Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Corso di Dottorato in Ingegneria Industriale

The influence of thermal insulation in a building refurbishment from the perspective of a Rating System, LCA and thermal analysis

Ph.D. Dissertation of:
Massimiliano Bagagli

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XXXIV edition - new series

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Abstract

Environmental challenges seem to be increasingly on the agenda. The predicted climate changes, although still uncertain in their magnitude, appear to be getting closer and closer and some effects already seem to be manifesting themselves. The challenge for the future in the field of construction is a design that with the help of increasingly effective tools succeeds in meeting the new environmental goals. Bringing such considerations into the field of design means not stopping at what has been done so far, which is mainly based on the analysis of energy flows. New perspectives require a holistic and strategic approach that takes into account all environmentally relevant aspects of building activity at the individual building level. For this reason the research goal is to combine some aspects of the analysis of the energy flows of a reference building with an LCA assessment, which makes possible to broaden the view to other impacts and on a wider time scale, and, as third branch of the research, with an evaluation of environmental sustainability through a rating systems. The three tools have been applied to a real case consisting in the refurbishment of an existing industrial building converted in a residential building. Once the three phases are completed some variations of the main parameters of the building are applied and recorded by the three analysis tools. The main objectives are to analyze the building with the three tools and to verify if applied changes, related to insulation used, on the reference building are recorded by the three different tools.

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Introduction

Over the past decade, the international community has become aware that the planet will face various impacts of climate change due to both natural and human causes. While there is no broad consensus on how fast and how our climate is changing, in the scientific and public debate is evident the growing awareness that some degree of climate change seems to be inevitable. Given the certainty that global temperatures will rise to a certain extent in the coming time, the challenge is to adapt lifestyles in terms of a greater degree of resilience to the changes to come. Transferring these considerations to the building sector, it is clear that an approach closely linked to the analysis of energy flows is no longer sufficient to deal with predictions for the future. New perspectives require a holistic and strategic approach that takes into account all environmentally relevant aspects of building activity at the individual building level.
Translated in terms of a research project the goal is to combine some aspects of the analysis of the energy flows of a reference building with an LCA assessment, which makes possible to broaden the view to other impacts and on a wider time scale, and, as third branch of the research, with an evaluation of environmental sustainability through one of the most widely used rating systems in Italy, the ITACA Protocol. Once the three phases are completed some variations of the main parameters of the building are applied and recorded by the three analysis tools. The innovative character of the research is to investigate the same building in three different ways and to see how the different analysis tools react to variations in the some parameters of the building and if correlations between them can be established.
In essence, the study starting from a real case study (the refurbishment of an existing building) develops in three different lines:

- Energy
- Life Cycle
- Rating System assessment

The main objectives are to analyze the building with the three tools and to verify if applied changes on the reference building are recorded by the three different tools. Other authors have previously studied a reference building according to only one of the three lines of intervention. In this case the attempt is to analyze with three different tools the same building and some possible variations and, ultimately, to investigate how the three different approaches react.
Basically, given a reference building, energy modelling, LCA analysis and sustainability assessment will be carried out. For the energy modelling the most recent specific software has been used according to the technical standards in force; for the LCA evaluation the software SimaPro has been used; for the sustainability assessment the chosen rating system has been ITACA Protocol and specifically the most recent version UNI 13:2019 Reference Practice will be used.
the purpose of the present study is to verify how starting from a real case, the refurbishment works of an existing building from industrial to residential, three environmental energy analysis tools such as thermal software, a rating system and an LCA assessment can be

applied. Changes in the insulation used are then made to the same real case and an attempt is made to see if and how the three tools mentioned above are able to detect the variations. The way tools are able to detect modifications then it may allow to foresee what can happen when a change is applied. In the present study the attempt is not only to apply introduced tools to real case study and to modifications but also to see if it is possible foreseeing the variation of a tool inducted by a change in some aspect, and specifically on insulation. It is to clearly state that it is not the scope of this study to make a judgment as to which type and use of insulation is to prefer. It is also to clearly affirm that no optimization of the refurbishment works using the three tools is the goal of the present study even if some considerations on different impact of materials used will be made.

To do what was specified in the premises above several steps have to be completed; chapters 1-3 are a sort of introduction in which tools, like some rating systems and LCA methodology, and building are presented.

In chapters 4-6 tools are applied to the case study and results from their use is shown.

In chapter 7 tools are applied to two different case studies in which insulation has been modified. Basically in Case study B the insulation of vertical walls, and precisely rock wool, has been changed with a renewable one, wood fiber, while in Case study C apart from the modifications in the previous case study, which are maintained, also the rest of insulation with polystyrene present in walls and floors is replaced with wood fiber. Comparisons between Case study A and B or C are also made. The goal is not only to apply the three tools but also to verify how they detect these changes.

Finally in chapter 8 some conclusions are given.

More in detail in the first chapter a general overview of the principal rating systems is given together with some considerations on the impact of the building sector.

In the second chapter, the normative sources governing the execution of an LCA study are briefly described, namely the technical standards UNI EN ISO 14040 and 14044. A brief description of the software used for LCA evaluations is also offered.

In the third chapter, the case study is presented, its previous function and appearance is described, and the changes that the redevelopment project has involved in terms of architectural choices and analysis of the envelope elements and systems designed.

In the fourth chapter, the results of applying an LCA analysis to the renovated part of the building are presented. The goal and scope of the study is stated, the functional unit is defined, the limits of the LCA study and the requirements of the data used are delimited. An inventory of all collected data is then made before moving on to the analysis of the data mediated by the software application. The results are showed according to the three main phases of the LCA and finally, general considerations on the evaluation achieved are offered.

In the fifth chapter, the part concerning the chosen rating system, the ITACA Protocol, is introduced. The reasons for the choice of the ITACA Protocol in a wide range of other rating systems are described. The structure and functioning of the protocol is then explained and finally, the results of its application to the renovated part of the building are presented.

In the sixth chapter, the results of the application of thermal software are introduced. The extensive body of legislation concerning energy analysis is briefly described from the point of view of both current legislation and technical regulations. The main energy indexes obtained from calculations with the chosen energy modelling software are presented.

In the seventh chapter, the three analysis tools are used on two further case studies that differ from the first one due to changes in the insulators used. The changes introduced by the two new case studies are briefly described and then the thermal software, ITACA Protocol and LCA analysis are applied. The results are compared to those obtained for the first case study and some considerations are made as to how sensitive the three tools are to the changes introduced and how they perceive them.

Finally, the eighth chapter summarizes the results achieved and draws some conclusions.

Chapter 1.

Green building assessment tools

1.1. Impact of building sector

The identification of effective strategies to control climate change is one of the most important challenges to achieve sustainability. The close correlation between energy consumption and the emission of greenhouse gases means that one of the priority actions to be taken is the definition of concrete strategies to reduce this consumption and, more in general, to avoid environmental impacts. Various studies have shown that the building sector is responsible for the majority of global greenhouse gas emissions. Therefore, action in the building sector to reduce energy consumption would result in a significant reduction in greenhouse gas emissions.
Different phases of the building process have different impacts and this expenditure, together with other environmental impacts, can be significantly reduced through studies and applications aimed at improving the sustainability of buildings.
A building can be considered as an organism and therefore is a very complex and vast system because of several aspects such as:

- Longevity: a building, whatever its intended purpose, is required to have a period of time in which the use of the building is possible and safe, on average over fifty years and it can be extended;
- Space: a building occupies a large space but, on the other hand, in order to avoid waste and increase profits from sales, a building is always the result of optimizing space;
- Need to satisfy comfort: a building has to assure comfort which is the result of the correct integration of plant equipment and control of the interaction between the physical characteristics of the building and the environment;
- Costs: all the above mentioned aspects have to deal with their costs.

In the following chapters the complexity of a building and how to simplify it will be one of the main issues, especially when talking about LCA and rating systems. Complexity can be also found when talking about energy consumption and environmental impacts. The building sector involves activities from different sectors and therefore the extent of the environmental load connected to it can only be understood from a transversal point of view. Five distinct moments can be identified for the consumption of energy in buildings each of which concerns one or more sectors of final use. The first corresponds to the production of building materials and components, which is associated with an energy consumption, called embodied energy. The second and third phase are the energy used to transport the materials from the

manufacturing industries to the construction site and the energy used in the construction process, called grey energy. Energy is then consumed in the operational phase, for the activities that take place in the building when it is occupied. Finally, part of the energy is consumed in the demolition process of buildings, while a positive contribution comes from the recycling, when this occurs, of certain materials and components.
It is significant that these different consumptions can be associated with the LCA phases to underline a connection between energy consumption and environmental loads. In other words when an energy consumption is found it does not go alone but it is connected with other impacts. The previous consideration is important when a research on energy consumption and other impacts of the building process is carried out.
In order to minimize the effect of some aspects of the construction industry that have great impacts some actions could be taken; the following aspects represents a general overview of the most significant ones:

- Construction materials: there is a need for more environmentally friendly materials because up to 50% of extracted materials are used into construction process. Once in place, they account for up to 40% of all energy use. Besides, the same materials, when they enter the waste stream, account for approximately 50% of all waste generated before recovery;
- Energy efficiency in buildings: construction, operation and subsequent demolition of buildings are responsible for about 40% of final energy consumption and a similar percentage of greenhouse gas emissions; however, the potential to reduce greenhouse gas emissions in buildings is greater than in any other sector and, consequently, represents the most significant emissions in order to pursue the international objectives of reduction;
- Management of construction and demolition waste: construction and demolition waste is the largest waste stream in the EU by weight, with increasing difficulties of disposal in many parts of Europe. Reduction and recycling strategies are desirable in order to reduce the consumption associated with new production processes.
- Health in buildings: the quality of the confined environment in buildings is essential for the health of its occupants; problems caused by humidity and mould can be avoided through good building practices. Appropriate bioclimatic solutions and good ventilation can also reduce the need for air conditioning during the summer months and the amount of energy required for winter heating.
- Urban sustainability and sustainable architecture: the quality and operational efficiency of buildings and infrastructure are of key importance for urban sustainability. Furthermore, implementing principles and measures in the design process can lead to improve the overall performance of buildings and, as consequence, to a more sustainable architecture.

To investigate the previous points a rating system can be a good instrument but it is necessary to choose the most appropriate; in the present thesis the ITACA Protocol – UNI PDR 13/19 has been used but it is not the only one available. There are many rating systems and in order to understand the reasons of the choice it seems appropriate to give an overview of the other instruments and this is the theme of the next chapter.

1.2. Environmental assessment methods for buildings

The need for unassailable technical tools and assessments has prompted designers, builders and all the stakeholders involved in construction to develop environmental certifications of buildings, to demonstrate and monetize the quality of the building itself. Measuring the performance of buildings is therefore a necessity in order to be able to verify the impact on the environment, the efficiency of the use of resources and the effects of design choices on human health. This has led to the development of methods for the environmental assessment of buildings, which make it possible to issue a certification on the degree of energy-environmental quality of the building.

Basically, environmental sustainability protocols fall into two categories, namely qualitative or "score" methods and quantitative methods. Qualitative methods are based on lists of criteria, each of them giving a score as result. The final evaluation is an overall score which is an expression of the building's level of sustainability. While these protocols, which are currently the most widespread thanks to their relative simplicity, have the merit of spreading the culture of a housing model based on environmental sustainability, and of guiding designers by providing them with a series of criteria to follow, they also suffer from the limitation of being affected by subjectivity, both in the attribution of scores and in the phase of weighing. In some cases weighing phase arbitrarily introduces a hierarchy of environmental problems. Criteria included in these protocols can be either a "scenario" kind or needing some calculations. In both cases, even when they are calculated on the basis of some international standard, they may be affected by non-objective considerations during weighing phase.

On the other hand, quantitative methods, based on the LCA methodology, make it possible to draw up a rigorous balance sheet of all the environmental effects of a process throughout its life cycle. They have the advantages of being transparent and objective and they also allow to make comparisons between two different projects. The main problem they have is the availability and quality of data, often very difficult to find, they may be of great importance for the owner of the data who is reluctant to spread them, or referring to very general situations.

In Italy, the most widespread are ITACA Protocol, LEED, CasaClima, based on the analysis of requirements and the attribution of scores that take into account the performance of buildings in energy and environmental terms. Precisely by virtue of the adaptability and replicability of these methods, many regions in Italy have adopted and regulated these assessment tools within specific processes, to promote and disseminate the principles of environmental sustainability and provide technicians with guidelines for quality design. Besides, several universities are actively engaged in improving calculation methodologies and continuously updating the results obtained.

The following paragraphs introduce some of the methods of environmental assessment of buildings used in different countries around the world, all based on scoring systems. In Chapter 2 a broad discussion of the methodological aspects of Life Cycle Analysis will be presented.

1.2.1 SBTool

SBTool (formerly GBTool) is a generic framework for rating the sustainable performance of buildings and projects. It may also be thought of as a toolkit that assists local organizations to develop local SBTool rating systems. SBTool can be used by authorized third parties to establish adapted SBTool versions as rating systems to suit their own regions and building types. It can also be used by owners and managers of large building portfolios, to express in a very detailed way their own sustainability requirements to their internal staff or as briefing material for competitions.
SBTool takes into account region-specific and site-specific context factors, and these are used to switch off or reduce certain weights, as well as providing background information for all parties.
SBTool is based on the philosophy that a rating system must be adapted to local conditions and to the generic building types to be assessed, before its results can become meaningful. The system is therefore designed as a generic framework, with local research-based organizations being expected to define local context conditions and typical performance characteristics of the building types to be assessed, and to develop appropriate weights and performance benchmarks for these. The system has been designed to facilitate such a regional calibration; in fact, the system requires the insertion of regionally meaningful benchmarks.
SBTool comes from Green Building Challenge (GBC), an international project initiated in 1996 and coordinated, until 2000, by Natural Resources Canada (NRC). As of January 2001, a new organization, the International Initiative for Sustainable Built Environment (ISBE), took over the management and development of the GBC. During the first years of activity GBC developed a tool, GBTool, SBTool derives from this first attempt. SBTool is the basis for the development of other rating system and among them ITACA Protocol.
SBTool allows the assessment of the environmental impact of a construction during the different phases of the life cycle through the assignment of a performance score and the subsequent classification in a quality scale. The performance is evaluated against the main issues related to the sustainability of the built environment which are: impact on the site, resource consumption, environmental loads, indoor environmental quality, management of technical systems, long-term performance and socio-economic aspects.
The evaluation criteria are organized into four hierarchical levels: evaluation areas, categories, and performance criteria. Depending on performance against each criterion, the building receives a score that can range from -1 +5. Zero is the "benchmark", i.e. it represents the minimum acceptable performance determined by reference to standards and regulations or to the construction practice in the geographical area to which the building under analysis belongs. The system handles both numerical data from external calculation programs and qualitative assessments. In the scale of scores 3 represents the best available construction practice, 5 represents excellence. Scores obtained against each criterion are weighted and aggregated to determine category scores, which in turn are combined to determine area and performance scores. The weighted aggregate of these results in the overall score for the building, which may range from -1 to +5.
Ths framework is the same for ITACA Protocol and rating systems as they derive from SBTool.

The main advantage is that SBtool, developed with a language that reflects the problems and characteristics of the place where it is applied, is effective and sensitive to local problems. In addition, the system is potentially capable of making assessments for the four phases of the life cycle using specific benchmarks for each phase. Based on context characteristics, weights are updated as well as context information that is useful to users of the tool. The system can be applied to very large projects or individual buildings, residential or commercial, new construction, renovations, or both simultaneously.

1.2.2 ITACA Protocol – UNI PDR 13/19

The ITACA Protocol is, at national level, one of the most widespread tools for assessing the level of energy and environmental sustainability of buildings; as other rating systems it allows to verify the environmental performance of a building from different points of view: human health, expenditure of energy, water and other resources; it also promotes the construction of increasingly innovative buildings and the use of sustainable materials produced with low energy consumption and able to guarantee high levels of comfort. The Protocol gives an objective and comparable evaluation using indicators and verification methods compliant with the technical standards and national laws.
ITACA is the acronym for Institute for Innovation and Transparency of Procurement and Environmental Compatibility and it has been working on environmental sustainability of buildings since 2001 establishing an Interregional Working Group for Sustainable Building. The goal was to provide Regions with tools to support territorial policies and to promote environmental sustainability in the construction sector. The basis was the GBTool and later on SBTool. Since the approval of the first version of the Protocol, in 2004, this instrument has been adopted by many Regions and municipal administrations in various initiatives aimed at promoting and encouraging sustainable construction through the approval of regional laws, building regulations, tenders, urban plans, etc.
At present they are 13 out of 20 Italian regions have adopted ITACA Protocol as environmental sustainability assessment tool. Figure 1 shows the overall situation of the Regions using, having used or about to use ITACA Protocol.

Figure 1: Regions using, having used or about to use ITACA Protocol

The Protocol derives from the SBTool international evaluation model, developed as part of the Green Building Challenge research process. The contextualization of the international method to the Italian territory took into account national characteristics. The starting point for the definition of the evaluation system are the determination of the areas of assessment and environmental impact:

- the identification of criteria that make it possible to measure the environmental performance of the building;
- the definition of reference performance (benchmark) considered the national and international legislation in force;
- the weighting of criteria in order to determine their importance;
- the final aggregation of scores to determine the overall performance.

This articulation determines the hierarchical structure of the Protocol divided into Areas, Categories and Criteria. The Evaluation Areas, which are the macro themes that determine the sustainability characteristics of the intervention, are:

- Site Quality
- Resources Consumption
- Environmental Loads
- Indoor Environmental Quality
- Service Quality.

In 2014, the 2011 Residential ITACA Protocol was replaced with the new UNI/PdR 13: 2015 Reference Practice "Environmental sustainability in buildings - Operational tools for assessing sustainability". The document was then updated and published in July 2019 as UNI/PDR 13/19.


PRASSI DI RIFERIMENTO UNI/PdR 13.1:2015

Sostenibilità ambientale nelle costruzioni - Strumenti operativi per la valutazione della sostenibilità
Edifici residenziali

Environmental sustainability of construction works - Operational tools for sustainability assessment
Residential buildings

Il documento specifica i criteri sui quali si fonda il sistema di analisi multicriteria per la valutazione della sostenibilità ambientale degli edifici residenziali, ai fini della loro classificazione attraverso l'attribuzione di un punteggio di prestazione. Oggetto della valutazione è un singolo edificio e la sua area esterna di pertinenza.

Il documento si applica ai fini del calcolo del punteggio di prestazione di edifici residenziali, di nuova costruzione o oggetto di ristrutturazione.

Pubblicata il 30 gennaio 2015 ICS 91.040.01

ITACA
Istituto per l'innovazione e trasparenza degli appalti e la compatibilità ambientale

ENTE ITALIANO DI NORMAZIONE

Figure 2: PDR UNI 13/19 –ITACA Protocol

The Practice contains criteria and rules on the evaluation of new and renovated buildings and it is divided into 3 sections: Section 0 is about general framework and methodological principles; Section 1 and Section 2 which specify the criteria for the assessment of environmental sustainability and the calculation of the performance score of buildings for residential and non-residential use (for offices, commercial, school, industrial and hospitality). The update of the document in 2019 took into account the approval of the Ministerial Decree (DM) 11 October 2017 which contains the "Minimum Environmental Criteria (CAM) for design services and works for new construction, renovation and maintenance of public buildings" trying to standardize the criteria indicators to the reference benchmarks of the Decree. The latest update is of great importance because it allows to verify easily the compliance of a building to the requests of DM 11 October 2017 and represents an important point for all the stakeholders.

1.2.3 BREEAM

Conceived in the UK in 1988 by the Building Research Establishment, the Building Research Establishment Environmental Assessment Methodology (BREEAM) was launched in 1990. So far it has been used in over 500.000 certified buildings all around the world and more than two million buildings have been registered for assessment since its launch in 1990. The scheme is composed of the following nine categories describing sustainability through benchmark criteria, including:

- Energy: building operational energy and CO2 emissions
- Management: management policy, commissioning, site management and procurement
- Health and Wellbeing: indoor and external issues (noise, light, air, quality, etc.)
- Materials: environmental impacts of building materials
- Transport: transport-related CO2 and location-related factors
- Water: building consumption and efficiency
- Waste: construction and operational waste management
- Pollution: water and air pollution
- Land Use & Ecology: site and building footprint and ecological value and conservation
- Innovation

A percentage-weighting factor is assigned to each category, and the overall number of 112 available credits is proportionally assigned. However, there are some constraints on the credit assignment: indeed, a minimum achievement is required for some categories. Figure 3 shows BREEAM categories and criteria.

Figure 3: BREEAM categories and criteria

The score levels that can be assigned to a building are: Outstanding, Excellent, Very Good, Good, Exceeded and Acceptable. The rating is applied on a voluntary basis and is performed by a BRE-approved certifier, the BREEAM Accredited Professional or BREEAM AP. They develop and operate a number of BREEAM versions, each designed to assess the sustainability performance of buildings, projects or assets at various stages in the life cycle, and these include:

- BREEAM Communities for the master-planning of a larger community of buildings
- BREEAM New Construction: Buildings for new build, domestic and non-domestic buildings
- BREEAM New Construction: Infrastructure for new build infrastructure projects
- BREEAM In-Use for existing non-domestic buildings in-use
- BREEAM Refurbishment and Fit Out for domestic and non-domestic building fit-outs and refurbishments

Certification is achieved by combining three levels: Design Stage (DS), Post-Construction Stage (PCS) and Post-occupancy Stage (POS). The certificate issued is conceived as a way to ensure the environmental quality of the building product and make it visible, with the additional aim of increasing its value from a commercial point of view. The building types analyzed by BREEAM are many and are:

- Residential
- Office
- Industrial
- Retail
- Public (non-housing)
- Education
- Healthcare
- Prison
- Law Court
- Multi-residential accommodation or supported living facility
- Residential institution (long term stay)
- Residential institution (short term stay)
- Non-residential institution
- Asembly and Leisure
- Bespoke: Building types not listed must undergo a scoping and tailoring exercise to facilitate an assessment and rating.

1.2.4 LEED

Developed in 1998 in the United States, following demand from private citizens for quality guarantees when purchasing green buildings, the U.S. Green Building Council (USGBC), a non-governmental organisation comprising representatives from industry, academia and government, was founded with the aim of developing a standard for assessing the efficiency of buildings.
The protocol contains a number of mandatory prerequisites, against which a positive assessment must be achieved, otherwise access to the next stages will be denied. The system is based on the attribution of 'credits' for each requirement. Compliance with the form allows the credits to be awarded, while non-compliance results in a score of zero. The procedure does not include a weighting system. The sum of the credits makes up the 4 levels of certification: basic, gold, silver, platinum. The LEED certification framework can be summarized in five categories:

- Building Design and Construction (BD+C): for new construction or major renovations. It also includes applications for Schools, Retail, Hospitality, Data Centers, Warehouses & Distribution Centers and Healthcare;
- Interior Design and Construction: for complete interior fit-out projects. It also includes applications for Retail and Hospitality;
- Operations and Maintenance (O+M): for existing buildings that are undergoing improvement work or little to no construction. It also includes applications for Schools, Retail, Hospitality, Data Centers, and Warehouses & Distribution Centers;
- Neighborhood Development: for new land development projects or redevelopment projects containing residential uses, nonresidential uses, or a mix. Projects can be at any stage of the development process, from conceptual planning to construction;
- Homes: for single family homes, low-rise multi-family (one to three stories) or mid-rise multi-family (four to six stories).

The building certification in version 4.0 of the American protocol is based on a checklist divided into eight categories: Transport and Location (LT), Site Sustainability (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), Indoor Environmental Quality (IEQ), Innovation (I), Regional Priority (PR).
The design of the building must have features that will achieve the maximum score for each area. The maximum score achievable is 110 points and corresponds to LEED Platinum certification. The minimum score for certification is 40 points, corresponding to LEED Basic certification.
Certification is voluntary and the assessment procedure is carried out by the project group (applicant) in the form of self-certification, with subsequent provision of explanatory documentation certifying achievement of the objectives set during the project phase. The USGBC then verifies the compliance of the documentation and issues the certification (levels: Certificate, Silver, Gold, Platinum).
Like the BREEAM system, LEED recognizes a professional figure, the LEED AP, capable of providing support to the project team throughout the design and construction of the building.
There are four main steps to get LEED certification:

1. Registration: all projects pursuing certification must register on the LEED platform;
2. Application: all relevant documentation, calculations and analysis have to be send for evaluation;
3. Review: the application is checked in terms of completeness, determining which credits the designed building meets. If the building fails any prerequisites, an opportunity to revise documentation will be given;
4. Certification: if the project meets all the relevant requirements, it will receive a certification.

Figure 4 summarizes a whole process of certification from designing to certification for the constructed building.

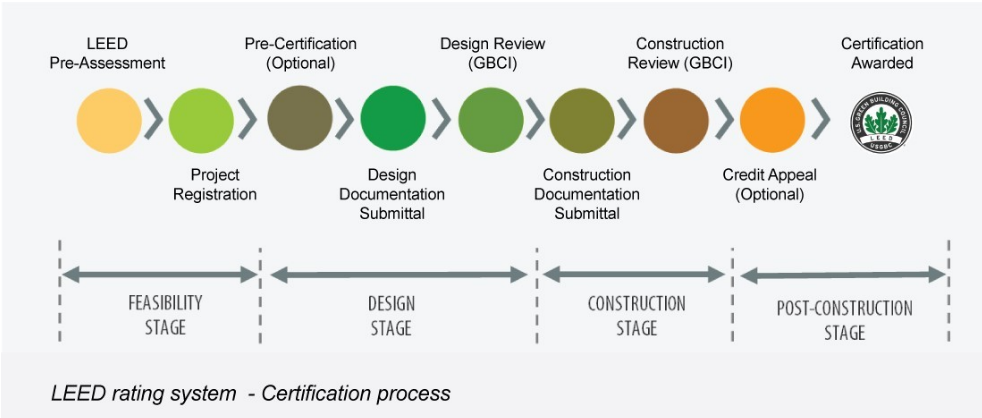


Figure 4: LEED whole process of certification from designing to certification

1.2.5 HQE

The Haute Qualité Environnementale standard HQE was developed in 1994 in France by the HQE association. This association supports stakeholders, designers, partners, developers, and users during a project's phases and aims to guarantee a high environmental quality of buildings. HQE covers buildings throughout their life cycle, that is, throughout their design, construction, operation, and renovation. It is addressed to nonresidential and residential buildings, and detached houses. Furthermore, a specific scheme for the management system of urban planning and development projects is also available. The environmental performance requirements are organized into four topics that together include 14 categories as shown in Figure 5. Topics are almost the same for all building types, but the targets are arranged differently for residential buildings and non-residential buildings.

THEME	RELATED TARGETS
THEME 1: Energy	4. ENERGY
THEME 2: Environment	1. SITE
	2. COMPONENTS
	3. WORKSITE
	5. WATER
	6. WASTE
	7. MAINTENANCE
THEME 3: Health	12. SPACES QUALITY
	13. AIR QUALITY
	14. WATER QUALITY
THEME 4: Comfort	8. HYGROTHERMAL COMFORT
	9. ACOUSTIC COMFORT
	10. VISUAL COMFORT
	11. OLFACTORY COMFORT

Figure 5: HQE topics and categories

A building project obtains an assessment for each target expressed according to three ordinal levels: basic, performing, and high Performing. To be certified, a building must achieve the high performing level in at least three categories and the basic level in a maximum of seven categories. This rating system does not weight each category by a weighting factor, because they are considered to have the same importance throughout the assessment framework.

1.2.6 Green Star

Green Star is a voluntary sustainability rating system for buildings in Australia and then also adapted for New Zealand and other countries. It was launched in 2003 by the Green Building Council of Australia (GBCA). Green Building Council of Australia (GBCA), established in 2002, is a not-for-profit industry association that promotes sustainability in the built environment or green building. GBCA founded, together with other national green building councils, the World Green Building Council with member councils in over 70 countries worldwide including BREAAM, CASBEE, GBC, HQE, LEED and VERDE.
Green Star assesses the important elements of a project's sustainability across key categories. Each category includes benchmark for a lower-carbon, healthy project. Points are awarded for successfully meeting these criteria. The total number of points awarded decides the final Green Star rating.

Figure 6: New Zealand Green Star rating

Green Star can be applied to different kinds of project; available frameworks can be applied to:

- Green Star Buildings;
- Green Star Homes – launched in August 2021, Green Star Homes is a standard assessing the health, resilience and energy efficiency of residential buildings;
- Green Star Interiors – it is an assessment of the interior works;
- Green Star Performance – it evaluates the operational efficiency of existing buildings;
- Green Star Communities – it is an evaluation of the sustainability of projects at the neighborhood, precinct or community scale.

Green Star takes a holistic approach, considering not just direct environmental impacts like materials or water use, but broader transport, indoor environment quality, and management implications of a project. In the following figure Green Star impact categories are summarized:

Figure 7: Green Star impact categories

1.2.7 Minergie

Minergie is a registered quality label for new and refurbished low-energy-consumption buildings. This label is mutually supported by the Swiss Confederation, the Swiss Cantons and the Principality of Liechtenstein along with Trade and Industry. It has been the Swiss standard for comfort, efficiency and value preservation since 1998. Its primary focus is comfortable living and working conditions for the users of new and renovated buildings. A high-quality building envelope and controlled air exchange play a major role in the Minergie requirements. Other distinctive features of Minergie buildings include their very low energy consumption and the maximum possible use of renewable energies.

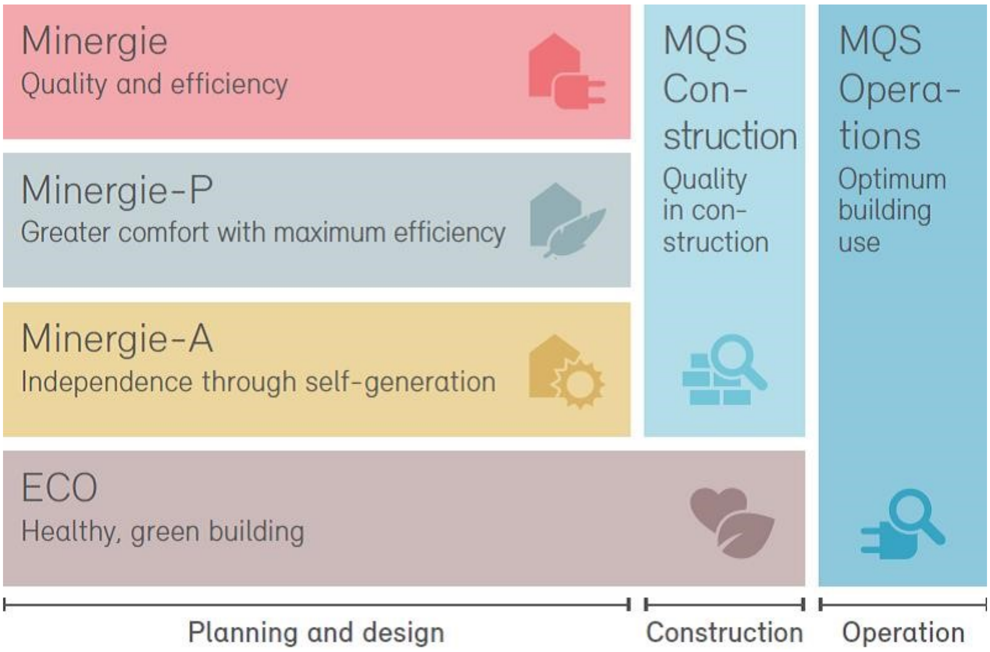


Figure 8: Minergie framework

The three Minergie building standards, Minergie, Minergie-P and Minergie-A, ensure maximum quality and efficiency starting from the planning phase. They are complemented by three combinable additional products: ECO takes the issues of health and construction ecology into account; MQS Construction (Minergie quality system for construction) is aimed at clients and planners who want a guarantee of high quality construction. MQS Operations (Minergie quality system for operation) optimises the use of the building services systems, thereby ensuring maximum comfort.

1.2.8 CASBEE

CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) is a building assessment system created in Japan in 2001 by representatives from academia, industry and government who came together in a non-governmental organization called Japan Sustainable Building Consortium.
It was launched on the international market in 2005 and, since 2011, it has become mandatory in 24 Japanese municipalities. CASBEE is structured to have several schemes that depend on the size of a building and address the four main building life phases:

- CASBEE for Predesign, for use in site selection and building planning;
- CASBEE for New Construction, to be used in the first three years after building completion;
- CASBEE for Existing Buildings, to be used after at least one year of operation;
- CASBEE for Renovation, which is intended to support a building refurbishment.

To fulfill the specific purposes, CASBEE also features a huge batch of supplementary rating systems that are relevant when the basic version cannot be used, such as detached houses, temporary constructions, heat island effect, urban development, and cities and market promotions.
To obtain certification, it is necessary to assess the performance (indoor air quality, service quality, environmental quality on the project site), environmental quality and environmental loads (energy consumption, consumption of resources and materials, quality of the environment outside the project site) of the building throughout its entire life cycle.
The CASBEE assessment is a measure of the BEE (Building Environmental Efficiency) indicator, which is given by the ratio between the two metrics built environmental quality (Q) and built environmental load (LR).

BEE =Q/LR

Q calculates the "improvement in everyday amenities for the building users, within the virtual enclosed space boundary" and LR quantifies the "negative aspects of environmental impact that go beyond the public environment". Q and LR range between 0 to 100 and are computed based on three subcategories, tabulated on a score sheet shown in Figure 9.

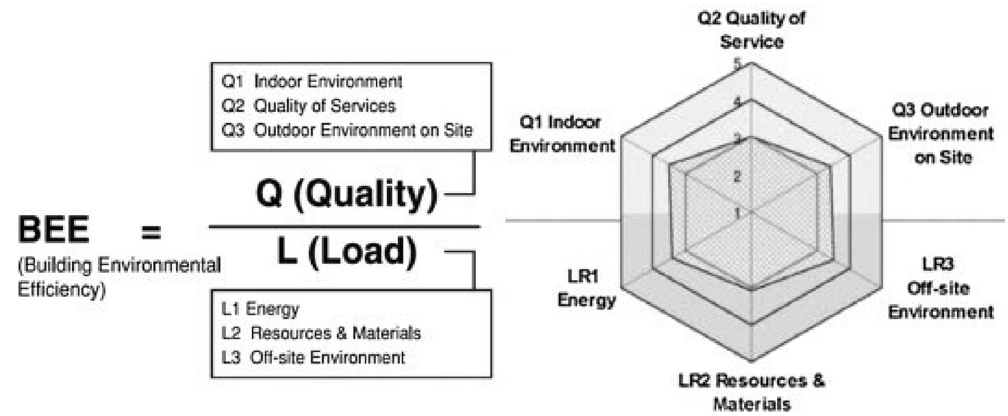


Figure 9: BEE as Q and LR ratio

BEE is expressed as the gradient of a line on a graph that has LR on the x-axis and Q on the y-axis. Based on the BEE value, a level of performance is associated with a given project. The values calculated in each category are represented on a radar chart as shown in Figure 10.

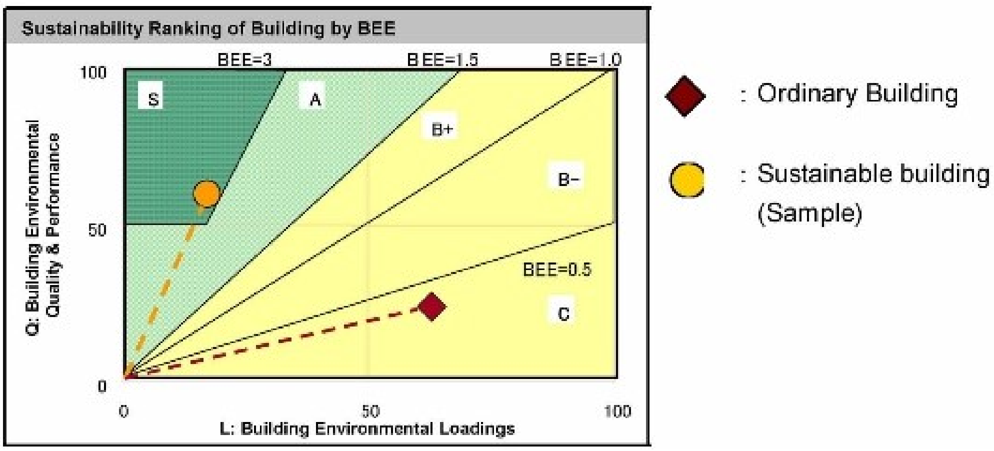


Figure 10: LR-Q graph

The assessment results sheet applies weights, using coefficients for each item and the Q and LR values and produces, as a last step, an overall score conveyed through the BEE index. This index is used to assess the six categories covered by the CASBEE evaluation: indoor environment, quality of service, outdoor environment (on-site), energy, resources and materials, and off-site environment.

1.2.9 Casaclima

Casaclima is an energy certification method for buildings developed in 2002 by CasaClima Agency, an Italian Regional Environmental Protection Agency.
The main certificate is the one dedicated to residential buildings and is named CasaClima Nature. CasaClima Nature assesses sustainability based on the following criteria:

- Overall energy efficiency of the building
- Environmental impact of the materials used in construction
- Efficient use of water resources
- High indoor air quality and low emission materials
- Measures to protect against radon gas

- Use of natural light
- Acoustic comfort

Based on the CasaClima Nature protocol, the CasaClima Agency has developed an entire group of certifications for different kinds of application:

- ClimaHotel for the hotel business
- CasaClima Welcome for B&Bs and small accommodations
- CasaClima Work&Life for tertiary buildings
- CasaClima Wine for wineries
- CasaClima School for school buildings

1.2.10 Passivhaus

The Passivhaus standard was developed by the Passivhaus Institute (PHI) in Darmstadt, founded in 1996. Greatest attention is given to energy aspects as for a building to comply with the standard, it must meet the following criteria:

- The Space Heating Energy Demand is not to exceed 15 kWh per square meter of net living space (treated floor area) per year or 10 W per square meter peak demand.
- The Renewable Primary Energy Demand, the total energy to be used for all domestic applications (heating, hot water and domestic electricity) must not exceed 60 kWh per square meter of treated floor area per year.
- In terms of Airtightness, a maximum of 0.6 air changes per hour at 50 Pascals pressure, as verified with an onsite pressure test (in both pressurized and depressurized states).
- Thermal comfort must be met for all living areas during winter as well as in summer, with not more than 10 % of the hours in a given year over 25 °C.

