Doctoral School in Environmental Engineering

Life Cycle Thinking:

Strategies for Sustainable Renovation of Existing Buildings

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This thesis is the result of many hours of intense work,
uncountable hours of commuting by train, bus and walking,
long days spent to read papers and books and test my ideas
(sometimes great and sometimes absurd),
always accompanied by my troubles and health problems.
Being a PhD student has been very hard,
but in this period I have learnt to defend my own opinions
and to win over my shyness;
and after three years I feel more aware of my skills
and of my way of being.
This is the reason because for the first time
I want to dedicate something to myself.
Maybe it is strange and unusual,
but this thesis is for me,
because I owe it to myself.

General Index

SUMMARY

Life Cycle Thinking: Strategies for Sustainable Renovation of Existing Buildings

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The project focuses on developing strategies for interventions of sustainable renovation, with the awareness that re-using existing buildings allows to reduce the impact on the environment and also to maintain our cultural sources and ecosystems.

The largest part of the European building stock is composed of buildings older than 30 years that will continue to account for the major portion of it also for the decades to come. These buildings are very important because of their economic, social-cultural and environmental value. Often built stock needs interventions of renovation in order to meet the actual standard of performance, both from energetic and functional point of view. Recent changes in human life style oblige to modify spaces in a quick way and this necessity has reduced the life of our buildings. For this reason it is fundamental operate on existing buildings reducing the waste production, by using the strategies of the design for de-construction and the reversible design. To do this, LCA is the best method, because it allows measuring objectively the buildings impact and the environmental benefits of renovations and also it can help in defining the most appropriate materials.

This work presents the analysis of the restoration projects of two industrial buildings in a sustainability perspective. Industrial buildings were chosen as case studies because of their big sizes, good accessibility, flexible internal partitions and large pertinence areas, features which make them good candidate for rehabilitation. The focus point is how to convert this existing estate in a sustainable way, in order to reduce the need for new constructions and optimize the intrinsic qualities of forsaken industrial spaces.

The first part of the work focused on the literature analysis and on a review of the current regulatory standards and existing tools for assessing sustainability of construction works, both new and retrofitted. Aspects related to environmental, economic and energy assessments have been investigated, proposing their integration in three progressive steps. At first it has been studied how integrating energy certification with environmental performance; after that also the methodology for the integration of environmental performance with economic cost has been studied and then a first attempt to relate together these three different concerns has been proposed, testing it on a first case study. Furthermore, analysis on this case study aimed to understand how different material choices could affect environmental savings coming from building retrofitting and reuse.

However, as underlined before, in order to avoid the risk of new process of abandonment, also the possibility to assess buildings adaptability over the time has been studied. Thus, in addition to environmental, energy and economic aspects and benefits in restoring a fifth parameter expressing buildings adaptability has been taken into account for better assessing sustainability of an intervention.

To relate together these five parameters, characterized by different units of measurement, Multi-Criteria Analysis has been used, with the aim to find a single value able to communicate the sustainability level of the designed retrofitting alternatives. This developed methodology has been then tested applying it on the second case study, of which the project of renovation has been designed. Once the methodology was validated, a simplified operational-tool has been developed for comparing different design solutions and giving a contribution to decision makers for designing interventions of renovation which can be sustainable under multiple aspects, in a whole sustainability perspective.

INTRODUCTION

In light of the climate change, developed and developing countries are facing resource scarcities problems and ecological issues: global warming, ozone layer depletion, deforestation, destruction of natural habitats, loss of biodiversity, which are all products of a too intensive human activity on the planet.

The discussion on how reducing these human negative impacts on the environment is one of the most important topic in the scientific community and all the international policies are addressing towards an increased environmental awareness, with the aim to guarantee a more sustainable development. To achieve sustainability goals, countries are asked to reduce the current standards of production and use of resources, according to the *"environment carrying capacity"* of the planet, modifying production and consumption models, promoting the eco-efficiency, minimizing the use of non-renewable resources, avoiding the use of pollutant substances, recycling waste, stemming the bio-diversity erosion and the modification of the land-use.

