid, like a normal brickwork in fired bricks, with a clay mortar or a traditional one. They often have no-structural function, but they can if the loads are not excessive.

The production is usually manual but lately, especially in the United States, it is also produced by organized factories.

In Italy, this technique has long traditions in Sardinia (with the name Ladiri), Calabria (Breste), Abruzzo and Piemonte (Tortona area).

Fig. 23:: Production of adobe bricks

Fig. 24: Shibam, example of a village build with the adobe technique in Yemen

Blocks: Depending on the production process, the blocks are divided into: Compressed, Extruded or Drawn. For the first ones, small mechanical or manual presses are used (optimal pressure 2 - 4 N/m); if well stabilized, they can also be used outside. Drawn and extruded blocks, in general, are made with normal production plants, but without the firing phase. The estimated energy savings are 35 - 60%.

The Compressed Blocks is the technique which I have more knowledge, because of my experiences with Terrabloc.

Fig.25: Structural wall with Terrabloc Bricks, Switzerland

Fig.26: Industrial production of Terrabloc Bricks, Switzerland

Pisé: Monolithic walls formed by superimposing blocks (50 cm at a time) obtained by transferring and compacting damp earth into formworks (rectangular or with special shapes). Processes can be manual or automated (pneumatic compactors, cranes, etc.). Also, I had the pleasure to have some experience in the production and installations of this kind of element in a project with Lehmag, another Swiss start up that allowed me to mature a wider sensitivity in the evaluation of this material.

In Italy, Pisè is widespread in Piemonte: "the 30% of the building between Tortona, Alessandria and Novi Ligure" *(G. Scudo, 2001)*; it is also a technique that is developing in a lot of other European countries currently.

Fig.27: Lehmag Project With Pisè technique, Switzerland

Fig.28: Preparation of Pisè elements by Lehmag , Switzerland

Earth-straw and earth lightened: Mixture of liquid earth (Barbottina) with vegetable aggregates (straw - wood) or lightened materials (pumice - expanded clay) that confer good thermal insulation capacities. These mixtures can be shaped by hand and stacked to create walls (Bauges or Massone), used to cover wooden support grills (Torchis) or thrown on formworks between two formworks and compacted.

"The dough with wooden scales was developed by the Architekturwerkstatt of Lübeck and used since 1985 […] the system is patented and requires the technical supervision of Architektur-werkstatt." *(G. Scudo, 2001).*

In this technique it is not possible to produce elements with a load-bearing function, so they fit inside structures with wooden or concrete skeletons.

Fig.29: Example of Torchis technique

Fig.30: Example of Bauges technique

3D printing: In recent years, several companies have been trying to merge the technological progress of robotics with the raw earth techniques. A virtuous example from this point of view is WASP, an Italian manufacturer of 3D printers which, in recent years, has also launched in the design of 3D printed houses in raw earth.

Fig.31: Example of printed raw earth wall by WASP, Italy

Fig.32: Tecla, a project by WASP

Finally, we have the plasters, and here we can have 3 scenarios:

1. **Clay plaster on a wall in raw earth**: the continuity of material guarantees an excellent adhesion. Sandier first part forms a resistant skeleton, while the final layers are finer (the addition of vegetal fibres increases the cracking).

2. **Plaster of other material on wall in raw earth**: rough surface is necessary to facilitate the adhesion of the plaster. They have to accompany the deformations of the wall - due to thermal and hygrometric variations - so it must be neither too rigid nor have a poor dimensional stability. It must also be waterproof but permeable to steam.

3. **Clay plaster on wall of other material**: Studies carried out by Prof. Gernot Minke show that hygrometric adjustment affects the first centimetres of a wall in clay; this makes the clay suitable for internal solutions. In addition, the integration of radiant panels allows you to adjust the microclimate. In case of surfaces not enough rough, you have to prepare a background or apply support grids to adhere the dough.


Fig.33: Clay plaster on a wall in raw earth


Fig.34: Plaster of other material on wall in raw earth


Fig.35: Clay plaster on wall of other material

Each of these techniques needs a particular type of land, so every area of the world has developed techniques based on the climate and characteristics of the local matter.

Durability

To use the earth as a construction material, it is necessary a good foundation to avoid rising humidity, a good roof to be insensitive to heavy rainfall and, depending on the technique, protective plasters can be helpful to ensure breathability to moisture, which in case of accumulation would condense. Water infiltrations and stagnations increase the weakening of bonds, the detachment between the different grains, the biotic activity (molds, lichens, etc.) and saline infiltrations, which, at a macroscopic level, provoke failure and expansion.

The performances depend on the nature of the earth and the technique adopted. The numerous secular buildings compensate the poor statistical data, showing that a good maintenance guarantees the conservation. In addition, the material can be rehydrated and reused or easily disposed of.

In the light of my experiences, I think it is necessary to rediscover the raw earth and all those materials with low environmental impact to re-evaluate the potential benefits in relationship with contemporary buildings. For this reason, we decided to develop a workflow that would allow to have objective results thus helping the actors involved in a project to make decisions taking into account different environmental parameters and not only costs.

6.3 Methodology

To develop a workflow which evaluate the environmental impact of the project, I was inspired by the concept of "distributed model" *(Negendahl, K., 2015)* that is the absence of a central model: the data are created in all relevant tools and can be transferred from one to the other.

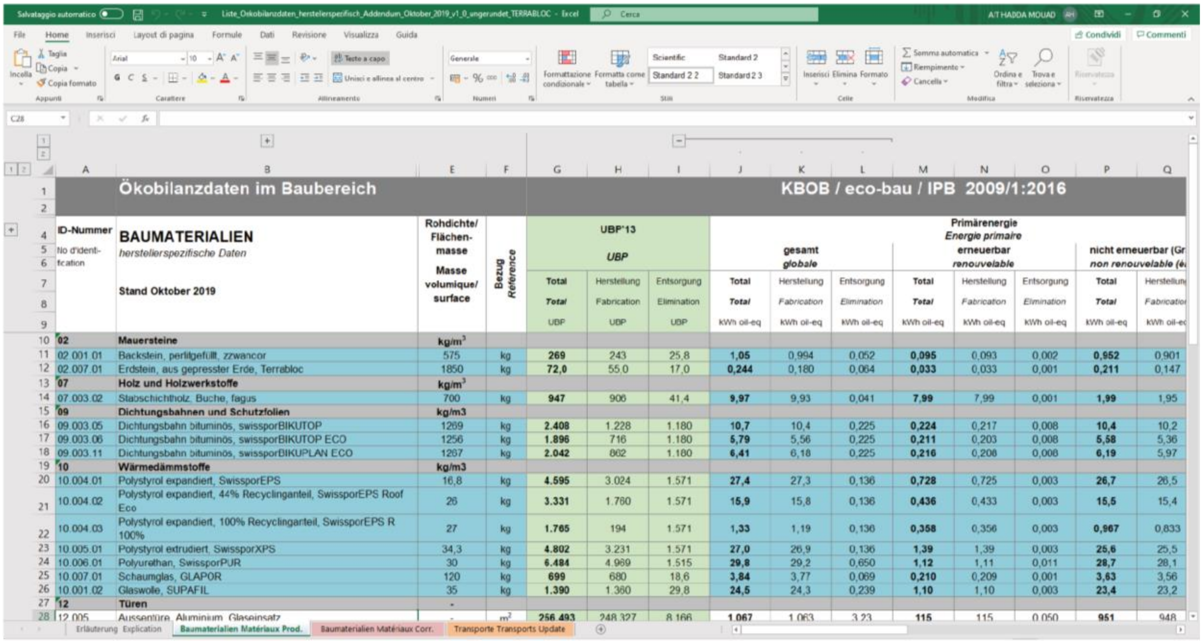
To manage this data transfer, it is important to understand the concept of "middleware tool": a program that has the task of intercepting, convert, sort and make readable all the data involved. In this case the middleware will be Dynamo, a Visual Programming Language (VPL) coupled bidirectionally with Revit, which in addition to the management and modification of geometries, allows to manage non-geometric data, giving the operators the possibility to create customized scripts.