All of the above criteria are achieved through intelligent design and implementation of the 5 Passive House principles: thermal bridge free design, superior windows, ventilation with heat recovery, quality insulation and airtight construction.
Certification can be achieved by new buildings and refurbishment of existing buildings. The Passive House Classes are Classic, Plus or Premium depending on the use of renewable energy sources.

1.2.11 Nordic Swan

The Nordic Swan Ecolabel has developed environmental requirements for a number of different goods and services, among them construction materials, houses and other buildings. The Nordic Swan Ecolabel was established in 1989 by the Nordic Council of Ministers as a voluntary ecolabelling scheme for the nordic countries Denmark, Finland, Iceland, Norway and Sweden. The Nordic Swan Ecolabel makes requirement of the building's energy use, chemical products, building products/goods and a number of indoor environmental aspects that are relevant to the health and the environment. The Nordic Swan Ecolabel also makes requirements of quality management in the construction process, and the handover of the building to the residents and administration/operations. Nordic Swan Ecolabelled buildings are assessed on the basis of a lifecycle perspective and:

- Have low energy consumption
- Fulfil strict environmental and health requirements on construction products, materials and chemical products
- Ensures a good indoor environment and low emissions
- Have a quality-assured construction process.

Nordic Ecolabelling's criteria for "Small houses, apartment buildings and buildings for schools and pre-schools" make it possible to achieve the Nordic Swan Ecolabel for the following newly constructed buildings:

- Small houses;
- Apartment buildings;
- Buildings for pre-schools and schools/educational buildings;
- Extensions to existing buildings. The extension must be a residential building, pre-school or school, and only the extension will be ecolabelled;
- Homes for the elderly;
- Cottages/holiday homes and holiday apartments.

1.2.12 DGNB

DGNB certification (Deutsches Gütesiegel Nachhaltiges Bauen) is a German voluntary certification system. This rating system has been developed since 2007 by the association "Deutsches Gütesiegel Nachhaltiges Bauen, Sustainable Building Council", formed by professionals in the building sector, in cooperation with the German Federal Ministry of Transport, Building and Construction. Building sector, in cooperation with the German Federal Ministry of Transport, Building and Urban Development.
The certification is mainly diffused in the country of origin, but lately it is spreading also in other countries because of the need to improve the quality of the building in other countries due to its peculiarity of taking into account the life cycle of materials and costs of materials. The DGNB assigns buildings a classification (gold, silver or bronze) based on the scores obtained in the following evaluation categories: ecological quality, economic quality, socio-cultural and functional quality, technical quality, process quality, location quality (this is considered but does not influence the score). In the criteria "Environment 1.1 - Life Cycle Impact Assessment" and "Environment 2.1 - Life Cycle Impact Assessment - Primary Energy" the LCA analysis is indicated as a tool for the calculation of a series of environmental impact indicators. In particular, the LCA analysis "weighs" 13.5% of the total score in the certification.

1.2.13 VERDE

The VERDE sustainability certificate stands for Valoración de Eficiencia de Referencia de Edificios (Building Reference Efficiency Evaluation) and it is a sustainability certificate that measures the environmental, economic and social impact of buildings. VERDE was developed by Green Building Council Spain association to foster a more sustainable architecture. At present, GBC España only certifies residential and office buildings. In the assessment of an office building to obtain the VERDE sustainability certificate are considered the following parameters: site selection, location and planning project, indoor space quality, energy and ambience, quality of service, natural resources and socioeconomic impact. There are 6 levels of VERDE certification. Final evaluation is measured in green leaves. The more leaves obtained (from 0 to 5) show a better commitment towards environment.

Chapter 2.

Life Cycle Assessment: UNI EN ISO 14040 and 14044

2.1. Origins and definition

The origin of the LCA methodology (acronym for Life Cycle Assessment) can be traced back to the early 1960s with the publication of studies concerning the energy loads associated with some industrial productions. According to Vigon et al. (1993), one of the first studies in the LCA field, concerning the total energy requirements for the production of chemical intermediates and products, was presented in 1963 at the World Energy Conference by Harold Smith. In the following decade, the problem of the depletion of raw materials and energy resources encouraged more in-depth studies, mainly focused on optimizing the management of energy resources.

Between the end of the 1960s and the beginning of the 1970s, there was a gradual transition from analyses focused mainly on energy consumption to analyses that took into account both the consumption of raw materials and energy resources; representative of this period are two important reports in which an attempt was made to predict the effects of an increase in world population on the demand for raw materials and energy: "The Limits to Growth" (Meadows et al. , 1972) and "A Blueprint for Survival" (Goldsmith et al., 1972).

It was also during this period that the concept of "resource and environmental profile analysis" was introduced, particularly in the United States. The concept of resource and environmental profile analysis was introduced at the same time, particularly in the USA, which allowed the production chain to be followed from extraction of the raw materials used to disposal, using the 'from cradle to grave' approach, quantifying the use of resources and the release of pollutants into the environment throughout the product's life cycle.

In 1969, the Coca Cola Company launched a study, commissioned by the EPA (Environmental Protection Agency) from the MRI (Midwest Research Institute), which can be considered a reference point in the development of the LCA methodology. The aim of the study was to compare the entire life cycle of different types of beverage containers in order to identify the optimal solution in terms of raw material demand, energy demand and emissions into the environment: for the first time, a study was carried out on products and no longer on individual industrial processes.

The quantification of resource consumption and environmental impacts of products was developed under the name REPA (Resource and Environmental Profile Analysis) in the United States, while in Europe it was called Eco-balance. The acronym LCA was actually used for the first time during the SETAC (Society of Environmental Toxicology and Chemistry) congress in 1990.

SETAC in the "Guideline for Life-Cycle Assessment: a code of practice" has given the most accurate LCA definition so far: Life Cycle Assessment represents *"a process to evaluate the* *environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life-cycle of the product, process, or activity, encompassing extracting and processing raw materials; manufacturing; transportation and distribution; use, re-use, maintenance; recycling, and final disposal."*

This definition has been taken over by ISO (International Standard Organisation), in the standard ISO 14040, which states that *"LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)."*

2.2. LCA structure

2.2.1 ISO14040 and ISO 14044

The ISO 14040 and ISO 14044 standards describe how to carry out a complete LCA study for any type of product, so they are not product-specific standards, but standards containing general requirements applicable to all products, regardless of their nature.

ISO 14040 is the main standard as it specifies the structure of the LCA study, the principles and requirements for conducting the study and then disseminating it in reports, but it does not go into the specific details of the assessment techniques.

The definition of the goal and scope of an LCA is dealt with in ISO 14044 together with the subsequent phase of analyzing the inventory of flows in and out of the system. It is through this phase that an LCA study takes shape first identifying the reason for which the study is carried out, then defining the boundaries of the system and the necessary data for compiling the inventory of flows and finally taking into consideration all the processes that characterize the system.

Then, an assessment is made of the impacts associated with the flows of the inventory of the previous phase. The result is a model based on representative category indicators of impacts related to emissions (outflows) or natural resource use (inflows).

The conclusion of the process is the phase of interpretation of the results, in which the impacts are quantified, thus allowing possible comparative studies to assess the environmental sustainability of a product compared to another, or of a renewed production cycle compared to the previous cycle. It is the phase in which the life cycle assessment leads to measurable results that can support decision-making, especially if used in combination with appropriate technical-economic assessments.

To better understand the overall methodology of an LCA, consider Figure 11 which shows the input and output elements in the system considered.

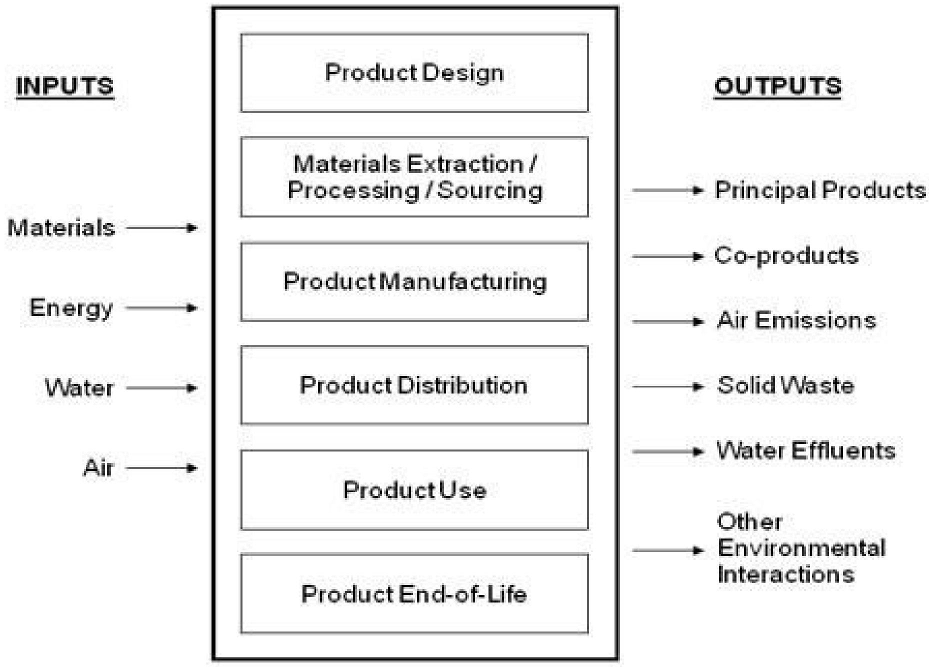


Figure 11: Overall LCA framework

Using several exclusion criteria, it is possible to exclude input and output elements that do not significantly change the overall conclusions of the study.
LCA studies comprise four phases according to ISO 14040 and ISO 14044 described as follows:

- Goal and scope: it is the preliminary phase in which the aims of the study are defined, namely the intended application, the reasons for carrying out the study and the intended audience. Main methodological choices are made in this step, in particular the exact definition of the functional unit, the identification of the system boundaries, the identification of the allocation procedures, the studied impact categories and the Life Cycle Impact Assessment (LCIA) models used, and the identification of data quality requirements.
- Life Cycle Inventory (LCI): it involves the data collection and the calculation procedure for the quantification of inputs and outputs of the studied system. Inputs and outputs concern energy, raw material and other physical inputs, products and co-products and waste, emissions to air/water/soil, and other environmental aspects. Data collected concern foreground processes and background processes. Data are validated and put in relationship to the process units and functional unit.
- Life Cycle Impact Assessment (LCIA): LCI results are associated to environmental impact categories and indicators. This is done through LCIA methods which firstly classify emissions into impact categories and secondly characterize them to

common units so as to allow comparison (details on the LCIA are presented in the section below).

- Life Cycle Interpretation: results from LCI and LCIA are interpreted in accordance to the stated goal and scope. This step includes completeness, sensitivity and consistency checks. Uncertainty and accuracy of obtained results are also addressed in this step.

Figure 12 shows the four phases previously described:

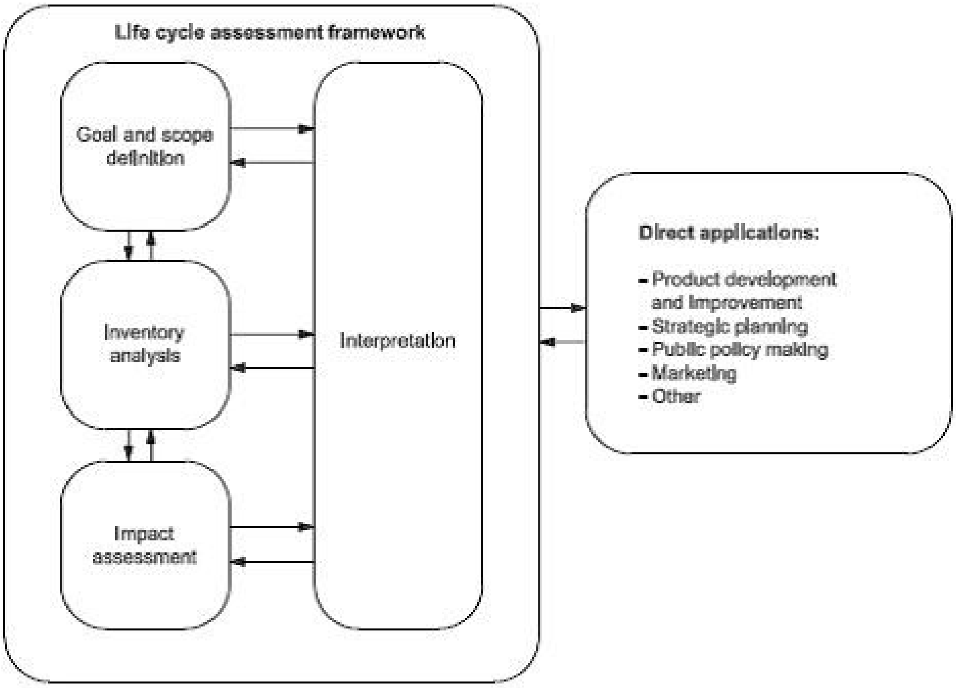


Figure 12: LCA stages

An LCA study can have different boundaries and three approaches can be identified:
- "from cradle to grave": the study starts with the raw materials in their natural state and considers all the processes and operations involved in the life cycle of the product until its disposal as waste.
- "from cradle to gate": only the early stages of the life cycle (extraction and production) are considered and the ecoprofile of the product is defined. This approach is useful when comparing different systems.
- from gate to gate": only one production unit (or a department of the manufacturing company) and assess the environmental load it is responsible for. This is referred to as an "eco-balance".

In the following the LCA four phases are explained more in detail.

2.2.2 Goal and scope definition

The goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application. On these will depend the final result, the time spent and the resources used.
Due to the iterative nature of LCA, the scope may have to be refined during the study. The goals of an LCA has to state unambiguously which is the intended application for the study, the reasons for carrying out the study, the intended audience, meaning to whom the results of the study are intended to be communicated and whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

Moreover the scope must include the following items:

- the product system to be studied;
- the functions of the product system or, in the case of comparative studies, the systems;
- the functional unit;
- the system boundary;
- allocation procedures;
- impact categories selected and methodology of impact assessment, and subsequent interpretation to be used;
- data requirements;
- assumptions;
- limitations;
- initial data quality requirements;
- type of critical review, if any;
- type and format of the report required for the study

As specified in the UNI EN ISO 14040:2006 *"LCA is an iterative technique, and as data and information are collected, various aspects of the scope may require modification in order to meet the original goal of the study."*
Some of the previous items, as stated by ISO 14044:2006, should be clearly described:

a. Function and functional unit: "*the scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied. The functional unit shall be consistent with the goal and scope of the study. One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense). Therefore the functional unit shall be clearly defined and measurable. Having chosen the functional unit, the reference flow shall be defined. Comparisons between systems shall be made on the basis of the same function, quantified by the same functional unit in the form of their reference flows. If additional functions of any of the systems are not taken into account in the comparison of functional units, then these omissions shall be explained and documented. As an alternative, systems associated with the delivery of this function may be added to the boundary of the other system to make the systems more comparable. In these cases, the processes selected shall be explained and documented."*

b. System boundary: *"the system boundary determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study. The criteria used in establishing the system boundary shall be identified and explained. Decisions shall be made regarding which unit processes to include in the study and the level of detail to which these unit processes shall be studied.*
The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study. Any decisions to omit life cycle stages, processes, inputs or outputs shall be clearly stated, and the reasons and implications for their omission shall be explained.
Decisions shall also be made regarding which inputs and outputs shall be included and the level of detail of the LCA shall be clearly stated."

c. LCIA methodology and types of impacts: *"it shall be determined which impact categories, category indicators and characterization models are included within the LCA study. The selection of impact categories, category indicators and characterization models used in the LCIA methodology shall be consistent with the goal of the study."*

d. Types and sources of data: *"data selected for an LCA depend on the goal and scope of the study. Such data may be collected from the production sites associated with the unit processes within the system boundary, or they may be obtained or calculated from other sources. In practice, all data may include a mixture of measured, calculated or estimated data. Inputs may include, but are not limited to, use of mineral resources (e.g. metals from ores or recycling, services like transportation or energy supply, and use of ancillary materials like lubricants or fertilisers).*
As part of emissions to air, emissions of carbon monoxide, carbon dioxide, sulfur oxides, nitrogen oxides, etc. may be separately identified.
Emissions to air, and discharges to water and soil, often represent releases from point or diffuse sources, after passing through pollution control devices. These data should also include fugitive emissions, when significant. Indicator parameters may include, but are not limited to:

- *biochemical oxygen demand (BOD),*
- *chemical oxygen demand (COD),*
- *absorbable organic halogen compounds (AOX),*
- *total halogen content (TOX)*
- *volatile organic chemicals (VOC)*

In addition, data representing noise and vibration, land use, radiation, odour and waste heat may be collected."

e. Data quality requirements: *"data quality requirements shall be specified to enable the goal and scope of the LCA to be met. The data quality requirements should address the following:*
a) time-related coverage: age of data and the minimum length of time over which data should be collected;
b) geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study;

c) technology coverage: specific technology or technology mix;
d) precision: measure of the variability of the data values for each data expressed (e.g. variance);
e) completeness: percentage of flow that is measured or estimated;
f) representativeness: qualitative assessment of the degree to which the data set reflects the true population of interest (i.e. geographical coverage, time period and technology coverage);
g) consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;
h) reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study;
i) sources of the data;
j) uncertainty of the information"

f. Comparisons between systems: *"in a comparative study, the equivalence of the systems being compared shall be evaluated before interpreting the results. Consequently, the scope of the study shall be defined in such a way that the systems can be compared. Systems shall be compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs, and outputs and impact assessment. Any differences between systems regarding these parameters shall be identified and reported. If the study is intended to be used for a comparative assertion intended to be disclosed to the public, interested parties shall conduct this evaluation as a critical review."*

2.2.3 Life cycle inventory analysis (LCI)

Life cycle inventory analysis (LCI) is usually the main (and also the most complex) phase of an LCA and consists in collecting and quantifying the input and output flows for a given product system as well as organising them in an analogue model over the whole life cycle.
The primary objective of this phase is therefore the computation of all raw materials that have been used and the estimation of air, water and soil emissions generated during the life cycle, with reference to the functional unit.
The inventory analysis must provide as complete and objective a representation of reality as possible. For this purpose, the quality of the data and information implemented in the model is crucial. The inventory data to be collected in order to describe the system under examination can be derived from literature studies, referenced books, government documents, statistical sources, market information, technological data and can be divided into:
- Primary data: data specific to the system under study, the result of field measurements and interviews with process operators or experts; they are characterised by a high level of representativeness of the process under study.
- Secondary data: average sector data from literature studies or environmental databases.
- Proxy data: primary or secondary data relating to a process that is similar to the one analysed, but not representative; usually used when representative data are not available.

The complexity of a Life cycle inventory analysis (LCI) is clearly shown in Figure 13 where the different phases of LCI are summarized.

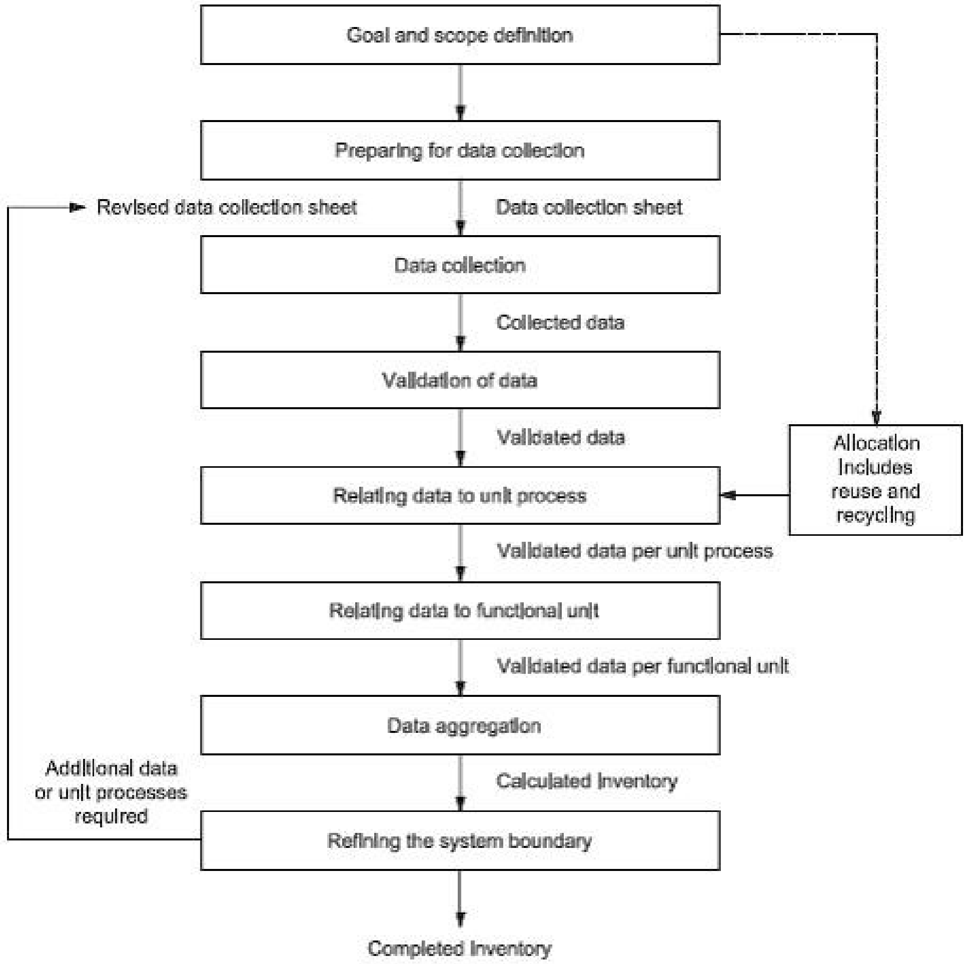


Figure 13: Simplified procedures for inventory analysis

Of great importance is the allocation procedure as it involves considerations on reuse and recycling and it has to be implemented with great care. As stated in the ISO 14040:2006 *"the process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. Sometimes, issues may be identified that require revisions to the goal or scope of the study."*

2.2.4 Life cycle impact assessment (LCIA)

Starting from the results of the LCI, the life cycle impact assessment phase aims to assess the extent of potential impacts on human health and the environment. In particular, inventory data are associated with specific environmental impact categories and indicators. In addition, the LCIA phase provides information for the subsequent life cycle interpretation phase.
The impact analysis phase consists of three mandatory and three optional phases shown in the following Figure 14.

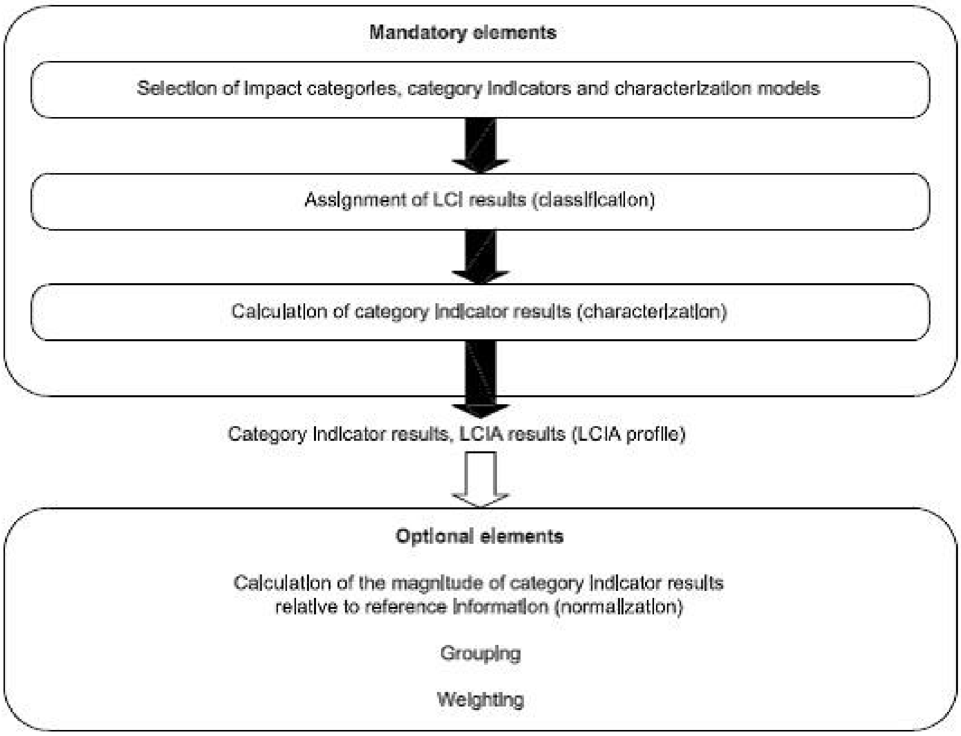


Figure 14: Elements of the LCIA phase

It has to take into consideration that LCIA addresses only the environmental issues that are specified in the goal and scope. Therefore, LCIA is not a complete assessment of all environmental issues of the product system under study. LCIA cannot always demonstrate significant differences between impact categories and the related indicator results of alternative product systems. Besides the lack of spatial and temporal dimensions in the LCI results introduces uncertainty in the LCIA results.

2.2.5 Life cycle impact interpretation

Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together or, in the case of LCI studies, the findings of the inventory analysis only. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations.
The results of the LCI or LCIA phases shall be interpreted according to the goal and scope of the study, and the interpretation shall include an assessment and a sensitivity check of the significant inputs, outputs and methodological choices in order to understand the uncertainty of the results.
The relationship of the interpretation phase to other phases of LCA is shown in Figure 15.

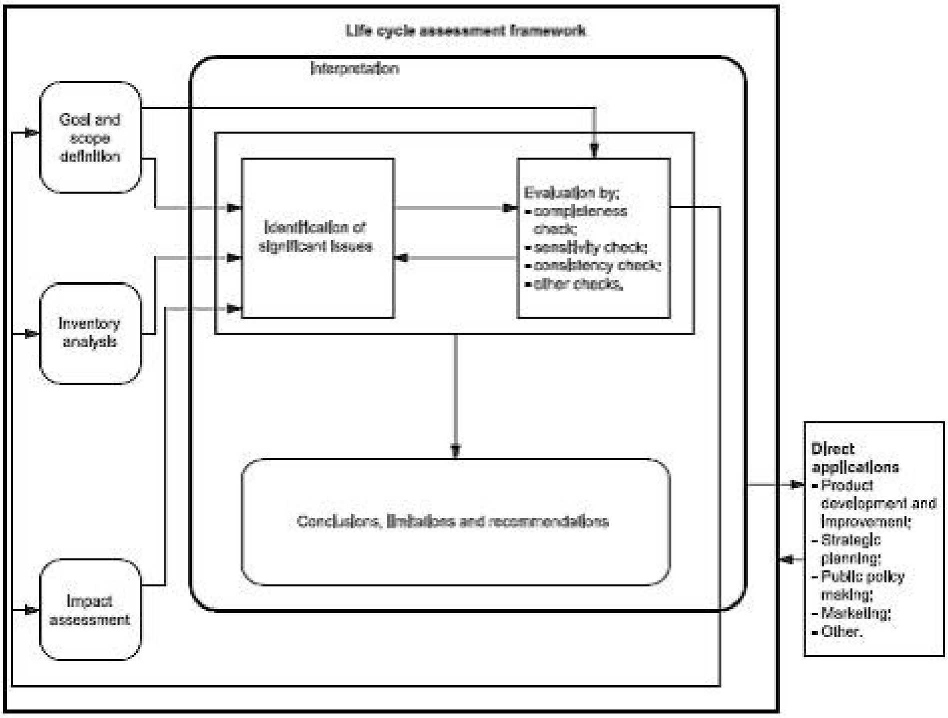


Figure 15: Relationships between interpretation phase and other LCA phases

The life cycle interpretation phase comprises several elements as depicted in Figure 15, as follows:

a. identification of the significant issues based on the results of the LCI and LCIA phases of LCA;
b. evaluation that considers completeness, sensitivity and consistency checks;
c. conclusions, limitations, and recommendations.

a. The objective of the identification is to structure the results from the LCI or LCIA phases in order to help determine the significant issues, in accordance with the goal and scope definition. Examples of significant issues are:

- inventory data, such as energy, emissions, discharges, waste
- impact categories, such as resource use, climate change
- significant contributions from life cycle stages to LCI or LCIA results, such as individual unit processes or groups of processes like transportation and energy production.

b. The objectives of the evaluation element are to establish and enhance confidence in, and the reliability of, the results of the LCA or the LCI study, including the significant issues identified in the first element of the interpretation. During the evaluation a completeness check, a sensitivity check and a consistency check are run out. The completeness check has the objective of ensuring that all relevant information and data needed for the interpretation are available and complete. The sensitivity check has the objective of assessing the reliability of the final results and conclusions by determining how they are affected by uncertainties in different aspects such as data, allocation methods, etc. The consistency check has the objective of determining whether the assumptions, methods and data are consistent with the goal and scope.

c. The objective of conclusions is to draw conclusions, identify limitations and make recommendations for the intended audience of the LCA.

2.2.6 Reporting and review

The results and conclusions of the LCA must be communicated fairly, completely and accurately to the interested audience. Results, data, methods, assumptions, and limitations should be transparent and presented in sufficient detail to allow the user to understand the complexities and steps involved in LCA. The report should also allow the results and interpretation to be used in a manner consistent with the objectives of the study.
The critical review process should ensure that:

- the methods used to perform the LCA are consistent with ISO 14040 and 14044;
- the methods used to perform the LCA are scientifically and technically sound;
- the data used are appropriate and reasonable in relation to the objective of the study;
- the interpretations reflect the identified limitations and the objective of the study;
- the report of the study is transparent and consistent.

The desired scope and type of critical review shall be defined at the stage of defining the scope of the LCA and the decision on the type of critical review shall be recorded.
The critical review may be carried out by an internal or external expert. In this case, an independent LCA expert should carry out the review. The review statement, the performer's comments and any response to the recommendations made by the reviewer should be included in the LCA report.

2.3. Software

The software used in the case study is SimaPro. Developed by Pré Consultants, it is today one of the most widespread and established software for LCA analysis worldwide.
The main features of the software are:

- Intuitive graphical interface and organised according to the ISO 14040 standard.
- Possibility of inserting new processes, materials, impact assessment methods or modifying those already implemented and adapting them to the case study.
- Ability to model even the most complex systems in a systematic and transparent manner.
- Possibility of performing uncertainty analyses using the Monte Carlo analysis.
- Possibility of using a "Wizard" section for guided model creation.
- Availability of different environmental databases.
- Availability of different impact assessment methods.
- Possibility to import and export data, graphs and tables, thanks to compatibility with other software (e.g. Excel).
- Detailed end-of-life construction with the possibility of implementing different disposal and recycling scenarios.
- Assessment of impacts for each stage of the model.
- Analysis of critical environmental issues, easily identifiable in the tree view of the life cycle.
- Ability to customise analysis results by choosing how they are grouped and presented.
- Sensitivity analysis, modelling of various parameters including non-linear relationships and evaluation of alternative scenarios for the system analysed.

In order to give some information on SimaPro it is possible to go through the software framework using as reference Figure 16. The bar at the left hand side is called the LCA Explorer. It provides access to all functions in SimaPro. The upper part of the Explorer screen contains project or library specific data; the lower part contains general data that is not stored in projects or libraries. The buttons in the toolbar execute frequently needed commands.

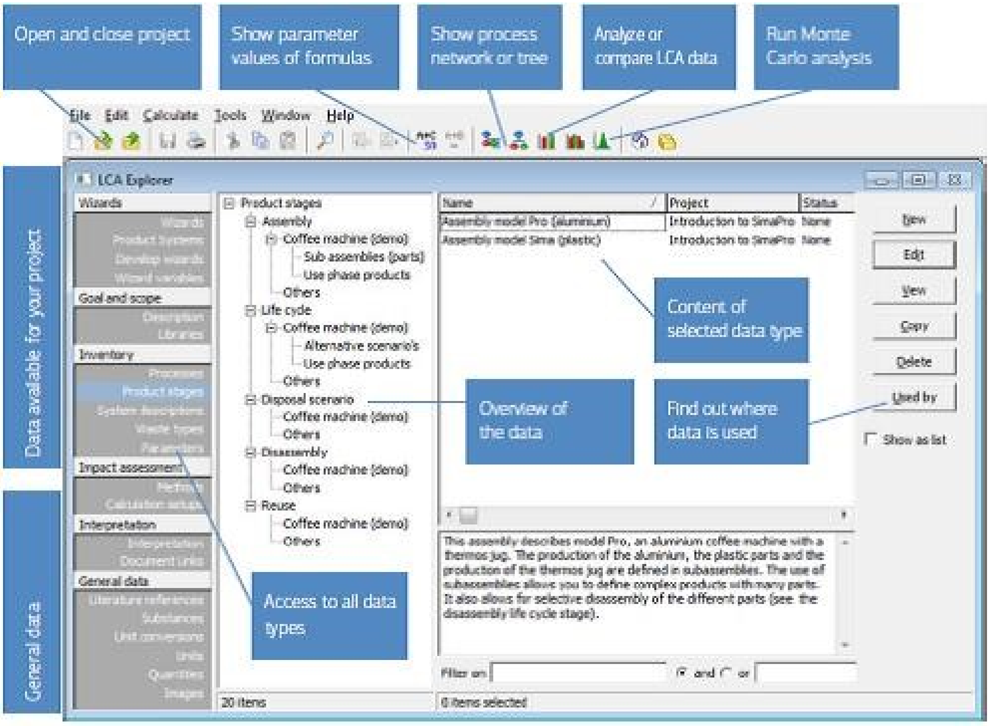


Figure 16: Overview of SimaPro Explorer

LCA Explorer is divided into several sections: goal and scope, inventory, impact assessment, interpretation.

Goal and scope

In this section, a description of the LCA should be entered, defining the author, client, objective of the study and functional unit. In addition, it is necessary to select the libraries that will be used in the course of the study. Libraries are a particular type of project as they contain data relating to processes already present within the software; a process present in a library, after being copied and renamed, can at any time be modified or integrated in a flexible manner, adapting it to the needs of the case being studied. Each library has its own specific field of application, which is described in detail in order to allow the user to exclude libraries that are not useful for their project.

Libraries implemented within SimaPro are:

- Agri-footprint (economic allocation, gross energy allocation, mass allocation)
- Ecoinvent 3 allocation (system, unit)
- Ecoinvent 3 consequential (system, unit)
- ELCD
- EU & DK Input Output Database
- Industry data 2.0

- LCA Food DK
- Swiss Input Output Database
- USA Input Output Database
- USA Input Output Database System Expansion
- USLCI

The main database used was Econinvent 3 of Swiss origin, which includes more than 10.000 processes in the following industrial sectors, mostly relating to activities in Switzerland and Western Europe concerning energy, transport, building materials, chemicals, washing products, paper and cardboard, agriculture and pollutant treatment. Other data were taken from company-specific publications.
Processes within the databases can be either unit or system processes; a unit process displays a unit operation of the production cycle, while a system process displays both the unit operation and all upstream operations. The Ecoinvent and USA input-output libraries provide both versions for each process; unit processes are preferable for greater transparency, while system processes are useful when visual immediacy is required, especially in complex systems. System processes have been used in the present study.

Inventory
The inventory section allows the construction of new processes or the modification of existing processes. A new process needs some fields to be completed: process name, products avoided, known inputs from nature, known inputs from technosphere, emissions to air, emissions to water, emissions to soil, known outputs to technosphere, waste and emissions to treatment. The processes already implemented in the software are grouped into categories and sub-categories according to the specific field to which they relate.
There are also different phases available for the construction of the product life cycle: assembly, life cycle, disposal scenario, disassembly and reuse.

Impact assessment
The impact assessment section allows the selection of the method from those available in the designed library in order to evaluate environmental impacts. It can also be selected the set of standardisation and weighting in case a choice has to be made. Among the main methods the Eco-indicator 99 method, developed since 1999 by Prè Consultants on behalf of the Dutch Ministry of the Environment, is one of the most widely used in Europe. It is a powerful tool for LCA practitioners, as it allows the aggregation of the results of an LCA into easily understandable and usable units or numbers, called Eco-indicators.
The method evaluates three types of environmental damage: Human Health, Ecosystem Quality and Resources. Each damage category is subdivided into impact categories.
In Figure 17 the framework of Eco-indicator 99 method is shown.