In 1972 the concept of sustainable development was introduced for the first time in the report *The Limits to Growth*. In this report it is underlined the necessity to reduce the level of resources use for avoiding the world collapse within 100 years and to reach a condition of ecological and economic stability, sustainable far into the future. In that year, the first United Nation summit on man and environment took place in Stockholm, Sweden. This conference is widely recognized as the beginning of modern political and public awareness of global environmental problems.

A further step towards a major awareness of environmental problems was made in 1987 with the publication of the Brundtland report, titled *Our Common Future*, written by the World Commission on Environment and Development. Within the report sustainable development is defined as *«development that meets the needs of the present without compromising the ability of future generations to meet their own needs»* [1].

It is well known that all over the world construction industry is one of the biggest contributor to social and economic development of a country, but, at the same time, this sector is also one of the major responsible of the environmental damages, such as high energy consumption rate, solid waste generation, greenhouse gasses emissions, resources depletion. Worldwide, building construction industry consumes 40% of the materials entering the global economy and generates about 50% of global carbon dioxide emissions and the agents of acid rain. And, just in the European Union, the construction and building sector is responsible for roughly 40% of the overall environmental burden.

For such reasons European policies in the last decades mainly focused on the necessity to increase the threshold of buildings performance, improving their energy performance. Despite the presence of these regulations for building energy efficient constructions, «*the slow rate of replacement of existing buildings (between 0.5 and 2% per year) is such that it would be a considerable length of time before they had a significant impact. As emphasized in the 3rd European Minister's Conference on sustainable housing, existing buildings must also be made more sustainable by retrofitting them or ensuring that sustainability is a key consideration in their refurbishment. Improving the energy efficiency of existing buildings is one of the most cost-effective ways of meeting the Kyoto climate change commitments*» [2].

This means that building new constructions in a sustainable and virtuous way is not enough: it could be more beneficial retrofitting the existing building stock, that has an incidence of 40% on the European built heritage and of nearly 60% just in Italy. By improving the energetic quality of the 10% of the entire Italian stock it could be possible to achieve a reduction in carbon dioxide emissions equal to 10-11%, quantity that is higher than that one that is possible to reach realizing new buildings for the next 20 years. This concept is totally according to Richard Moe, President of the National Trust for Historic Preservation (USA): *«No matter how much green technology is employed in its design and construction, any new building represents a new impact on the environment. The bottom line is that the greenest building is one that already exists»* [3].

In the last years the attention was paid mainly on strategies for a sustainable design of new buildings, omitting the discussion about the importance of improving and re-using existing buildings. By the way, it is impossible do not consider these estate, since the widest part of the Italian building stock is composed of buildings realized before 1973, year of the first energy regulation exit. Of this buildings, 17,5 millions consume about 200-250 kWh/m^{2}year and other 8,8 millions consume 150 kWh/m^{2}year. These high values of consumption demonstrate that Italian buildings are behind the actual evolving standards of performance and people often prefer to build new buildings that can better meet the needs of the contemporary society. Anyway this practice is very dangerous because continuing to construct new buildings we will have only an increase in buildings number and in territory consumption, do not considering that new buildings of today will be existing buildings of tomorrow.

Furthermore, renovation is more complicated than new construction as different buildings require different solutions, and even more so in protected buildings. Although their low level of performance, these existing buildings can be considered very important from a sustainability perspective and their renovation has several advantages over demolition and reconstruction.

Existing (and ancient) buildings can have an environmental, economic and cultural-social value. As it is well known this meets the definition of sustainability given in Brundtland Report (1987), in which it was defined like combination of three different systems: the environmental system, the economic system and the social system.

Their environmental value is due to the embodied energy in construction materials and to the land saving, considering that the adaptation of the building stock to meet evolving requirements can reduce the need for new constructions. From an economic point of view, existing buildings are important because they can be driver for urban regeneration and for tourism; furthermore they also have a social-cultural value, because they contribute to the sense of pride and heritage in local communities, transmitting to the people a sense of place and an aesthetic and educational value. Because of all these values it is possible to consider the built heritage like a good example of sustainability. The difficult thing is to prove objectively these affirmations using appropriate data and tools.