Then the VPL will have the task to extrapolate the data from the Revit e.g. model areas, volumes, densities, material etc. and insert them in an excel file where will be the information on environmental impacts taken from a reference database; in my case, it will be KBOB Eco-bau, a material based Swiss database which collects data on materials that are commonly used in the AEC sector, energy sources, types of transport and waste treatment and divides them into four impact categories:

- **UBP**: From the German "UmweltBelastungsPunkte", are the Ecopoints, which quantify the environmental impacts resulting from the use of material, energy resources, land, air and soil, through a method based on the rarefaction of resources
- **Renewable Primary energy**: Cumulative energy from renewable sources i.e hydraulic power, biomass, solar energy, wind, geothermal.
- **Non-renewable Primary energy**: cumulated energy from fossil resources, nuclear and even wood taken from primary forest deforestation.
- **GWP**: Global Warming Potential, assessment of the effect of different greenhouse gases in relation to a reference substance, CO_2.

This information is based on surface (m^2) or mass (kg), so the reference units, depending on the case, will be one of them. The tool will then read the LCA information and create a link with the BIM objects.

If values from other databases are used, the results may not be consistent due to different methodologies or different impact categories being considered.



ID-Nummer / No d'identification	BAUMATERIALIEN herstellerspezifische Daten, Stand Oktober 2019	Rohdichte/ Flächenmasse / Masse volumique/ surface	Bezug / Référence	UBP'13 UBP: Total / Total / UBP	Herstellung / Fabrication / UBP	Entsorgung / Elimination / UBP	Primärenergie gesamt / globale: Total / Total / kWh oil-eq	Herstellung / Fabrication / kWh oil-eq	Entsorgung / Elimination / kWh oil-eq	erneuerbar / renouvelable: Total / Total / kWh oil-eq	Herstellung / Fabrication / kWh oil-eq	Entsorgung / Elimination / kWh oil-eq	nicht erneuerbar (Gr / non renouvelable (é: Total / Total / kWh oil-eq	Herstellung / Fabricatio / kWh oil-e
02	**Mauersteine**	**kg/m³**												
02.001.01	Backstein, perlitgefüllt, zzwancor	575	kg	**269**	243	25,8	**1,05**	0,994	0,052	**0,095**	0,093	0,002	**0,952**	0,901
02.007.01	Erdstein, aus gepresster Erde, Terrabloc	1850	kg	**72,0**	55,0	17,0	**0,244**	0,180	0,064	**0,033**	0,033	0,001	**0,211**	0,147
07	**Holz und Holzwerkstoffe**	**kg/m³**												
07.003.02	Stabschichtholz, Buche, fagus	700	kg	**947**	906	41,4	**9,97**	9,93	0,041	**7,99**	7,99	0,001	**1,99**	1,95
09	**Dichtungsbahnen und Schutzfolien**	**kg/m3**												
09.003.05	Dichtungsbahn bituminös, swissporBIKUTOP	1269	kg	**2.408**	1.228	1.180	**10,7**	10,4	0,225	**0,224**	0,217	0,008	**10,4**	10,2
09.003.06	Dichtungsbahn bituminös, swissporBIKUTOP ECO	1256	kg	**1.896**	716	1.180	**5,79**	5,56	0,225	**0,211**	0,203	0,008	**5,58**	5,36
09.003.11	Dichtungsbahn bituminös, swissporBIKUPLAN ECO	1267	kg	**2.042**	862	1.180	**6,41**	6,18	0,225	**0,216**	0,208	0,008	**6,19**	5,97
10	**Wärmedämmstoffe**	**kg/m3**												
10.004.01	Polystyrol expandiert, SwissporEPS	16,8	kg	**4.595**	3.024	1.571	**27,4**	27,3	0,136	**0,728**	0,725	0,003	**26,7**	26,5
10.004.02	Polystyrol expandiert, 44% Recyclinganteil, SwissporEPS Roof Eco	26	kg	**3.331**	1.760	1.571	**15,9**	15,8	0,136	**0,436**	0,433	0,003	**15,5**	15,4
10.004.03	Polystyrol expandiert, 100% Recyclinganteil, SwissporEPS R 100%	27	kg	**1.765**	194	1.571	**1,33**	1,19	0,136	**0,358**	0,356	0,003	**0,967**	0,833
10.005.01	Polystyrol extrudiert, SwissporXPS	34,3	kg	**4.802**	3.231	1.571	**27,0**	26,9	0,136	**1,39**	1,39	0,003	**25,6**	25,5
10.006.01	Polyurethan, SwissporPUR	30	kg	**6.484**	4.969	1.515	**29,8**	29,2	0,650	**1,12**	1,11	0,011	**28,7**	28,1
10.007.01	Schaumglas, GLAPOR	120	kg	**699**	680	18,6	**3,84**	3,77	0,069	**0,210**	0,209	0,001	**3,63**	3,56
10.001.02	Glaswolle, SUPAFIL	35	kg	**1.390**	1.360	29,8	**24,5**	24,3	0,239	**1,10**	1,10	0,003	**23,4**	23,2
12	**Türen**	-												
12.005	Aussentüre, Aluminium, Glaseinsatz	-	m²	**256.493**	248.327	8.166	**1.067**	1.063	3,23	**115**	115	0,050	**951**	948

Fig.36: Database KBOB ecobau

The VPL will have the task of reading data from Excel, making calculations and importing results to Revit, thus creating an exchange of data that give real-time results for each change in the project.

We chose to use a VPL (and no other formats such as IFC) for greater flexibility in calculations and data management, and especially to facilitate the integration of external data into a project. Additionally, it is possible to create output that can feed IFC formats. Formats like IFC prescribe object relationships through attribute data; instead, dynamic models "provide better support in terms of BPS tool diversity, flexibility of feedback and multidisciplinary collaboration during the early design stages" *(Negendahl 2015).*

Moreover, it is true that a VPL does not have the same convenience as a standardized format (IFC, gbXML) for data transfer. Therefore, each dynamic model made with a VPL is highly customizable, (allowing the finding of different solutions to solve same interoperability issues), so it is more difficult to understand the scripts for people who did not participate in its creation.

Despite that, it is the best way to integrate a Building Performance Simulation (BPS) process like LCA into a geometric design process bypassing a whole range of issues. For example, initially it was thought to carry out this research with Tally, a Revit plugin that allows the users to have access to the complete information about the materials, products and structures and with these data quantifies a building or material's embodied environmental impacts to land, air, and water system.

The main problem with Tally is the databases: they are American which means they cannot be used in a European context since the production processes (as well as the energy sources) are different.

In addition, although the application has a well-stocked database, it does not allow the addition of new materials from other databases.

The only way to add raw earth in Tally was to create a concrete custom, in other word to create a mix by dosing the components of the CLS (sand, cement, water and various aggregates), thus obtaining results very different from a real scenario. So, we tried to figure out a way to have a flexibility for the database selection and for the calculations method in a BIM based LCA workflow.

The focus of the workflow is the middleware tool, Dynamo, where we extract information about materials and geometries (areas, volumes, etc.) from the BIM model and the environmental information from the KBOB database; all these data are then put together on Dynamo where calculations are performed to obtain environmental impacts. The results are exported in Excel in order to be able to make the graphs and in Revit to be able to assign the environmental impact to the single elements.