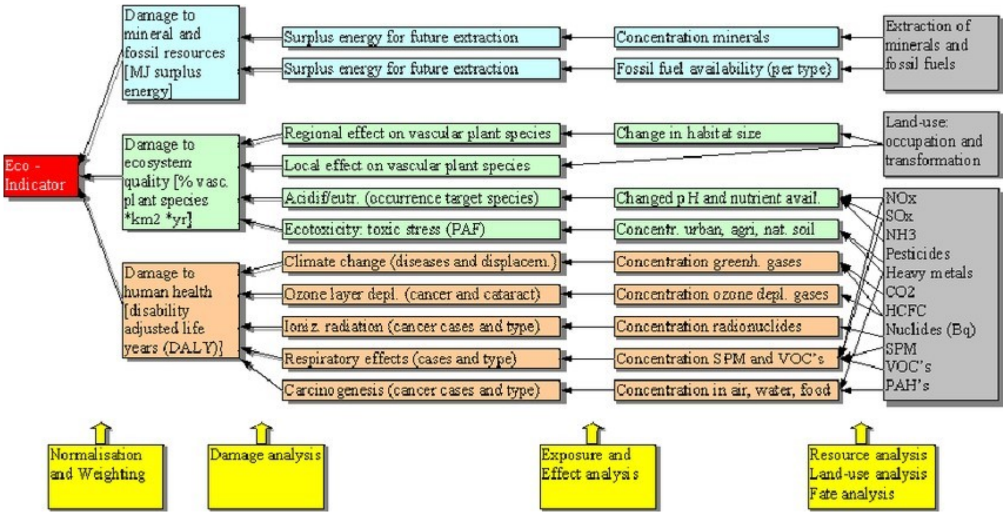


Figure 17: Eco-indicator 99 framework

Interpretation

Interpretation phase can be managed by the user according to the specificities of the analysed system and the objective of the study. In general, a synthetic document must be produced which, in addition to reporting the main results, highlights the limits and potential of the LCA methodology applied to the case under examination.

Chapter 3.

Case study

3.1. Description and location of the building

The project has involved the conversion of an existing industrial building into a social housing building in Tolentino. Figure 18 shows the localization of the building and the premises.

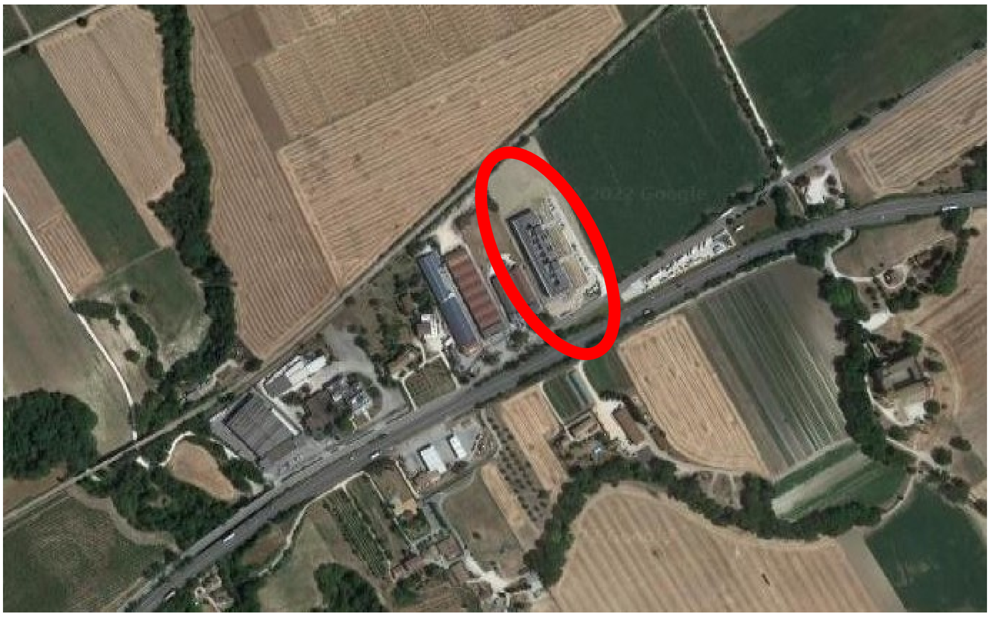


Figure 18: Localization of the building

The parcel on which the building is located is rectangular in shape with a surface area of approximately 15.000 m2, as can be seen in Figure 19. The existing building was constructed using precast reinforced concrete system both for the structure and the cladding. The parallelepiped-shaped building has 2 floors with a flat roof and dimensions of approximately 104,90x29,60x8,80 m for a total area of 6.130 m2. Figure 20 shows the previous appearance of the building.

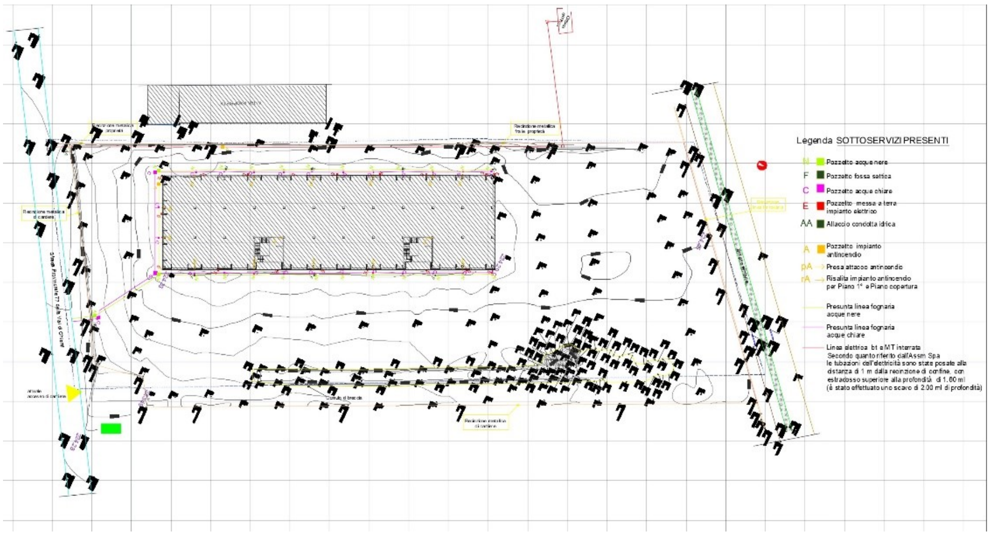


Figure 19: Parcel of the building

Figure 20: Building before renovation

The aim of the intervention was to remodel the existing building and to arrange pertinential spaces for a portion of the parcel with a surface area of approximately 10.444 m2. The renovation has allowed the construction of a block of 46 residential units. The final appearance of the building is shown in Figure 21.

Figure 21: Building after renovation

3.1.1 Architectural design

The load-bearing structure remained the same as before, apart from specific interventions due to the fact that original floors have been cut to have inner courtyards and terraces have been added. Rockwool insulation has been added to the floors in different sizes between the roof and the floors of the residential units. This difference is also due to the fact that the units now have floor heating.
The external shell originally consisted of 20 cm thick prefabricated reinforced concrete panels lightened with polystyrene and pre-finished, to which a 10 cm thick rock wool coat was added. The original panels had a washed gravel finish and were interspersed with a series of identical large double-height openings which on the first floor became arcades forming loggias with recessed niches and small projections. This system of openings characterized all the elevations, interrupted only on the main front by two towers finished in reinforced concrete, containing the staircase-lift system. An image of the previous appearance of the building, the original ground floor plan, images of ground floor and first floor at the

beginning of the renovation works and original roof plan and roof appearance are provided in Figures 22, 23, 24, 25, 26 and 27.

Figure 22: Building original appearance

Figure 23: Building original ground floor plan

Figure 24: Ground floor at the beginning of the renovation works

Figure 25: First floor at the beginning of the renovation works

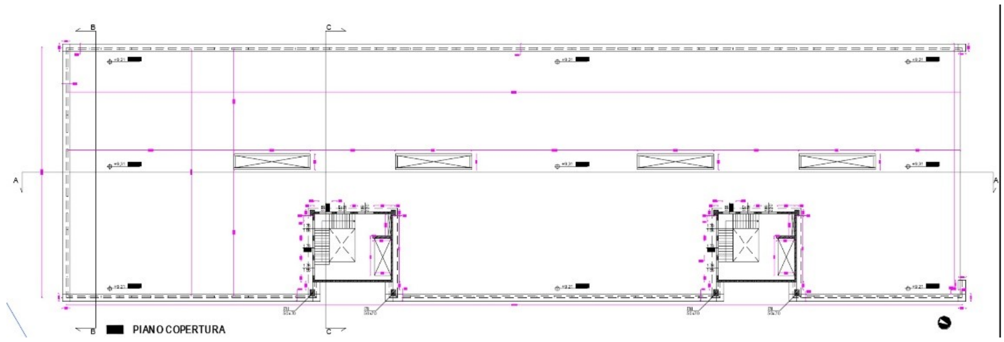


Figure 26: Building original roof plan

Figure 27: Roof original appearance

Compared to the original building, all the openings have been revised and apart from the windows of the bathrooms, the window frames reach up to 2.4 m. Terraces have also been added and the arches on the first floor have been remodeled. Besides two sides of the external walls had to be replaced completely. The floors were cut to create internal courtyards with a system of walkways and stairs connecting the floors and the internal parts of the courtyards.

In addition, due to the new residential use of the building, self-supporting terraces were mounted on the external walls. The walls facing the inner courtyards were built from scratch and are either balloon frame panels with rock wool or metro-therm insulation and concrete panels with EPS insulation.

An example of a self-supporting terrace where the self-supporting structure is shown in Figure 28.

Figure 28: Self-supporting terrace

Figures 29, 30 and 31 describe the final result of the intervention by providing pictures of the inner courtyards and walkways.

Figure 29: Inner courtyard at ground level

Figure 30: Walkways of the inner courtyard at first floor level

Figure 31: Walkways of the inner courtyard at ground floor level

The final result in terms of floor plans is provided in Figures 32 and 33 where changes due to terraces, internal division in residential units and inner courtyards look clear.

Figure 32: Ground floor level plan

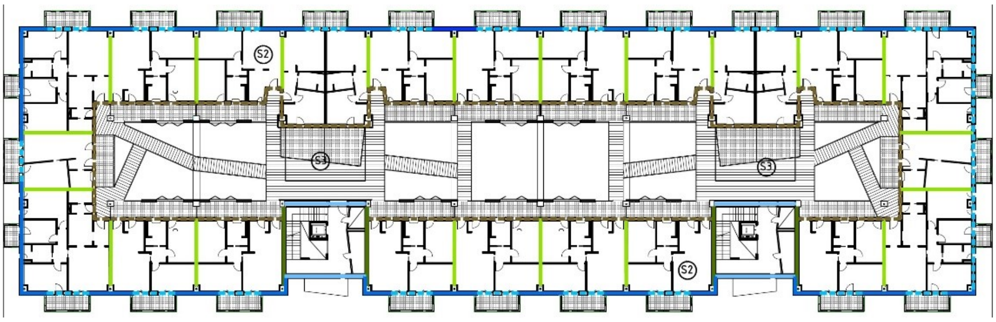


Figure 33: First floor level plan

The building consists of 46 residential units of 7 different types with floor areas ranging from 42 to 92 m2. In the building there are also, in addition to the technical rooms, two stairwells with a lift. The list of the various types of housing units with the number of inhabitants expected for each of them is shown in Figure 34.

TIPOLOGIA	PIANO P_0	PIANO P_1	TO-TALE	PERSONE PER UNITA’	TOTALE NUMERO DI PERSONE
J1	2	2	4	2	8
J2	0	4	4	2	8
K	2	0	2	3	6
W1	2	14	16	4	64
W2	10	0	10	4	40
X	2	0	2	4	8
Y	4	4	8	5	40

Figure 34: Types of housing units and number of expected inhabitants

In all the flats there are two opposing views, towards the outside and towards the inner courtyard. Each unit can be divided into two parts: one half for the entrance/living room and the other half dedicated to bedrooms and bathrooms. The flats in the corners of the building have in addition to the others two external fronts. For this reason the larger unit type (type Y) with 3 bedrooms and two bathrooms have been allocated in the corners. School and sports facilities are also planned in the parcel. The various types of flats and the relative envelope elements are represented in the following Figures 35, 36, 37, 38, 39, 40 and 41.

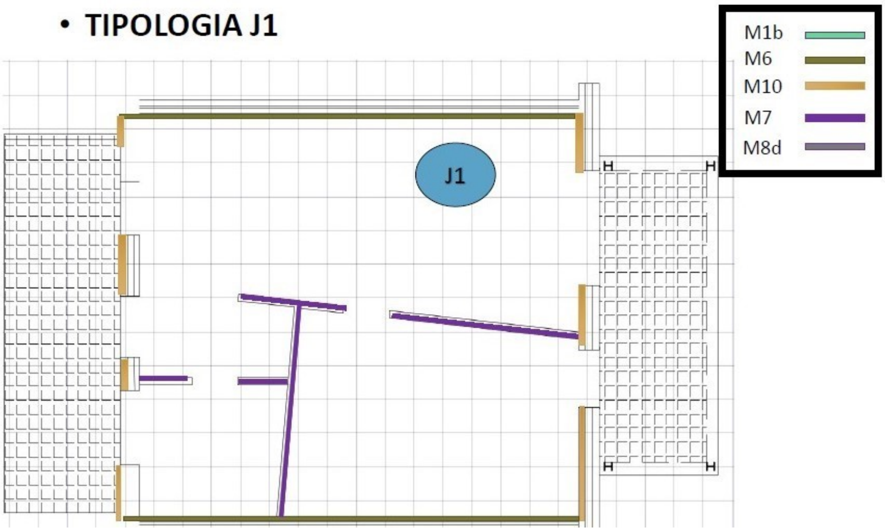


Figure 35: J1 unit type

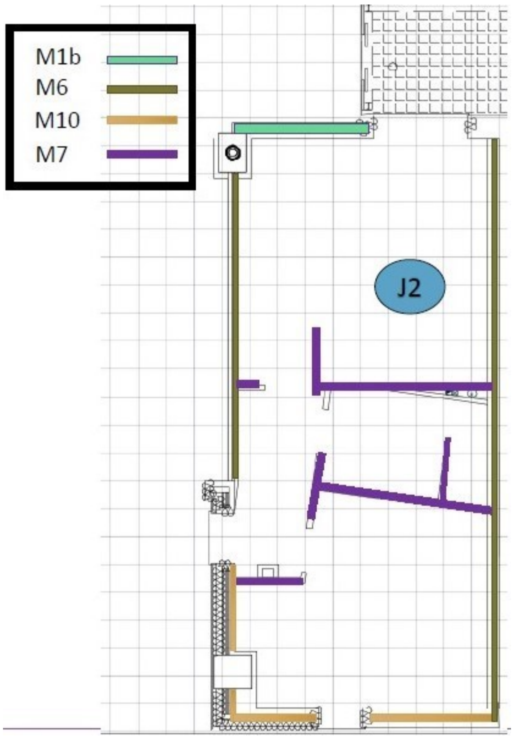


Figure 36: J2 unit type

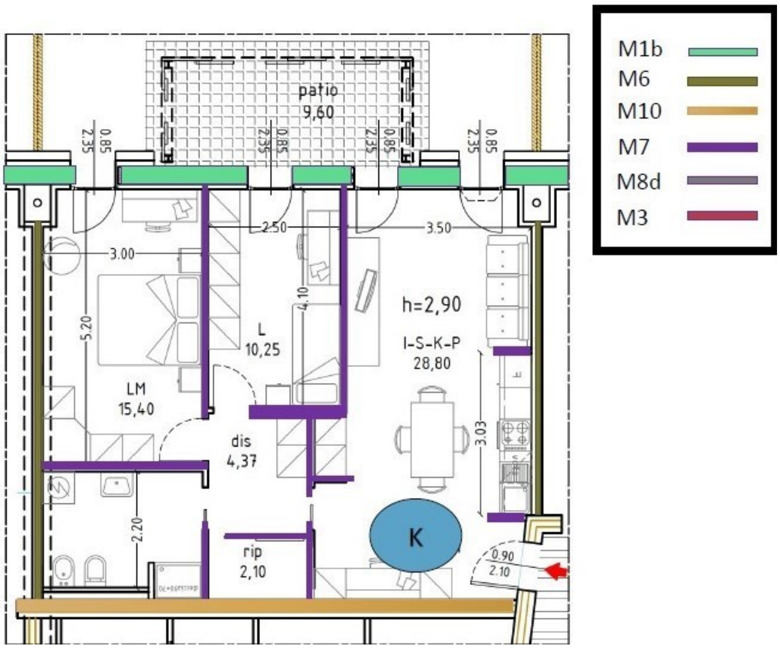


Figure 37: K unit type

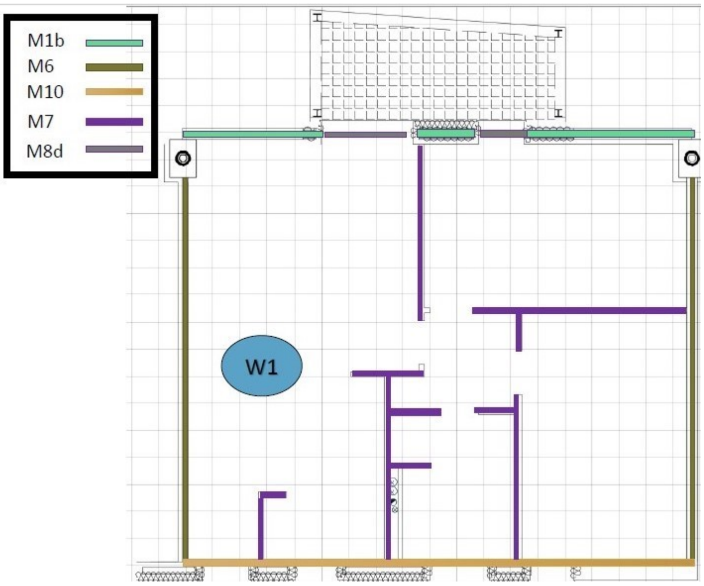


Figure 38: W1 unit type

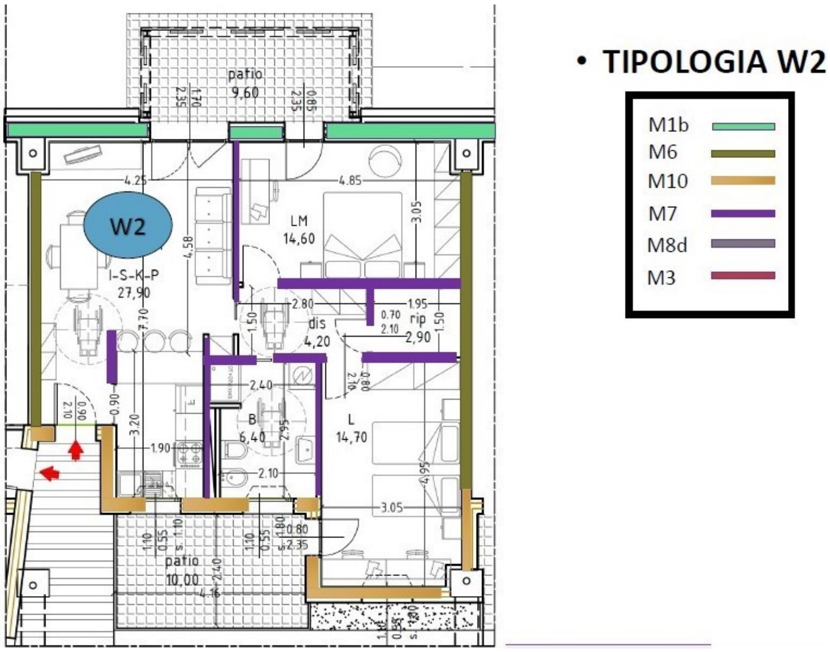


Figure 39: W2 unit type

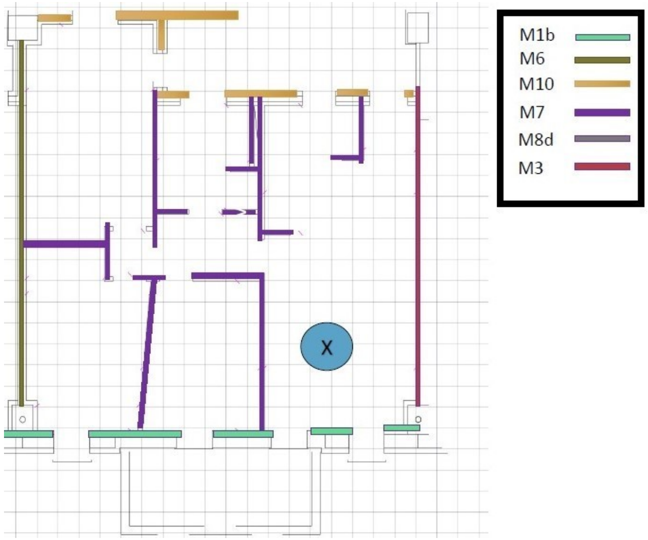


Figure 40: X unit type

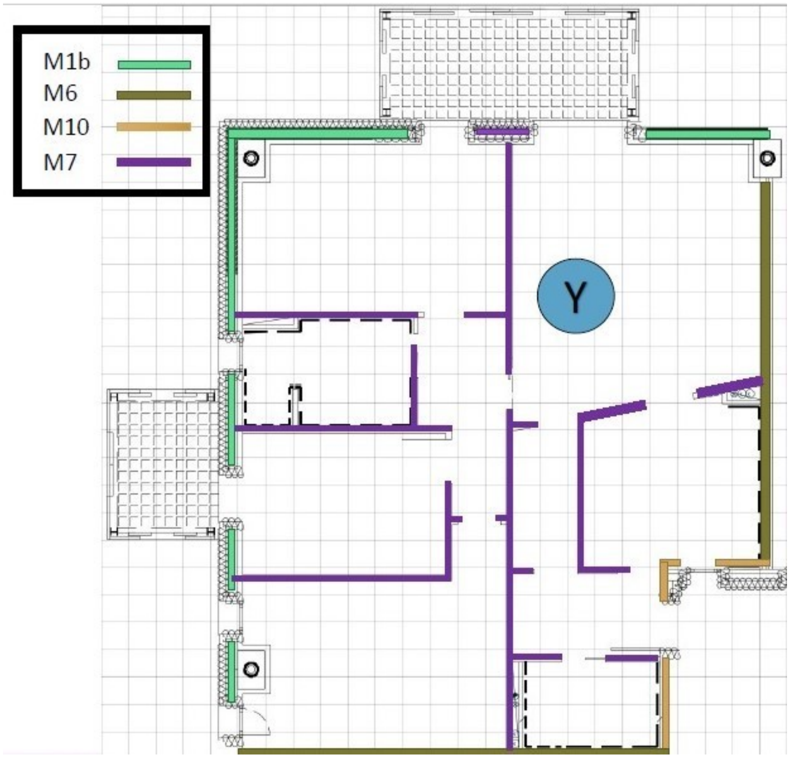


Figure 41: Y unit type

3.2. Envelope

The building envelope consists of a number of elements made up of different components and materials of varying thickness. These elements that can be divided into:
1. Vertical opaque elements;
2. Roof or ground horizontal opaque elements;
3. Transparent closures.

Other elements, both horizontal and vertical such as internal floors o walls between units, can be inside the building. They are not strictly part of the envelope but they have to be considered when investigations on thermal or environmental aspects are conducted. The thermal and surface mass characteristics of the vertical and horizontal components, of the transparent closures of the building envelope involved in the intervention are given below.

1. External vertical opaque elements

The external vertical opaque elements in the building are listed below. In the following cross-section and main thermal characteristics are provided for each one:

- M1b wall with precast reinforced concrete panels
- M2 reinforced concrete wall
- M3 hollow brick wall (building units/staircase)
- M8d wall with METRO-THERM panel (EPS insulation)
- M10 balloon frame panel (rock wool insulation)

Other internal vertical opaque elements are:

- M6 wall between units
- M7 unit internal partitions

M1b wall with precast reinforced concrete panels
Surface mass: 323,63 kg/m²

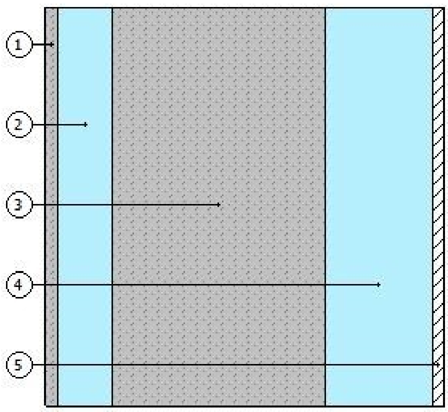


Figure 42: M1b cross section

Cod	Name		λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m^3]	[m]	[(m^{2}K)/W]	[W/(m^{2}K)]
M1b		Internal surface resistance				0,13	
	1	Gypsum fibre boards (Fermacell)	0,33	1150	0,0125	0,038	
	2	Rockwool	0,033	75	0,05	1,515	

	3	Precast reinforced concrete panel	0,59	1400	0,2	0,339	
	4	Rockwool	0,033	75	0,1	3,030	
	5	Plaster	1,15	1800	0,01	0,009	
		External surface resistance				0,040	
					0,3725	**5,101**	**0,196**

Table 1: M1b cross section data

M2 reinforced concrete wall
Surface mass: 340,88 kg/m²

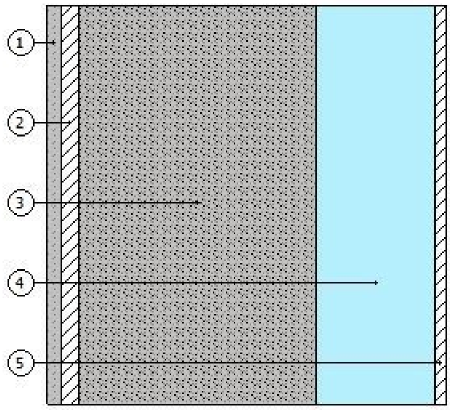


Figure 43: M2 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m3]	[m]	[(m2K)/W]	[W/(m2K)]
M2		Internal surface resistance				0,13	
	1	Gypsum fibre boards (Fermacell)	0,33	1150	0,0125	0,038	
	2	Internal plaster	0,53	1500	0,015	0,028	
	3	Reinforced concrete wall	0,58	1400	0,2	0,345	

	4	EPS panel	0,036	60	0,1	2,778	
	5	Plaster	1,15	1800	0,01	0,009	
		External surface resistance				0,040	
					0,3375	3,367	0,297

Table 2: M2 cross section data

M3 hollow brick wall (building units/staircase)
Surface mass: 196,63 kg/m²

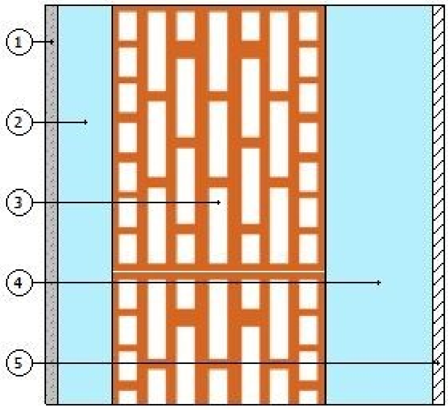


Figure 44: M3 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m^3]	[m]	[(m^{2}K)/W]	[W/(m^{2}K)]
M3		Internal surface resistance				0,13	
	1	Gypsum fibre boards (Fermacell)	0,33	1150	0,0125	0,038	
	2	Rockwool	0,033	75	0,05	1,515	
	3	Hollow brick	1,63	765	0,2	0,123	

	4	Rockwool	0,033	75	0,1	3,030	
	5	Plaster	1,15	1800	0,01	0,009	
		External surface resistance				0,13	
					0,3725	**4,975**	**0,201**

Table 3: M3 cross section data

M8 wall with METRO-THERM panel (EPS insulation)
Surface mass: 291,53 kg/m²

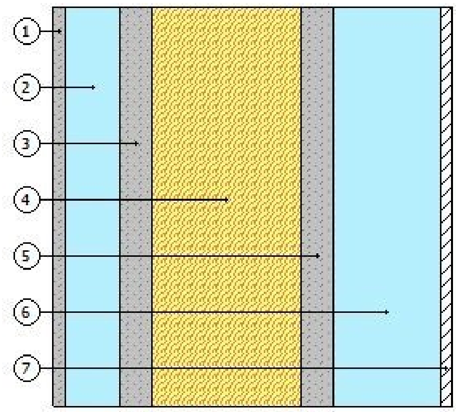


Figure 45: M8 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m^3]	[m]	[(m^{2}K)/W]	[W/(m^{2}K)]
M8		Internal surface resistance				0,13	
	1	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,0125	0,038	
	2	Rockwool	0,033	75	0,05	1,515	
	3	Mortar	1,2	1800	0,03	0,025	

	4	Polystyrene panel (Metro-therm)	0,25	1010	0,14	0,560	
	5	Mortar	1,2	1800	0,03	0,025	
	6	EPS panel	0,036	60	0,1	2,778	
	7	Plaster	1,15	1800	0,01	0,009	
		External surface resistance				0,04	
					0,3725	**5,120**	**0,195**

Table 4: M8 cross section data

M10 balloon frame panel (rock wool insulation)
Surface mass: 70,63 kg/m²

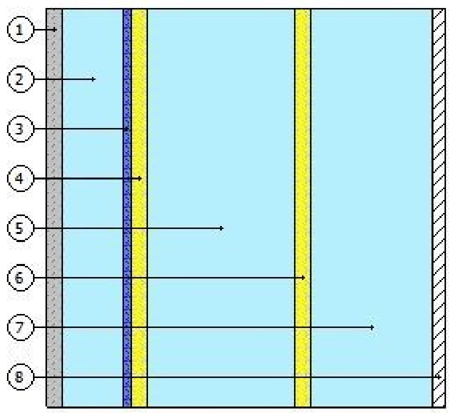


Figure 46: M10 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m³]	[m]	[(m²K)/W]	[W/(m²K)]
M10		Internal surface resistance				0,13	
	1	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,0125	0,038	
	2	Rockwool	0,033	75	0,05	1,515	

	3	Highly breathable membrane	0,31	250	0,007	0,023	
	4	OSB3 wood panels	0,13	650	0,0125	0,096	
	5	Rockwool	0,033	75	0,12	3,636	
	6	OSB3 wood panels	0,13	650	0,0125	0,096	
	7	Rockwool	0,033	75	0,1	3,030	
	8	Plaster	1,15	1800	0,01	0,009	
		External surface resistance				0,04	
					0,3245	**8,613**	**0,116**

Table 5: M10 cross section data

M6 wall between units
Surface mass: 34 kg/m²

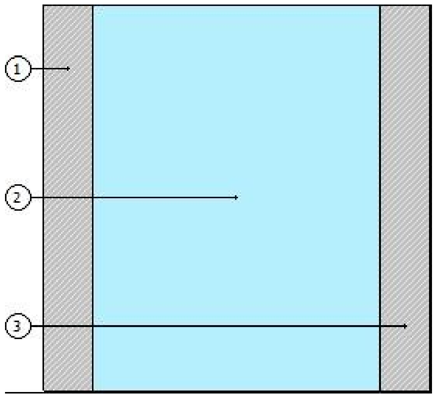


Figure 47: M6 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m^3]	[m]	[(m^{2}K)/W]	[W/(m^{2}K)]
M6		Internal surface resistance				0,13	
	1	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,0125	0,038	

	2	Rockwool	0,033	75	0,07	2,121	
	3	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,0125	0,038	
		External surface resistance				0,13	
					0,095	**2,457**	**0,407**

Table 6: M6 cross section data

M7 unit internal partitions
Surface mass: 88 kg/m²

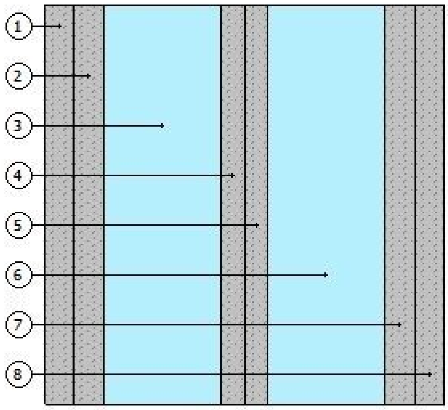


Figure 48: M7 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(m K)]	[Kg/m³]	[m]	[(m²K)/W]	[W/(m²K)]
M7		Internal surface resistance				0,13	
	1	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,0125	0,038	
	2	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,0125	0,038	
	3	Rockwool	0,033	75	0,05	1,515	

	4	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,01	0,030	
	5	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,01	0,030	
	6	Rockwool	0,033	75	0,05	1,515	
	7	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,0125	0,038	
	8	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,0125	0,038	
		External surface resistance				0,13	
					0,17	**3,502**	**0,286**

Table 7: M7 cross section data

2. Roof or ground horizontal opaque elements
The roof or ground horizontal opaque elements in the building are listed below. In the following cross-section and main thermal characteristics are provided for each one:

- S4 Roof
- S2 Unit internal floor
- S0 Ground floor

S4 Roof
Surface mass: 682,73 kg/m²

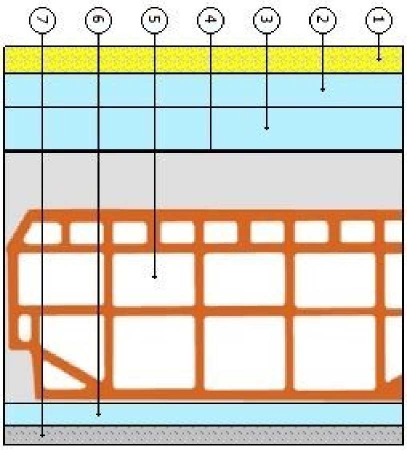


Figure 49: S4 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m^3]	[m]	[(m^{2}K)/W]	[W/(m^{2}K)]
S4		Internal surface resistance				0,04	
	1	Sand and Gravel	2	1700	0,05	0,025	
	2	Rockwool	0,033	75	0,06	1,818	
	3	Rockwool	0,033	75	0,08	2,424	
	4	Waterproofing membrane	0,2	1100	0,004	0,020	
	5	Precast reinforced concrete floor (existing)	2,7	1173	0,46	0,170	
	6	Rockwool	0,033	75	0,04	1,212	
	7	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,035	0,106	
		External surface resistance				0,13	
					0,729	**5,946**	**0,168**

Table 8: S4 cross section data

S2 Unit internal floor
Surface mass: 865,33 kg/m²

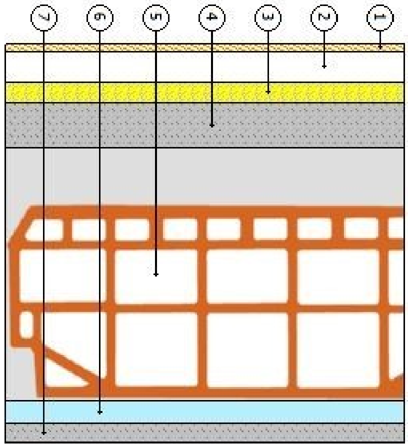


Figure 50: S2 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m^3]	[m]	[(m^{2}K)/W]	[W/(m^{2}K)]
S2		Internal surface resistance				0,17	
	1	Stoneware tiles	1,3	2300	0,015	0,012	
	2	Screed for radiant system	1,65	2200	0,054	0,033	
	3	Extruded polystyrene sheets	0,8	30	0,04	0,050	
	4	Lightweight concrete	1,08	1600	0,08	0,074	
	5	Precast reinforced concrete floor (existing)	2,7	1173	0,46	0,170	
	6	Rockwool	0,033	75	0,04	1,212	
	7	Gypsum fibre boards (Ferma-cell)	0,33	1150	0,035	0,106	
		External surface resistance				0,17	
					0,724	**1,997**	**0,501**

Table 9: S2 cross section data

S0 Ground floor
Surface mass: 781,0 kg/m²

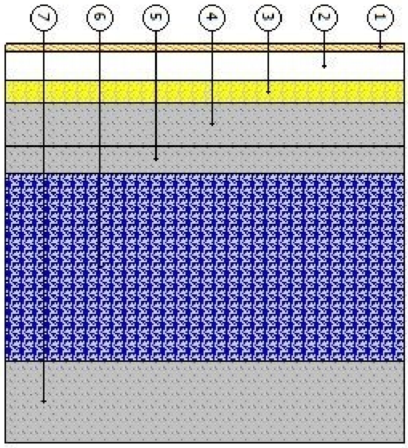


Figure 51: S0 cross section

Cod		Name	λ	ρ	Width	R	U
			[W/(mK)]	[Kg/m^3]	[m]	[(m^{2}K)/W]	[W/(m^{2}K)]
S0		Internal surface resistance				0,17	
	1	Stoneware tiles	1,3	2300	0,015	0,012	
	2	Screed for radiant system	1,65	2200	0,054	0,033	
	3	Extruded polystyrene sheets	0,8	30	0,04	0,050	
	4	Lightweight concrete	1,08	1600	0,08	0,074	
	5	Reinforced concrete	1,91	2400	0,05	0,026	
	6	Recycled polypropylene form-work for foundations	0,22	910	0,35	1,591	
	7	Lean concrete	1,15	400	0,15	0,130	
		External surface resistance				0,04	
					0,739	**2,126**	**0,470**

Table 10: S0 cross section data

3. Transparent closures
Five different types of windows have been installed in the building with U-values ranging from 1,6 W/(m2K) to1,7 W/(m2K). Shape and dimensions of each type are provided below.