_ Notes

[1] definition of sustainable development according to the report *Our Common Future*, written by the World Commission on Environment and Development and known as Brundtland Report;

[2] citation from the document by the European Community: *Towards a thematic strategy on the urban environment*, 2004;

[3] citation from an interview to Richard Moe, president of the National Trust for Historic Preservation of USA: *Sustainable Stewardship - Historic Preservation's Essential Role in Fighting Climate Change*, published in The Minnesota Preservationist, Vol. 11, No .2: pp.3-5, 2008.

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Chapter 1

EXISTING ESTATE POSITION

This chapter analyzes the current situation of the Italian existing estate, investigating which kind of buildings are good candidates for going under renovation. With this analysis both residential and non-residential buildings were selected because of their "reuse-potential".

Afterward, a focus investigation on the industrial estate is described: often underestimated, industrial buildings constitute an important part of our cities, because of their social and cultural value. Furthermore, the process of restoration of these buildings allows to save resources for new constructions and to reduce land consumption. This makes of buildings good candidate to be rehabilitated.

1.1 _ Investing in building renovation

1.1.1 Overview

A research presented during the 2012 Green Economy festival underlined the critical situation of the Italian building stock: it is the oldest stock in European countries and 5% of buildings need of urgent interventions of renovations, while 40% need exceptional maintenance interventions. This is mainly due to the relevant presence of historical nucleus on the territory and to the high rate of buildings constructed in the period between Fifties and Eighties.

In fact the largest part of the building stock was built after the Second World War, when population started to grow again. Especially during the “economic boom” of the Sixties, known as *economic miracle*, a huge number of constructions was built for answering to the needs of new homes and factories. The demands for new buildings that characterized that period of expansion strongly contributed in modifying the shape of Italian cities: closed to the historical center, new multi-stories apartments buildings and productive buildings were built.

Today, while those residential building are still occupied and subjected to renovation processes for maintaining or increasing their economic value on the market, aged industrial buildings, subjected to a quick aging process are instead forsaken and totally left to a degradation state.

1.1.2 Italian buildings position

The building sector refers to two main categories of buildings: residential buildings and non-residential buildings. As explained in the final report of the *ENTRANZE project* [1], while residential buildings are quite homogenous and can further be divided into well-defined sub-categories (single/two-family houses and apartments blocks), non residential buildings are more heterogeneous, since they includes several building categories, such as, office buildings, hospitals, schools and universities, hotels and restaurants, factories and productive buildings, storages, buildings in wholesale and retail trade.

Focusing the attention on the situation of the Italian building stock, it is possible to observe that it is composed for the 55% of buildings older than 40 years. This value rises the 70% when considering medium size cities and exceeds the 76% for big cities. For what concerns residential sector, the tendency to invest in building renovation is yet spread. In the last ten years people investments increased of the 15%: if during Nineties renovation activity involved the 43,5% of dwellings (data source: ISTAT), in the period 2001-2011 the percentage of renovated dwellings raised up to 58,6%, with 17,6 millions of involved houses on a total number of 30 millions (data source: CRESME 2012). The major part of these interventions was aimed to the substitution and modernization of plants, especially for heating and cooling, as illustrated below in *Table 1.1*.

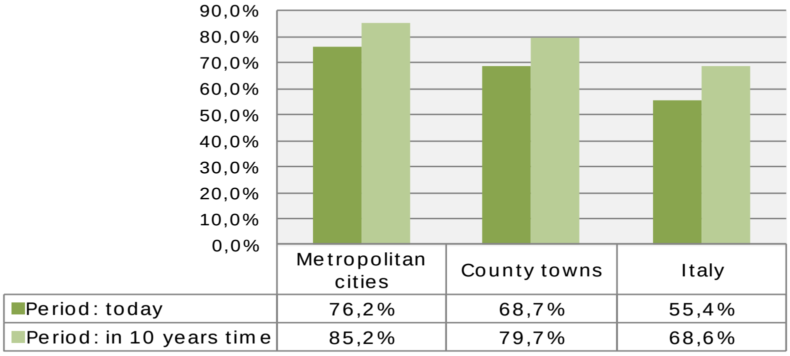
Dwellings restoration	**Year**	
	2001	***2011***
Existing dwellings	27.269.000	30.038.000
	100%	100%
Retrofitted dwellings in last 10 years	11.871.000	17.613.000
	44%	59%
Plants and equipment	9.729.000	12.524.000
	36%	42%
Structures	1.833.000	2.756.000
	7%	9%
Aesthetic appearance	7.825.000	9.214.000
	29%	31%