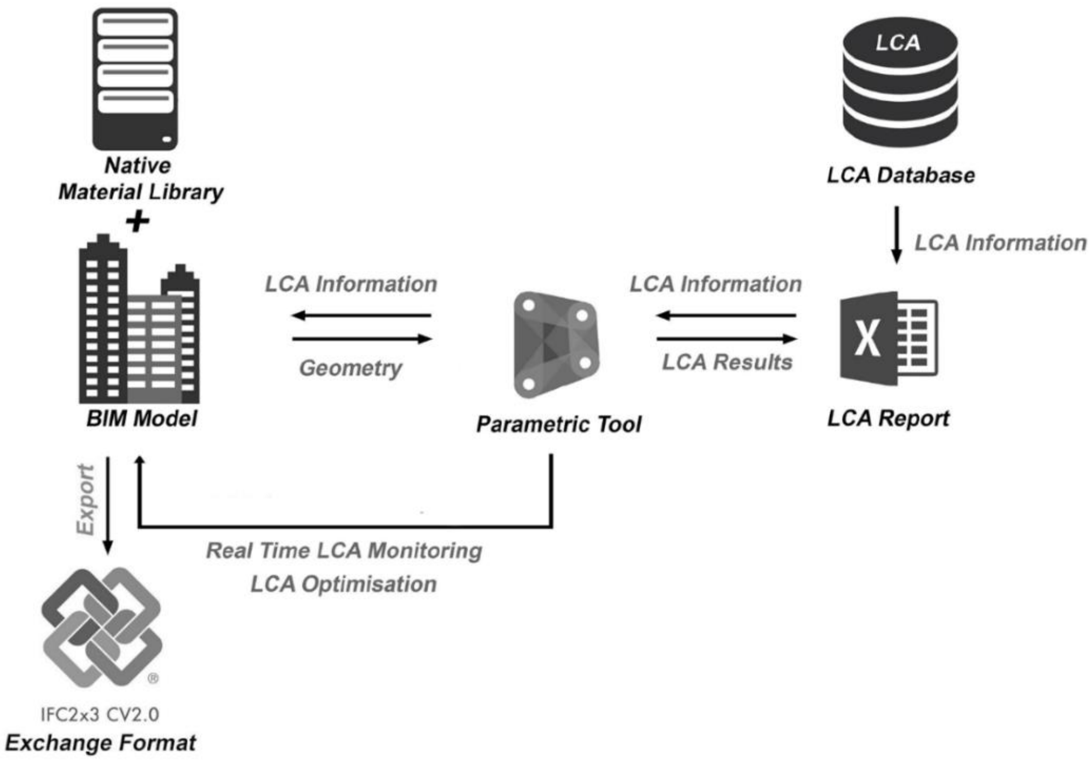


Fig.37: Personal re-elaboration of Dynamic BIM-LCA Approach

In order to have sorted impacts, we created an Excel file (Fig.20) where the names of the Revit' materials or categories are exported from Dynamo, while the numerical values of the impacts are compiled manually from the KBOB database.

We decided to work with a script for each category of Revit (e.g. walls, windows etc) since a single script for a whole project would mean submitting huge amount of calculations to the PC, with the constant risk of crash. For this reasons, 8 different scripts (that follow the same subdivision of pag 30-31) have be made. This means that, to have the complete analysis, you will have to run all these scripts one after another to feed two Excel files: one related to impacts results (Fig.38) and one with calculations (Fig.39).

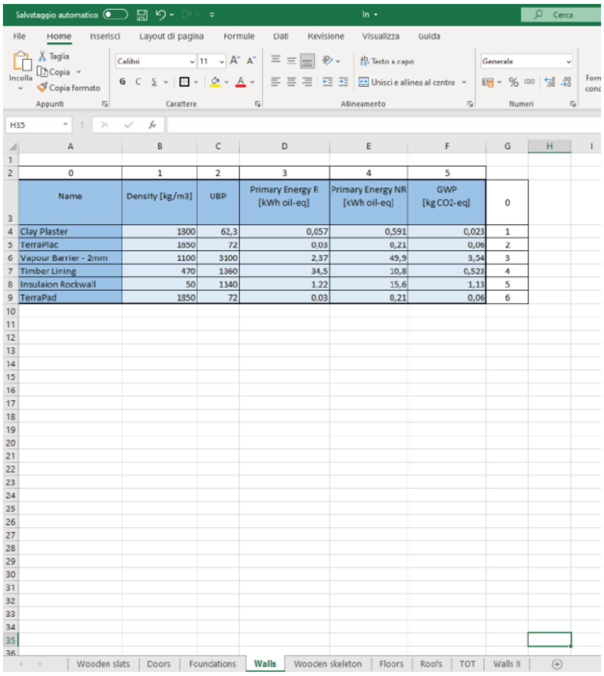


Fig.38: Input Data about the impact manually filled

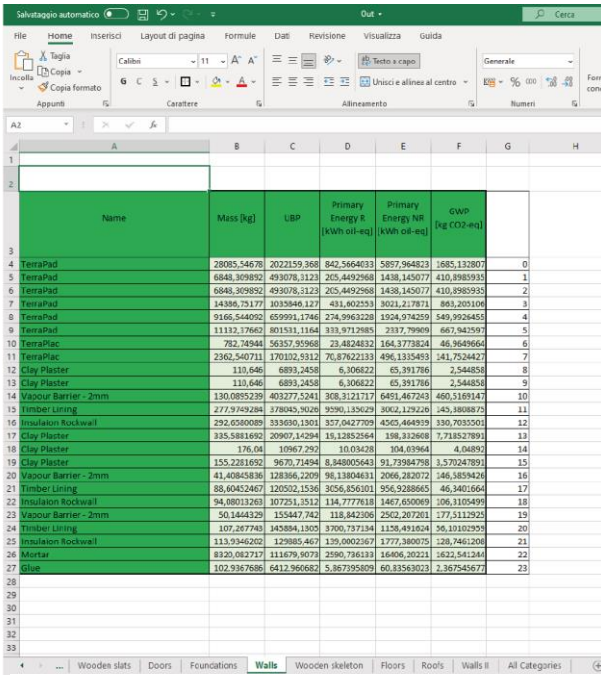


Fig.39: Output Data about the calculations performed

6.4 Material Mapping

As mentioned above, Revit has a hierarchy structure by categorizing different component of the model.

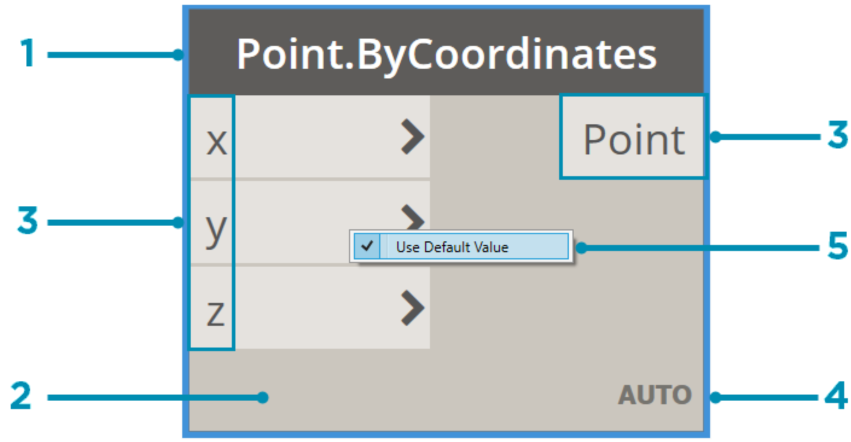
In order to develop this workflow, it was firstly necessary to find a method to link information of materials used in the BIM model with LCA database libraries, where materials have all relevant information.

In all the studies analysed, this link was created associating the ID of Revit's materials with an identification code in the LCA database chosen.

The main problem of this methodology is that for all elements that have layers (e.g walls, floors, roofs etc.) it is not possible to obtain an ID for each layer, and this involves extra manual work and also a higher probability of error.

Therefore, we decided to develop a name-based workflow to map all the relevant elements for the LCA. This approach requires manual work but allows you to work by categories, elements or material, giving the possibility to adapt more easily to different databases.

From the practical point of view, Dynamo works with nodes (Fig. 40), that is "objects you connect to form a Visual Program. Each Node performs an operation - sometimes that may be as simple as storing a number or it may be a more complex action such as creating or querying geometry." *(The Dynamo Primer, 2020)*



1. Name - The Name of the Node with a Category.Name naming convention
2. Main - The main body of the Node - Right-clicking here presents options at the level of the whole Node
3. Ports (In and Out) - The receptors for Wires that supply the input data to the Node as well as the results of the Node's action
4. Lacing Icon - Indicates the Lacing option specified for matching list inputs (more on that later)
5. Default Value - Right-click on an input Port - some Nodes have default values that can be used or not used.