Window 0,85 x 2,4 m
U-value 1,62 W/(m2K)

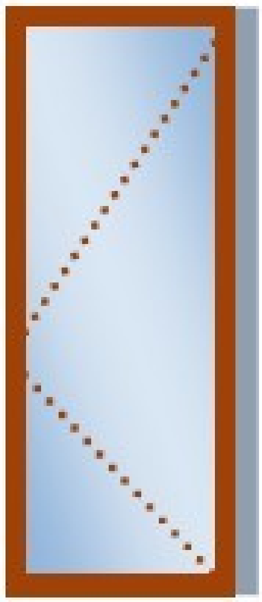


Figure 52: Window 0,85 x 2,4 m

Window 1,70 x 2,4 m
U-value 1,64 W/(m2K)

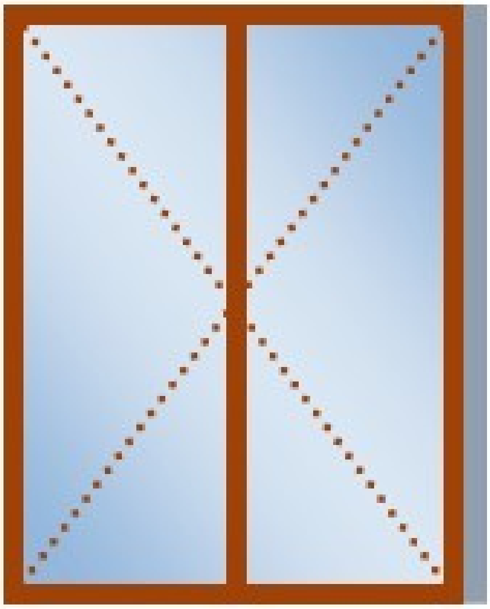


Figure 53: Window 1,70 x 2,4 m

Window 1,10 x 0,55 m
U-value 1,76 W/(m2K)

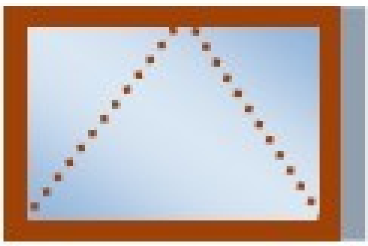


Figure 54: Window 1,10 x 0,55 m

Window 0,60 x 2,4 m
U-value 1,72 W/(m2K)

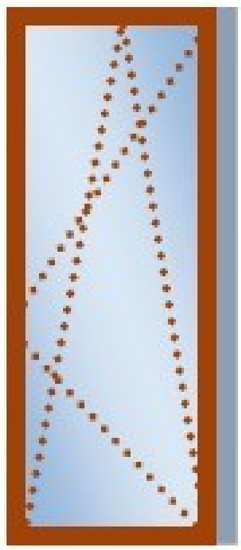


Figure 55: Window 0,60 x 2,4 m

Window 0,90 x 2.4 m + 0,60 m
U-value 1,74 W/(m2K)

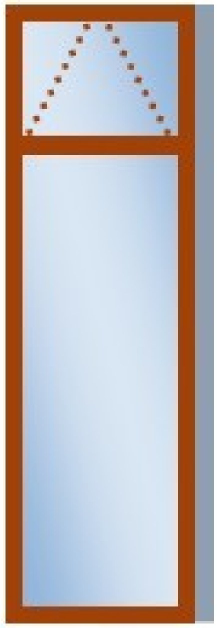


Figure 56: Window 0,90 x 2,4 m

3.3. Systems

The building has been equipped with the following mechanical and electrical installations, some of which have been centralised even though the building is divided into two blocks of flats: Staircase A and Staircase B. The centralised systems are the following:

- Central heating plant with hybrid system for each staircase
- Metering system for each apartment
- Winter heating system with radiant floor
- Water-sanitary system
- Solar thermal system for domestic hot water

The proposed solutions, in compliance with the regulations and legislation in force, are characterised by reliability, economic management and containment of energy consumption. The following factors have been considered in the design choices:

- simplicity of functioning to obtain considerable reliability of the system and its components;

- maximum standardisation of the components to guarantee easy availability in the future, both in the case of modifications and replacement during maintenance or due to ageing;
- divisibility of each section of the system to obtain flexible, economic and easily controlled management;
- adaptability of the systems to the building structures, especially with a view to ensuring easy accessibility during maintenance and control operations;

A general overview of the central heating plant with hybrid system for each staircase is given in the following Figure 57.

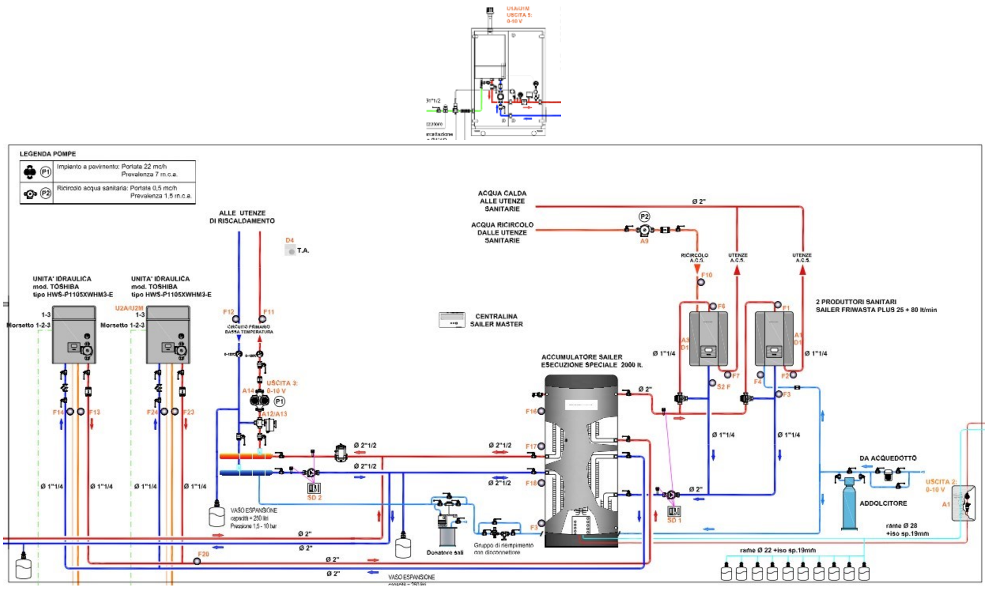


Figure 57: General scheme of the central heating plant

Figure 57 shows the main elements of the system: each central plant has two11 kW heat pumps and one 24 kW gas boiler for heating, two 1,2 kW heat pumps for domestic hot water, a hot water storage tank and the connections to the solar panels, the radiant floors and bathrooms and kitchens. 24 kW gas boiler for heating operates as integration to heat pumps heating.
A plant designed in this way is configured as a hybrid system, i.e. a plant in which there are several heat generators powered by different energy sources, in this case a fossil fuel and a source considered renewable. In hybrid systems, the plant's control unit gives priority to the most convenient generator at any given time according to the operating conditions, always ensuring maximum energy efficiency. In practice, with outside temperatures below -4 degrees, the only working generator is the boiler; for temperatures between -4 and +3 degrees, the heat pumps are activated and help the boiler, which thus reduces its consumption. If the

outside temperature rises above +3 degrees, the boiler switches off and the heat pumps cover the entire heat demand.
Domestic hot water, depending from the season, is provided by two smaller heat pumps and/or solar panels located on the roof. Hot water not used is stored in a hot water storage tank. To provide electricity for the heat pumps 23 kW PV panels have been installed on the roof. The solar thermal system consists of 12 flat-type solar panels of 2,5 m2 each, installed on the roof of the building, designed both for the production of domestic hot water and for supplementing space heating. A schematic diagram of the system is provided in Figure 58.

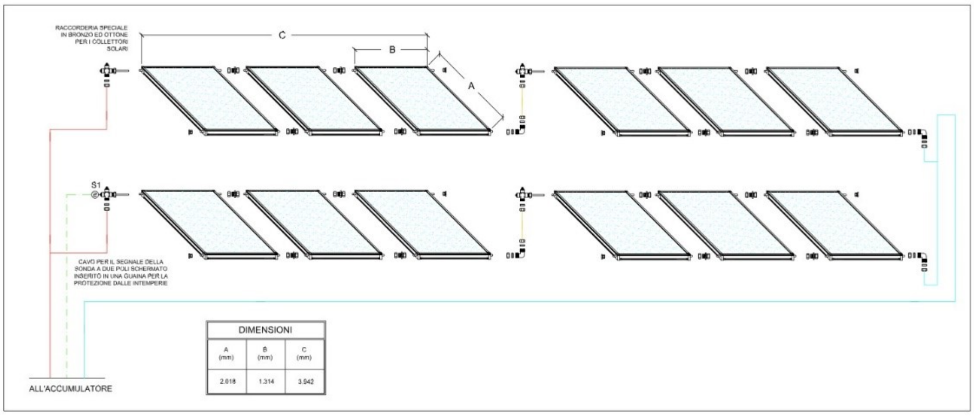


Figure 58: Schematic diagram of solar panel system

In all the residential units heating system is with radiant floor, In Figure 59 an example for the J1 unit type is shown.

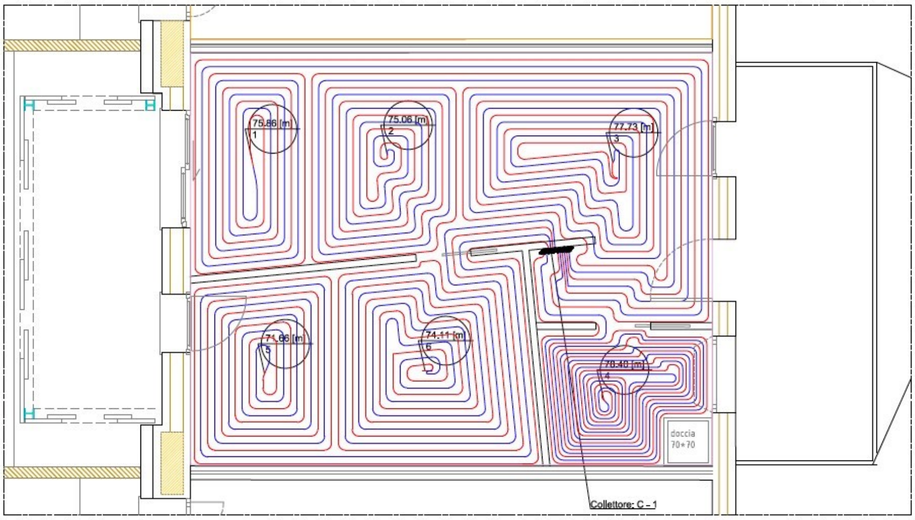


Figure 59: J1 unit type heating system with radiant floor

In each apartment a metering system has been installed to measure heating and domestic hot water. Each metering module is connected to a digital room chronothermostat to manage it; the module inside will collect data and determine how much each unit has consumed.
The photovoltaic system consists of 92 polycrystalline modules with a total power of 23 kW. The electricity produced is used for the lifts, the lighting of the stairs and as support for the heat pumps for heating the 46 residential units.
In the following Figure 60, 61 and 62 a general overview of the central heating plant, details of the heat pumps and a view of the renovation works are provided.

Figure 60: General overview of the central heating plant

Figure 61: Details of the heat pumps

Figure 62: View of the renovation works

Chapter 4.

Results of LCA application

Understanding the energy dynamics of the building system makes it possible to identify those choices aimed at reducing environmental impact and improving energy efficiency. Being able to assess a building according to a Rating System broadens the vision as this tool embraces multiple aspects and also includes the relationship between the building and its surroundings. The LCA is a tool that allows for an even more accurate environmental assessment, taking into account many aspects, from the extraction of raw materials to the disposal of the product or system at the end of its life.
However, accuracy may be limited by the accessibility of data, their availability and quality, as well as by the choices of those conducting the study, e.g. the level of detail with which to conduct the analysis, the scope, and the boundaries of the system. For this reason, the aspects that most influence the quality of a LCA study are the application of reliable methodologies and the possibility of accessing databases with the certainty of finding complete information.
In this chapter, the building LCA is presented by introducing a building component classification model used in the inventory analysis phase.

4.1 Goal and scope definition of the study

As foreseen by the UNI EN ISO 14040 and 14044 technical standards, the statement of the goal and scope of the LCA study is an integral part of it and therefore in the present case the goal is the LCA assessment of the building refurbishment described in chapter 3 through the application of the methodology standardized by UNI EN ISO 14040 and 14044 and following steps foreseen by the same. The application of the methodology shows how the procedure can be adapted to the specificities of the environmental impact assessment of buildings.

4.2 Field of application

The building taken into consideration was an industrial building which has become residential after redevelopment. For the purposes of the present study a lifespan of 50 years was assumed.

4.2.1 Functional unit

The functional unit is a reference to which input and output flows can be linked. In the cases examined, the functional unit chosen is the entire building, i.e. material and energy input and output flows are quantified in relation to the building as a whole. This makes it possible to compare results for different phases of the building's life cycle or to compare different solutions, e.g. in the use of materials or components, for the same building.

4.2.2 System boundaries

Defining the boundaries of the system means firstly establishing which process units to include in the life cycle analysis. The building system is broken down into process units, i.e. all those elements, materials and components, that make up the building and that are affected by material and energy flows during their life, i.e. during production, transport, installation and assembly, use and disposal.
To break down the building and identify the functional units, the UNI 8290: 1981 standard “Classification of the technological system” (In Italian "Classificazione del sistema tecnologico”) was used. Although a rather outdated standard, it is still a very effective tool for breaking down the building into its constituent parts to a very advanced level of detail and for this reason it is still used.
The UNI 8290 Standard identifies a criterion for the classification and articulation of the building system into several levels according to a vision based on rationality and homogeneity. The characteristics of the building system are examined by the Standard according to a detailed scheme set out on three levels, where the lower level arises from the decomposition of the upper aggregate level, and all this according to the approach proper to top-down analysis. This scheme is divided into the following three groups:

- Classes of technology units (in Italian “Classi di unità tecnologiche”)
- Technological units (in Italian “Unità tecnologiche”)
- Classes of technical elements (in Italian “Classi di elementi tecnici”)

The standard only comprises for these three levels but states that other levels are possible if certain conditions are met. For the present study, the decomposition of the building continued up to the sixth level. The other three levels identified were as follows:

- Subsystems
- Components
- Sub-components

The first level (Classes of technology units) comprises eight classes which are reported in the following:

1. Support structures
2. Enclosures
3. Internal Partition
4. External partition
5. Services supply systems

6. Safety systems
7. Internal equipment
8. External equipment

An example of the decomposition performed can be seen in the following Table 11, in which it can be seen how from the Class of technology unit (level 1) it is possible to go until the individual layer of a cross section (level 6) which therefore represents the smallest part of the building system and corresponds to the process unit that identifies the level of detail with which data are collected.

Classi di unita tecnologiche	Unità tecnologiche	Classi di elementi tecnici	Sub sistemi	Componenti	Sub Componenti
Chiusura (3.2)	Chiusura orizzontale inferiore (3.2.2)	3.2.2.1. Solai a terra	3.2.2.1.2 Solaio su spazio aerato	Solaio in latero cemento	cls per getti
					armature e staffature
					laterizi
				Massetto di sottofondo	sottofondo cls allegerito
				Strato di impermeabilizzazione	guaina anticalpestio
				Strato di isolamento termico	Isolante EPS-XPS
					pannello isolante pavimento NZEB
					massetto impianto radiante
				Pavimentazione	piastrelle in ceramica
				Strato di drenaggio	ghiaia

Table 11: Example of the decomposition from level 1 to level 6 according to UNI 8290

For an entire building a standard decomposition implies some hundreds of layers, each of them with information to find.

These steps, however carefully conducted, inevitably involve the introduction of approximations and assumptions made by the life cycle assessment performer. The breakdown of the building goes on to detail the individual sub-components, which in turn are

industrial products requiring their own LCA. In order to facilitate the assessor's task and to reduce the level of detail or to limit the arbitrariness of the individual assumptions made, it would be desirable to implement national building databases that allow the assembly of sub-components into components. Having a database that allows the individual layers to be assembled into the component would make such a tool much more accessible.
For the present study reference was made to all the databases loaded in the software used, including Ecoinvent, Agri-footprint, ELCD, USLCI, Swiss Input Output Database and EU & DK Input Output Database; in addition, for some specific materials, Environmental Product Declarations (EPDs) were used. All the databases used are an indispensable support for carrying out this type of analysis, although they are not specifically designed for the construction sector. Furthermore, they mainly refer to European or non-European average data, so there is no guarantee of a perfect match with Italian materials and production processes.
Establishing the system boundaries means not only defining the process units, but also the life cycle phases to be included in the study as illustrated in the following Figures 63, 64 and 65.

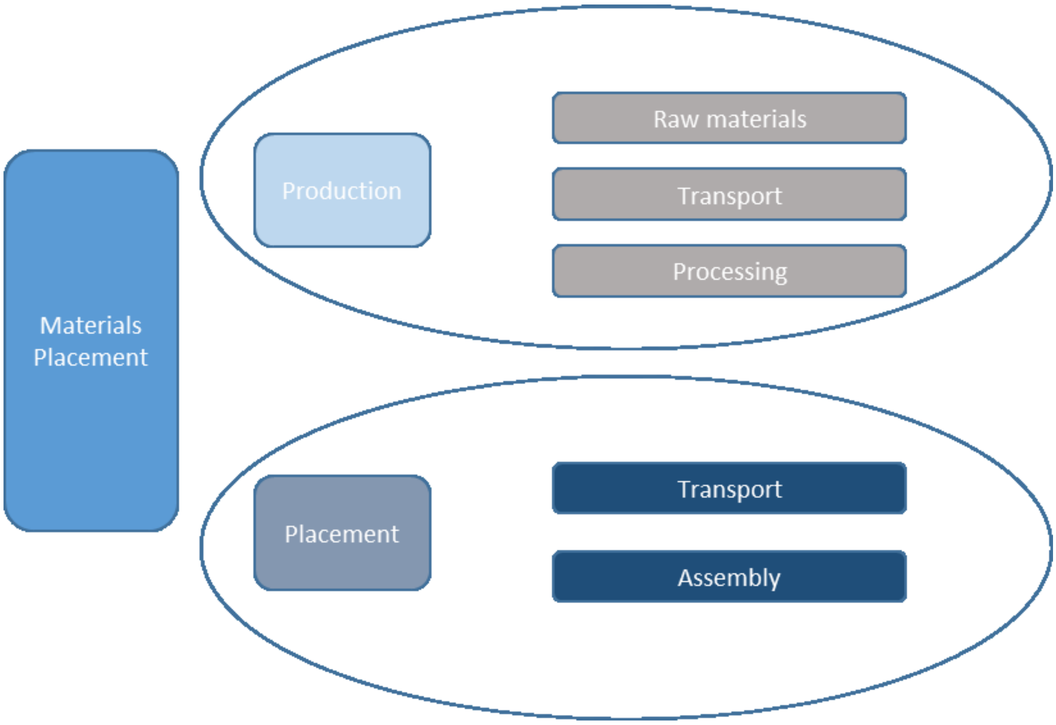


Figure 63: I Phase; Materials Placement

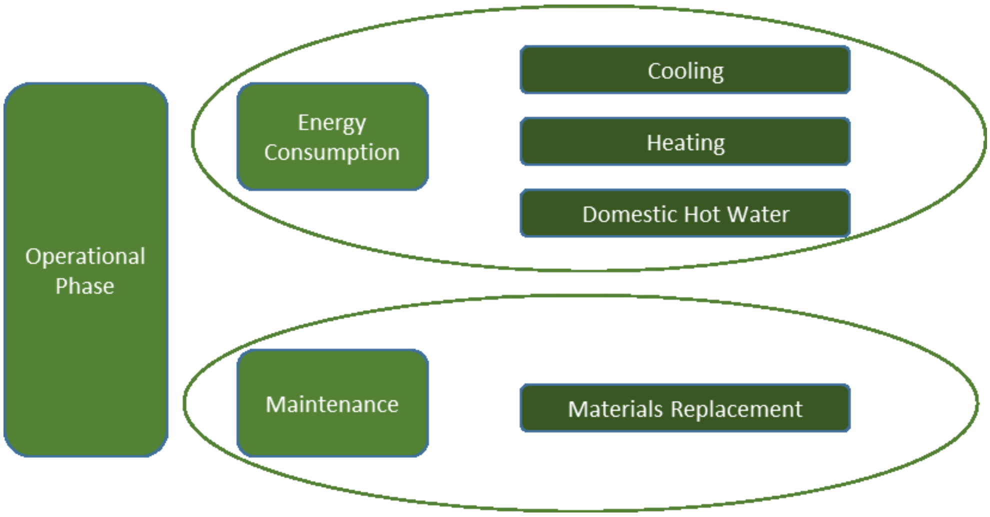


Figure 64: II Phase; Operational Phase

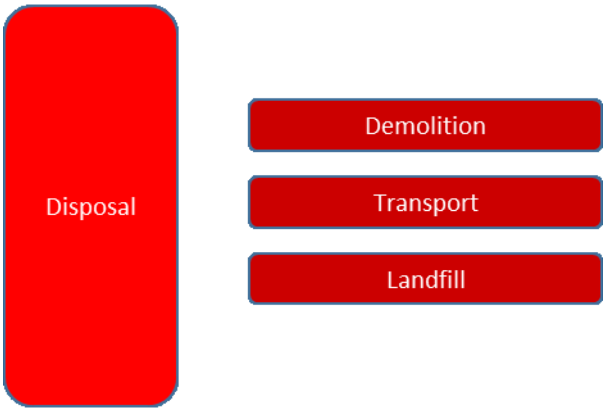


Figure 65: III Phase; Disposal

Three main phases were used in this study:

- I Phase: Materials Placement - always bearing in mind that the study concerns the refurbishment of an existing building from industrial to residential, in this phase the production of materials was considered, thus the extraction of raw materials, transport to the related industries for treatment and processing; but also the installation phase which includes transport from the production company to the construction site and the assembly of the components. For a new building this phase would be slightly different including, for instance, the excavation of the site for the construction works;

- II Phase: Operational Phase - the building is used by users. Assumed energy consumptions for this phase include consumption for heating, domestic hot water production and cooling. During this phase, which has been assumed to be 50 years, maintenance is planned for certain elements of the building;
- III Phase: Disposal - demolition of components, transport from building to landfill. No recyclable materials were assumed as the analysis of the cross sections showed that recycling possibilities are limited.

Ultimately, the boundaries of the system are also defined by the inflows and outflows of matter and energy. In deciding which input flows to study, the mass criterion was taken into account in the first instance, that is, those inputs considered negligible in weight in relation to the total were left out, while making sure that these were not of such environmental significance that they could not be excluded.
As a final step in defining the system boundaries, it is necessary to determine which releases into the environment are to be assessed. These are grouped according to impact categories, which vary according to the method used for assessment. In the present study, the following methods were used:

- Cumulative Energy Demand (CED) assessing MJ of primary energy from different energy sources as impact, thus primary energy consumption is the object of the evaluation;
- IPCC GWP 20 assessing kg of CO2 equivalent as impact, therefore the assessment refers to climate change. The present method has been preferred to the similar IPCC GWP 100 which is doing similar evaluations but in a time scale of 100 years instead of 20 because a shorter horizon, such as 20 years, would much better reflect the true effects of gases with a short atmospheric lifetime on the climate such as refrigerants and methane;
- Eco-indicator 99 (H) has eleven impact categories, which in turn are grouped into three damage categories: damage to human health, damage to ecosystem quality, damage to resources. The damage assessments in relation to the three safeguard areas, are comparable and therefore can be summed up into a single score, the Eco-indicator expressed in Point (Pt) or MilliPoint (MPt), which represents the overall performance of the investigated system in energy-environmental terms.

4.2.3 Data quality requirements

The qualitative and quantitative data included in the inventory were collected for each process unit within the system boundaries. The data used are of various kinds, firstly those provided by the project documentation. Secondly, reference was made to the software databases, in which the life cycle assessments of many materials in use in the construction industry are included. Where data were not available in sufficient detail, EPDs were sought. Data from the energy simulation in Chapter 6 was used to determine the energy consumption during the operational phase.
Unfortunately, the scarcity of systems-specific data in the different sources consulted led to the exclusion of systems from the present study. This is the major simplification that had to

be made. Another assumption made was the assessment of only the materials used in the refurbishment, so all existing materials were not included in the simulations. Including also what had been produced, assembled and used in the previous industrial function of the building would have altered the considerations of impacts due to the refurbishment materials. Finally, in the assessment according to the selected Rating System the materials were all considered to be of non-local origin and therefore a distance of at least 300 km between the place of production and the construction site was also assumed for the transport impact assessment.

4.3 Inventory analysis

During the inventory analysis phase, all operations were carried out to decompose the building in accordance with the scheme provided by UNI 8290. The decomposition led to the calculation of the material quantities used. Each material identified was then searched in the databases mentioned and was associated with a reference material taken from these sources. For processing, assembly, transport, maintenance, decommissioning and landfill, energy and material consumption were associated. For each process included in the life cycle, materials and processes were then associated to make up the overall picture.
During the inventory phase some additional assumptions were made:

- Transport: all transports for all phases take place by means of diesel-powered trucks with a capacity of 16 t;
- First assembly and assembly of materials for maintenance: electrical consumption estimated as 1.8÷2% of the "total embodied energy". Total embodied energy refers to the energy used for a material to be extracted, refined, processed until the component with the required physical and shape characteristics is obtained, transported and finally assembled, in other words all the energy required for the first stage of material placement.

During the Disposal phase has been assumed that all materials are taken to landfill without recycling: this is a choice that is made for materials that cannot be recycled due to lack of quality (mixed and inseparable materials), lack of time or space for disassembly or lack of market for the recycled product. In the case study, the cross sections analysis showed that the materials used are not separable.

4.4 Results analysis

There are several assessment methods that can be used to quantify the impacts of the various life cycle phases and for an overall assessment. Each assessment method is capable of evaluating certain impact categories. As already mentioned in the present study, the methods used were the following

- Cumulative Energy Demand (CED);
- IPCC GWP 20;

- Eco-indicator 99 (H).

In the following results of the assessment are presented for each phase and for the full life cycle and calculated for each method.

4.4.1 I phase: Materials Placement

Calculations relating the Materials Placement phase include production, transport of materials from production site to construction site and impacts due to assembly.

Cumulative Energy Demand (CED)

In the following Figure 66 part of tree graph of impacts calculated with CED method for Materials Placement is shown.

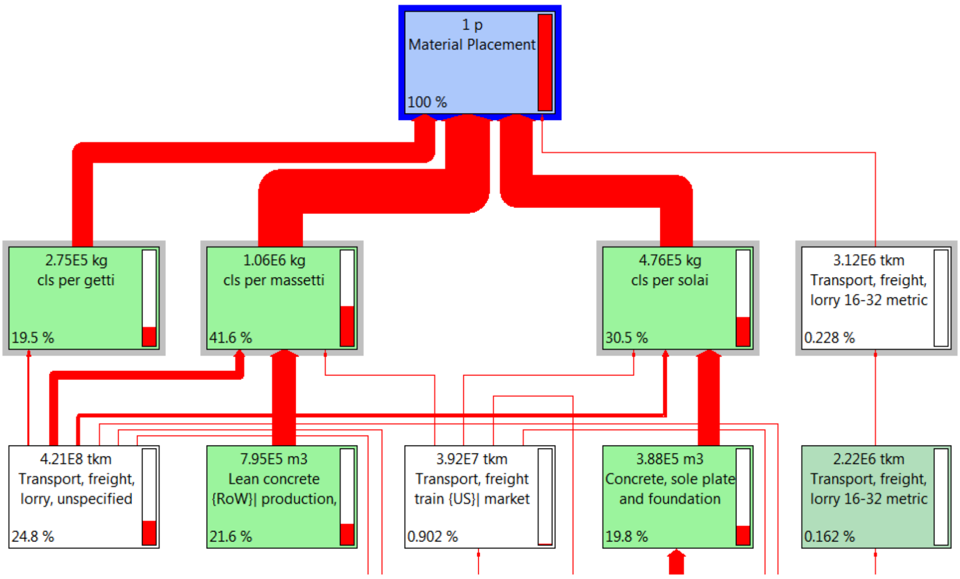


Figure 66: Tree graph of impacts calculated with CED method for Materials Placement

It is clear the great influence of concrete in impacts calculated with CED method as the first three contributions are due to the three types of concrete used in the refurbishment works. Also the next Figure 67 confirms the influence of concrete in the evaluation as the first three columns represent the cumulative energy demand for the three types of concrete.

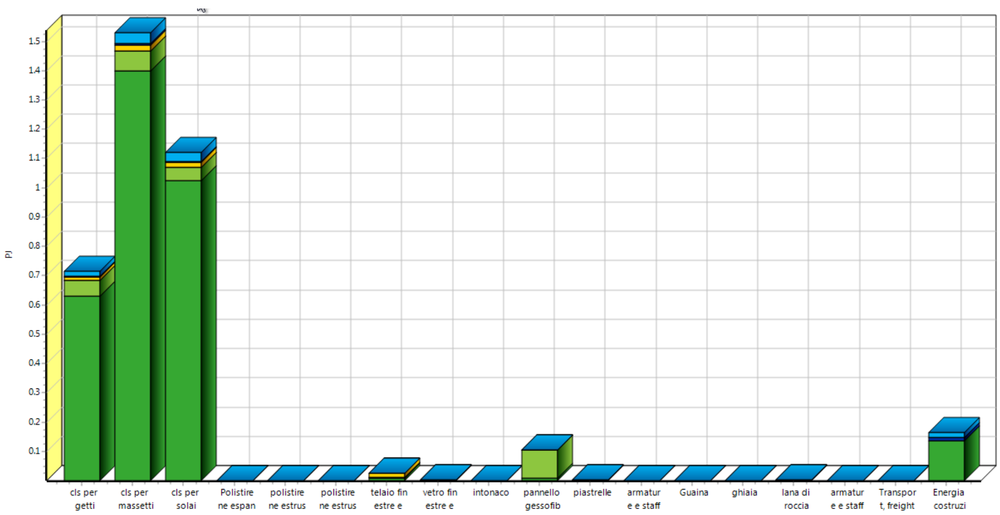


Figure 67: Cumulative energy demand for each material, Material Placement phase

Concrete, in terms of weight is the main material used in the refurbishment works. In the following Figure 68 the weight of each material, in percentage on the total weight of the materials added during the refurbishment works, different types of concrete are around 57% of total.

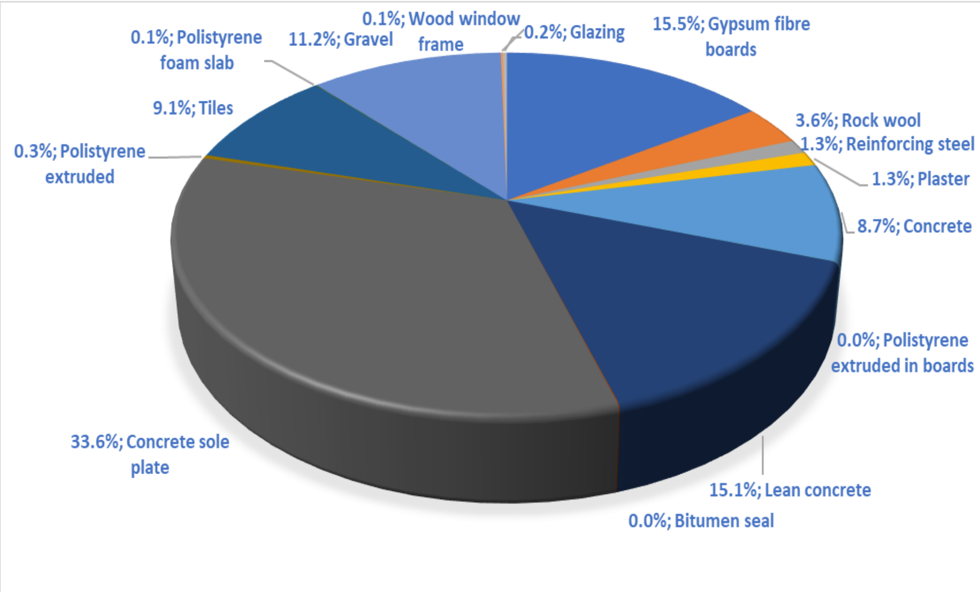


Figure 68: Weight of each material, in percentage on the total weight

In the evaluation of the predominant impact of concrete in the quantification of the impacts calculated using the CED method, it must also be taken into account that the redevelopment work involved the replacement of two entire sides of side walls by re-proposing the pre-existing façade composed of reinforced concrete panels with the addition of a significant amount of insulation, as it is evident from the energy index values calculated in Chapter 6. In addition, further vertical envelope elements were introduced given by the internal walls facing the courtyards created. It should also be considered that the industrial origin of the building determines a redevelopment that is certainly different from that represented by the works for the improvement of the envelope's energy characteristics alone, since heavy structural work has been carried out. Therefore, if one wants to limit the analysis of the influence of the various materials that generally in a building redevelopment case have an effect on the energy efficiency of the building it is appropriate, at least for the moment, to exclude concrete, and consequently also the steel used, from any impact considerations. All simulations of each phase and all scenarios, even the alternative ones presented in chapter 7, have however been carried out both with the presence of cement and steel and without them with also the recalculation of the energy used during the assembly and during the transports foreseen in the different phases.
In following Figure 69 the percentages of the weight of materials once concrete and steel are excluded is shown.

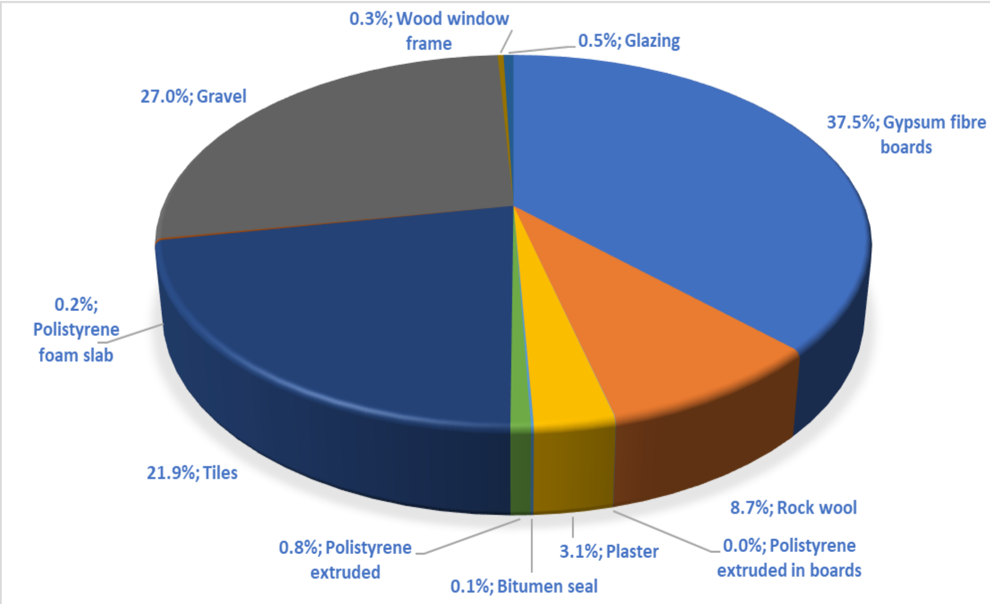


Figure 69: Percentages of the weight of materials, concrete and steel excluded

The consequence of the exclusion of concrete and steel is that primary energy consumption from other materials comes to light. Main primary energy consumption is now due to gypsum fiberboards while insulations account for almost 2%. In Figure 70 and 71 consumptions are shown.

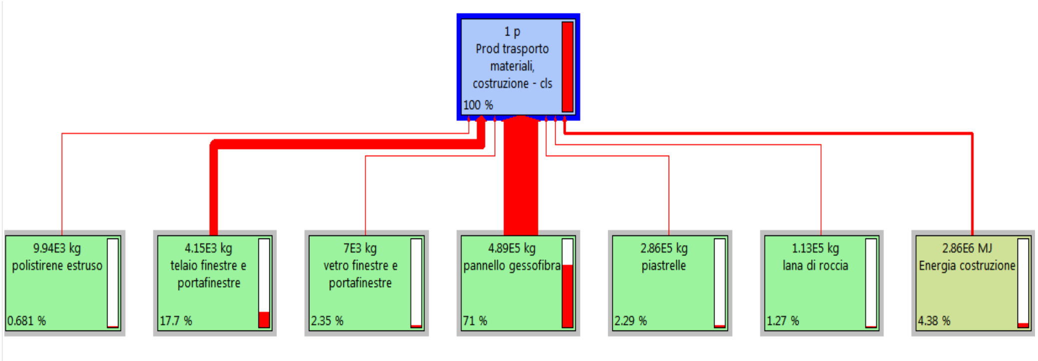


Figure 70: Tree graph of primary energy consumptions, CED method, no concrete and steel

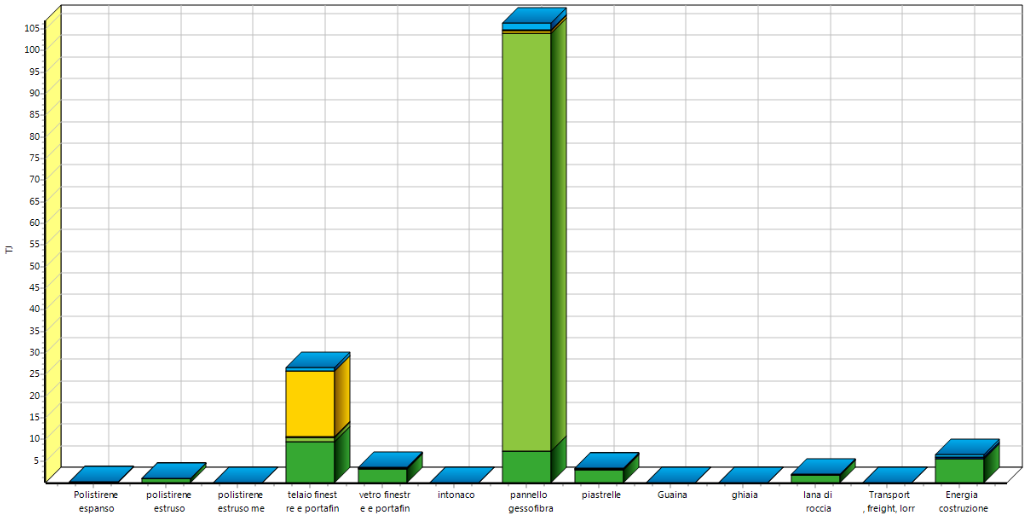


Figure 71: Primary energy consumptions for each material, CED method, no concrete and steel

IPCC GWP 20

Following the considerations about the influence of concrete on impacts and the reasons for its exclusion from calculations, together with steel, results from simulation using IPCC GWP

20 method can be obtained. In the following Figure 72 the tree graph of impacts calculated with IPCC GWP 20 method for Materials Placement is shown.