Table 1.1 _ Dwellings restoration activity in 2001 and 2011 (CRESME 2012)

Several factors stimulated and advocated the investments of Italians in building renovations: at first the old age of the building stock and the obsolescence of its components, the choice to personalize bought buildings, the necessity to meet European standards for what concerns specific sectors (electric plants, heating technologies, etc.), the short life-cycle of plants, policies of incentives (36 and 55% deductions), and, lastly, the increase of dwellings prices induced a lot of people to content of their own home, intervening with restyling or renovation operations.

Furthermore, in light of the economic crisis, in the last period people preferred to invest in building renovation of its property, rather than investing in new constructions. Another important aspect has to be considered: for many people the house coincide with “richness”. Maintaining or renovating the house means maintaining the capital, since in most of cases it is the only investment made by a single person or a family.

However, despite the great potential for building renovation on the Italian territory, there is not yet a whole project of restoration of the real estate, but only several and small forms of interventions, mainly oriented to change building components, old plants and to upgrade the aesthetic aspect of aged buildings. At this rhythm, in county towns, in ten years, the 80% of houses will be constituted of buildings older than forty years and in metropolitan areas their percentage will reach the 85% (*Graph 1.1*).



Graph 1.1 _ Percentage of Italian buildings older than 40 years (CRESME 2012)

Thinking of the building life-cycle these values of percentage assume a high relevance. A CRESME analysis made at the end of Eighties on buildings durability, in which international stakeholders were interviewed, identifies an average buildings age of forty years. After this period building products need of interventions of restoration in order to guarantee the qualitative base standards. In 2020 buildings older than forty years will be 12 millions and most of them have been never subjected to any type of intervention since their construction. Nowadays, the maintenance condition of the building stock indicates that more than 22% of buildings is in a bad position: 19,9 in a mediocre condition, while 2,2% in an awful condition, with a total of 2,6 millions of buildings with evident needs of renovation (*Table 1.2*).

Construction period	**Building position**				
	Excellent	***Good***	***Mediocre***	***Bad***	***Totale***
before 1919	316.700	1.049.615	680.381	103.563	2.150.259
	14,7%	48,8%	31,6%	4,8%	100,0%
1919 - 1945	193.696	691.480	436.613	62.026	1.383.815
	14,0%	50,0%	31,6%	4,5%	100,0%
1946 - 1961	279.450	913.295	425.106	41.978	1.659.829
	16,8%	55,0%	25,6%	2,5%	100,0%
1962 - 1971	444.051	1.142.554	357.587	23.765	1.967.957
	22,6%	58,1%	18,2%	1,2%	100,0%
1972 - 1981	619.516	1.114.754	237.164	11.772	1.983.206
	31,2%	56,2%	12,0%	0,6%	100,0%
1982 - 1991	450.912	709.981	123.812	5.797	1.290.502
	34,9%	55,0%	9,6%	0,4%	100,0%
1992 - 2001	367.438	346.595	54.807	3.087	771.927
	47,6%	44,9%	7,1%	0,4%	100,0%
after 2001	382.931	133.147	15.445	1.065	532.588
	71,9%	25,0%	2,9%	0,2%	100,0%
Total	**3.054.694**	**6.101.421**	**2.330.915**	**253.053**	**11.740.083**
	26,0%	52,0%	19,9%	2,2%	100,0%

Table 1.2 _ Buildings position in relation to their construction period (CRESME 2012)