Fig.40: Anatomy of a Node

Through the nodes, a formalization structure has been created, where instructions and relationships are defined through a graphical interface, the script. However, a visual program is not always the optimal solution, and there is often a risk to create a chaotic scripts and lacking in functionality. For this, there is also the possibility to expand the functionality of Dynamo through Python, a powerful programming language that permits you to create an instruction writing through conditional statements and looping. In the case of this work, it was necessary to create a node with Python to map the materials (Fig.41).

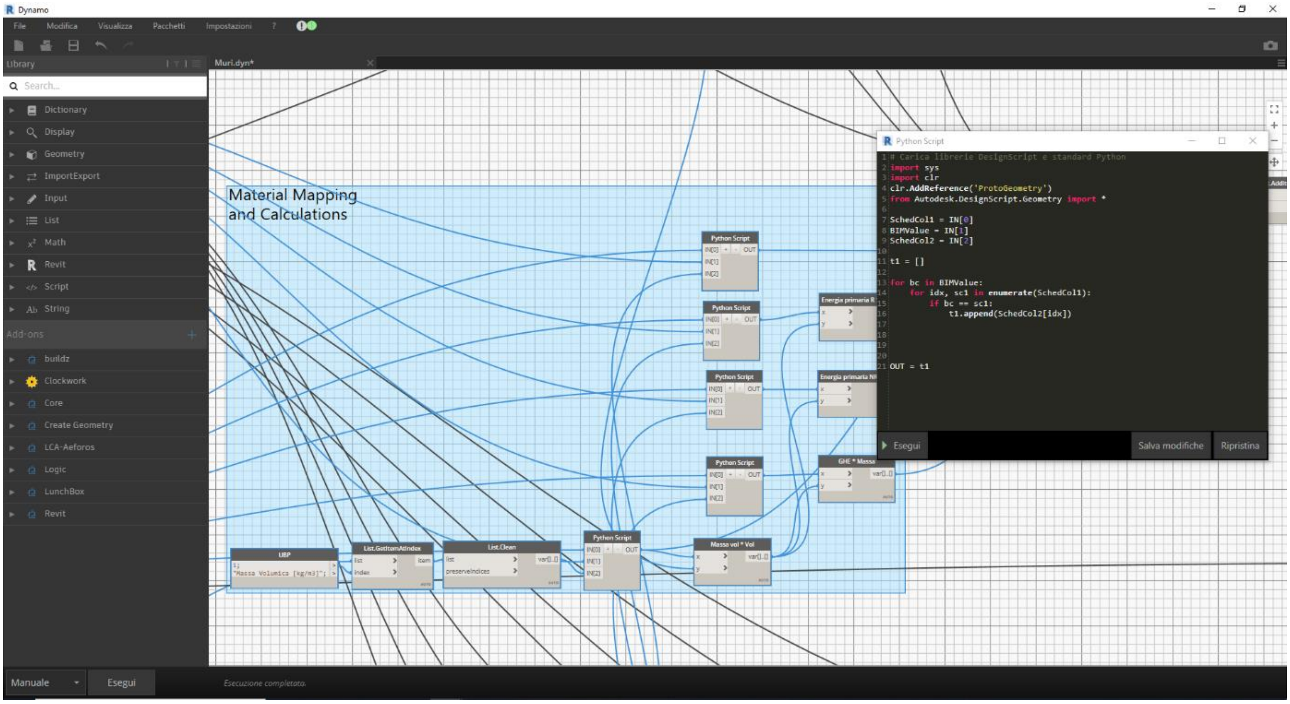


Fig.41: Custom node to map materials

Such node will read the names of the Revit' materials taken univocally and the values assigned to it manually from the KBOB database (Fig.input), then it will compare the names of the Input spreadsheet (Fig.input), with the list of the project materials in Revit and, if there is a match between the input from excel and the list of Revit's project materials, the corresponding value will be appended. After that, the result will be the list of values of the environmental impacts of individual materials. Then, to calculate impacts, the geometric values extracted from the BIM model will be multiplied for the impact value calculated from the LCA database. Below we have an example about the GWP impact.

$$\text{Density} * \text{Volume} * \text{GWP per kg of material} = \text{GWPImpact}$$

$$Kg/m^3 * m^3 * KgCO_2eq/kg = KgCO_2eq$$

After the first test, we noticed that some components had unrealistic impacts on climate change, although the model had a LOD good enough to perform the climate calculations.

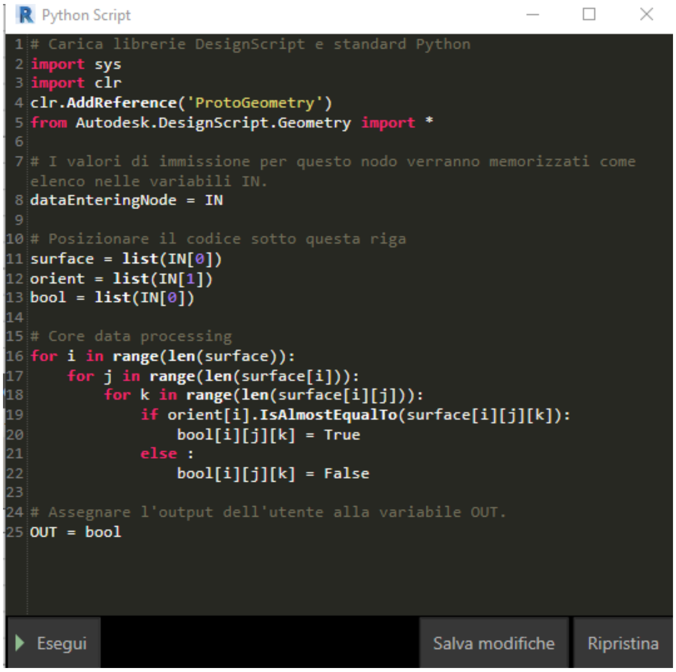


Figure 42: Phyton Script for doors in windows surfaces

Following several attempts we understood that for the doors and windows Dynamo was not calculating the layer's area, but the total area of all surfaces of the parallelepipeds. To solve this problem, it was necessary to create another node with Phyton to make Dynamo able to have the good values.

7 Results

After the tests on the project, we had the proof that it is possible to have a continued environmental analysis over the design process, and this is the strength of this workflow: it is possible to assess the impact of choices from the early stages. However, we are still far from having real-time monitoring. Although performing the analysis takes a few minutes, as the project progresses there is always the need to optimize the algorithms; despite that we can say that we have reached the pre-set goal.

We decided to present the results in the following 3 ways:

- A breakdown into groups of categories to calculate the impact of the entire building
- Through a focus on the walls, in which we evaluated the impact of the materials that compose the walls of the entire project and those of a variant.
- Lastly, we have created a shared parameter for each category of impact analysed: UBP, Renewable Primary Energy, Non-Renewable Primary Energy and Global Warming Potential.

  This allowed to have the results directly on Revit: indeed, for each instance, it is possible to display the environmental impact by selecting directly the object (Fig.43).