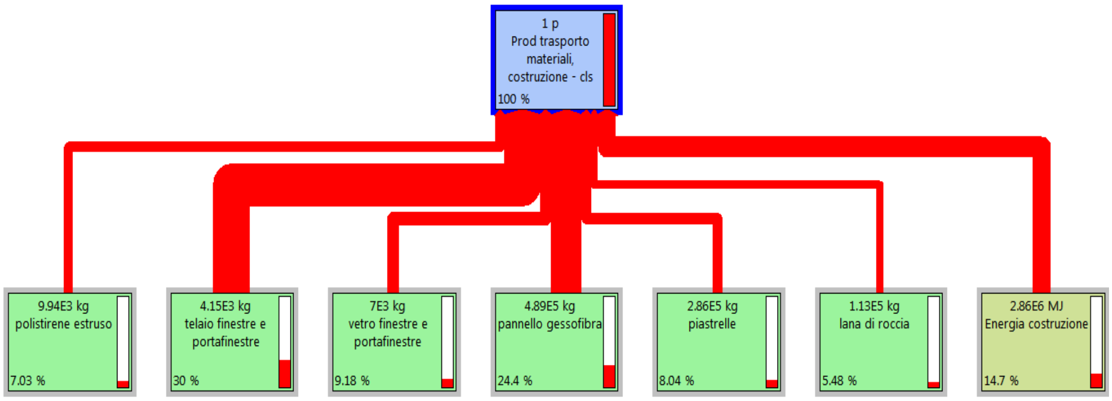


Figure 72: Tree graph of CO2eq, IPCC GWP 20 method, no concrete and steel

Above Figure 72 shows the impact in terms of CO2eq emissions. Main contribution is due to Gypsum fiberboards while insulation accounts for an overall 15%, which is quite remarkable considering they are 2% of overall weight. Extruded polystyrene is responsible for the 7% of CO2eq emissions while rockwool for 8% in the Material Placement phase.

Ecoindicator 99 (H)

Presented results are witn no concrete or steel contribution for the already explained considerations. Eco-indicator 99 (H) score is expressed in MilliPoint (MPt) which represent a damage assessments in relation to three areas: human health, ecosystem quality and resources. Following Figures 73 and 74 show the tree graph of impacts calculated with Ecoindicator 99 (H) method for Material Placement and the impact for any single material expressed in Millipoints and split for the three areas of damage.

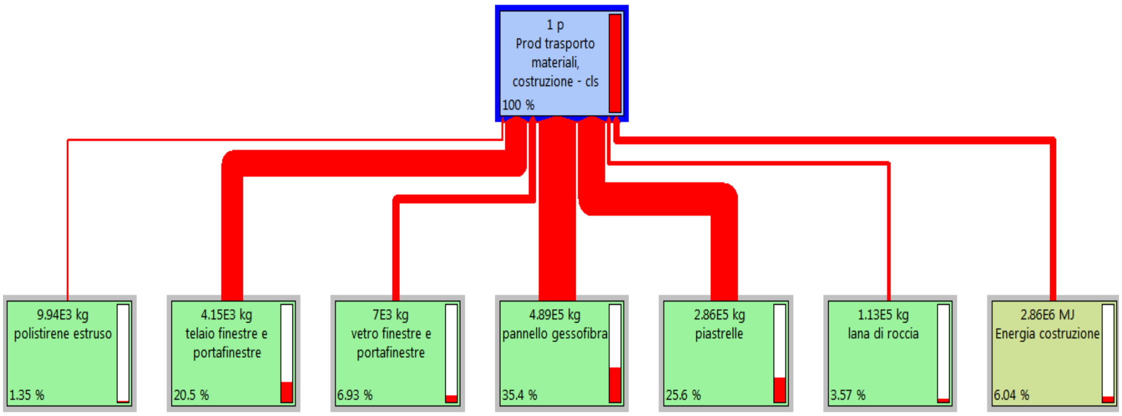


Figure 73: Tree graph of Millipoints, Ecoindicator 99(H) method, no concrete and steel

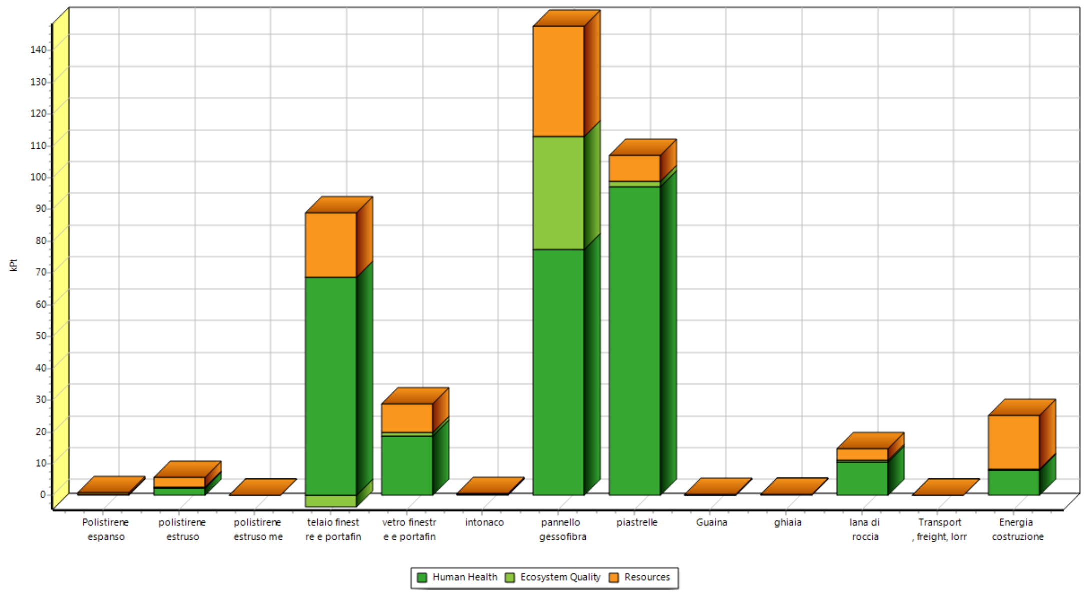


Figure 74: Millipoints for each material and for each area of damage, Ecoindicator 99 (H) method, no concrete and steel

Main contribution in terms of Millipoints is due again to gypsum fiberboards but also tiles and wood window frames have a significant impact. The main damage is for human health with the one for resources at the second place.

4.4.2 II phase: Operational Phase

Calculations relating the Operational phase include impacts during operational phase and from materials replaced during maintenance. Assumptions on replaced materials during the 50 years of building lifespan include windows, plaster and waterproof sheath.

Cumulative Energy Demand (CED)

In the following Figure 75 and 76 the tree graph of main impacts calculated with CED method for Operational phase is shown.

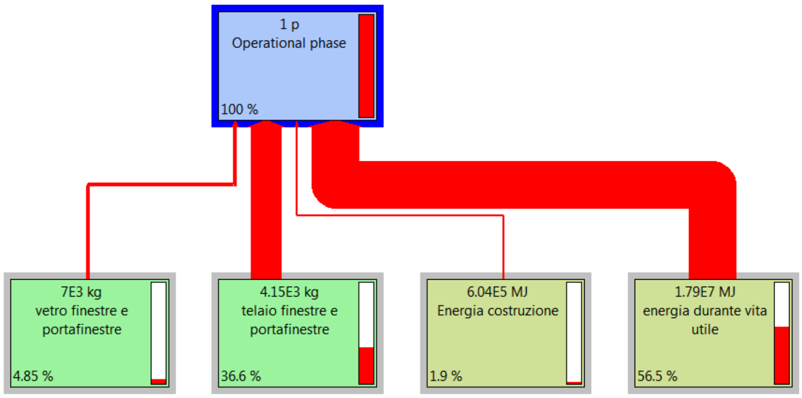


Figure 75: Tree graph of primary energy consumptions, CED method, no concrete and steel

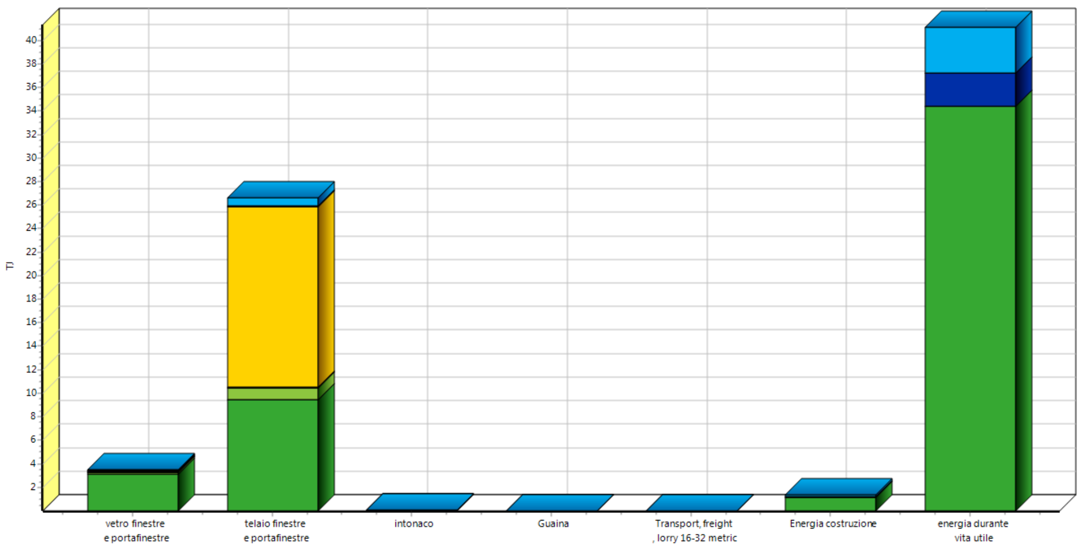


Figure 76: Primary energy consumptions for each material, CED method, no concrete and steel

Main primary energy consumption is due to energy consumption during Operational phase with 56% of total consumption.

IPCC GWP 20

In the following Figure 77 part of tree graph of impacts calculated with IPCC GWP 20 method for Operational phase is shown.

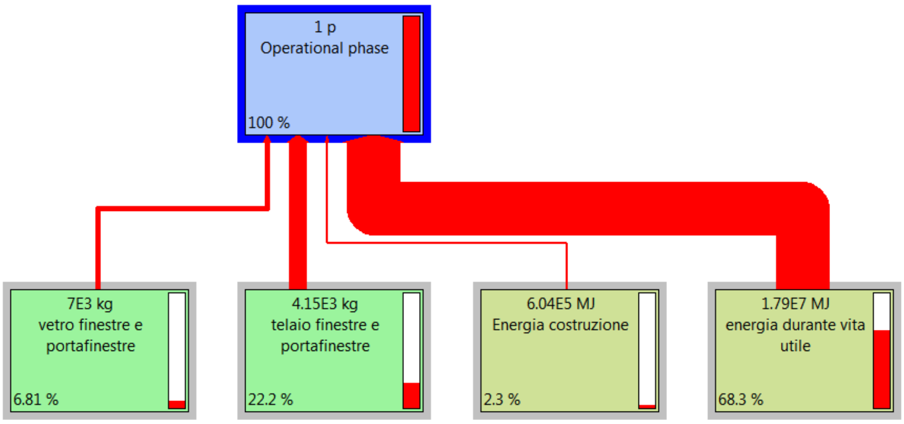


Figure 77: Tree graph of CO2eq, IPCC GWP 20 method, no concrete and steel

Main contribution in terms of CO2eq emissions is due to energy consumption during Operational phase with an overall 68,3%.

Ecoindicator 99 (H)

In the following Figure 78 part of tree graph of impacts calculated with Ecoindicator 99 (H) method for Operational phase is shown.

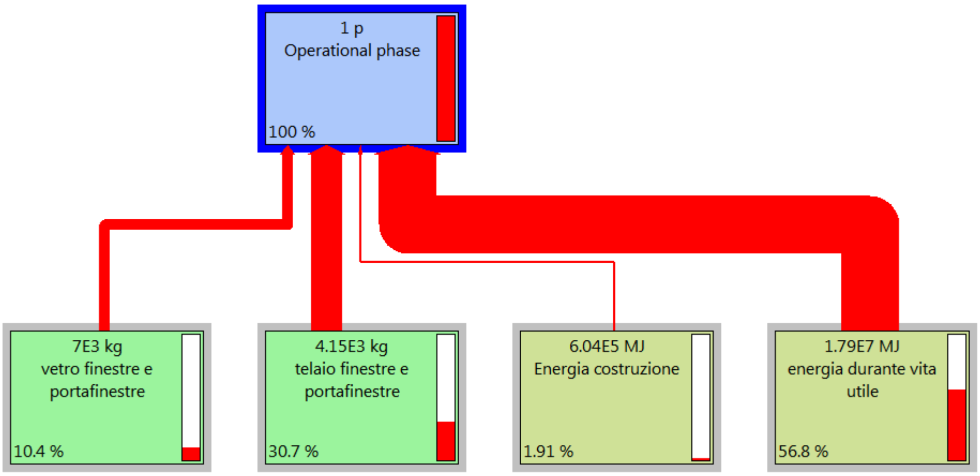


Figure 78: Tree graph of Millipoints, Ecoindicator 99(H) method, no concrete and steel

Main contribution in terms of Millipoints is due again to energy consumption during Operational phase and wood window frames. Following Figure 79 shows the impact for any single material expressed in Millipoints and split for the three areas of damage. The main damages are on human health and resources.

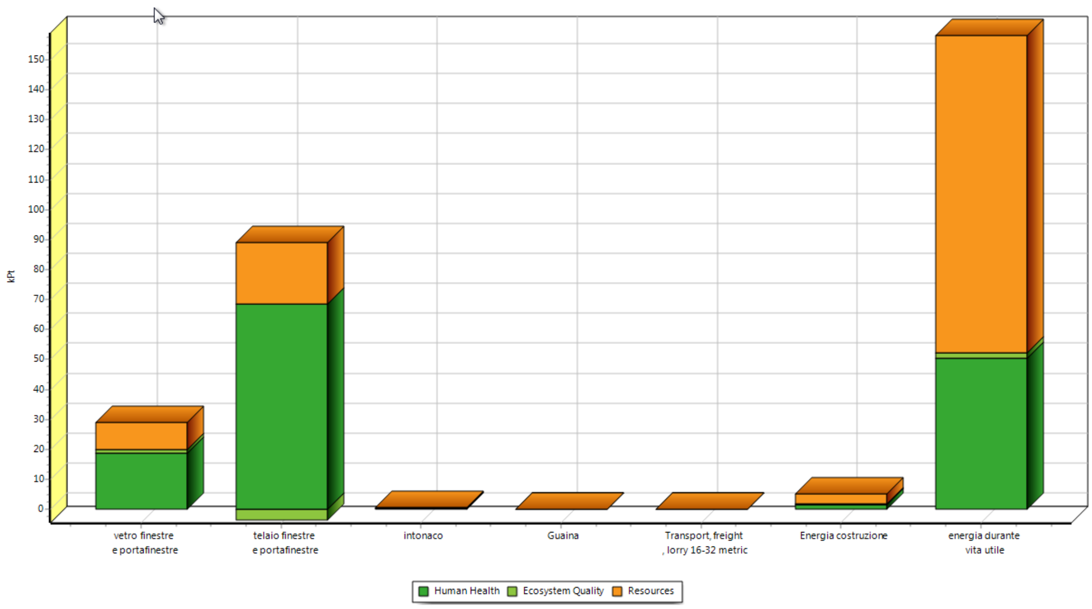


Figure 79: Millipoints for each material and for each area of damage, Ecoindicator 99 (H) method, no concrete and steel

4.4.3 Full Life Cycle

Full Life Cycle calculations include impacts during all previous phases, the Disposal phase via landfilling including transport

Cumulative Energy Demand (CED)

In the following Figure 80 the tree graph of main impacts calculated with CED method for Full Life Cycle is shown.

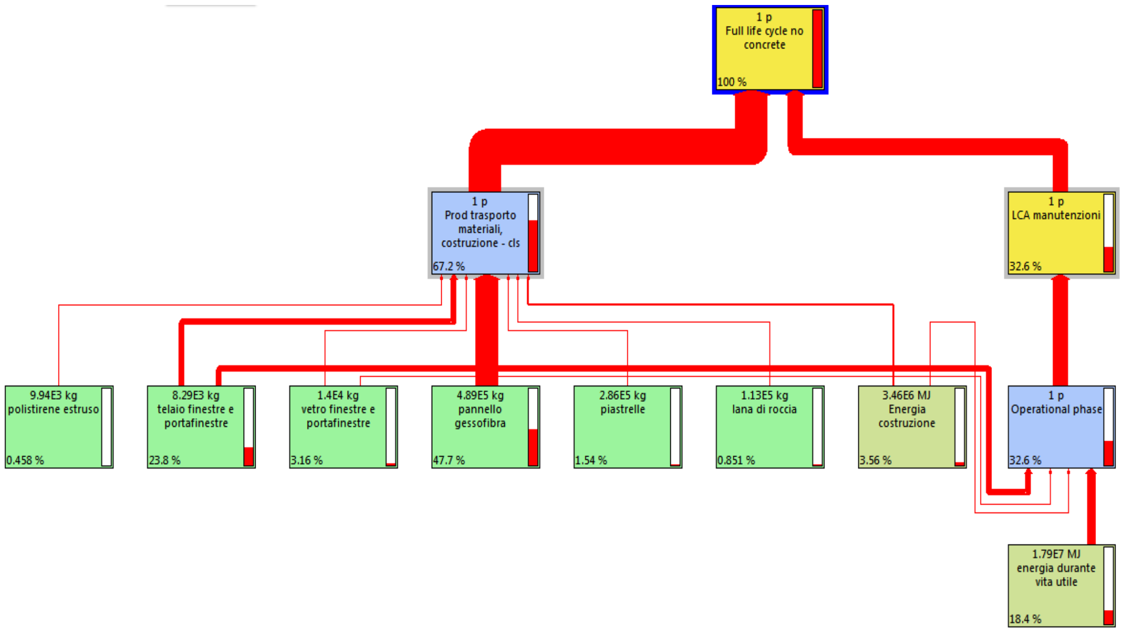


Figure 80: Tree graph of primary energy consumptions, CED method, no concrete and steel

Main primary energy consumptions are due to Gypsum fiberboard, with 47,7% of total consumption and energy consumption during Operational phase with 32,6%. Insulations account for an overall 1,3%.

IPCC GWP 20

In the following Figure 81 part of tree graph of impacts calculated with IPCC GWP 20 method for Full Life Cycle is shown.

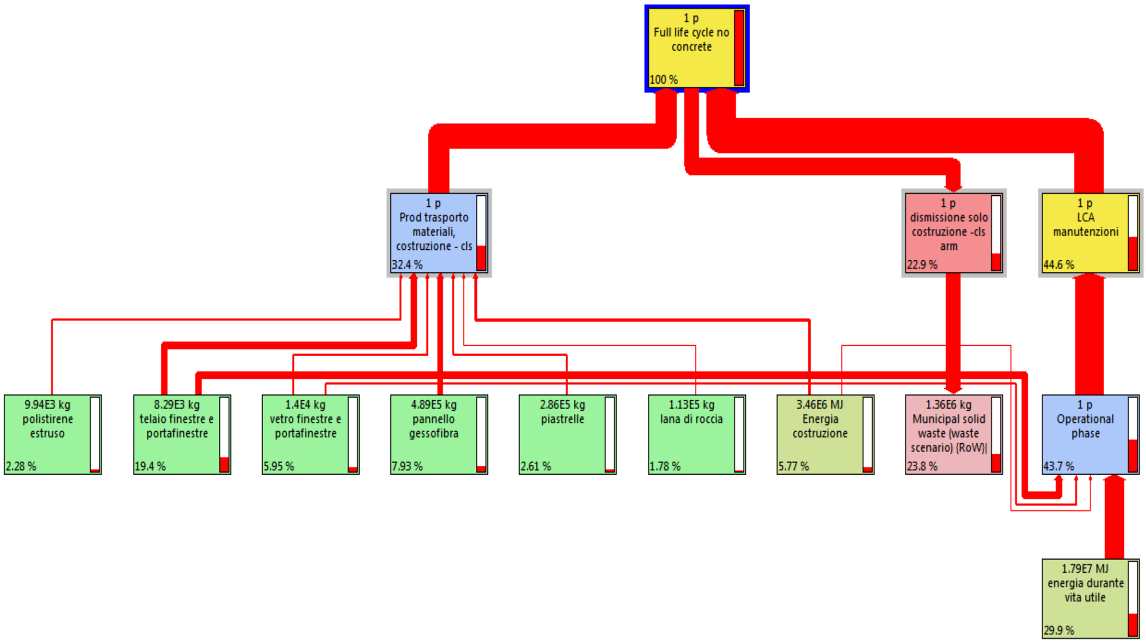


Figure 81: Tree graph of CO2eq, IPCC GWP 20 method, no concrete and steel

Above Figure 81 shows in terms of CO2eq emission the contribution of different phases, processes and materials. It is quite interesting that Operational phase is the main contributor to CO2eq emissions while insulations account for almost a 4% of total.

Ecoindicator 99 (H)

In the following Figure 82 part of tree graph of impacts calculated with Ecoindicator 99 (H) method for Full Life Cycle is shown.

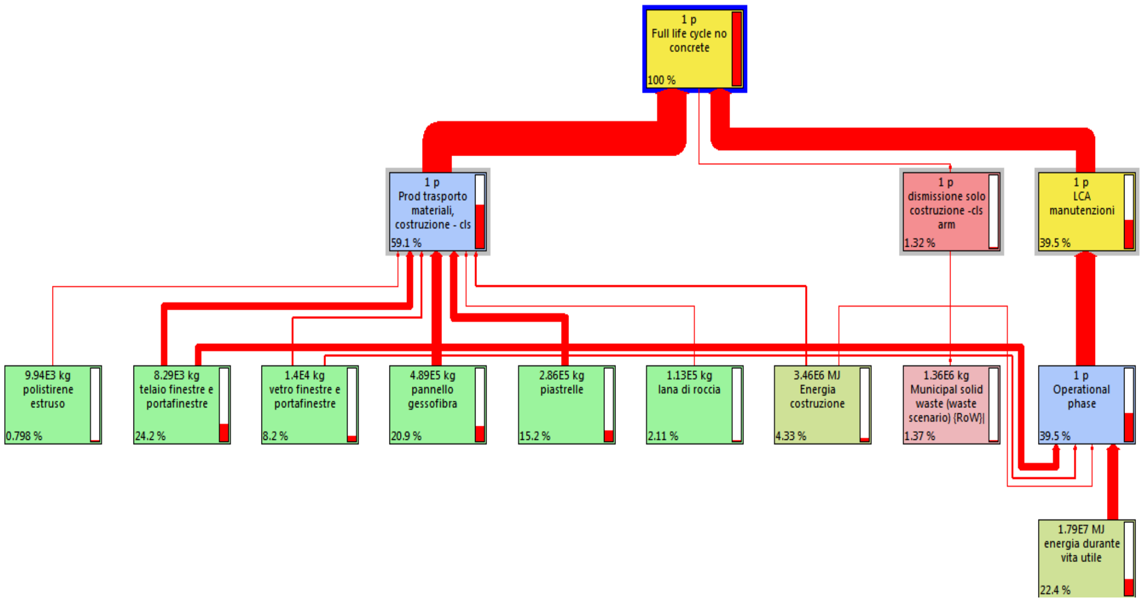


Figure 82: Tree graph of Millipoints, Ecoindicator 99(H) method, no concrete and steel

Above Figure 82 shows in terms of Millipoints the contribution of different phases, processes and materials. It is quite interesting that Materials Placement phase is the main contributor while insulations account for almost a 2,9% of total. Among other materials wood window frames and gypsum fiberboards have a significant impact.

Following Figure 83 shows the impact for any single material expressed in Millipoints and split for the three areas of damage. The main damages are on human health and resources.

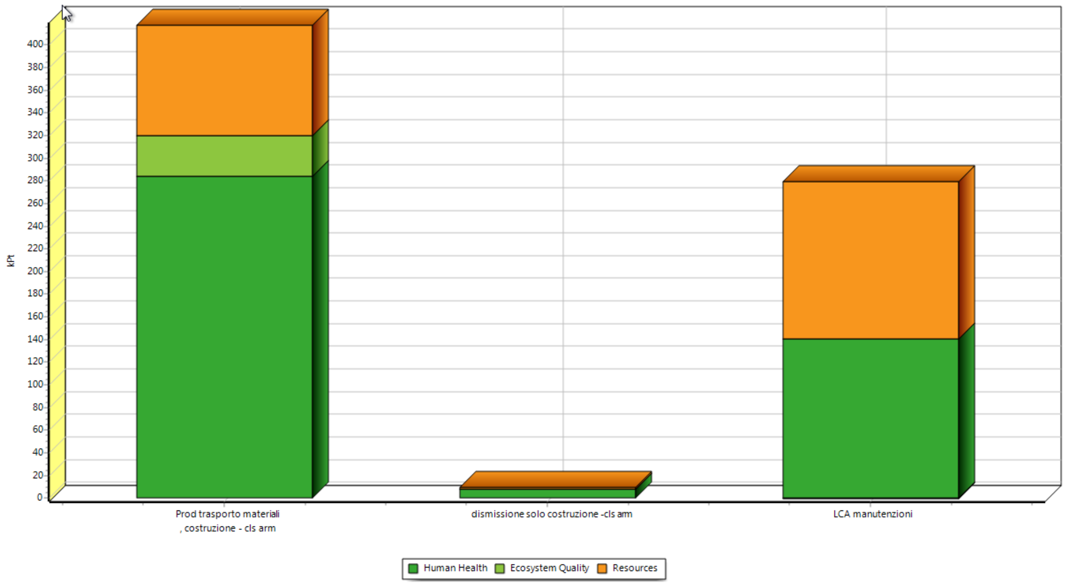


Figure 83: Millipoints for each material and for each area of damage, Ecoindicator 99 (H) method, no concrete and steel

4.5 Considerations on LCA analysis

The refurbishment works of the building not only involved the energy efficiency improving of the envelope but also the reconstruction of the infill on two external sides of the building and the construction of the vertical walls facing the inner courtyard. These works strongly influenced the first results of the LCA analysis as the reconstruction of the external walls made of reinforced concrete panels not only represented the largest part of the material used, in terms of mass, but also had the greatest impact as verified with all the evaluation methods used. Therefore, aiming in particular to analyze the environmental impact of the insulation and taking note that the work as carried out deviates from the usual case study of the energy requalification of a building, it was decided not to consider the impacts due to the concrete and steel, and new simulations were carried out taking these exclusions into account. The simulations using the Cumulative Energy Demand (CED), IPCC GWP 20 and Econindicator 99 (H) methods showed that in the Materials Placement phase, the material with the greatest impact for all models is gypsum fiberboard and that the weight of insulation varies from 2% in the CED method to 15% in the IPCC GWP 20 method. However, it must be taken into account that the total mass of insulation is 9.5% of all materials, excluding cement and steel, with rock wool alone accounting for 8.7%. Between the two insulations polystyrene seems to have the greater impact. As can be seen in Table 12 it represents only a small fraction of the total weight of the insulations but still has a significant impact in all evaluation models.

Insulation	% on total weight of insulation	Weight Ratio	% in impact due to insulation CED method	CED Ratio	% in impact due to insulation IPCC GWP 20 method	IPCC GWP 20 Ratio	% in impact due to insulation Ecoindicator 99 (H) method	Ecoindicator 99 (H) Ratio
Rockwool	91,3	1	65,1	1	43,8	1,28	72,5	1
Polystirene extruded	8,7	10,46	34,9	1,86	**56,2**	1	27,5	2,63

Table 12: Insulation percentages and ratios for mass and related impacts with the evaluation methods, Materials Placement phase

Above Table 12 shows polystyrene impacts calculated using the three different methods of assessment. Although it represents the smaller part on insulations in terms of mass it has remarkable impacts especially for CO2eq emissions for Materials Placement phase.
For the Operational phase simulations show that energy consumption during Operational phase is constantly at first place as source of impact for all the three evaluation methods.
For the Full Life Cycle the materials with greater impact are gypsum fiberboards and wood window frame that are constantly in the first two places according the three models. The impact of insulation varies from around 1,3% in the CED method to 3,9% in the IPCC GWP 20 method. Impacts of the two different insulations in all evaluation models for the Full Life Cycle are substantially confirmed and are the ones provided in previous Table 12.

Chapter 5.

ITACA Protocol – PdR UNI 13/19 application

5.1. The reasons for a choice

The rating system chosen for the research part concerning rating systems is the ITACA Protocol - PDR 13/19. As already said in Chapter 1 ITACA Protocol is, at national level, one of the most widespread tools for assessing the level of energy and environmental sustainability of buildings.
One of the reasons that led to this choice was undoubtedly its being well-known and widespread, the other is its connection with the legislation related to energy e sustainability in the constructions field and with technical standards. ITACA is a public body as it was founded by the Conference of Italian Regions, therefore, given its genesis, the attention towards the norms issued by the state or technical standards cannot but be maximum. The criteria of which the ITACA Protocol is composed, when they deal with environmental issues that are regulated by the legislator, i.e. when there is a legal limit or where a technical standard plays an important role, take these references as the minimum level of fulfilment of the criteria. This characteristic of being so attentive to standards is one of the strengths of the ITACA Protocol and differentiates it from almost all other rating systems that have only rarely been adapted to the national reality. An example of this is the correlation between ITACA Protocol and Ministerial Decree (DM) 11 October 2017 which contains the "Minimum Environmental Criteria (CAM) for design services and works for new construction, renovation and maintenance of public buildings"; Minimum Environmental Criteria (CAM) are the environmental requirements defined for the various stages of the purchasing process operated by the public administration, aimed at identifying the best design solution, product or service from an environmental point of view along the life cycle, taking into account market availability. Their systematic and homogeneous application allows the dissemination of environmentally oriented technologies and products and produces a leverage effect on the market, inducing less virtuous economic operators to adapt to the new demands of the public administration.
For the reasons already explained, it is clear that the introduction of a public building regulation of such importance cannot but have consequences for the ITACA Protocol, which is always so attentive to new national regulations. As a consequence of the introduction of the decree, the Protocol was modified, and the changes that led to the current version were induced precisely by the innovations contained in the decree.
Therefore, it can be said that the ITACA Protocol is well known, widespread and takes the legislation related to energy and sustainability in the constructions field and the technical standards very much into account; all these reasons make understand how useful design tool

ITACA Protocol is, and for these considerations it seemed the most appropriate choice to use it for the research.

5.2. ITACA Protocol framework

ITACA Protocol is a multicriteria building environmental sustainability assessment framework and, as other rating systems, it allows to verify the environmental performance of a building from different points of view: human health, expenditure of energy, water and other resources; it also promotes the construction of increasingly innovative buildings and the use of sustainable materials produced with low energy consumption and able to guarantee high levels of comfort. The Protocol gives an objective and comparable evaluation using indicators and verification methods compliant with the technical standards and national laws. The Practice contains criteria and rules on the evaluation of new and renovated buildings and it is divided into 3 sections: Section 0 is about general framework and methodological principles; Section 1 and Section 2 which specify the criteria for the assessment of environmental sustainability and the calculation of the performance score of buildings for residential and non-residential use (for offices, commercial, school, industrial and hospitality).
The starting point for the definition of the evaluation system are:

- the determination of the areas of assessment and of greater environmental impact;
- the identification of criteria that make it possible to measure the environmental performance of the building in question;
- the definition of reference performance (benchmark) considered the national and international legislation in force with which to compare those of the building for the purpose of assigning a score
- the attribution of weight to the criteria that determine its importance;
- the final aggregation of scores to determine the final synthetic score that defines the degree of improvement of the overall performance compared to the standard level.

One of the key point in the entire procedure af assessment is the determination of the score for each criterion and, eventually, the overall score. For each criteria, a score is assigned from -1 to +5. Score 0 represent the benchmark (law limits if available or typical acceptable practice) and positive score correspond to better practice. Negative score means that the building in a particular aspect is poor of quality, less than the benchmark. The total score is calculated by multiplying the score of each criteria by its appropriate weight and then adding the scores of all criteria. Therefore there are some steps to follow to obtain the overall score for a building:

- Assign a score to the environmental indicator for each criterion;
- Weight the score for each criterion with reference to the importance of that criterion in the Category;
- Add the weighted scores of the criteria of a single Category;

$$S_{i,j} = \sum_{k=1}^{N_c^{(i,j)}} \omega_{i,j,k}\ s_{i,j,k}$$

- Weight the score for each Category with reference to the importance of that Category in the Area;

$$S_i = \sum_{j=1}^{N_c^{(i)}} w_{i,j}\ S_{i,j}$$

- Add the weighted scores of the Categories of a single Area;
- Add the scores of all the Areas taking into account the different importance of each Area.

$$S_{QE} = 0{,}05\ S_{A3} + 0{,}45\ S_B + 0{,}2\ S_C + 0{,}2\ S_D + 0{,}1\ S_E$$

$$S = 0{,}1\ S_{QL} + 0{,}9\ S_{QE}$$

The final score is composed by Sql, which represents the score for the location, and Sqe as score for the building.
The weights of each area and each category within the same area are shown in the following Table 13. It is important to note, as already expressed in the previous equation, that the overall score is given by the sum of the result obtained from Category A.1, which represents the quality of the site (Sql), and the sum of the result from Category A.3 and areas B, C, D and E (Sqe).

Evaluation Areas weights		
	Weight	Weight
Category A.1 Site selection	100%	
Location quality		10%
Category A.3 Project infrastructure and services	5%	
Area B: Energy and resource consumption	45%	

Area C: Environmental loadings	20%	
Area D: Indoor environmental quality	20%	
Area E: Service quality	10%	
Building quality		90%

Table 13: Weights of each area and each category in ITACA Protocol

The described articulation shows the hierarchical structure of the Protocol divided into Areas, Categories and evaluation criteria. In following Figure 84 the hierarchical structure of ITACA Protocol is shown for Area A.

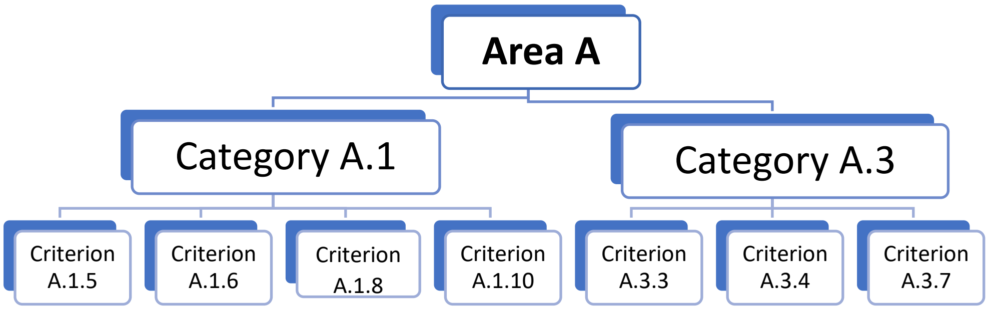


Figure 84: Hierarchical structure of Area A

The Evaluation Areas, which are the macro themes that determine the sustainability characteristics of the intervention, are: Site Quality, Resource Consumption, Environmental Loads, Indoor Environmental Quality and Service Quality. With reference to the context and location of the building, the tool adapts by allowing the exclusion from the global system of criteria whose indicators cannot be evaluated due to the intrinsic characteristics of the building or the place of intervention. In the following a complete list of Areas and Categories is given.

Area A – Site quality
Cat. A.1 Site selection
Cat. A.3 Project infrastructure and services

Area B – Energy and resource consumption
Cat. B.1 Not renewable primary energy
Cat. B.3 Energy from renewables
Cat. B.4 Eco-friendly materials
Cat. B.5 Use of drinking water

Cat. B.6 Envelope performance

Area C – Environmental loadings
Cat. C.1 CO2 emissions
Cat. C.3 Solid waste
Cat. C.4 Wastewater
Cat. C.6 Impact on project site

Area D – Indoor environmental quality
Cat. D.2 Indoor air quality and Ventilation
Cat. D.3 Air temperature and relative humidity
Cat. D.4 Daylighting and illumination
Cat. D.5 Noise and acoustics
Cat. D.6 Electromagnetic emissions

Area E – Service quality
Cat. E.2 Functionality and efficiency
Cat. E.3 Controllability
Cat. E.6 Maintenance of operating performance
Cat. E.7 Social aspects

Criteria have a common structure where some information are always displayed:

- Type of project (new or renovation)
- Name of criterion
- Criterion code
- Evaluation area
- Category
- Environmental goal or intent
- Criterion weight
- Performance indicator
- Score
- Assessment method
- Information source
- Standards or references.

Following Figure 85 represents an example of a criterion with some information displayed.