The discussion is more complicated for non-residential buildings. Non-residential building stock is constituted by a lower number of units (4,3 millions) of which the 79,8% is occupied by tertiary activities, while the remaining 20,2% is composed of industrial buildings, as shown in *Table 1.3* below:

non-residetial buildings	*tertiary sector*	3.430.000 79,8%
4.300.000	*industry sector*	870.000 20,2%

Table 1.3 _ Italian non-residential buildings

Tertiary sector is widely differentiated and it is composed of 1,3 millions commercial units, 0,6 millions offices, 0,3 millions restaurants, 73000 schools, 61000 hotels and 1,1 millions of units for “other services” (transportation, communication, insurances, banks, healthcare facilities).

The largest parts of these units are often located in buildings with a dominating residential function: shops, restaurants, other services at ground level or offices, hotels, private schools at intermediate floors and just a small part of them is located in detached buildings. Thus, it is quite common that tertiary activities have to relate with building envelopes and plants systems very similar to residential ones. However, the retrofitting of these spaces place a great role in enhancing the quality of the built Italian stock, since they occupy nearly 0,8 m^2 of surface.

For what concerns industrial buildings, the situation is totally opposed. Usually these buildings are big sizes detached constructions, since productive activities need wide dedicated spaces in which operate. If many tertiary activities are located in urban centers, modern industrial buildings are far from the cities center. In the city centers only aged industrial buildings are which are considered differently from other constructions.

The main difference consists of the perception of their economic value. While residential and commercial buildings are accounted as an effective economic asset for their owners and for such reason they are well maintained and subjected to restoration or retrofitting process, the widest part of the industrial building estate inside urban areas has been forsaken few decades after their construction because of its functional obsolescence.

1.2 _ A special concern on industrial buildings

1.2.1 Overview

Industrial architecture saw its beginning in England in the second half of XVIII century during the first industrial revolution. In few decades the industrialization process involved most European countries and, at the end of the XIX century mills and factories were diffused in all developed countries, rapidly changing cities' shapes and skylines.

The introduction at the beginning of XX century of concrete and steel technologies for building structures together with the development of the productive technologies deeply changed the construction of industrial architectures.

After a first industrialization period between the two world wars, Italy was interested by a great industrial expansion in the years of Fifties and Sixties, during the Italian economic miracle, when a large number of factories was built, in order to meet the international increasing demand of industrial products. The process of construction of this typology of buildings had a great role in changing our cities. New wide productive areas were constructed in proximity of the borders of the historical centers.

Unfortunately, the major part of these building was subjected to a fast aging process, due to the technological revolution which characterized the last years of the last century and also to the new logistic needs of the industrial sector.

The necessity to have larger areas for productive activities and the tendency to sum in the same place more activities, leaded to a progressive abandonment of the existing industrial constructions, which were considered obsolescent and inadequate to answer the production necessities and for this reason totally left to a degradation state.

An intensive construction activity involved the country until the end of Sixties and later in Nineties, causing a rapid increase of the built surface of the country and consequently a progressive saturation of the territory. During these cycles of expansion the first industrial buildings, which originally were on the cities' boundaries, were included inside the new enlarged limits of the city center, generating the problem of the integration of these structures inside the urban areas.

Nevertheless, despite the retardation respect to the recent European standards, the strategic position of these type of buildings and their sizes make them good candidate for rehabilitation.

1.2.2 Industrial buildings architecture

The beginning of the industrial architecture is seen in the simple mill buildings of late 1700, considered precursors of the modern factories and usually built with wooden or masonry structure and characterized by redundant forms and rhythmic regular openings (*Figure 1.1*).
According to L. Jevremovic, M. Vasic, M. Jordanovic *«these mills fit into the landscape and their scale and materials making little impact on their surroundings. Their conglomeration monopolized and blocked rivers and canals that fed the millwheels that provided power for their machines. These first mills reflected building technology of their time and responded to the realities of fire and workplace safety»* [2].