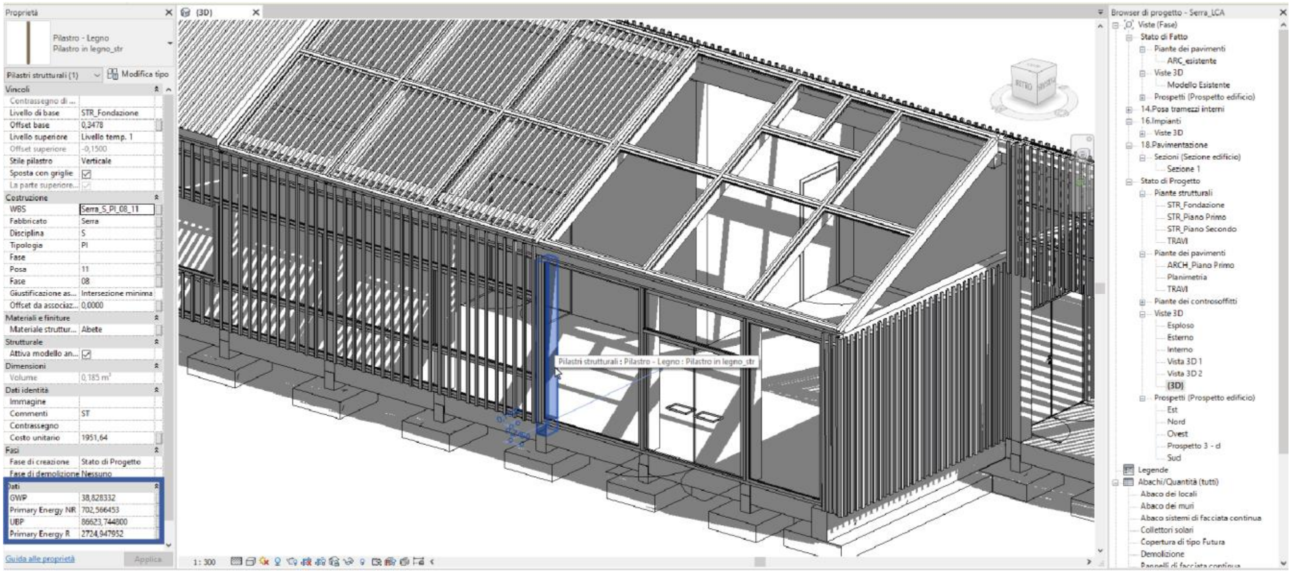


Fig.43: Impact categories in the BIM model via shared parameters

Therefore, the tool can give results to a macro scale, such as category groups, but you can also examine, in depth, a part or evaluate variants of the project. In my case I decided to analyse the walls but, with the same procedure, you can evaluate other categories.

In the following pages, results are presented through stacked column chart that have been generated thanks to excel outputs linked to the BIM model. This means any change in the project will also be reflected in the Excel chart.

RESULTS
By categories

In the following classification the results are presented according to a division into categories

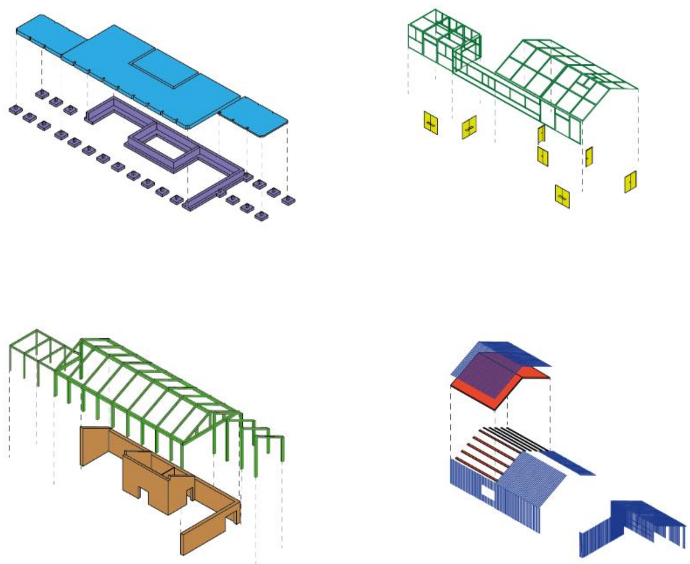


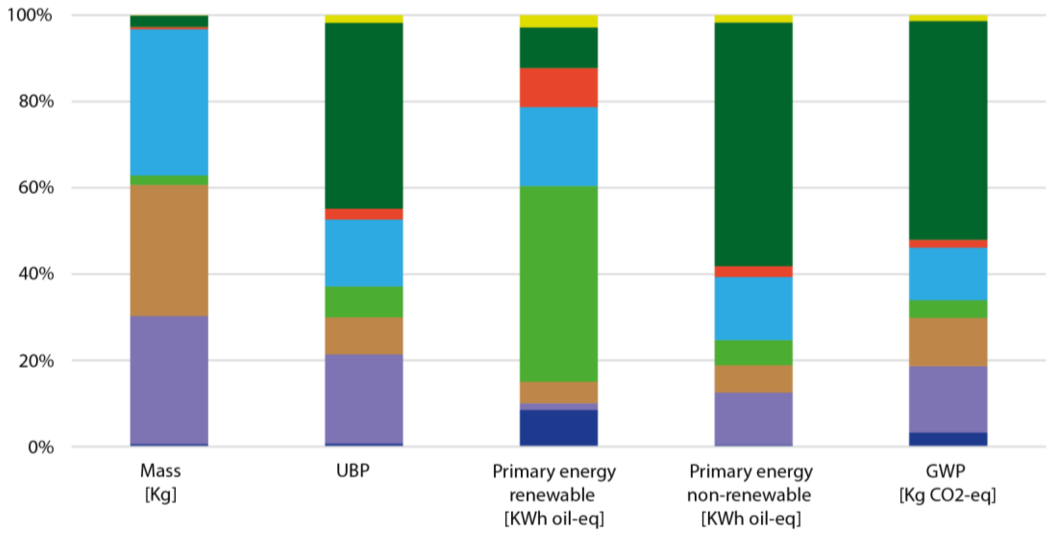
Figure 44: Categories analyzed

Each category presented in the graphs corresponds to one or more categories of Revit, for example to the group of wooden skeleton belong elements of the Revit's category pillars and structural frame.

We decided to use a different classification compared to Revit, sorting the groups of categories with a colour code (see the image above). Therefore, in order to facilitate the reading of the results, the scripts have been adapted to this need.

Analysing the results table, it can be noted that in the masses column the walls, floors and foundations represent the heavier elements, so the mainly elements of the project. Nevertheless, it is interesting to note that the distribution of the environmental results is not related to the masses: in fact, raw earth walls have very low impacts if we consider the weight of material present in the project. On the contrary, curtain walls elements, despite representing only 3% of the total weight, occupy the largest slice in the UBP, primary energy from non-renewable sources and GWP. Finally, about the primary energy from renewable sources, it is evident that wood is widely the most performing material.

RESULTS
By categories



Name	Mass [kg]	UBP	Primary Energy R [kWh oil-eq]	Primary Energy NR [kWh oil-eq]	GWP [kg CO2-eq]
Wooden slats	1%	1%	8%	0,4%	3%
Foundations	30%	21%	2%	12%	15%
Walls	30%	9%	5%	6%	11%
Wooden skeleton	2%	7%	45%	6%	4%
Floors	34%	16%	18%	15%	12%
Roofs	1%	2%	9%	3%	2%
Curtain walls elemens	3%	43%	9%	56%	51%
Doors	0,1%	2%	3%	2%	1%

Name	Mass [kg]	UBP	Primary Energy R [kWh oil-eq]	Primary Energy NR [kWh oil-eq]	GWP [kg CO2-eq]
Wooden slats	1843	639737	38665	3355	2348
Foundations	90164	19095917	7051	111619	11159
Walls	92299	7959751	22598	58351	8132
Wooden skeleton	6615	6582373	207063	53386	2950
Floors	102934	14389008	83372	134674	8813
Roofs	1556	2300643	41014	23363	1378
Curtain walls elemens	8177	39787148	43030	519095	36716
Doors	225	1655920	12958	15594	1000
Tot building	303818	92410501	455755	919442	72499

STRUCTURAL WALLS

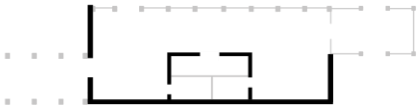

Fig 45: Terrapad

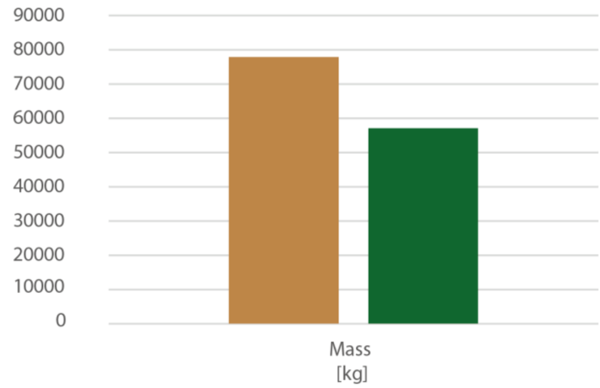

Fig. 46: Fire Bricks

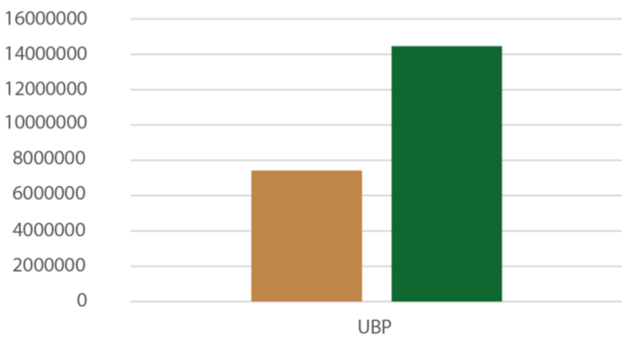
In the following graphs we compared the structural walls of the Terrapad version and the fire bricks one. Numbers are expressed with different units of measure (unlike the other graphs, where the values are expressed in percentages). For this reason, there are 4 different graphs, each one with its unit of measure and scale of numbers. The only exception is UBP, which is eco-points with a single score obtained from the combined results of a life cycle assessment and provides an environmental impact summary based on Swiss environmental policy. This creates a dimensionless value.