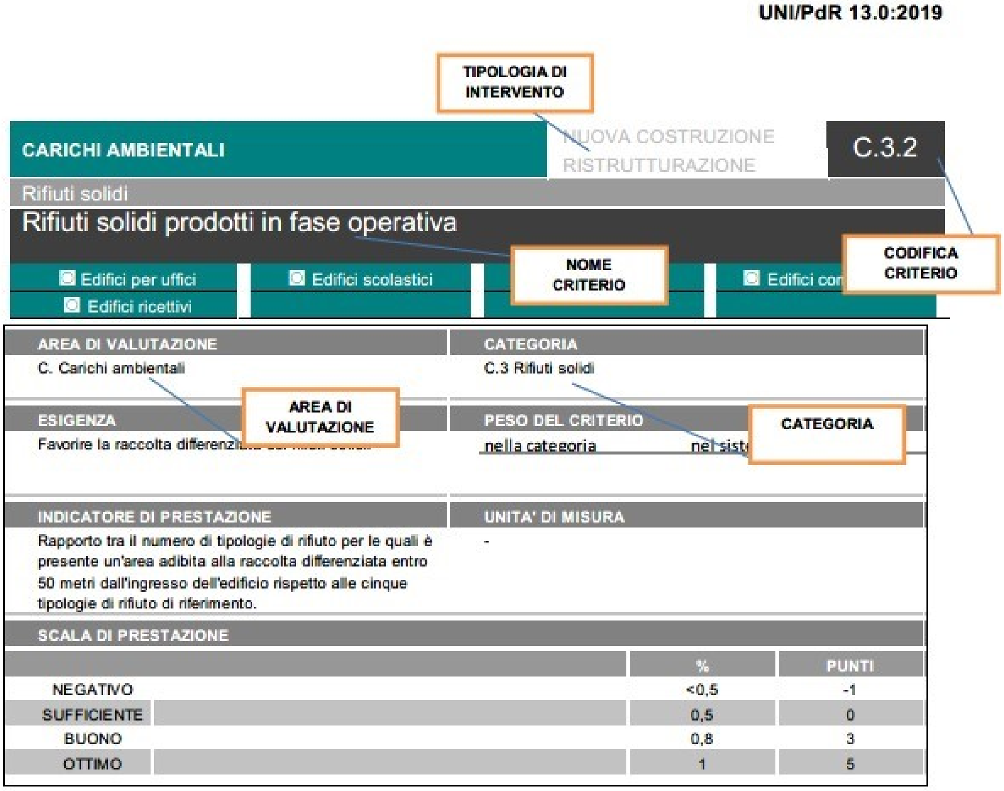


Figure 85: Example of a criterion

The number of criteria contributing to the assessment is not the same for all buildings. Depending on the building type, this number changes. The following table shows the relevant number of criteria for each building type and for each evaluation Area.

Evalua-tion Area	Offices	Schools	Retail	Indu-strial	Hospita-lity	Residen-tial
A	7	8	6	6	7	7
B	16	16	16	16	16	15
C	6	6	6	6	6	6
D	9	9	5	5	9	7

E	5	6	5	4	5	3
TOTAL	**43**	**45**	**38**	**37**	**43**	**38**

Table 14: Number of criteria for each building type and for each evaluation Area

The building relates to the residential column with the exclusion of some criteria whose indicators cannot be evaluated due to the intrinsic characteristics of the building or the place of intervention.

5.3. Results

The results of the application of the ITACA Protocol - PDR 13/19 have been divided by evaluation Areas. The following Table 15 shows the results for Area A. The results are shown per individual criterion whose identifier is a 3-digits code of the type L.1.1.

Area A: Site quality	
A.1	**Site selection**
A.1.6	**Public transport accessibility**
Score	1,5
A.1.10	**Proximity to infrastructures**
Score	5
A.3	**Project infrastructure and services**
A.3.4	**Support for bicycle use**
Score	-1
A.3.10	**Support for green mobility**
Score	0

Table 15: Results for Area A

Scores from Area A shows a bad performance for the Category A.3. No solutions to support green mobility have been provided.
The following Table 16 summarizes the results for Area B.

Area B: Energy and resource consumption	
B.1	**Not renewable primary energy**
B.1.2	**Not renewable primary energy demand**
Score	5
B.1.3	**Global primary energy demand**
Score	3,08
B.3	**Energy from renewables**
B.3.2	**Renewable energy for thermal use**
Score	5
B.3.3	**On site electricity from renewables**
Score	5
B.4	**Eco-friendly materials**
B.4.1	**Reuse of existing structures**
Score	5
B.4.6	**Recycled materials**
Score	-1
B.4.7	**Materials from renewable sources**
Score	0
B.4.8	**Local materials**
Score	-1
B.4.10	**Disassembled materials**
Score	-1
B.4.11	**Certified materials**
Score	0,5
B.5	**Use of drinking water**
B.5.1	**Drinking water for irrigation purposes**
Score	0,83
B.5.2	**Indoor drinking water**
Score	5
B.6	**Envelope performance**
B.6.1	**Useful thermal performance index for winter air conditioning**
Score	2,69
B.6.2	**Useful thermal performance index for summer air conditioning**

Score	1,13
B.6.3	**Heat transfer by transmission**
Score	2,87
B.6.4	**Solar radiation control**
Score	5

Table 16: Results for Area B

Scores from Area B shows a good performance for the Categories related to energy B.1, B.3 and B.6. In Chapter 3 and 5 a full description of installed systems, renewable sources and envelope cross sections testify the attention to the issue. On the contrary, apart from the criterion related to reuse of existing structures, the others included in Category B.5 shows as a poor attention has been given to the use of materials with the characteristics assessed by ITACA Protocol.
The following Table 17 summarizes the results for Area C.

Area C: Environmental loadings	
C.1	**CO2 emissions**
C.1.2	**Expected emissions in the use phase**
Score	5
C.3	**Solid waste**
C.3.2	**Solid waste generated during use phase**
Score	5
C.3.3	**Reuse of excavated soil**
Score	5
C.4	**Wastewater**
C.4.1	**Wastewater sent to sewer**
Score	5
C.4.3	**Soil permeability**
Score	5
C.6	**Impact on project site**
C.6.8	**Heat island effect**
Score	0,03

Table 17: Results for Area C

Scores from Area C shows an excellent performance for all the Categories apart from the criterion related to heat island effect.
The following Table 18 summarizes the results for Area D.

Area D: Indoor environmental quality	
D.2	**Indoor air quality and Ventilation**
D.2.1	**Effectiveness of natural ventilation**
Score	-1
D.3	**Air temperature and relative humidity**
D.3.2	**Summer operating temperature**
Score	0
D.4	**Daylighting and illumination**
D.4.1	**Natural lighting**
Score	-1
D.5	**Noise and acoustics**
D.5.6	**Acoustic quality of the building**
Score	0
D.6	**Electromagnetic emissions**
D.6.1	**Magnetic fields at industrial frequency (50 Hertz)**
Score	3

Table 18: Results for Area D

Scores from Area D shows a poor performance for almost all the Categories. This result is probably due to the situation of operating on an existing building where choices are not possible.
The following Table 19 summarizes the results for Area E.

Area E: Service quality	
E.3	**Controllability**
E.3.5	**B.A.C.S.**
Score	4

E.6	Maintenance of operating performance
E.6.5	**Availability of technical documentation**
Score	5
E.6.6	**Availability of technical documentation (B.I.M.)**
Score	0

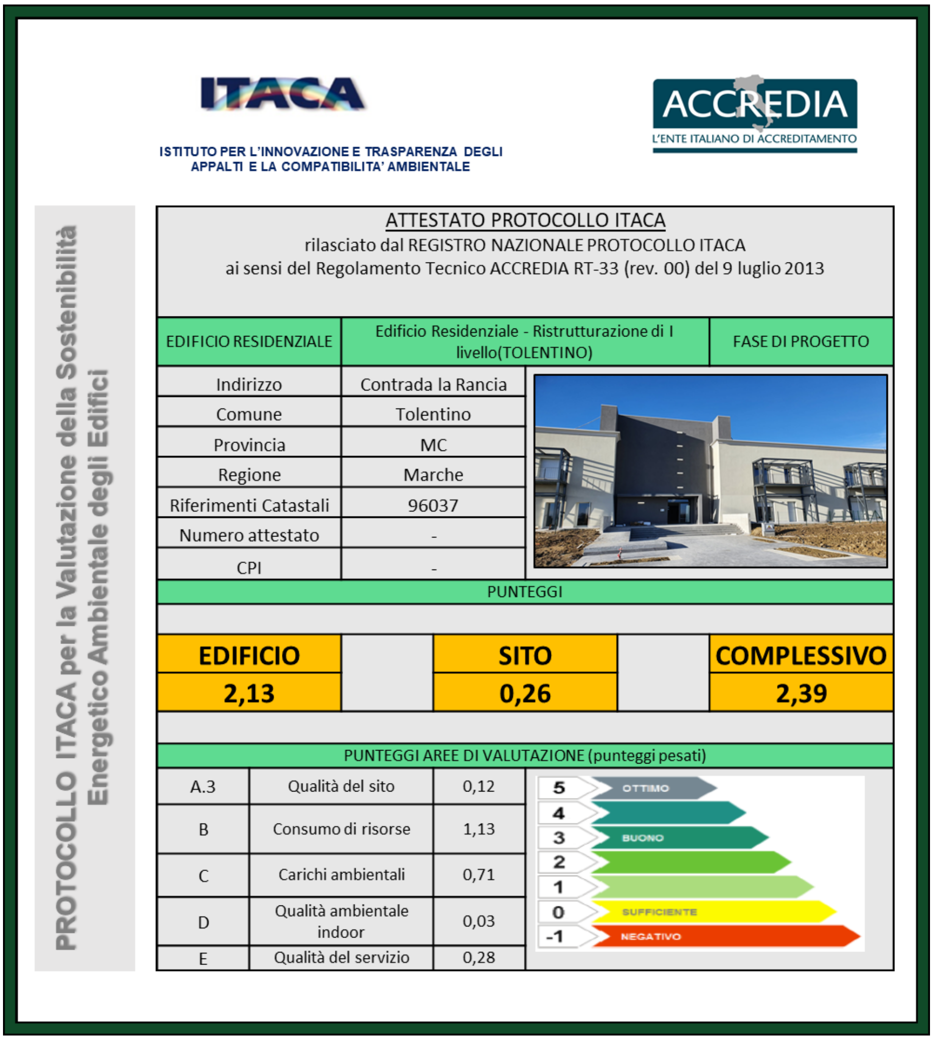
Table 19: Results for Area E

Scores from Area E shows a good performance apart from the criterion related to use of B.I.M. on the design stage.
In the following Table 20 overall result for Category A.3 and Areas B, C, D and E are summarized. Scores in Table 20 take into account the weighting process described in Paragraph 5.2.

Category A.3 Project infrastructure and services	0,12
Area B: Energy and resource consumption	**1,13**
Area C: Environmental loadings	**0,71**
Area D: Indoor environmental quality	**0,03**
Area E: Service quality	**0,28**

Table 20: Weighted results for Category A.3 and Areas B, C, D and E

The results show how in areas B and C the building achieves a very good performance while the performance of the other areas is more disappointing. Another fact that can be grasped is how the weight of Area B, already highlighted in section 5.2, influences the overall result.
The design team had to work on an existing structure and therefore many of the results obtained are influenced by the pre-existing situation on which they could not intervene as if they were designing a new building from scratch.
As a conclusion of the process of application of ITACA Protocol – PDR 13/19 it is possible to obtain a certificate in which main information on the building and scores for each Area and for the whole building are provided. Following Figure 86 shows an example of ITACA Protocol certificate for the building.



ITACA

ISTITUTO PER L'INNOVAZIONE E TRASPARENZA DEGLI APPALTI E LA COMPATIBILITA' AMBIENTALE

ACCREDIA

L'ENTE ITALIANO DI ACCREDITAMENTO

PROTOCOLLO ITACA per la Valutazione della Sostenibilità Energetico Ambientale degli Edifici

ATTESTATO PROTOCOLLO ITACA

rilasciato dal REGISTRO NAZIONALE PROTOCOLLO ITACA

ai sensi del Regolamento Tecnico ACCREDIA RT-33 (rev. 00) del 9 luglio 2013

EDIFICIO RESIDENZIALE	Edificio Residenziale - Ristrutturazione di I livello(TOLENTINO)	FASE DI PROGETTO
Indirizzo	Contrada la Rancia	
Comune	Tolentino	
Provincia	MC	
Regione	Marche	
Riferimenti Catastali	96037	
Numero attestato	-	
CPI	-	

PUNTEGGI

EDIFICIO	SITO	COMPLESSIVO
2,13	0,26	2,39

PUNTEGGI AREE DI VALUTAZIONE (punteggi pesati)

A.3	Qualità del sito	0,12
B	Consumo di risorse	1,13
C	Carichi ambientali	0,71
D	Qualità ambientale indoor	0,03
E	Qualità del servizio	0,28

Figure 86: Example of ITACA Protocol certificate for the building

The building reaches an overall evaluation 2,39 points in a range from -1 to 5 which represents a good result especially considering it is an assessment of a renovated building and many elements were already present and not modifiable.

Chapter 6.

Thermal software application

6.1. Legislation and reference standards

The earliest examples of Italian technical regulations on energy efficiency and the environment are decades old. Even if a new regulatory framework amended previous regulation, a considerable set of laws, decrees and standards are in force.
The purpose of the present study is not to give an exhaustive list of all the regulations on energy efficiency, but it is useful to have an overview of the most important ones. For the same reason, a list of the technical standards is not given.
While methods of calculation and technical standards have changed during the years, the main indexes on energy efficiency are still indicated in a report whose first example was in the Law n.10 of the 17th of January 1991 on the rational use of energy, energy saving and the development of renewable sources of energy. Those indexes still represent the basis for the calculation of energy consumption of a building due to heating, cooling and domestic hot water (DHW), which are extremely important for the purpose of the present report.
Mandatory uses of renewables in buildings are regulated by the Decree n.28 of 3rd of March 2011, implementation of the Directive 2009/28/CE on the promotion of the use of energy from renewable sources. In the Decree n.28 minimum percentages of energy from renewables to be guaranteed are given.
Of great importance is the Decree 26th of June 2015 on the setting out of minimum requirements and a common framework for calculating energy performance. Methods of calculation of energy indexes and limits in terms of envelope and system performance are provided.
The newest regulation in this brief overview is the Decree n.48 of the 10th of June 2020 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Decree n.48 contains a whole series of amendments and updates to previous legislation that it is important to take into consideration. All the regulations reported above apply to the studied building, since the social housing building is a new construction
The assessment of energy performance in the building–plant system is performed under both winter and summer conditions. The assessment is based upon the energy performance index EP, which expresses the primary energy demand (PED) referred to the useful area, expressed respectively in kWh/m2 per year) and which is calculated according to the instructions provided by the law.
The EP is a standardized performance indicator whose value may change according to the technical and technological solutions adopted. For this reason, when choosing the energy production system and/or the envelope components, it is important to weigh the different

solutions that can be adopted. The goal should be to evaluate the energy feasibility of each possible solution with a goal of maximizing energy efficiency while meeting the regulatory restraints imposed by the law.

PED is associated with regulated energy use during the operational phase of the building life-cycle and it has to be calculated ex-ante according to the national methodologies for asset design assessment and expressed as kWh/m2 per year. In Italy the national methodologies for asset design assessment are included in the Decree 26th of June 2015.

In Italy primary energy demand (PED) do not have an absolute threshold value as it changes for each building. To calculate PED and other requirements the "reference building" is used. The "reference building" is defined as a virtual building which has the same localisation and is geometrically equivalent to that considered in the project, but with thermo-physical characteristics corresponding to the minimum energy requirements in force. To demonstrate that the designed building complies with the regulation two different calculations are made: one for the designed building with its own thermo-physical characteristics and the other for the reference building. The reference building represents a threshold, a limit not to be exceeded. Its thermo-physical characteristics are a sort of maximum allowance. If the calculation gives better values of the requirements for the designed building than those calculated for the reference building, then the project complies with the legislation, otherwise the designer has to change something to get back within the threshold set by law.

It should be remembered that legislation and regulations identify the building services as a single block: however, during the assessment of energy performance, it is advisable to distinguish the energy requirements for: cooling, heating, domestic hot water, lighting, ventilation and transport. This characterization allows an energy audit to be performed in a more comprehensible manner so as to evaluate possible inefficiencies in energy transformation operations.

The overall PED value for a building is given by some elements (PED for heating, domestic hot water, cooling, ventilation, lighting and transport) and it is expressed as follows in terms of not renewable energy.

$$EP_{gl,nren} = EP_{H,nren} + EP_{W,nren} + EP_{V,nren} + EP_{C,nren} + EP_{L,nren} + EP_{T,nren}$$

Where:

- $EP_{H,nren}$: primary energy demand for heating
- $EP_{W,nren}$: primary energy demand for domestic hot water
- $EP_{V,nren}$: primary energy demand for ventilation
- $EP_{L,nren}$: primary energy demand for lightining
- $EP_{T,nren}$: primary energy demand for transport
- $EP_{C,nren}$: primary energy demand for cooling.

It is also possible to write the above equation in terms of renewable energy or not renewable plus renewable energy but, as the main objective is to minimize the use of not renewable energy, it is more interesting to focus on the reported expression.

Calculation of the main energy indexes are made taking into consideration some standards. A not comprehensive list of the principal standards is provided in the following.

UNI/TS 11300-1:2014: Energy performance of buildings - Part 1: Evaluation of energy need for space heating and cooling. The technical specification provides data and methods for evaluating of energy need for space heating and cooling. The technical specification defines the procedures for the national application of UNI EN ISO 13790:2008 according to monthly method for evaluating of energy need for space heating and cooling. The technical specification is aimed at all the possible applications provided by the UNIEN ISO 13790:2008: evaluation of the project (design rating), energy assessment of buildings through the calculation under standard conditions (asset rating) or a specific climatic and operating conditions (tailored rating).
UNI/TS 11300-2:2019: Energy performance of buildings - Part 2: Evaluation of primary energy need and of system efficiencies for space heating, domestic hot water production, ventilation and lighting for non-residential buildings. The technical specification provides data and methods for evaluating: the energy need for hot water production, systems efficiencies and primary energy need for space heating and hot water production, primary energy need for ventilation, primary energy need for lighting of non-residential buildings. The technical specification applies to newly design systems, retrofitting or to existing systems - for heating only - mixed or combined heating and domestic hot water - for producing only hot water, for ventilation only systems, for combined ventilation and space heating systems, for lighting systems in non-residential buildings.
UNI/TS 11300-3:2010: Energy performance of buildings - Part 3: Evaluation of primary energy and system efficiencies for space cooling. This standard specifies data and procedures for the calculation of the energy performance of buildings relating to space heating and cooling and domestic hot water production. This standard is a national guideline for immediate and univocal application of technical specifications elaborated by CEN to support the Directive 2002/91/EC "Energy Performance of Buildings". This standard is divided into 3 parts: Part 1 - Determination of building energy need for space heating and cooling Part 2 - Determination of primary energy and system efficiencies for space heating and domestic hot water production. This Part 3 provides data and methods for the determination of: - seasonal average efficiency of the conditioning system- annual specific need of primary energy for space cooling.
UNI/TS 11300-4:2012: Energy performance of buildings - Part 4: Renewable energy and other generation systems for space heating and domestic hot water production. The technical specification calculates the energy demand for space heating and domestic hot water production if there are subsystems that provide useful thermal energy generation from renewable energy or generation methods other than the flame combustion of fossil fuels treated in UNI / TS 11300-2. The following subsystems for production of heat and / or electricity are considered: solar thermal systems, combustion biomass generators, heat pumps, photovoltaic systems and cogenerators. They are also considered the district heating substations.
UNI/TS 11300-5: Energy performance of buildings - Part 5: Evaluation of energy performance for the classification of building. This technical specification provides methods calculation to determine unambiguously and reproducibly applying technical standards cited in the normative references:
- the primary energy demand of buildings on the basis of the energy delivered and exported;
- the share of energy from renewable sources.

This technical specification also provides explanations and calculation methods concerning, in particular:
1) the evaluation of the contribution of renewable energy in the energy balance;
2) the assessment of the electricity exported;
3) the definition of the compensation modes of needs with electricity through electricity generated from renewable sources;
4) the assessment of electricity produced from cogeneration units.
UNI/TS 11300-6: Energy performance of buildings - Part 6: Evaluation of energy need for lifts, escalators and moving walkways. This technical specification provides data and methods for the determination of the electricity needs for the operation of equipment intended for lifting and transportation of persons or persons accompanied by things in a building, on the basis of the characteristics of the building and plant.
These calculation methods take into account only the electrical energy needs during periods of movement and stop of the operational phase of the life cycle.
UNI EN ISO 14683:2018: Thermal bridges in building construction - Linear thermal transmittance - Simplified methods and default values. This standard is the national version of the ISO 14683:2007. ISO 14683:2007 deals with simplified methods for determining heat flows through linear thermal bridges which occur at junctions of building elements. ISO 14683:2007 specifies requirements relating to thermal bridge catalogues and manual calculation methods.
UNI 10339:1995: Air-conditioning systems for thermal comfort in buildings. General, classification and requirements. Offer, order and supply specifications.
UNI EN ISO 13788: Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation. The internal surface temperature of a building component or building element below which mould growth is likely, given the internal temperature and relative humidity. The method can also be used to assess the risk of other internal surface condensation problems. The assessment of the risk of interstitial condensation due to water vapour diffusion. The method used does not take account of a number of important physical phenomena including the variation of material properties with moisture content; capillary suction and liquid moisture transfer within materials; air movement from within the building into the component through gaps or within air spaces; the hygroscopic moisture capacity of materials. The time taken for water, from any source, in a layer between two high vapour resistance layers to dry out and the risk of interstitial condensation occurring elsewhere in the component during the drying process.
UNI EN 15193: Energy performance of buildings - Energy requirements for lighting. This standard specifies the methodology for evaluating the energy performance of lighting systems for providing general illumination in residential and non-residential buildings and for calculating or measuring the amount of energy required or used for lighting in buildings. The method may be applied to new, existing or refurbished buildings. It also provides a methodology (LENI) as the measure of the energy efficiency of the lighting installations in buildings. This standard does not cover lighting requirements, the design of lighting systems, the planning of lighting installations, the characteristics of lighting equipment (lamps, control gear and luminaires) and systems used for display lighting, desk lighting or luminaires built into furniture. This standard does not provide any procedure for the dynamic simulation of lighting scene setting.

6.2. Energy performance of the building

The software used to calculate energy performance is Termo produced by Namirial. Termo is up-to-date with all the UNI/TS 11300 standards described above. Termo makes it possible to calculate the energy performance of any type of building, residential or otherwise, and for all the services envisaged by the standards, i.e.: heating, cooling, domestic hot water, ventilation, lighting and transport.
The software used returns the output of the Technical Report according to Law 10. The Technical Report according to Law 10 is a technical-descriptive document that defines the performance and efficiency of the building-installation system and was introduced by Law 10 of 1991. The Technical Report Law 10 is an energy project report that contains calculations and energy checks relating to the building-installation system and certifies compliance with the requirements of the regulations in force for limiting the energy consumption of buildings and their systems. Its complexity varies according to the building intervention that it defines, from the more articulated degree of a new construction to the simple replacement of the heat generator. The energy report, in addition to the graphic works (plans, elevations, sections), contains the following data:

- location: cadastral and climatic data
- characteristics, technical and construction data of the building
- data on installed systems
- indications to reduce energy consumption
- data on installed renewable sources
- certification and verification of compliance with the requirements.

The requirements include the compliance of the energy indexes with regulatory limits. In the following Table 21 climatic, technical and construction data of the building are shown.

Day degrees	1906 GG
Design minimum temperature of the air	-1,4 °C
Design maximum summer temperature	31,8 °C
Design minimum winter temperature	-5 °C
Volume of the air conditioned part of the building (V)	12.801,20 m^3
External area of the building containing the air conditioned volume (S)	7.303,15 m^2
S/V Ratio	0,57 m-1
Internal air conditioned area of the building	3.283,60 m^2

Table 21: Climatic, technical and construction data of the building

In Table 21 day degrees are mentioned; they represent for the conventional heating period the sum of daily average temperatures differing from the optimal 20 °C.
In chapter 3 cross sections, data on installed systems and data on installed renewable sources have been already provided.
In the following Table 22 values of the mandatory energy indexes to comply with of the building are shown.

H'T	0,31	W/m²K;
H'T,limit	0,58	W/m²K
EPH,nd	9,31	kWh/m2 year
EPH,nd,limit	19,37	kWh/m2 year
EPC,nd	29,25	kWh/m2 year
EPC,nd,limit	24,21	kWh/m2 year
EPgl,tot	30,34	kWh/m2 year
EPgl,tot,limit	64,13	kWh/m2 year
ηH	0,8267	
ηH,limit	0,5712	
ηW	0,8681	
ηW,limit	0,5481	

Table 22: Mandatory energy indexes to comply with of the building

In Table 22 shown energy indexes have the following meaning:

- H'T is the overall average coefficient of heat transfer by transmission per unit of dispersing surface area;

- H'T,limit is the minimum by Law of the overall average coefficient of heat transfer by transmission per unit of dispersing surface area; H'T has to be lower than H'T,limit as verified for the building;
- EPH,nd is the useful thermal performance index for winter air conditioning of the building;
- EPH,nd,limit is the minimum by Law of the useful thermal performance index for winter air conditioning of the building; EPH,nd has to be lower than EPH,nd,limit as verified for the building;
- EPC,nd is the useful thermal performance index for summer air conditioning of the building;
- EPC,nd,limit is the minimum by Law of the useful thermal performance index for summer air conditioning of the building; EPC,nd has to be lower than EPC,nd,limit and it is no verified for the building;
- EPgl,tot is the overall primary energy demand for the building (renewable + not renewable);
- EPgl,tot,limit is the minimum by Law of the overall primary energy demand for the building (renewable + not renewable); EPgl,tot has to be lower than EPgl,tot,limit as verified for the building;
- ηH is the average seasonal efficiency of the heating system;
- ηH,limit is the minimum by Law of the average seasonal efficiency of the heating system; ηH has to be higher than ηH,limit as verified for the building;
- ηW is the average seasonal efficiency of the domestic hot water production system;
- ηW,limit is the minimum by Law of the average seasonal efficiency of the domestic hot water production system; ηW has to be higher than ηW,limit as verified for the building;

The Italian EPC (energy performance certificate) is the document that provides the assessment of the energy consumption of a building, house or apartment. It is a control tool that synthesizes the energy performance of buildings with a scale from A4 to G (10 letter scale). At the time of buying or renting a property, besides being mandatory, it is useful to have information about energy consumption and to clarify the real value of high energy saving buildings.
For the building have been issued certificates for every residential unit and an overall certificate that is shown in the following Figure 87.

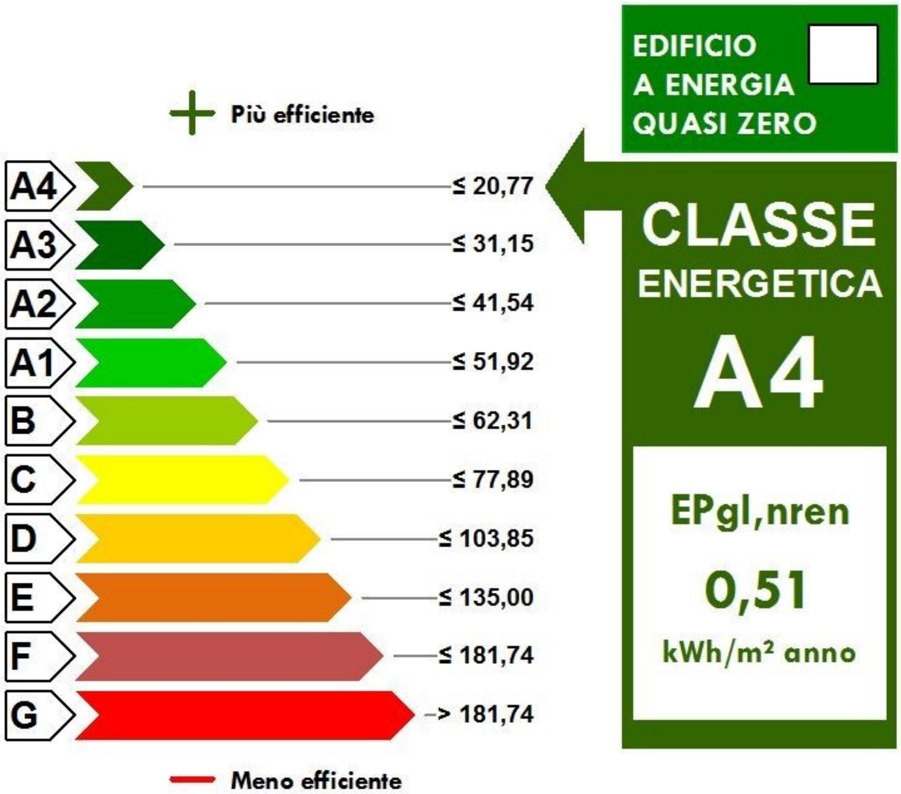


Figure 87: EPC of the building

The building reaches and excellent performance being much lower than the top class limit. Performance is expressed in terms of not renewable energy and the primary energy demand for the building EPgl,nren has a value of 0,51 kWh/m2 year which is much lower than the A4 class limit of 20,77 kWh/m2 year. Such a performance identifies the building as a probably "near-zero energy building" (NZEB).

The requirements to be classified as near-zero energy buildings (NZEB) are defined in national regulation implementing the EU Directives and are mandatory across EU Member States from 2021.

From 2021 new constructions are obliged by national/regional building regulations to comply with NZEB requirements. NZEB requirements correspond to different levels of performance across EU Member States. According to the EPBD Directive, a "nearly zero-energy building" (NZEB) means a building that has a very high energy performance and the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. The definition do not include an absolute threshold therefore the NZEB definition is different in each EU country and, as a result, there are uneven national standards for new buildings.

In Italy, the characteristics of an NZEB are established again by the Decree 26th of June 2015 on the setting out of minimum requirements and a common framework for calculating energy performance: NZEB are buildings, both new and existing, for which the performance requirements set out in the decree itself and the obligations for the integration of renewable sources set out in Legislative Decree 28/2011 on renewables are simultaneously met.

The national standard for NZEB includes also other minimum requirements in addition to the overall limit on energy consumption: the useful thermal performance indexes to be compared with the limit values of the reference building, the average global transmission heat exchange coefficient, the summer equivalent solar area per unit of useful surface, the efficiency of the winter and summer air conditioning systems, the efficiency on the production of domestic hot water and the limits on the transmittance of envelope elements.

It is possible to summarize the requirements for an NZEB building in Italy as having the highest level of EPC, according to the national standard, and meeting the requirements of the Decree 28/2011 on the use of energy from renewable sources. In the Decree n.28 minimum percentages of energy from renewables to be guaranteed are given.

Therefore there is no absolute threshold value to define a NZEB building as different requirements coming from different legislative sources have to be satisfied.
Anyway it can be said that the building meets the requirements for the NZEB definition.

Chapter 7.

Applying changes on the insulation of the reference building

7.1. Changes on the reference case study

The case study presented concerned the renovation of an industrial building converted to residential use. In addition to the modifications to the systems, the infill on two external sides of the building was also reconstructed and an inner courtyard was created with the consequent construction of the vertical walls facing it.
On the case study a thermal analysis, an ITACA Protocol analysis and an LCA analysis has been carried out; especially LCA analysis has been conducted with particular regard to the influence of insulation. In order to verify what influence the modification of the insulation in the case study may have on the results obtained, two alternative case studies were developed. Case study B involves replacing rock wool insulation with wood fiber in the external walls and in some internal walls; the replacement has been envisaged maintaining the same thermal resistance for three external walls out of four while for the internal walls and the fourth external wall total width has been maintained. It has not been possible to change width for the above elements of envelope as it would have meant changing the internal partition. Case study C, in addition to the modifications implemented in case study B, involves replacing all insulation, except for modest amounts of extruded polystyrene present in a panel used in an envelope element, with wood fiber. No modifications to systems have been introduced.
The two new case studies were analyzed with the tools already used in case study A to show how the changes to the insulators are captured by them.

7.1.1 Case B: walls with wood fiber

In Case study B rock wool insulation of vertical element of envelope has been replaced with wood fiber in the external walls maintaining the same thermal resistance of the element of envelope. The main characteristics of the new insulation are in the following:

- Thermal conductivity λ: 0,038 W/mK (previous rock wool 0,033 W/mK)
- Density ρ: 120 Kg/m3 (previous rock wool 75 Kg/m3)

The changes have affected the following external vertical elements:

- M1b wall with precast reinforced concrete panels
- M3 hollow brick wall (building units/staircase)
- M10 balloon frame panel

- M8d wall with METRO-THERM panel

Other internal vertical elements have been interested by changes and they are listed as follows:

- M6 wall between units
- M7 unit internal partitions

In the following Table 23 the main characteristics for the changed cross-sections are provided for each case study, highlighted in yellow the elements with the same or very close thermal resistance while in green with the same width:

	Weight kg/m2	Width m	Thermal resistance R (m2K)/W	Trasmittance U W/(m2K)
M1b Case A	323,63	0,3725	5,101	**0,196**
M1b wood Case B	333,14	0,3955	5,108	**0,198**
M3 Case A	196,63	**0,3725**	4,975	0,201
M3 wood Case B	203,38	**0,3725**	4,377	0,228
M10 Case A	70,63	0,3245	8,613	**0,116**
M10 wood Case B	87,70	0,3655	8,616	**0,116**
M8d Case A	291,53	0,3725	5,120	**0,195**
M8d wood Case B	294,74	0,3805	5,131	**0,195**
M6 Case A	34	**0,095**	2,457	0,407
M6 wood Case B	37,15	**0,095**	2,178	0,459
M7 Case A	88	**0,170**	3,502	0,286
M7 wood Case B	92,5	**0,170**	3,104	0,322

Table 23: Main characteristics of Case study A and Case study B cross-sections

Table 23 shows how all the elements with wood fiber insulation are heavier, due to their greater density, but at the same time, apart from the ones designed to have the same values, with lower thermal resistance because of higher thermal conductivity. For the same reason all the elements with wood fiber and same thermal resistance are wider.

7.1.2 Case C: whole insulation with wood fiber

In Case study C all insulation, except for modest amounts of extruded polystyrene present in a panel used in an envelope element has been replaced with wood fiber. Therefore, changes implemented for Case study B are included in Case study C and, in addition, an external vertical element more and all the three kinds of floor have been modified. The only exception is the vertical element M8d where a second layer of wood fiber has been added compared to the first modification already introduced in case B; so there are three different versions of element M8d, one for each case study. The introduced wood fiber is the same of Case study

B but in two floors a heavier kind has been inserted. All the modified elements have the same width of Case study A as changes would have meant altering the internal dimensions. The main characteristics of the heavier wood fiber are in the following:

- Thermal conductivity λ: 0,048 W/mK (lighter wood fiber 0,038 W/mK)
- Density ρ: 250 Kg/m3 (lighter wood fiber 120 Kg/m3)

Apart from the modifications affecting the vertical elements already described in Case study B further changes have affected the following elements of envelope:

- M2 reinforced concrete wall
- M8d wall with METRO-THERM panel
- S4 Roof
- S2 Unit internal floor
- S0 Ground floor

In the following Table 24 the main characteristics for the changed cross-sections are provided for each case study, all the elements have the same width:

	Weight kg/m2	Width m	Thermal resistance R (m2K)/W	Trasmittance U W/(m2K)
M2 Case A	340,88	**0,3375**	3,367	0,297
M2 wood Case C	346,88	**0,3375**	3,221	0,310
M8d Case A	291,53	**0,3725**	5,120	0,195
M8d wood Case C	300,74	**0,3805**	4,984	0,201
S4 Case A	682,73	**0,729**	5,946	0,168
S4 wood Case C	690,83	**0,729**	5,228	0,191
S2 Case A	865,33	**0,724**	1,997	0,501
S2 wood Case C	875,93	**0,724**	2,621	0,382
S0 Case A	781	**0,739**	2,126	0,470
S0 wood Case C	789,80	**0,739**	2,909	0,344

Table 24: Main characteristics of Case study A and Case study C cross-sections

Table 24 shows how all the elements with wood fiber insulation are heavier, due to their greater density. Better values of thermal resistance for Case study C elements S2 and S0 are due to the slab foam polystyrene used in Case study A which has higher values of thermal conductivity.

7.2 Influence of changes on the thermal analysis

In the following Table 25 main characteristics of the cross sections introduced in paragraphs 7.1.1 and 7.1.2 are summarized.

	Weight kg/m2	Width m	Thermal resistance R (m2K)/W	Trasmittance U W/(m2K)
M1b Case A	323,63	0,3725	5,101	**0,196**
M1b wood Case B	333,14	0,3955	5,108	**0,198**
M1b wood Case C	**Same as Case B**			
M3 Case A	196,63	**0,3725**	4,975	0,201
M3 wood Case B	203,38	**0,3725**	4,377	0,228
M3 wood Case C	**Same as Case B**			
M2 Case A	340,88	**0,3375**	3,367	0,297
M2 wood Case B	**Same as Case A**			
M2 wood Case C	346,88	**0,3375**	3,221	0,310
M10 Case A	70,63	0,3245	8,613	**0,116**
M10 wood Case B	87,70	0,3655	8,616	**0,116**
M10 wood Case C	**Same as Case B**			
M8d Case A	291,53	0,3725	5,120	**0,195**
M8d wood Case B	294,74	0,3805	5,131	**0,195**
M8d wood Case C	300,74	**0,3805**	4,984	0,201
M6 Case A	34	**0,095**	2,457	0,407
M6 wood Case B	37,15	**0,095**	2,178	0,459
M6 wood Case C	**Same as Case B**			
M7 Case A	88	**0,170**	3,502	0,286
M7 wood Case B	92,5	**0,170**	3,104	0,322
M7 wood Case C	**Same as Case B**			
S4 Case A	682,73	**0,729**	5,946	0,168
S4 wood Case B	**Same as Case A**			
S4 wood Case C	690,83	**0,729**	5,228	0,191
S2 Case A	865,33	**0,724**	1,997	0,501
S2 wood Case B	**Same as Case A**			
S2 wood Case C	875,93	**0,724**	2,621	0,382
S0 Case A	781	**0,739**	2,126	0,470
S0 wood Case B	**Same as Case A**			
S0 wood Case C	789,80	**0,739**	2,909	0,344

Table 25: Comparison of the main characteristics of Case study A, B and C cross-sections

The changes made result in different energy indices compared with Case Study A. In Table 26 below, the values found in Case Studies B and C are compared with those of Case Study A.