Figure 1.1 _ Massachusetts' Waltham Mills buildings (1816)

Before the electricity discovery, maximizing the daylight inside workspace was one of the most important things: thus the first industrial buildings were built with long and narrow shapes and internal open spaces in which it could be possible to accommodate the major number of machinery and workers as possible. Thanks to the narrowness of the building, light was allowed to enter in the centre of the structure and machinery could be located on both sides and powered from a single central shaft down the floor. Furthermore, the simplicity of the first industrial buildings was also due to their poor social importance, since they were considered as mere utilitarian structures and for this reason fully lacking of ornaments and frills.
In order to obtain the largest column-free interiors, most buildings of XIX century were multi-storied buildings, in which brick or masonry bearing walls were combined with heavy timber structural frames. This kind of structure not only encouraged workers to be efficient and productive, but was also effective in order to prevent fires. Inside industrial buildings no interior or exterior ornaments were designed and the presence of attics was

discouraged, while partition-free interiors and large windows were instead encouraged to facilitate putting out of fires.

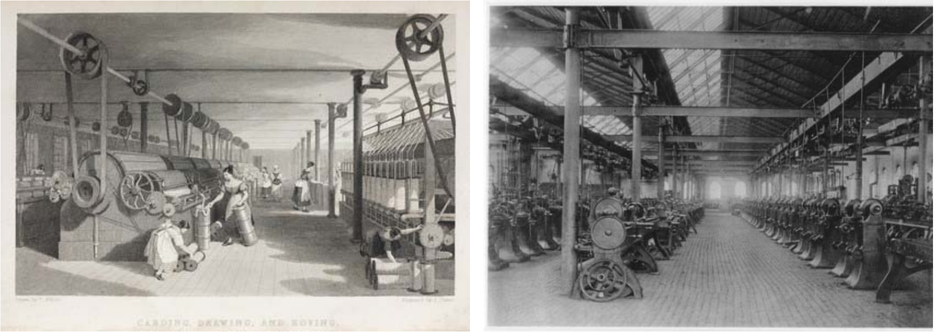


Figure 1.2 _ British cotton mill interior of 1835 (left)
Australian guns an pistol factory of 1850 (right)

Later, new ways of producing energy enhanced the development both of buildings and machinery. New industrial buildings needed of more resistant structures, able to bear higher loads and contemporary guarantee greater distances and more flexible and adaptable internal configurations.

The diffusion of concrete and steel structures had a great role in the changing the shape of industrial buildings. Thanks to these new materials, new typologies of constructions started to be built and in few years multi-storied buildings left the place to one-story factories, spread over many square meters. *«Industry definitely changed the landscape and population patterns by moving outside compact cities to where land was plentiful. This demanded a new and expanded road and rail system for materials and workers»* [3].

Until the beginning of XX century the attention of architects and designers was focused on important civic or commercial buildings and private residences, while industrial architecture continued to be designed in a simple and anonymous way, underlined by the exterior facades, totally undecorated independently from the material of which they were constituted (brick, wood or stone). As industrial uses became more important, architectural theory on how designing such kind of buildings were developed in order to answer the challenges posed by their development.

Around the early 1900s, the common perception of factories changed, and this building type started to be seen as worthy of architectural consideration, in order to dignify the workplace, enhance the production of goods as well as forge corporate identities.

Figure 1.3 _ Interior (left) and exterior (right) of two Italian hydroelectric centrals of the beginning of XX century.

The important social value of these buildings was highlighted by the drawn of the facades and the inner spatial configuration, which remind the structure of a gothic cathedral.

The role of industry sector increased a lot after the World War II, especially in the ‘50s and the ‘60s when urban growth of industrial centers initiated. Due to the increase in business opportunities also cities population grew, giving an answer to the new demand for workforce. Consequently, housing areas, services areas, roads and other infrastructural and communal facilities have been expanded. This growth, mainly involved free land on the cities’ borders, leading to an increase in traffic and in additional pressure on the road network that had to be expanded too.