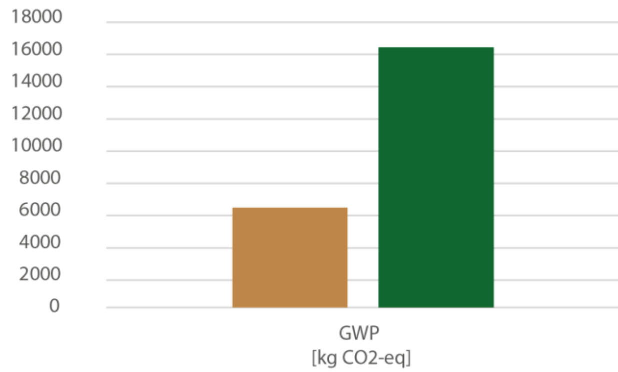
As expected, Terrapad walls have lower environmental impact values than fire bricks, especially in terms of primary energy because the process of producing Terrapads and products in raw earth in general, does not require firing in ovens.

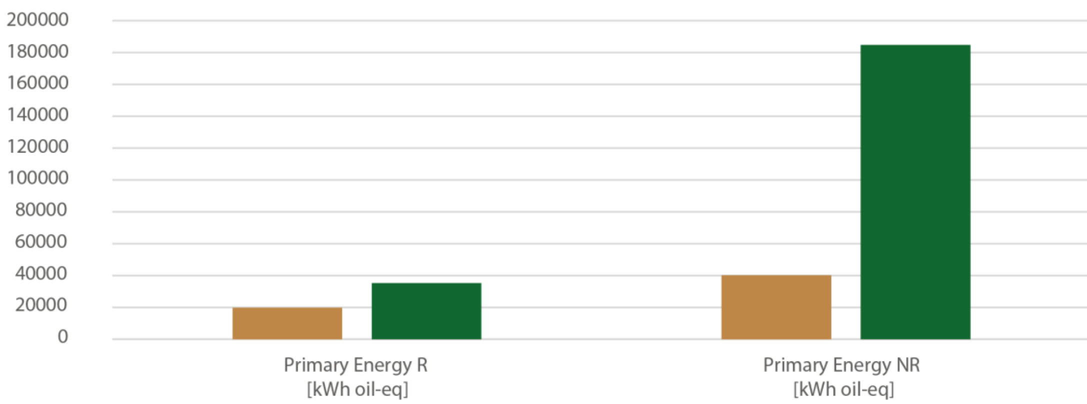
STRUCTURAL WALLS











Name	Thickness [cm]	Mass [kg]	UBP	Primary Energy R [kWh oil-eq]	Primary Energy NR [kWh oil-eq]	GWP [kg CO2-eq]
Terrapad walls	42,2	77821	7417783	19786	40139	6189
Fire brick walls	32,2	57047	14453884	35252	184695	16137

ENCLOSING WALLS

Fig 47: Terraplac

Fig 48: *Hollow bricks*

Fig 49*: Plasterboards panels*

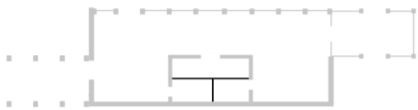
Graphs show the comparison between the non structural walls. We have three different versions : Terraplac, Holoow bricks and plasterboards panels.

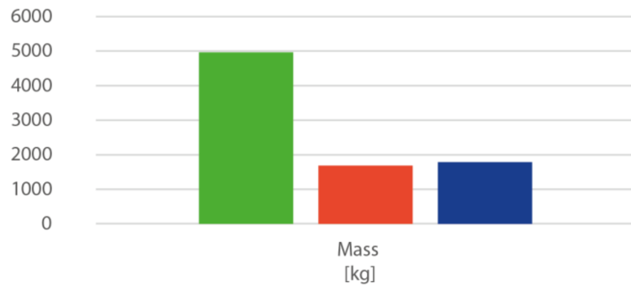
As previously, the reference numbers are expressed with different units of measure. For this reason, there are four different graphs, each one with its unit of measure and scale of numbers.

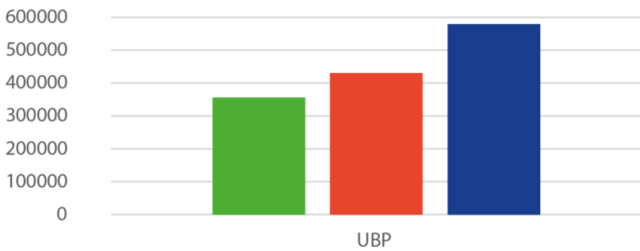
The first evidence is that the Terraplacs are almost three times heavier than the other walls, and this is their main weakness compared to competitors. Nevertheless, thanks to the introduction of expanded clay into the earth mix, Terrabloc has managed to decrease Terraplac density from 1850 to 1650 kg/m^3 thus introducing lighter earth elements in the market.

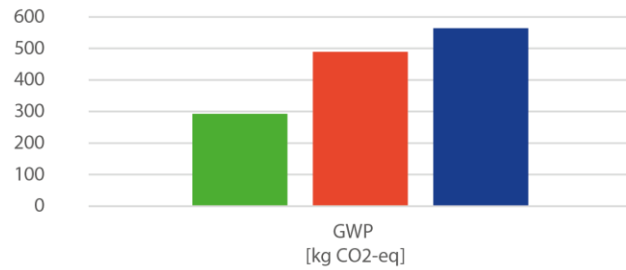
ENCLOSING

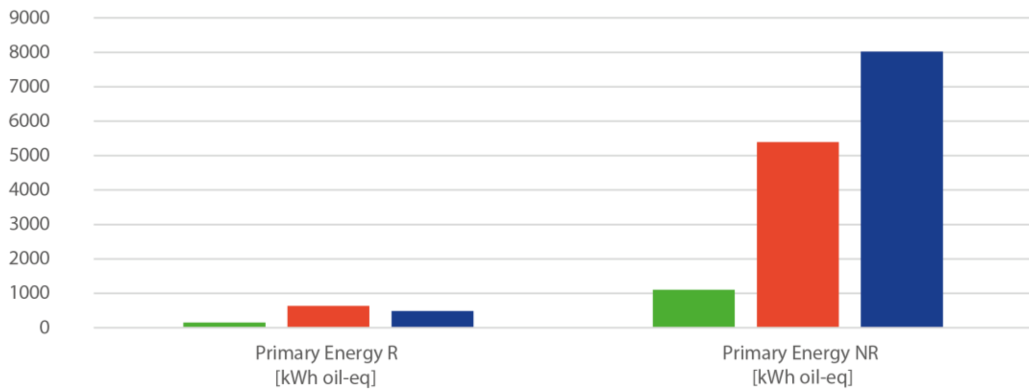
WALLS











Name	Thickness [cm]	Mass [kg]	UBP	Primary Energy R [kWh oil-eq]	Primary Energy NR [kWh oil-eq]	GWP [kg CO2-eq]
Terraplac walls	10	4968	356168	153	1103	292
Hollow bricks walls	10	1684	430766	633	5391	489
Plasterboards panels	10	1785	579800	484	8019	564