	Case study A	Case study B	Case study C

H’T W/m²K	0,31	0,25	0,32
H’T,limit W/m²K	0,58	0,58	0,58
EPH,nd kWh/m2 year	9,31	5,39	9,24
EPH,nd,limit kWh/m2 year	19,37	18,86	18,93
EPC,nd kWh/m2 year	29,25	32,76	29,3
EPC,nd,limit kWh/m2 year	24,21	24,35	24,36
EPgl,tot kWh/m2 year	30,34	25,88	30,29
EPgl,tot,limit kWh/m2 year	64,13	63,18	63,31
EPgl,nren kWh/m2 year	0,51	0,53	0,5
EPgl,nren,limit kWh/m2 year	20,57	22,25	22,3

Table 26: Main energy indexes for each Case study

The changes introduced in Case Study B improve the H'T index, as can also be seen from the EP,H,nd index, while the EP,C,nd index worsens.
The changes in Case Study C, on the other hand, bring H'T back to values very similar to Case Study A as also confirmed by the EP,H,nd parameter. These deviations are probably due to the worsening of the transmittance value of the roof, which, being very wide, increases transmission by dispersion. The parameter EP,C,nd, on the other hand, improves probably due to the inclusion of high-density wood fiber insulation.
However some considerations on thermal analysis are already possible and, on the basis of presented case studies, it can be affirmed that the deviations in the values of the various parameters are modest and the thermal analysis, although capable of capturing the differences in the various case studies, cannot give unambiguous indications. It has also to take into consideration that the response of the hybrid central heating system to the applied changes influences the energy indexes in a way that cannot be immediately recognizable and consequently they could be partly responsible for the obtained unambiguous indications.

7.3 Influence of changes on the ITACA Protocol analysis

The changes made with case studies B and C also change the assessment made with the ITACA Protocol.
The following Figure 88 show the certificates obtained with the changes due to Case study B.

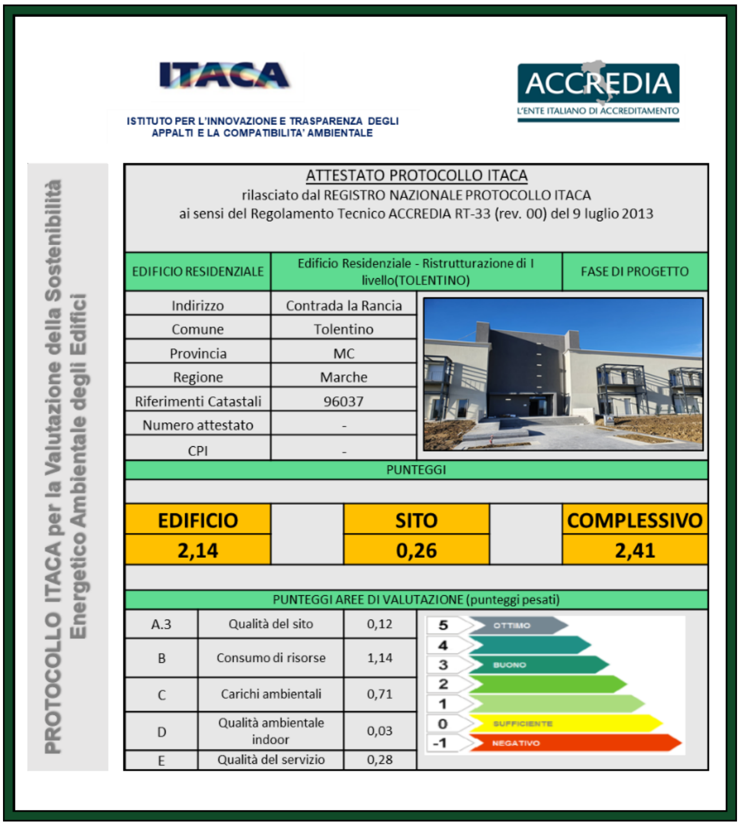


Figure 88: ITACA Protocol certificate for Case study B

The changes implemented in Case Study B increase the overall rating of the building to 2.41 from 2.39, in particular Rating Area B from 1.12 to 1.14.
Thus, however small the changes in the scores, the modifications implemented are recorded by the tool. Going into more detail, the criteria affected by the changes with the new scores compared to the ones of Case study A are shown in Table 27 below.

B.6	Envelope performance
B.6.2	Useful thermal performance index for summer air conditioning

Score	From 1,13 to 1,15
B.6.3	**Heat transfer by transmission**
Score	From 2,87 to 2,88

Table 27: Scores of the criteria affected by changes of Case study B

Compared to Case Study A, the differences can be found only in the indicated criteria. In some cases although the performance indicator changes, the criterion score does not change as the changes still do not allow the minimum score to be exceeded or the maximum score to be exceeded.
The following Figure 89 show the certificates obtained with the changes due to Case study C.

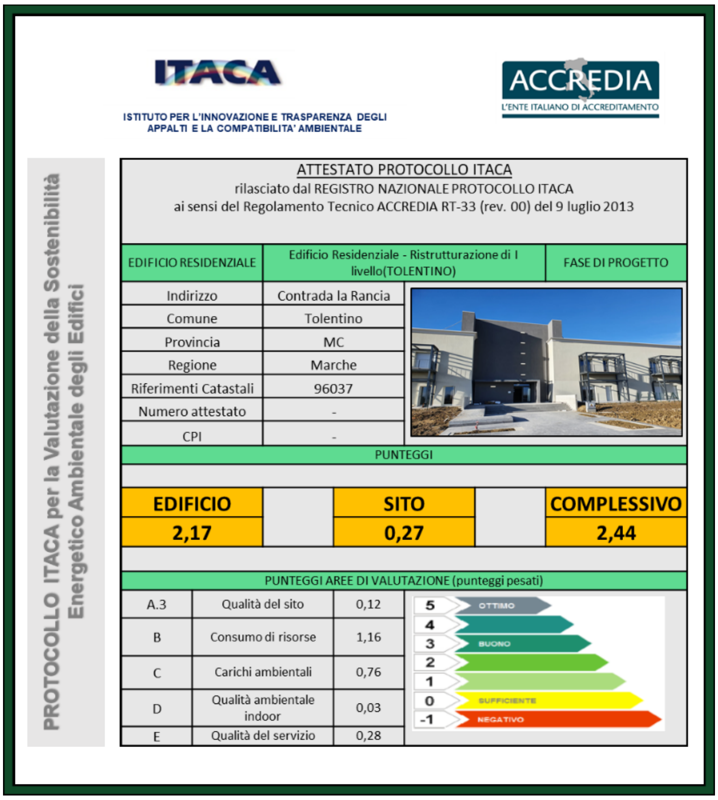


Figure 89: ITACA Protocol certificate for Case study C

The changes implemented in Case Study C increase the overall rating of the building to 2.44 from 2.39, in particular Evaluation Area B from 1.12 to 1.16 and Evaluation Area C from 0,71 to 0,76.

Also with Case Study C the changes in the scores are small, however the modifications implemented are recorded by the tool. Going into more detail, the criteria affected by the changes with the new scores compared to the ones of Case study A are shown in Table 28 below.

B.4	**Eco-friendly materials**
B.4.7	**Materials from renewable sources**
Score	From 0 to 1,1
B.6	**Envelope performance**
B.6.2	**Useful thermal performance index for summer air conditioning**
Score	From 1,13 to 1,14
B.6.3	**Heat transfer by transmission**
Score	From 2,87 to 2,98
C.6	**Impact on project site**
C.6.8	**Heat island effect**
Score	From 0,03 to 1,,8

Table 28: Scores of the criteria affected by changes of Case study C

Compared to Case Study A, the differences can be found only in the indicated criteria. Also for Case study C in some occasions although the performance indicator changes, the criterion score does not change as the changes still do not allow the minimum score to be exceeded or the maximum score to be exceeded.
The ITACA Protocol shows a certain response in recording the changes proposed in case studies B and C. Although the variations in scoring are modest, the modifications are nevertheless detected as 2 criteria are affected by the changes in Case study B and 4 in Case study C with consequent modifications to the evaluation Area and overall scores. It has to be said that ITACA Protocol is a tool whose aim is to give a broader evaluation of the building than the thermal analysis and this capability is also visible with the proposed changes which, although rather limited considering the whole building, are nevertheless detectable.

7.4 Influence of changes on the LCA analysis

In the following paragraphs, the consequences on the LCA analysis of the changes made in case studies B and C are analyzed. The introduction of wood fiber insulation, although leading to increases in terms of the mass of the materials involved in the building redevelopment, still has little effect on the redistribution of the percentages of all materials if cement and steel are also considered. Therefore, the reasons that led to the exclusion of cement and steel from the LCA analysis and that have been dealt with in Chapter 4 remain and hence all the following elaborations have been carried out considering only all the remaining materials as done previously. As already said previously all the simulations consider only the materials used in the refurbishment works and exclude materials already existing because previously used in the building.

7.4.1 Case B: walls with wood fiber

In Case study B total mass of insulation used in the building is as follows:

- Wood fiber: 188.800 kg
- Polystyrene: 12.000 kg
- Total mass of insulations: 200.800 kg, which represents 14,5% of total mass of materials used in the building. Mass of insulation increased for a 37,7% more comparing to Case study A.

While in Case study A the distribution of mass was as follows:

- Rock wool: 113.050 kg
- Polystyrene: 12.000 kg
- Total mass of insulations: 125.050 kg, which represented 9,5% of total mass of materials used in the building

It has to be said that the mass of the other materials, except insulations, is the same as Case study A.

Cumulative Energy Demand (CED)

In the following Figure 90 part of tree graph of impacts calculated with CED method for Materials Placement is shown.

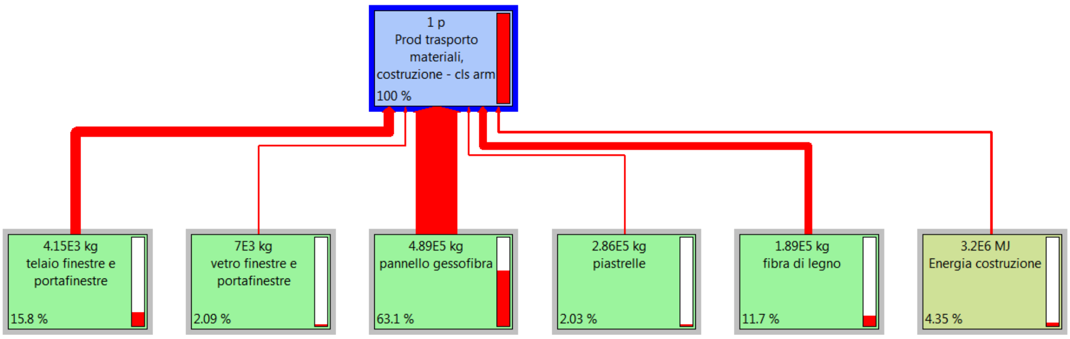


Figure 90: Tree graph of impacts calculated with CED method for Materials Placement, Case study B

Wood fiber insulation accounts for almost 11,7% while in Case study A for Materials Placement polystyrene and rock wool did not reach 2%.

In the following Figure 91 part of tree graph of impacts calculated with CED method for Full Life Cycle is shown.

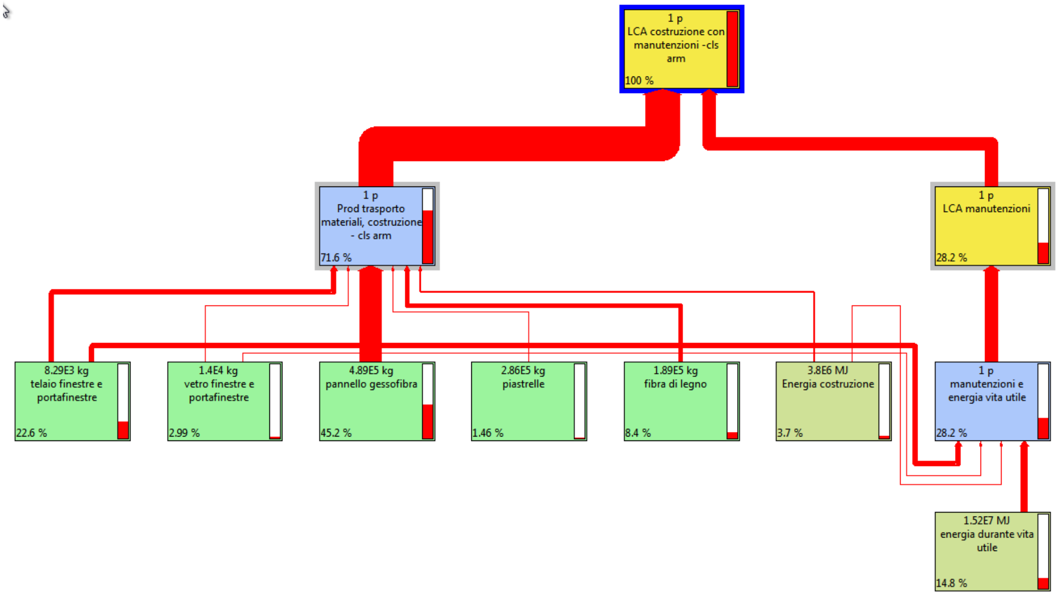


Figure 91: Tree graph of impacts calculated with CED method for Full Life Cycle, Case Study B

Wood fiber insulation accounts for almost 8,4% in Full Life Cycle while in Case study A polystyrene and rock wool reached 1,3%.

IPCC GWP 20

In the following Figure 92 part of tree graph of impacts calculated with IPCC GWP 20 method for Materials Placement is shown.

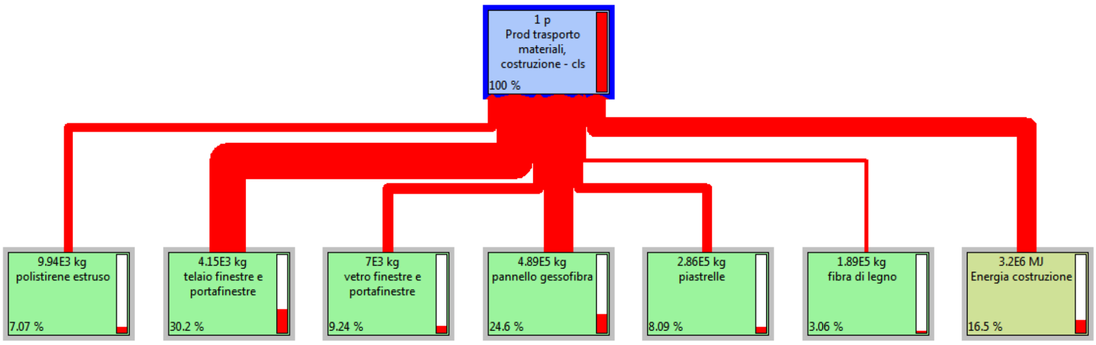


Figure 92: Tree graph of impacts calculated with IPCC GWP 20 method for Materials Placement, Case study B

Wood fiber insulation accounts for 3% and polystyrene for 7% while in Case study A for Materials Placement rock wool was almost 4,5% and polystyrene had the same percentage and the same mass.

In the following Figure 93 part of tree graph of impacts calculated with IPCC GWP 20 method for Full Life Cycle is shown.

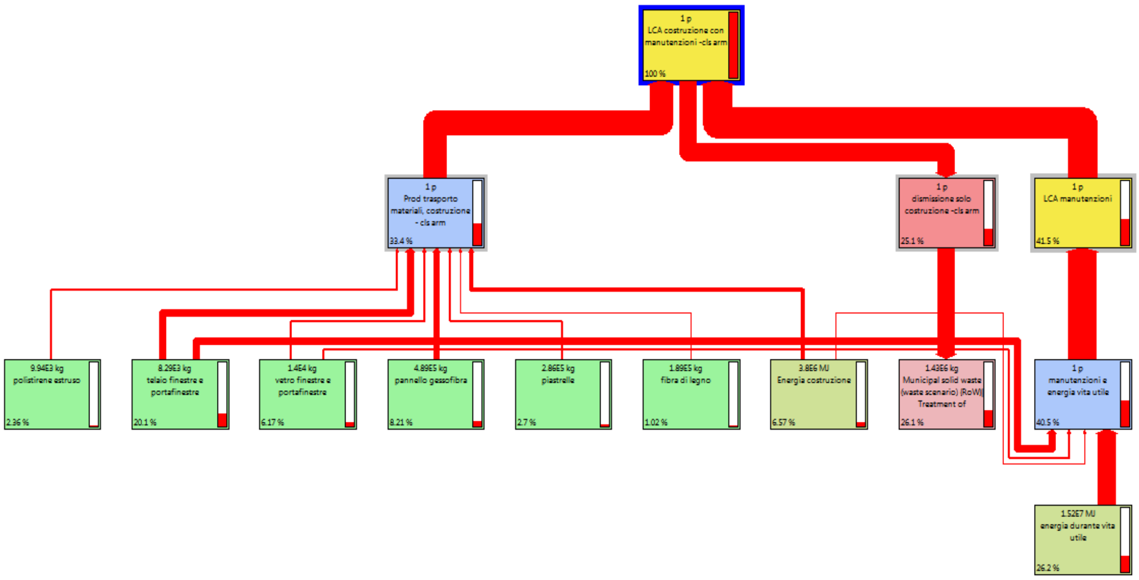


Figure 93: Tree graph of impacts calculated with IPCC GWP 20 method for Full Life Cycle, Case Study B

Wood fiber insulation accounts for almost 1% and polystyrene for 2,3% in Full Life Cycle while in Case study A rock wool was almost 1,8% and polystyrene had almost the same percentage and the same mass.

Ecoindicator 99 (H)

In the following Figure 94 part of tree graph of impacts calculated with Ecoindicator 99 (H) method for Materials Placement is shown.

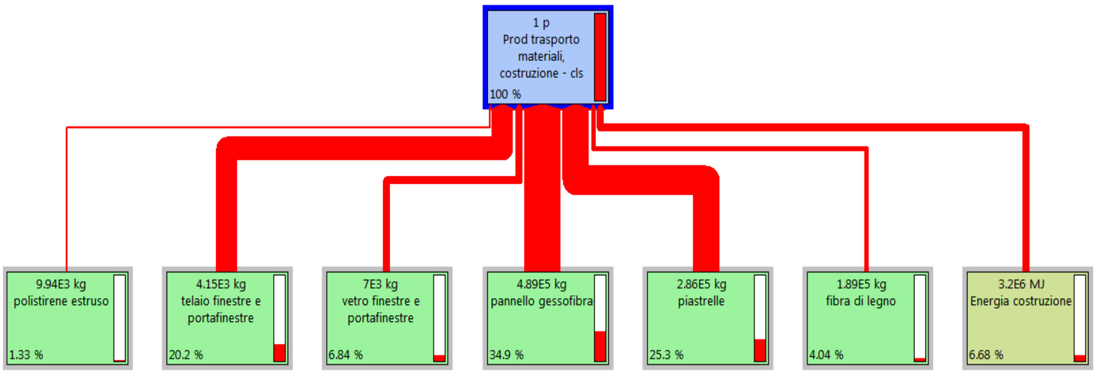


Figure 94: Tree graph of impacts calculated with Ecoindicator 99 (H) method for Materials Placement, Case study B

Wood fiber insulation accounts for 4% and polystyrene for 1,3% while in Case study A for Materials Placement rock wool was almost 3,5% and polystyrene had the same percentage and the same mass.
In the following Figure 95 part of tree graph of impacts calculated with Ecoindicator 99 (H) method for Full Life Cycle is shown.

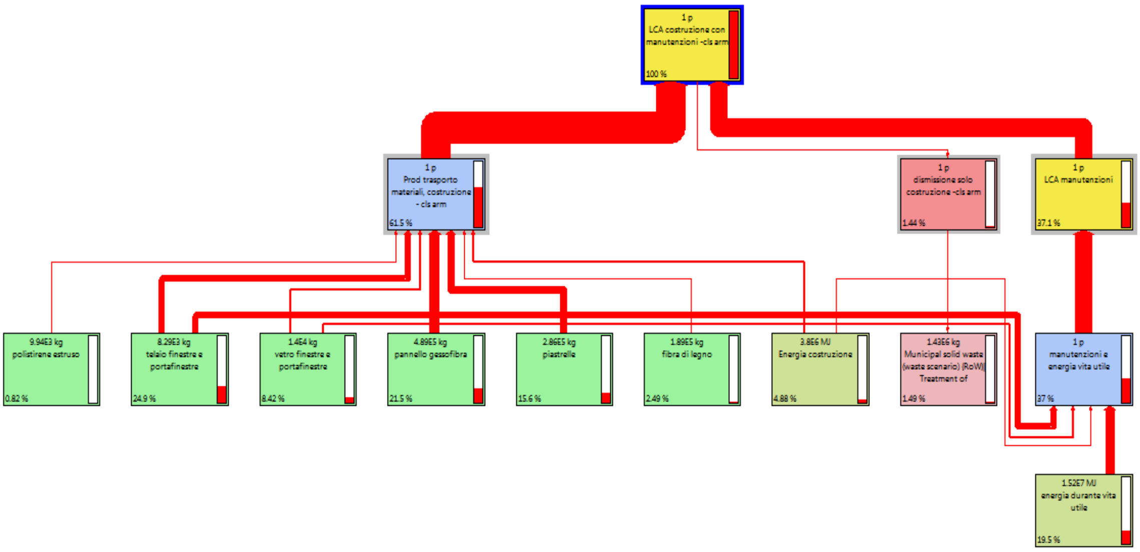


Figure 95: Tree graph of impacts calculated with Ecoindicator 99 (H) method for Full Life Cycle, Case Study B

Wood fiber insulation accounts for almost 2,5% and polystyrene for 0,8% while in Case study A for Full Life Cycle rock wool was almost 2,1% and polystyrene had almost the same percentage and the same mass.

7.4.2 Case C: whole insulation with wood fiber

In Case study C total mass of insulation is as follows:

- Wood fiber: 261.300 kg
- Polystirene: 350 kg
- Total mass of insulations: 261.650 kg, which represents 18,2% of total mass of materials used. Mass of insulation increased for a 109,2% more comparing to Case study A.

While in Case study A the distribution of mass was as follows:

- Rock wool: 113.050 kg
- Polystirene: 12.000 kg
- Total mass of insulations: 125.050 kg, which represented 9,7% of total mass of materials used

It has to be said that the mass of the other materials, except insulations, is the same as Case study A.

Cumulative Energy Demand (CED)

In the following Figure 96 part of tree graph of impacts calculated with CED method for Materials Placement is shown.

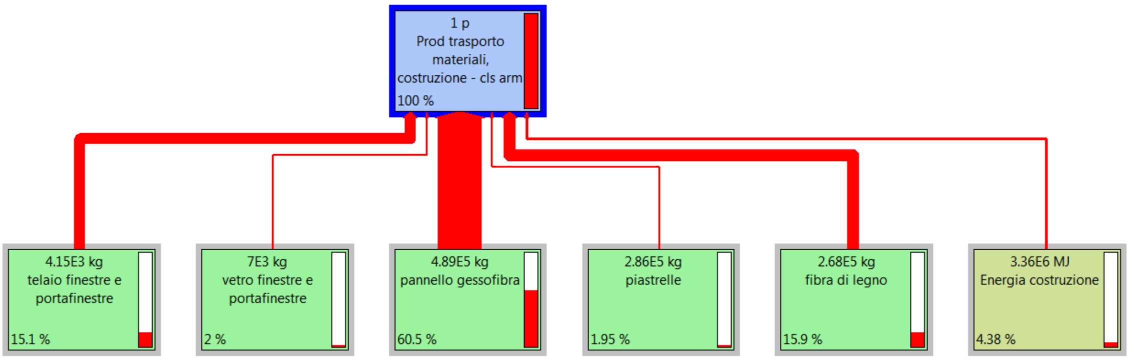


Figure 96: Tree graph of impacts calculated with CED method for Materials Placement, Case study C

Wood fiber insulation accounts for almost 15,9% while in Case study A for Materials Placement polystyrene and rock wool did not reach 2%.
In the following Figure 97 part of tree graph of impacts calculated with CED method for Full Life Cycle is shown.

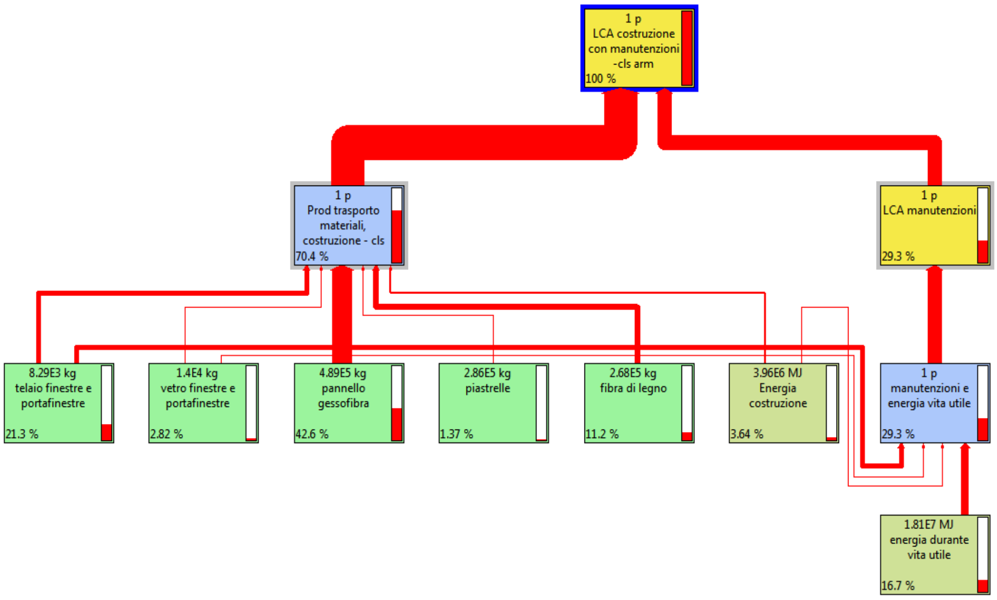


Figure 97: Tree graph of impacts calculated with CED method for Full Life Cycle, Case Study C

Wood fiber insulation accounts for almost 11,2% in Full Life Cycle while in Case study A polystyrene and rock wool reached 1,3%.

IPCC GWP 20

In the following Figure 98 part of tree graph of impacts calculated with IPCC GWP 20 method for Materials Placement is shown.

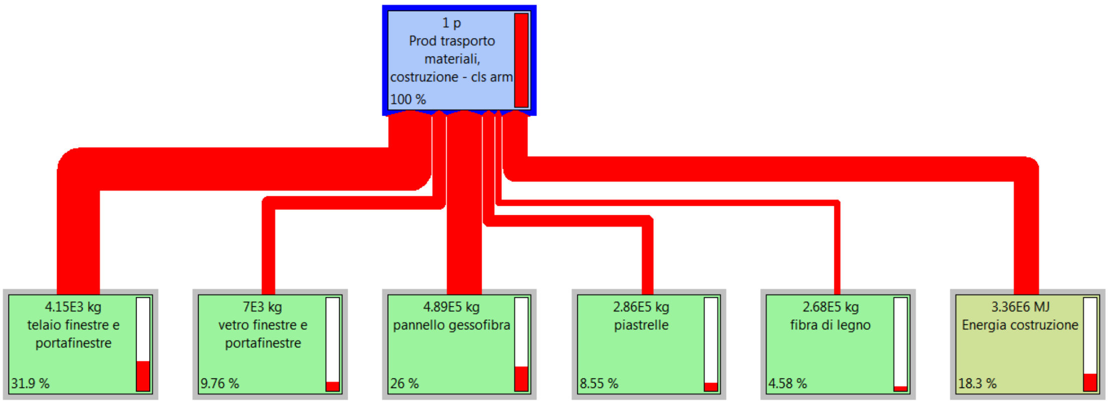


Figure 98: Tree graph of impacts calculated with IPCC GWP 20 method for Materials Placement, Case study C

Wood fiber insulation accounts for 4,5% while in Case study A for Materials Placement rock wool was almost 4,5% and polystyrene 7%.
In the following Figure 99 part of tree graph of impacts calculated with IPCC GWP 20 method for Full Life Cycle is shown.

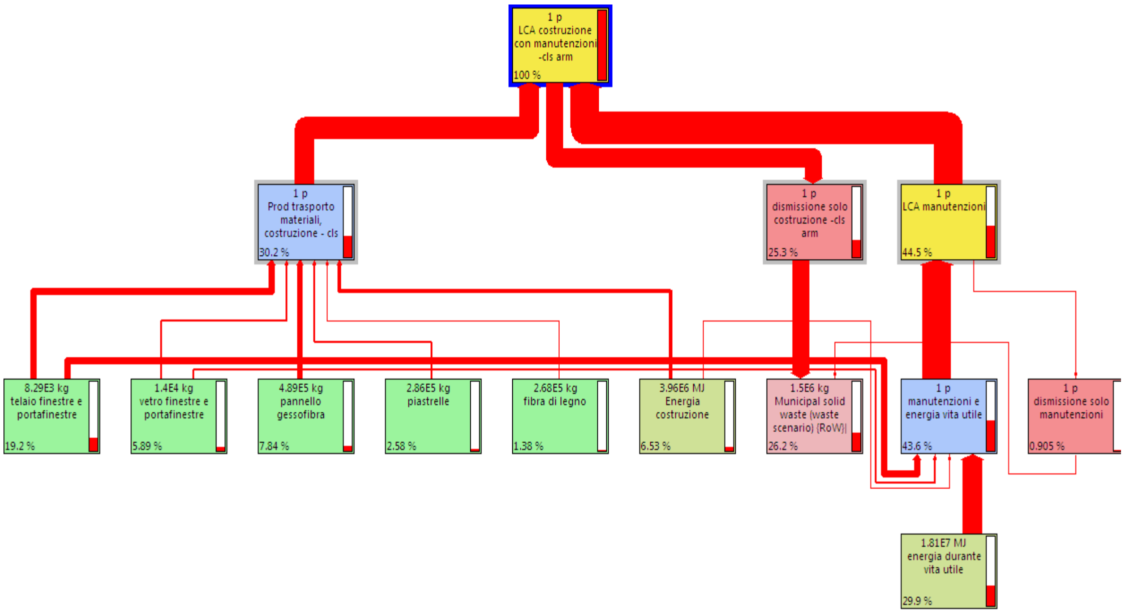


Figure 99: Tree graph of impacts calculated with IPCC GWP 20 method for Full Life Cycle, Case Study C

Wood fiber insulation accounts for almost 1,4% in Full Life Cycle while in Case study A rock wool was almost 1,8% and polystyrene had 2,3%.

Ecoindicator 99 (H)

In the following Figure 100 part of tree graph of impacts calculated with Ecoindicator 99 (H) method for Materials Placement is shown.

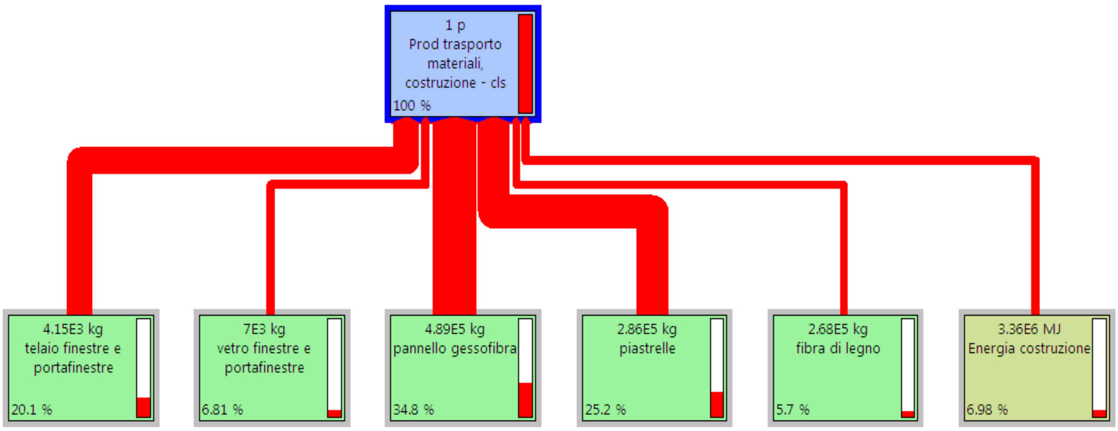


Figure 100: Tree graph of impacts calculated with Ecoindicator 99 (H) method for Materials Placement, Case study C

Wood fiber insulation accounts for 5,7% while in Case study A for Materials Placement rock wool was almost 3,5% and polystyrene had 1,3%.
In the following Figure 101 part of tree graph of impacts calculated with Ecoindicator 99 (H) method for Full Life Cycle is shown.

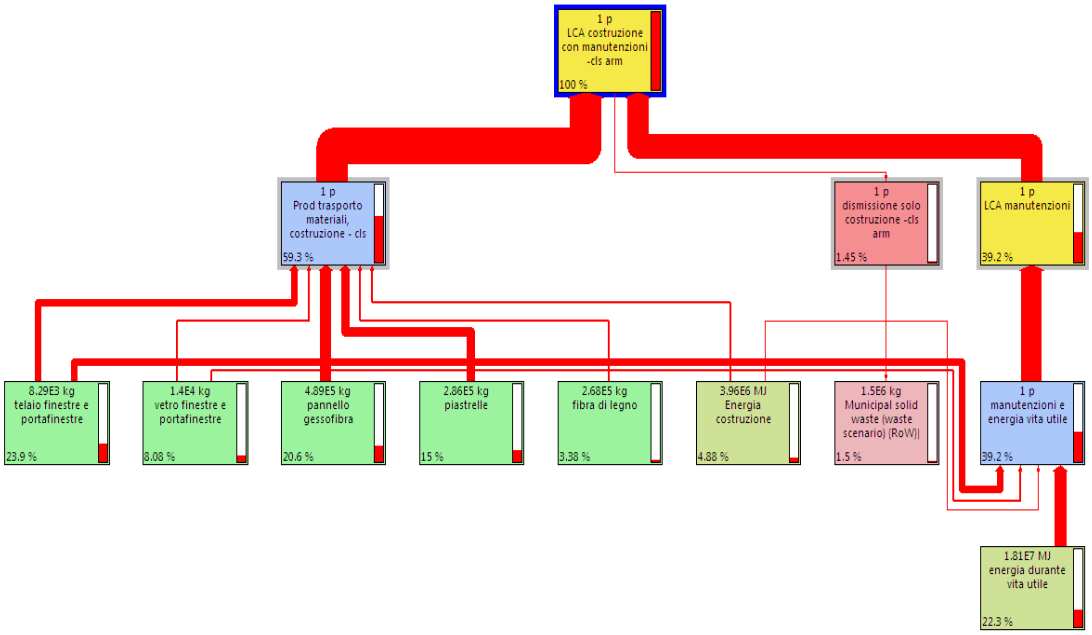


Figure 101: Tree graph of impacts calculated with Ecoindicator 99 (H) method for Full Life Cycle, Case Study C

Wood fiber insulation accounts for almost 3,4% while in Case study A for Full Life Cycle rock wool was almost 2,1% and polystyrene had 0,8%.

7.4.3 Overview of the influence of changes

In the following Table 29 the impact percentages of the insulations in the building are given for each case study, for each calculation method and for the Materials Placement and Full Life Cycle phases.

	CED Case A %	CED Case B %	CED Case C %	IPCC Case A %	IPCC Case B %	IPCC Case C %	Eco99 Case A %	Eco99 Case B %	Eco99 Case C %
	Materials Placement								
Polistyrene extruded	0,8	0,8	0	7	7	0	1,3	1,3	0
Rock wool	1,1	\	\	4,5	\	\	3,5	\	\
Wood fiber	\	11,7	15,9	\	3	4,5	\	4	5,7
	Full Life cycle								
Polistyrene extruded	0,4	0,4	0	2,3	2,3	0	0,8	0,8	0
Rock wool	0,8	\	0	1,8	\	\	2,1	\	\
Wood fiber	\	8,4	11,2	\	1	1,4	\	2,5	3,4

Table 29: Impact percentages of insulations for each case study and for each calculation method for Materials Placement and Full Life Cycle phases

Together with the above Table 29 following Table 30 showing the mass of each insulation for each case study and the percentage in terms of total weight of the building, excluding concrete and steel, has to be taken into account for further considerations.

	Case A kg	Case B kg	Case C kg	Case A %	Case B %	Case C %
Polistyrene extruded	12.000	12.000	350	0,8	0,8	0
Rock wool	113.500	0	0	8,7	\	\
Wood fiber	0	188.800	261.300	\	13,7	18,7

Table 30: Mass of each insulation and percentage on total weight of the building for each case study, concrete and steel excluded

As already mentioned in the introduction, the purpose of this study is not to evaluate from an environmental point of view which insulation is preferred or to propose an optimization of the building by means of the proposed case studies, but to verify whether the influence of the change of insulation is perceived by the instruments and with what degree of sensitivity. The tables above and others in the following could certainly also lead to a discussion on how the impacts of the insulators change according to the calculation method used and the mass, but

for the purpose of the study it is more interesting to observe how the instruments register the differences between the different insulations and between the same insulation.
Therefore, from the point of view of the ability to register changes by tools, LCA is shown to be the instrument most directly affected by changes. Basically with the exclusion of concrete and steel from the simulations for the reasons given in the previous chapters the other elements considered have constant mass in all the case studies. The only exception is the weight of the insulators which see their overall mass increase from Case Study A to Case Study C. But as seen above, the total mass of the insulation is a minor fraction of the total weight of the building elements considered and their variation is at most responsible for 5% of the total weight. Therefore, with constant quantities of non-insulating materials, the absolute impact of everything that is not insulating is constant for each case study and each calculation method. This means that the LCA analysis will see from one case study to the other only the absolute impact of insulators change and therefore the tool will show this in absolute and percentage terms as following figures of the Full Life Cycle for CED method and for each case study show.

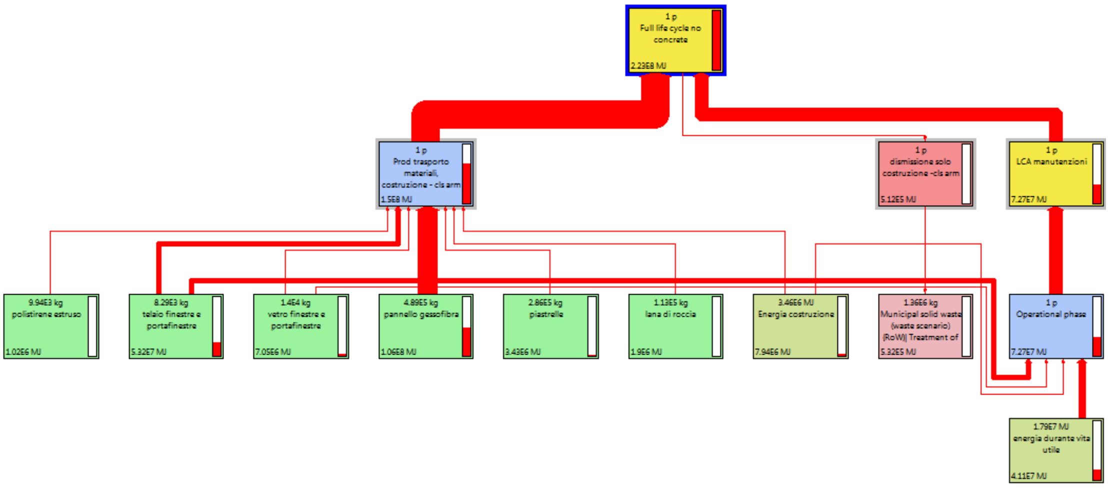


Figure 102: Tree graph of impacts calculated with CED method for Full Life Cycle, Case Study A, impact indicated in units of impact

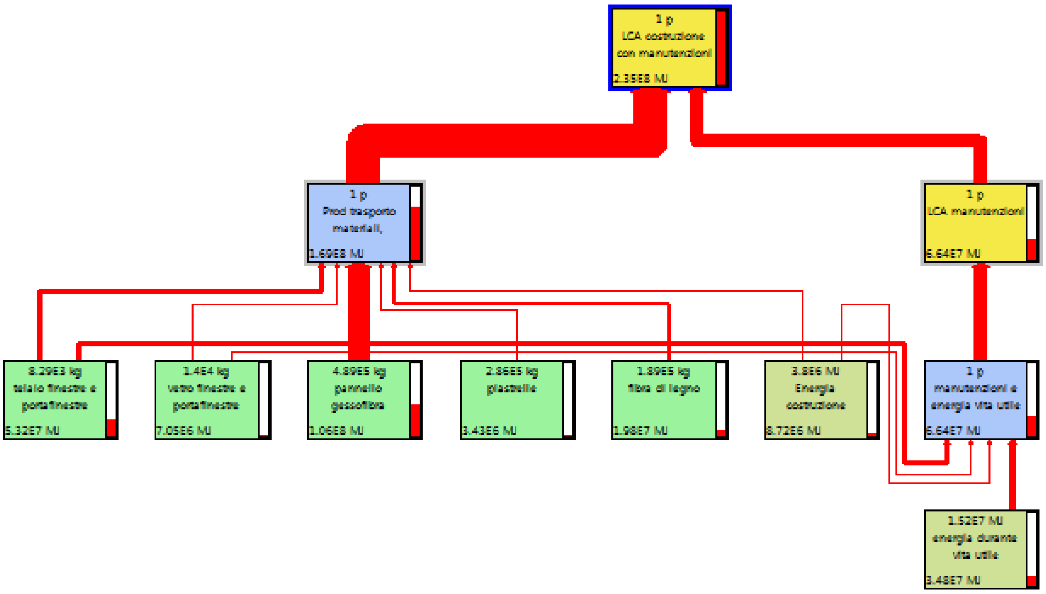


Figure 103: Tree graph of impacts calculated with CED method for Full Life Cycle, Case Study B, impact indicated in units of impact

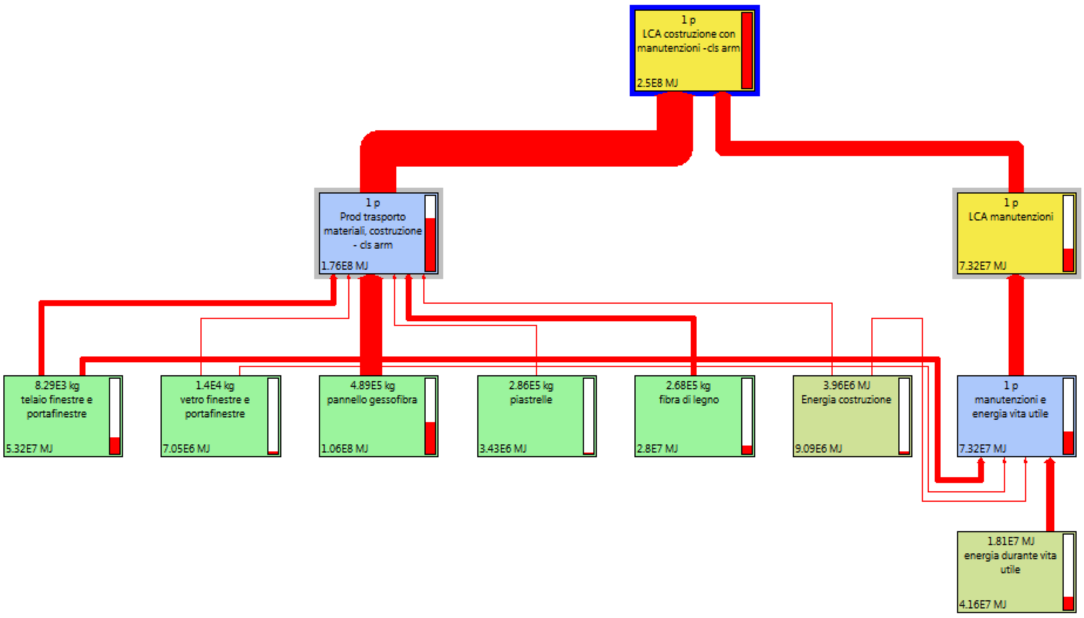


Figure 104: Tree graph of impacts calculated with CED method for Full Life Cycle, Case Study C, impact indicated in units of impact

Previous figures show the amount of each material and the consequent impact in the unit used by the method selected and not the percentage as in previous Figures 80, 91 and 97. The impact of each material except insulation is only the same and the same thing happens if tree graphs for Full Life Cycle concerning IPPC GWP 20 and Ecoindicator 99 (H) methods are analyzed in terms of quantity of unit of impact and not with percentage.
Something different happens for insulation. For example it is interesting to see what happens in the building with polystyrene: between Case Study A and Case Study B it does not change its mass as it is the rock wool that is replaced by the wood fiber and in fact the tool, for each calculation method used, does not change its rating either in absolute terms or as a percentage as can be seen from Table 29. On the other hand, wood fiber between Case Study B and Case Study C sees its mass increase considerably by more than 38% if Case Study C is taken as the reference. Between Case Study B and Case Study C, the only increase in the mass of the materials used in the renovation of the building is that of wood fiber since, as noted above, all other materials keep their mass constant and polystyrene, although passing from 12,000 to 350 kg and in practice becoming negligible, in Case B counted for only 0.8 % of the total weight of the materials considered. Therefore, in the situation outlined in which the only element that changes its mass between Case Study B and C is wood fiber, one should expect the impacts for that material to be the ones that change the most, and in fact the changes in impacts in absolute terms and in percentage terms show an increase not too dissimilar to the percentage increase in mass in almost all simulations.
To understand better it is useful to analyze following Tables 31, 32 and 33.

	Case study A		Case study B		Case study C	
	CED MJ	CED MJ/kg	CED MJ	CED MJ/kg	CED MJ	CED MJ/kg
Gypsum fibre boards	106000000	216.86	106000000	216.86	106000000	216.86
Rock wool	1900000	16.81				
Polistyrene extruded	1020000	102.66	1020000	102.66		
Wood fiber			19800000	104.87	28000000	107.16
Tiles	3430000	12.01	3430000	12.01	3430000	12.01
Wood window frame	53200000	12834.74	53200000	12834.74	53200000	12834.74
Glazing	7050000	1006.86	7050000	1006.86	7050000	1006.86

Table 31: Impact if main materials for each case study and for CED method, Full Life Cycle

	Case study A		Case study B		Case study C	
	IPPC kgCO2	IPPC kgCO2/kg	IPPC kgCO2	IPPC kgCO2/kg	IPPC kgCO2	IPPC kgCO2/kg

Gypsum fibre boards	811000	1.659	811000	1.659	811000	1.659
Rock wool	182000	1.610				
Polistyrene extru-ded	233000	23.450	233000	23.450		
Wood fiber			101000	0.535	143000	0.547
Tiles	267000	0.935	267000	0.935	267000	0.935
Wood window frame	1990000	480.097	1990000	480.097	1990000	480.097
Glazing	610000	87.118	610000	87.118	610000	87.118

Table 32: Impact of main materials for each case study and for IPCC GWP 20 method, Full Life Cycle

	Case study A		Case study B		Case study C	
	Ecoindicator Mpts	Mpts/kg	Ecoindicator Mpts	Mpts/kg	Ecoindicator Mpts	Mpts/kg
Gypsum fibre boards	148000	0.303	148000	0.303	148000	0.303
Rock wool	14900	0.132				
Polistyrene extru-ded	5630	0.567	5630	0.567		
Wood fiber			17100	0.091	24200	0.093
Tiles	107000	0.375	107000	0.375	107000	0.375
Wood window frame	171000	41.255	171000	41.255	171000	41.255
Glazing	57800	8.255	57800	8.255	57800	8.255

Table 33: Impact of main materials for each case study and for Ecoindicator 99 (H) method, Full Life Cycle

Tables 31, 32 and 33 show for main materials the impact for each case study and for each method of calculation for the Full Life Cycle phase expressed according to the unit of impact. Absolute values and values per kg of material are given. As noted previously for any not insulating material amount of impact for any unit remains constant as mass of these materials do not change. For insulations things are different as they change their mass through cases.
Even if, as said previously, the purpose of this study is not to evaluate the environmental impact of materials used however it is interesting to see the impact per kg of material of different materials. For example window wood frames appears as a material of great

environmental impact; probably the reason has to be searched in their being a composite material in which metals, plastics and processing have a consistent impact.
As the main focus of the present study it is the influence of insulation analyzed through different tools it is also interesting to go more in detail on impact per kg of material determined by insulations. Following Table 34 gives an overview of impacts for each method.

	Case A	Case B	Case C
	CED MJ/kg	**CED MJ/kg**	**CED MJ/kg**
Rock wool	16.81		
Polistyrene extruded	102.66	102.66	
Wood fiber		104.87	107.16
	IPPC kgCO2/kg	**IPPC kgCO2/kg**	**IPPC kgCO2/kg**
Rock wool	1.610		
Polistyrene extruded	23.450	23.450	
Wood fiber		0.535	0.547
	Mpts/kg	**Mpts/kg**	**Mpts/kg**
Rock wool	0.132		
Polistyrene extruded	0.567	0.567	
Wood fiber		0.091	0.093

Table 34: Impact per kg of material for insulations for each case study and for each method, Full Life Cycle

For CED method impacts polystyrene and wood fiber seems to be more energy demanding than rock wool in their life cycle as drawn in the present study.
For IPPC GWP 20 method polystyrene seems to produce much more emissions than rock wool and wood fiber.
Finally for Ecoindicator 99 (H) polystyrene seems to have a greater impact but differences are smaller than in other methods.
Differences in results obtained by wood fiber between Case study B and C can be attributed to the use of two different wood fibers in Case study C with different density: in Case study B only wood fiber with density of 150 kg/m3 has been used while for the floors of Case study C same insulation but with density of 250 kg/m3 has been figured out. LCA is extremely sensitive to amount of material used and the slight differences in results of Case study C ascribed to this characteristic.
Previous results have been obtained under the conditions of the present study and it has to be taken into considerations that assumptions made have a great influence on final scores.
As a final consideration, it can be said that LCA analysis is a tool able in recording the changes that occur as elements change and the consequent variations of the impacts follow a similar path than the one determined by variations.

LCA analysis proves to be a more sensitive tool to change than thermal analysis and the evaluation made with a rating system as it is capable of encompassing more phases and in greater detail while the other two focus more on the Operational phase. With regard to the construction sector, one certainly useful use could be that not only of the design but also of the optimization of existing buildings in need of improvement work, of which there are very many. A possible development of this study could in fact be that of an ex-post evaluation of the redevelopment carried out by trying to verify what the best choices could be from an environmental point of view analyzed through this tool.

Chapter 8.

Concluding Remarks

8.1. Conclusions

The present study comes from the general consideration that in the construction sector the main tools used for designing analyse the behaviour of the building during the operational phase. Therefore, most of the knowledge is dedicated to the energy consumption of the operational phase and little or nothing is known about the environmental impacts due to the materials used in their production, the processing undergone by them, their transport to the site, the building's construction processes, its maintenance and its decommissioning. And equally little is known about the building's relationship with its surroundings and therefore with the external appurtenances and the more or less urbanized area in which it is located.
From previous considerations for the building sector, it is clear that an approach closely linked to the analysis of energy flows is no longer sufficient to deal with the present needs of more information on environmental impacts caused by human activities with the aim of reducing them. A more holistic and strategic approach is required if the intention is to take into account the all environmentally relevant aspects of building activity.
In terms of a research project the goal is a combined analysis of a building going beyond the energy flows. To do so, considering as reference building a real case of refurbishment of an existing building, a thermal analysis, an evaluation through a rating system and an LCA assessment have been carried out. Once the three assessments have been completed some variations of the main parameters of the building, and specifically on insulation, have been applied and recorded by the three analysis tools. The purpose of the research is to investigate the same building in three different ways and to see how the different analysis tools react to variations in the some parameters of the building.
The three selected tools are a thermal software, which can be considered as the baseline tool as such tools are the main tool for designing but they are focused exclusively on energy flows, a rating system, and specifically one of the most widely used rating systems in Italy, the ITACA Protocol, which makes possible to broaden the view to other aspects than energy flows and takes into account the relationship between the building and the surroundings, and finally, on a wider time scale, a LCA analysis which is a tool able to estimate the environmental impacts of the building through the whole lifetime.
Once the three tools have been applied and results analyzed some changes have been made. At this point of the research the objective is to verify if applied changes on the reference building are recorded by the three different tools. Therefore new analysis have been carried out and new results have been obtained. The attempt is to analyze with three different tools the same building and some possible variations and, ultimately, to investigate how the three different approaches react.

Basically, given a reference building, which is an existing former industrial building converted into a residential one, energy modelling, LCA analysis and sustainability assessment have been carried out. For the energy modelling a specific software complying with the technical standards in force, Termo by Namirial, has been used; for the LCA evaluation the software SimaPro by Pré has been used; for the sustainability assessment the chosen rating system has been ITACA Protocol and specifically the most recent version UNI 13:2019 Reference Practice.
Following step was to operate some changes concerning one of the aspects more debated in building designing: insulation. Starting from the real case two different case studied have been defined, each of them with differences in insulation. Real case has only not renewable insulation while Case study has only wood fiber; Case study B has been outline using both renewable and not renewable insulation.
Changes in the insulation allow to see if and how the three tools mentioned above are able to detect the modifications. Scope of this study was neither to judge which type and use of insulation is to prefer, nor to run an optimization of the refurbishment works using the three tools, however some considerations on different impact of materials used have been made.
The detailed path to the above considerations has started from chapter 1 where a general overview of the principal rating systems is given together with some considerations on the impact of the building sector. Buildings have a certain degree of complexity and tools try to simplify it. Environmental assessment tools called rating systems are the subject of Chapter 1 as they allow the building to be broken down into different environmental aspects that are easier to deal with individually. Moreover, unlike the other tools, rating systems often also study the relationships between building and its surroundings and between building and environs. A general overview of the main methods used worldwide is given in the chapter.
Chapter 2 briefly describes the regulatory sources governing the execution of an LCA study, namely the UNI EN ISO 14040 and 14044 technical standards. The various steps that make up the procedure in accordance with these standards are then described. The LCA analysis has undoubtedly positive aspects such as the transparency of the method due to the fact that it offers quantitative, and therefore objective, results, its iterative character, which allows for subsequent improvements, the quantification and qualification of impacts and their subdivision between the various life cycle phases, and last but not least, the possibility of comparing different solutions. Finally, a brief description of the software used for LCA assessments is given.
In the Chapter 3, the case study is presented, its previous function and appearance is described, and the changes that the redevelopment project has involved in terms of architectural choices and analysis of the envelope elements and systems designed. The existing building was constructed using precast reinforced concrete system both for the structure and the cladding and it has been now converted into a residential building. Compared to the original building, all the openings have been revised and terraces have also been added. Besides two sides of the external walls had to be replaced completely. The floors were cut to create internal courtyards with a system of walkways and stairs connecting the floors and the internal parts of the courtyards. The walls facing the inner courtyards were built from scratch. Insulations are rock wool and EPS.
In the Chapter 4 LCA analysis has been applied to the renovated building. The goal and scope of the study is stated, the functional unit is defined which is represented by the entire building for a lifespan of 50 years.

In Chapter 4 are also defined the boundaries of the system therefore which is stated process units to include in the life cycle analysis. To break down the building and identify the functional units, the Italian standard UNI 8290: 1981 “Classification of the technological system” was used. Although a rather outdated standard, it is still a very effective tool for breaking down the building into its constituent parts to a very advanced level of detail and for this reason it is still used. The UNI 8290 Standard identifies a criterion for the classification and articulation of the building system into several levels according to a vision based on rationality and homogeneity. The standard defines three levels of decomposition but states that other levels are possible. For the present study, the decomposition of the building continued up to the sixth level as follows:

- Classes of technology units
- Technological units
- Classes of technical elements
- Subsystems
- Components
- Sub-components

The proposed decomposition inevitably involve the introduction of approximations and assumptions made by the life cycle assessment performer. For the present study reference was made to all the databases loaded in the software used, including Ecoinvent, Agri-footprint, ELCD, USLCI, Swiss Input Output Database and EU & DK Input Output Database; in addition, for some specific materials, Environmental Product Declarations (EPDs) were used. All the databases used are an indispensable support for carrying out this type of analysis, although they are not specifically designed for the construction sector. Furthermore, they mainly refer to European or non-European average data, so there is no guarantee of a perfect match with Italian materials and production processes.
Establishing the system boundaries means not only defining the process units, but also the life cycle phases. Three main phases were used in this study:

- Materials Placement: in this phase the production of materials was considered, thus the extraction of raw materials, transport to the related industries for treatment and processing; but also the installation phase which includes transport from the production company to the construction site and the assembly of the components;
- Operational Phase: energy consumptions for this phase include consumption for heating, domestic hot water production and cooling. During this phase maintenance is planned for certain elements of the building with their replacement;
- Disposal: demolition of components, transport from building to landfill. No recyclable materials were assumed as the analysis of the cross sections showed that recycling possibilities are limited.

In deciding which input and output flows were to take into consideration, the mass criterion was taken into account in the first instance considered negligible those inputs with little weight in relation to the total. For defining the system boundaries, it is also necessary to determine which releases into the environment are to be assessed. These are grouped according to impact categories and vary according to the method used for assessment. In the present study, the following methods were used:

- Cumulative Energy Demand (CED) assessing MJ of primary energy from different energy sources as impact, thus primary energy consumption is the object of the evaluation;
- IPCC GWP 20 assessing kg of CO2 equivalent as impact, therefore the assessment refers to climate change;
- Eco-indicator 99 (H) has eleven impact categories, which in turn are grouped into three damage categories: damage to human health, damage to ecosystem quality, damage to resources. The damage assessments in relation to the three safeguard areas, are comparable and therefore can be summed up into a single score, the Eco-indicator expressed in Point (Pt) or MilliPoint (MPt), which represents the overall performance of the investigated system in energy-environmental terms.

Once system boundaries are defined it is possible to collect data for calculations. The data used are of various kinds, firstly those provided by the project documentation. Secondly, reference was made to the software databases, in which the life cycle assessments of many materials in use in the construction industry are included. Where data were not available in sufficient detail, EPDs were sought. Unfortunately, the scarcity of systems-specific data in the different sources consulted led to the exclusion of systems from the present study. This is the major simplification that had to be made. Another assumption made was the assessment of only the materials used in the refurbishment, so all existing materials were not included in the simulations. Besides, in the assessment according to the selected Rating System the materials were all considered to be of non-local origin and therefore a distance of at least 300 km between the place of production and the construction site was also assumed for the transport impact assessment.

As it can be seen accuracy may be limited by the accessibility of data, their availability and quality. For this reason, the aspects that most influence the quality of a LCA study are the application of reliable methodologies and the possibility of accessing databases with the certainty of finding complete information.

Eventually at the end of Chapter 4 results for the building are presented calculated according with selected method or the assumed phases. However first results presented show the predominant impact of concrete in the quantification of the impacts. Therefore, it has to be considered that the redevelopment works involved the replacement of two entire sides of side walls by re-proposing the pre-existing façade composed of reinforced concrete panels and further vertical envelope elements were introduced given by the internal walls facing the courtyards created. Furthermore it has also to consider that the industrial origin of the building determines a redevelopment pretty different from that represented by the works for the improvement of the envelope's energy characteristics alone. But being the scope of the analysis to the influence of materials that generally in a building redevelopment case have an effect on the energy efficiency it has been decided to exclude concrete, and consequently also the steel used, from any impact considerations.

In Chapter 5 ITACA Protocol is introduced. The reasons for the choice of the ITACA Protocol in a wide range of other rating systems are described as ITACA Protocol is, at national level, one of the most widespread tools for assessing the level of energy and environmental sustainability of buildings. Another reason is its connection with the legislation related to energy e sustainability in the constructions field and with technical standards. The criteria of which the ITACA Protocol is composed, when they deal with environmental issues that are regulated by the legislator, i.e. when there is a legal limit or where a technical standard plays an important role, take these references as the minimum level of fulfilment of the criteria. This characteristic of being so attentive to standards is one of the strengths of the ITACA Protocol and differentiates it from almost all other rating systems that have only rarely been adapted to the national reality. Then the structure and functioning of the protocol is explained and finally, the results of its application to the renovated part of the building are presented.

In the sixth chapter, the results of the application of thermal software are presented. The extensive body of legislation concerning energy analysis is briefly described from the point of view of both current legislation and technical regulations. The main energy indexes obtained from calculations with the chosen energy modelling software are presented.

In Chapter 7 tools are applied to two different case studies in which insulation has been modified. Case study B involves replacing rock wool insulation with wood fiber in the external walls and in some internal walls; the replacement has been envisaged maintaining the same thermal resistance for three external walls out of four while for the internal walls and the fourth external wall total width has been maintained. It has not been possible to change width for the above elements of envelope as it would have meant changing the internal partition. Case study C, in addition to the modifications implemented in case study B, involves replacing all insulation with wood fiber. No modifications to systems have been introduced.

Then in Chapter 7 changes introduced by the two new case studies have been briefly described and consequently the thermal software, ITACA Protocol and LCA analysis have been applied again. The results have been compared to those obtained for the first case study. Regarding thermal analysis modifications introduced in Case Study B improve the H'T index, as can also be seen from the EP,H,nd index, while the EP,C,nd index worsens. The changes in Case Study C, on the other hand, bring H'T back to values very similar to Case Study A as also confirmed by the EP,H,nd parameter. The parameter EP,C,nd, on the other hand, improves. On the basis of presented case studies and limitedly to them the deviations in the values of the various parameters are modest and the thermal analysis, although capable of capturing the differences in the various case studies, cannot give unambiguous indications. It has also to take into consideration that results can be influenced by the response of the hybrid central heating system to the applied changes.

Thermal indexes and changes in the parameters are shown in the following Table.

	Case study A	Case study B	Case study C
H’T W/m²K	0,31	0,25	0,32
H’T,limit W/m²K	0,58	0,58	0,58
EPH,nd kWh/m2 year	9,31	5,39	9,24

EPH,nd,limit kWh/m2 year	19,37	18,86	18,93
EPC,nd kWh/m2 year	29,25	32,76	29,3
EPC,nd,limit kWh/m2 year	24,21	24,35	24,36

Table 35: Main energy indexes for each Case study

However some considerations on thermal analysis on the basis of presented case studies can be affirmed; evidences show that the deviations in the values of the various parameters are modest and the thermal analysis, although capable of capturing the differences in the various case studies, cannot give unambiguous indications. Also the response of the hybrid central heating system to the applied changes influences the energy indexes in a way that cannot be immediately recognizable and consequently they could be partly responsible for the obtained unambiguous indications.

Concerning the analysis conducted with ITACA Protocol on the two new case studies the changes implemented in Case Study B increase the overall rating of the building to 2.41 from 2.39, in particular Rating Area B from 1.12 to 1.14 while the changes implemented in Case Study C increase the overall rating of the building to 2.44 from 2.39, in particular Evaluation Area B from 1.12 to 1.16 and Evaluation Area C from 0,71 to 0,76.
Compared to Case Study A, the differences in the score of criteria can be found only in the indicated cases but in some occasions although the performance indicator changes, the criterion score does not change as the changes still do not allow the minimum score to be exceeded or the maximum score to be exceeded. For sure ITACA Protocol shows a certain response in recording the changes proposed in case studies B and C. Modifications affected in particular criteria concerning energy indexes, materials and heat effect. Although the variations in scoring are modest, the modifications are nevertheless detected with consequent modifications to the evaluation Area and overall scores. ITACA Protocol is a tool whose aim is to give a broader evaluation of the building than the thermal analysis and this capability is also visible with the proposed changes which, although rather limited considering the whole building, are nevertheless detectable.
Going into more detail, the criteria affected by the changes with the new scores for Case B compared to the ones of Case study A are shown in the Table below.

B.6	**Envelope performance**
B.6.2	**Useful thermal performance index for summer air conditioning**
Score	From 1,13 to 1,15
B.6.3	**Heat transfer by transmission**
Score	From 2,87 to 2,88

Table 36: Scores of the criteria affected by changes of Case study B

Also with Case Study C the changes in the scores are small, however the modifications implemented are recorded by the tool. Going into more detail, the criteria affected by the changes with the new scores compared to the ones of Case study A are shown in Table 28 below.

B.4	Eco-friendly materials
B.4.7	Materials from renewable sources
Score	From 0 to 1,1
B.6	Envelope performance
B.6.2	Useful thermal performance index for summer air conditioning
Score	From 1,13 to 1,14
B.6.3	Heat transfer by transmission
Score	From 2,87 to 2,98
C.6	Impact on project site
C.6.8	Heat island effect
Score	From 0,03 to 1,,8

Table 37: Scores of the criteria affected by changes of Case study C

Finally LCA analysis con cases studies B and C has been carried out. For each case the selected methods have been applied on each phase but particular attention has been given to the Full Life Cycle phase. Results show how LCA seems to be the instrument most directly affected by changes. Basically materials considered have constant mass in all the case studies. The only exception is the weight of the insulators which see their overall mass increase although they are a minor fraction of the total weight of the building and their variation is at most responsible for 5% of the total weight. Therefore, with constant quantities of non-insulating materials, their impact is constant for each case study and each calculation method. This means that the LCA analysis should see from one case study to the other only the absolute impact of insulators change and therefore the tool should show this in absolute and percentage terms. Calculations made show that it is exactly what happens. For insulation thing are different: polystyrene does not change its mass between Case study A and B as it is the rock wool that is replaced by the wood fiber and in fact the tool, for each calculation method used, does not change its rating. On the other hand, wood fiber between Case Study B and Case Study C sees its mass increase considerably. Besides in Case Study B and Case Study C, the only increase in the mass of the materials used in the renovation of the building is that of wood fiber while polystyrene almost disappears passing from 12,000 to 350 kg and in practice becoming negligible. Following Table shows the variations in mass for each insulation from Case A to B and C.

	Case A kg	Case B kg	Case C kg	Case A %	Case B %	Case C %
Polistyrene extruded	12.000	12.000	350	0,8	0,8	0
Rock wool	113.500	0	0	8,7	\	\
Wood fiber	0	188.800	261.300	\	13,7	18,7

Table 38: Mass of each insulation and percentage on total weight of the building for each case study, concrete and steel excluded

Therefore, in the situation described the rating of wood fiber has expected to increase and in fact the changes in impacts rating show an increase. In order to complete the analysis impacts of the main materials per kg of material are given and a focus on insulation has been made. From calculations for CED method impacts polystyrene and wood fiber seems to be more energy demanding than rock wool in their life cycle as drawn in the present study. For IPPC GWP 20 method polystyrene seems to produce much more emissions than rock wool and wood fiber. Finally for Ecoindicator 99 (H) polystyrene seems to have a greater impact but differences are smaller than in other methods.
Following Table summarizes the situation.

	Case A	**Case B**	**Case C**
	CED MJ/kg	**CED MJ/kg**	**CED MJ/kg**
Rock wool	16.81		
Polistyrene extruded	102.66	102.66	
Wood fiber		104.87	107.16
	IPPC kgCO2/kg	**IPPC kgCO2/kg**	**IPPC kgCO2/kg**
Rock wool	1.610		
Polistyrene extruded	23.450	23.450	
Wood fiber		0.535	0.547
	Mpts/kg	**Mpts/kg**	**Mpts/kg**
Rock wool	0.132		
Polistyrene extruded	0.567	0.567	
Wood fiber		0.091	0.093

Table 39: Impact per kg of material for insulations for each case study and for each method, Full Life Cycle

However LCA seems to be extremely sensitive to amount of material used and a tool able in recording the changes that occur as elements change. It has to be taken into consideration the assumptions made for the present study that surely have a consistent influence on final scores. The final consideration that can be drawn from the example represented by this study is that LCA analysis proves to be a tool that can more accurately capture changes in materials and specifically in insulation than thermal analysis and evaluation using a rating system. In addition to design, an LCA approach could also be of great help in the redevelopment of buildings, as its iterative nature and comprehensiveness of analysis appears extremely appropriate for an optimization process. In this respect, a possible development of this study could in fact be an ex-post evaluation of the redevelopment carried out by trying to verify which are the best choices analyzed through this tool. However, the shortcomings of the tool should not be overlooked, which lie mainly in the quantity and quality of the data. Some materials or installations present a very poor database or one that is not appropriate for national application. It would be appropriate to establish a survey and research system that addresses a product sector in its entirety and not with individual spot experiences that are only valid in that specific context. For the importance of the construction sector, it would be of great importance to have a series of analyses on the various types of materials. Integration with other tools, e.g. those also capable of analyzing the context in which a building is located or of verifying other aspects related to building equipment or indoor well-being, can also bring an improvement in the analysis capacity of LCA. In this sense a coupling with a rating system is certainly a valid solution as they tend to compensate for certain aspects.

References

[1] Cabeza F. et al. (2013) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review, Renewable and Sustainable Energy Reviews

[2] Asdrubali F. et al. (2019), Energy and environmental payback times for an NZEB retrofit, Building and Environment

[3] Cellura M. et al. (2017), Life Cycle Assessment applicata all'edificio, Editoriale Delfino

[4] Direttiva 2010/31/UE del Parlamento Europeo e del Consiglio del 19 maggio 2010 sulla prestazione energetica nell'edilizia.

[5] Asdrubali F. et al. (2013), Life cycle analysis in the construction sector: guiding the optimization of conventional Italian buildings, Energy Build

[6] Direttiva (UE) 2018/844 del Parlamento Europeo e del Consiglio del 30 maggio 2018 che modifica la direttiva 2010/31/UE sulla prestazione energetica nell'edilizia e la direttiva 2012/27/UE sull'efficienza energetica.

[7] Bernardi E. et al. (2017), An Analysis of the Most Adopted Rating Systems for Assessing the Environmental Impact of Buildings, MDPI

[8] DGNB. DNGB International Application. Available online: http://www.dgnb-system.de/en/system/international/

[9] BREEAM. BREEAM Official Web Page. Available online: http://www.breeam.org

[10] Tumminia G. et al. (2017), Life cycle energy performances of a Net Zero Energy prefabricated building in Sicily, Energy Procedia

[11] Verdaguer B. S. et al. (2017), Critical review of Bim-based LCA method to buildings, Energy and Building.

[12] GBC. Green Building Council Italia. Available online: http://www.gbcitalia.org/

[13] CASBEE. CASBEE Official Web Page. Available online: http://www.ibec.or.jp/CASBEE/english/

[14] Chastas P. et al. (2016), Embodied energy in residential buildings-towards the nearly zero energy building: a literature review, Build. Environ

[15] Paleari M. et al (2016), The assessment of the relevance of building components and life phases for the environmental profile of nearly zero-energy buildings: life cycle assessment of multifamily building in Italy, The International Journal of Life Cycle Assessment.

[16] Alshamrani O. S. et al. (2014), Integrated LCA-LEED sustainability assessment model for structure and envelope systems of school buildings, Building and Environment

[17] Pal S. K. et al. (2017), A life cycle approach to optimizing carbon footprint and costs of a residential building, Build. Environ.

[18] Ganassali S. et al. (2016), Valutazione LCA all'interno dei protocolli ambientali multicriteri per il settore edile delle costruzioni, Enea

[19] Corrado V. et al. (2017), A new procedure of energy audit and cost analysis for the transformation of a school into a nearly zero-energy building, Energy Procedia

[20] D'Agostino D. et al. (2019), What is a Nearly zero energy building? Overview, implementation and comparison of definitions, Journal of Building Engineering

[21] Meex E. et al. (2018), Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design, Build. Environ
[22] Mattoni B. et al. (2018), Critical review and methodological approach to evaluate the differences among international green building rating tools, Renewable and Sustainable Energy Reviews
[23] Evangelisti L. et al. (2015), Energy retrofit strategies for residential building envelope: an Italian case study of an early-50s building. Sustainability
[24] Bisegna F. et al. (2016), Influence of insulating materials on green building rating system results, Energies
[25] Green Star. Rating System. Available online: https://www.gbca.org.au/green-star/rating-tools/
[26] Minergie. Available online: https://www.minergie.ch/it/
[27] Istituto per l′innovazione e Trasparenza degli Appalti e la Compatibilità Ambientale (ITACA). Available online: http://www.itaca.org
[28] HQE. Available online: http://www.behqe.com/
[29] Asdrubali F. et al. (2020), LCA of a NZEB building with dynamic decarbonisation modelling, Energy
[30] International Standard Organization, ISO 14044, Environmental management — Life cycle assessment — Requirements and guidelines
[31] International Standard Organization, ISO 14040, Environmental management — Life cycle assessment — Principles and framework
[32] PRéConsultants, SimaPro 8.4, (2017). https://simapro.com/.
[33] Baglivo C. et al. (2019), Optimization of high efficiency slab-on-ground floor by multi-objective analysis for zero energy buildings in mediterranean climate. Journal of Building Engineering
[34] Principi P. et al. (2015), The contribution of the ITACA protocol in the control of the environmental quality in residential buildings and the subsequent contribution to the adaptation to climatic change, Energy Procedia
[35] Baglivo C. et al. (2015), Assessment of Cost-Optimality and Technical Solutions In High Performance Multi-Residential Buildings in The Mediterranean Area, Energy and Buildings
[36] Baglivo C. et al. (2014), Multi-criteria optimization analysis of external walls according to ITACA protocol for zero energy buildings in the Mediterranean climate, Build. Environ.
[37] Asdrubali F. et al. (2015), Comparison between environmental sustainability rating systems LEED and ITACA for residential buildings, Build Environ
[38] Fregonara F. et al. (2018), Economic–Environmental Sustainability in Building Projects: Introducing Risk and Uncertainty in LCCE and LCCA. MDPI
[39] Pan W. et al. (2018), Rethinking system boundaries of the life cycle carbon emissions of buildings, Renewable and Sustainable Energy Reviews

Appendix A.

ITACA Protocol

A.1. UNI/PdR 13.0:2019: Environmental sustainability of construction works - Operational tools for sustainability assessment - General framework and methodological principles

See attached document

A.2. UNI/PdR 13.0:2019: Environmental sustainability of construction works - Operational tools for sustainability assessment - Residential buildings

See attached document

A.3. UNI/PdR 13.0:2019: Environmental sustainability of construction works - Operational tools for sustainability assessment - Non-residential buildings

See attached document

Appendix B.

UNI EN ISO 14040 and UNI EN ISO 14044

B.1. UNI EN ISO 14040: 2006 Environmental management - Life cycle assessment - Principles and framework

See attached document

B.1. UNI EN ISO 14044: 2006 Environmental management - Life cycle assessment - Requirements and guidelines

See attached document

UNI 8290 Decomposition of the building

The documents attached to Appendix C illustrate the decomposition of the building in accordance with UNI 8290 in the three hypotheses:
- building as constructed
- building with wood fiber as insulation in the perimeter walls
- building in which all insulation is wood fiber

C.1. UNI 8290 decomposition without wood fiber

See attached document

C.2. UNI 8290 decomposition with wood fiber in the perimeter walls

See attached document

C.3. UNI 8290 decomposition with wood fiber as insulation

See attached document