RESULTS

Wall focus: Terrabloc version

Fig 50: TerraPad

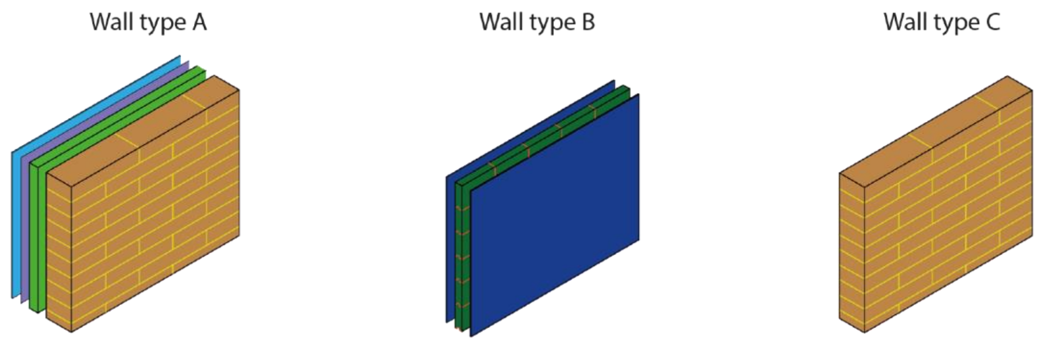
Fig 51: TerraPlac

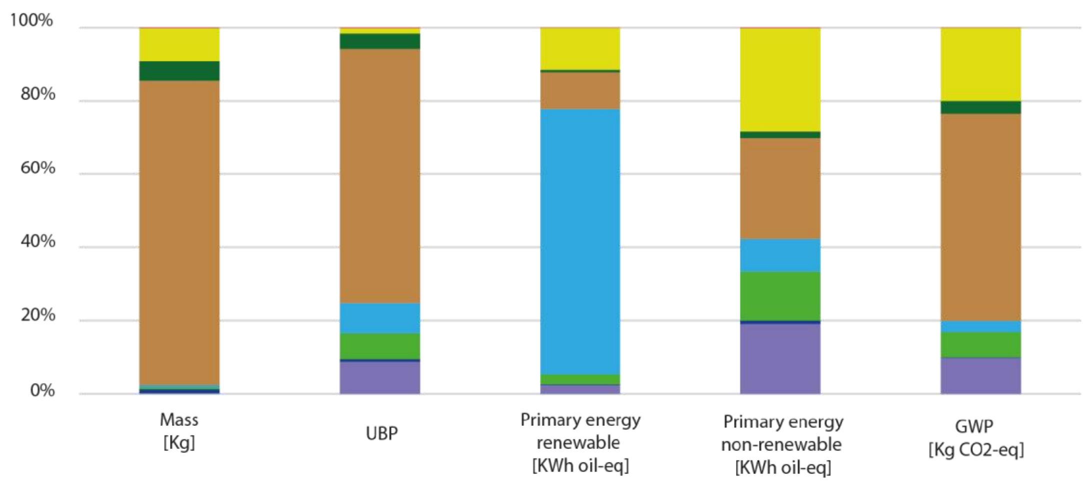
This following tables represents a deepened analysis for each type of wall, structural and not, of the raw earth version of the project. The analysis is carried out by breaking down the layers of the walls and taking into account all its parts, including mortar.

Here, as for the wooden skeleton, you can see that the wood occupies the largest slice of renewable primary energy; it is also interesting to note that the vapour barrier, despite the occupies only two millimeters thick, has very high environmental impact values.

RESULTS

Wall focus: Terrabloc version





Name	Thickness [cm]	Mass [kg]	UBP	Primary Energy R [kWh oil-eq]	Primary Energy NR [kWh oil-eq]	GWP [kg CO2-eq]
Vapour Barrier	0,2	221	687091	525	11060	785
Clay Plaster	1	888	55332	51	525	20
Insulation Rockwall	10	500	570767	611	7810	566
Timber Lining	1	473	644432	16348	5118	248
TerraPad	30	76467	5505684	2294	16058	4588
TerraPlac	8	4810	346361	144	1010	289
Mortar	1	8320	111680	2591	16406	1622
Clay Glue	0,4	157	9808	9	93	4
Tot wall		91840	7931155	22572	58081	8121

RESULTS

Wall focus: Fire brick version

Fig 52: *Fire bricks*

Fig 53: *Hollow bricks*

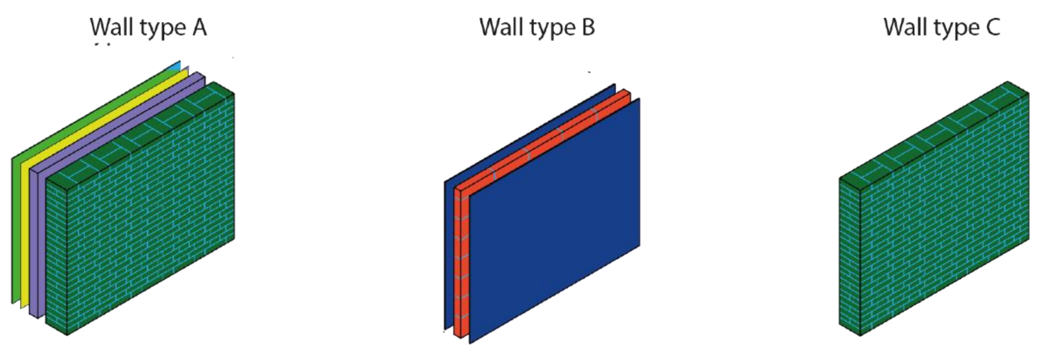
Here the analysis of the fire bricks version of the project, to create a comparison with the version in raw earth. The analysis is carried out with the same logic as the previous one.

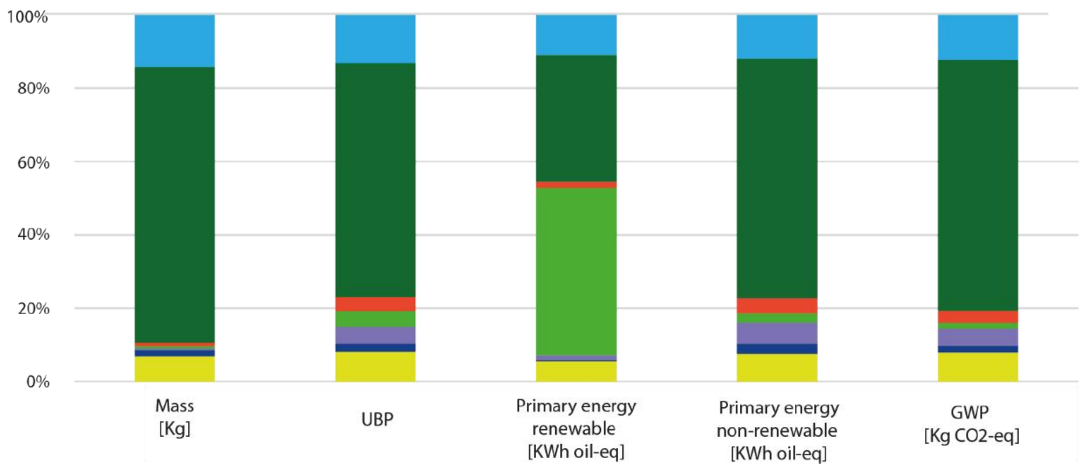
The stratigraphies are similar, the only differences are the bricks and mortars that have binding function because here we have classic cement mortars while in the clay version they are all clay-based.

Comparing the two graphs you can immediately notice the difference between Terrabloc elements and those in Fire Bricks. Despite the elements in the earth have higher thicknesses and densities the impacts are significantly lower in all categories.

RESULTS

Wall focus: Fire brick version





Name	Thickness [cm]	Mass [kg]	UBP	Primary Energy R [kWh oil-eq]	Primary Energy NR [kWh oil-eq]	GWP [kg CO2-eq]
Plaster	2	4036	1214977	1974	14572	1324
Hollow brick	8	1009	346098	105	5217	310
Vapour Barrier	0,2	220	683364	522	10000	780
Timber Lining	1	471	640938	16259	5090	246
Insulation Rockwall	10	498	567651	607	7768	563
Fire brick	20	44252	9602653	12346	126118	11417
Mortar	1	8346	1978003	3923	22951	2061
Tot wall		58833	15033684	35737	192715	16701

8. DISCUSSION

The LCA is a widespread methodology in different field in the industry and the BIM allows to extract material data efficiently, thus providing substantial reduction in effort needed to compile the LCI.

From the chart you can clearly understand which materials or categories have the highest environmental impacts. The possibility work in the BIM model and, in parallel, update all these outputs has made us understand this workflow is a really powerful tool and the results obtained from this research are even higher than our initial expectations. Nevertheless, during development of this thesis, we found several drawbacks which may be the starting point for future improvements.

8.1 Limitations

8.1.1 Lack standardized database.

There is no standard database for compiling the LCI and through the tool developed in this thesis, you can as well integrate data from other sources (also other impact categories). The calculations used to develop the environmental impact are often made using different models. For this reason, if you use data from different sources, the results will not always be comparable with each other.

In addition, in most studies related to the BIM based LCA that I have analysed, the link between the LCA database and the BIM library was created through the identification codes of each database. The main weakness of this approach is the absence of a standard Database, because as you change Database, all the script will have to be modified in a such way that the dynamic model can read the new information.

8.1.2 Need to automate the whole process

Generally, the different disciplines involved in a BIM project have different modelling practices. To work properly with this workflow, it is essential to establish from the beginning what disciplines will be included in the analysis, so that everyone will reach the same standards and requirements to fit in the BIM based LCA workflow.

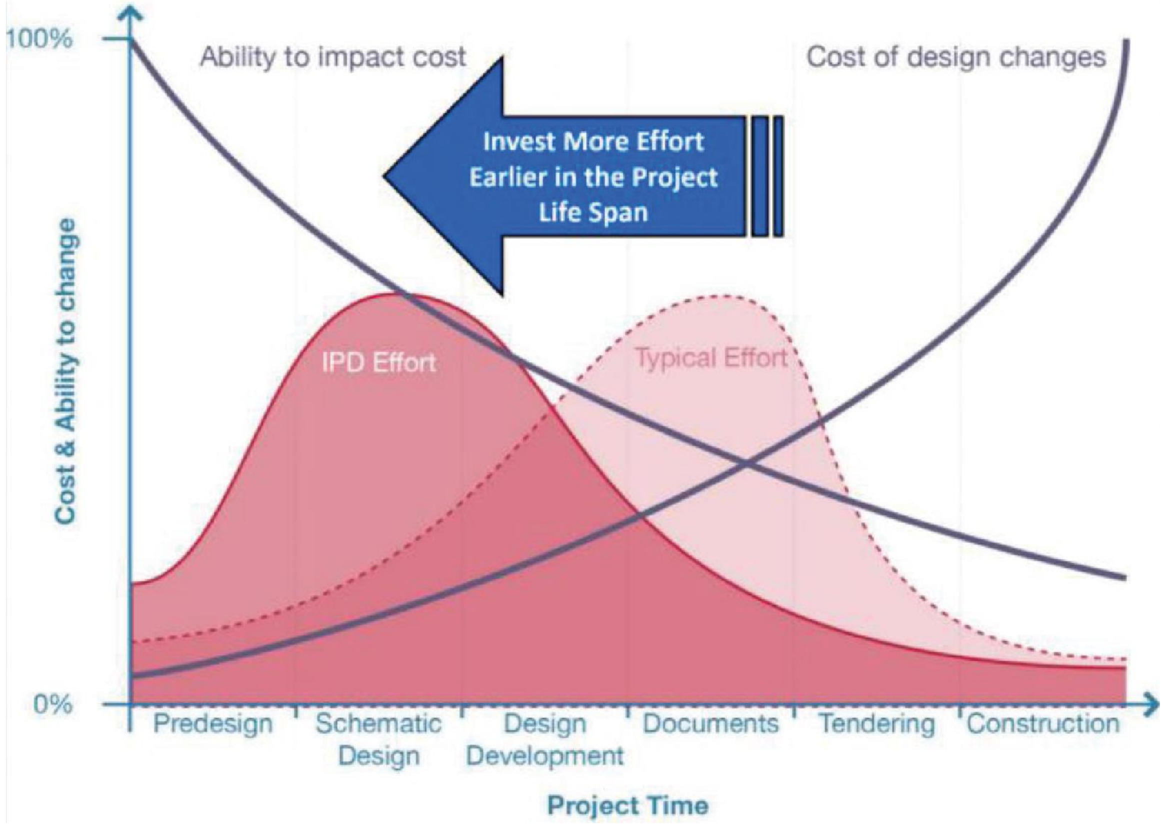


Fig. 54: Macleamly curve

According to Macleamly curves (Fig. 45), in an Integrated Project Delivery (IPD), the global effort will move to the early stages. As a result, time to make decisions would decrease and designers would be demotivated to integrate LCA into their workflows due to the timing of the analyses. For this reason, many people agree that automation of analysis is one of the keys to the dissemination of these practices.

8.1.3 Level of information

The objects representation can affect the analysis. This means that you need a level of representation that allows, at least, to have the correct volumes of the different parts. In this regard, EN 17412-1 provides details on how specify the Level of Information Need, thus avoiding the information wastage.

In the specific case of my project, for example for the hollow bricks used in the comparison of the two walls, we had to consider the percentage of voids in the bricks and add this information it in the calculations, because in the 3D model the walls were modelled as a single solid block. Other similar examples are the mortar in walls or the kg of reinforcement in the concrete; all these elements were not modelled, but their information have been created to perform the calculations and to enhance the level of information.

Finally, we have not found studies that examinate the variation of the analysis to vary the LOD, therefore the level of uncertainty related to different LODs makes it difficult to compare.

8.1.4 Human error

Even though this workflow and those analysed are developed in a way to minimize the human error, material mapping still requires a part of manual work and this increases the error probability. In the case of this workflow, errors can be linked to the compilation of the LCA information from the LCA database to the Excel file.

8.2 Potential improvements

The integration of the LCA into the BIM process is still far from being fully automatic, but there is still room for improvement. The main weakness of this process is the link between the LCA database and the BIM library.

In addition, to optimize algorithms in future improvement, topics such as the cloud computing in order to process the huge amount of data produced, or delegate material mapping to an artificial intelligence, are very stimulating.

Another point that complicates the development is the fact that the government authorities have no strong strategies to spread the LCA analysis in the AEC sector, failing to encourage material producers to consider the impact of their products, thus feeding the databases. Terrabloc is a virtuous example of manufacturing of building material that has decided to consider the environmental impact to improve the product also from this point of view. But this is individual a choice and we cannot refer to the virtuosity of individual companies to improve the sustainability of the AEC sector; on the contrary, we need a boost from the institutions.

Always because this lack of standards homogenization, it is difficult to judge if one element is sustainable or not just based on a static value. The creation of a common threshold could facilitate this type of evaluation and a BIM model could have, for example, information coming from different databases. At this point, technologies could be developed to create multi-criteria analysis to evaluate building uniqueness.

9. CONCLUSIONS

In this thesis, we analysed the integration of LCA in the BIM process with the goal of automating the process. The creation of the tool and the test carried out in the bioclimatic greenhouse of Trompone, got us to understand that the total automation of the process is not yet feasible, but most of the phases can be automated and the margins for improvement are still significant. To be able to perform this type of analysis, you do not have to be a LCA experts, but you need to have some basic knowledge of VPL language.

We managed to develop a workflow to analyse the environmental impacts of a project from the early stages creating understandable results for all stakeholders, including those with little technical knowledge, thus helping them to make decisions and also taking into account environmental impacts.

However, the dissemination of the LCAs in the AEC sector is not so obvious: on the one hand because of technological maturity, but mostly cause of the legislative authorities that struggle to make this type of analysis mandatory and push the community to work in synergy in order to develop this cultural revolution in the AEC sector.

In conclusion, it is necessary to integrate methodologies that assess the environmental impact of a construction in the workflow of designers. This work demonstrates that even more research on these topics is necessary, but there are already methodologies that can meet specific needs and contribute to the development of this collective awareness that is becoming increasingly urgent.

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