Architectural aesthetic of this period is still under the influence of Modern movement and the International style; in this phase there was an intensive use of modern materials as reinforced concrete, iron and glass, but also some new materials such as asbestos, later plastic, etc. were introduced on the construction market. Despite in this period some great industrial architectures were built, they found little appreciation among the population or in some cases a total contempt and the indifference of the people versus industrial architecture became its worst enemy, more than the flow of time. The banality and low quality characterizing a large part of building constructions of the post-war period had a relevant role in affecting people mind. Completely forgotten and abandoned in a state of general indifference, most industrial buildings of the post-war period had the same destiny of the other buildings of the time, further worsened by their reputation of building with a low value. However, industrial heritage of the second half of XX century is the greatest and most common worldwide, although it is not jet perceived and evaluated rightly.

Thus, the need to realize the value of this part of the built heritage constitutes an important step for preserving their precarious condition.

Figure 1.4 _ Diemme Filtrations, Lugo, Italy (left)
and an abandoned industrial building of Sixties in Saratoga, Wyoming (right)

The end of the last century saw many changes in society and, consequently, shifts in industry and in cities structure.

The deindustrialization process of developed countries caused changes in economic structure, decline in employment in manufacturing, accompanied by a development of the tertiary sector with an increase in employment in services. Technical innovations leaded to radical changes in spaces organization and facilities; factories were progressively concentrated in functional areas outside from the city burdens in order to use land more efficiently and to maximize productivity. Buildings at first located on the city outskirts (distributive warehouses, industrial buildings, infrastructural facilities, etc.) due to the intensive urban growth were included inside the new expanded city structure. Furthermore a huge number of industrial complexes are being relocated outside national borders, in sites with lower costs of production and lower taxes, increasing the deindustrialization phenomena.

The question of the industry decay leaded to similar problems and processes in the most of cities worldwide. The relocation of the industrial functions in new areas, outside the city, left everywhere empty sites inside the urban city core, often in very significant locations, where ruined factories are the only occupants.

Time passage rendered these buildings functionally obsolescent and only the capability of seeing and understanding their beauty is the path for rescuing these constructions, promoting their renovation. The allure of the industrial aesthetic cannot be dismissed, and in many instances, is crucial to the success of their redevelopment.

The simple, wide-open spaces of factories and warehouses, with their clear expression of construction materials are captivating features for new generations, which started to renew the industrial estate, giving to abandoned buildings new functions and dignity.

1.2.3 Industrial buildings: advantages in retrofitting

Nowadays, it is fairly common meeting forsaken industrial buildings inside the urban areas. Their presence oblige to reflect on the possibility to convert these abandoned constructions to new functions, effectively reintroducing them inside the urban structure. Although their little appreciation, industrial buildings are characterize by a high historic, social and cultural value, since they constitute an element of memory and identification for the community.

Figure 1.5 _ Interior (left) and exterior (right) of two Italian forsaken industrial buildings

Abandoned buildings are often considered marginal elements of the urban context: this means to belittle not only their physical structure but also the importance of what they testify. Working on forsaken industrial areas necessarily means facing with the imagine that people have of these places. Thus, the first necessary thing to do is identifying the threshold to respect and which is the level of historical, identification and memory values that the building has, in order to avoid a conflicting relationship with the citizen expectations. Under this perspective, it is possible to consider the retrofitting of the industrial forsaken estate like a process of conservation of a social history symbol. Reintroducing productive constructions into the active part of cities, connecting them with the surrounding environment, is the best way for assigning them a new importance.

In light of these consideration it is also fundamental to take into account that industrial buildings, usually characterized by big sizes, good accessibility, flexible internal partitions and large pertinence areas, are good candidates for rehabilitation, since they can be easily converted in a wide range of possible use destinations.

In the last years the discussion on how retrofitting Italian industrial areas and the awareness on the importance of this topic has progressively increased, leading to a new consciousness on the convenience in restoring such kind of buildings. The economic aspect plays a great role in this type of considerations; anyway in the set of the most considered parameters, the possibility of industrial buildings to be effectively retrofitted and converted to new functions is fundamental as well.

Also the facts that retrofitting aged buildings allows to save resources for new construction, to reduce land consumption and to adopt innovative technologies oriented towards energy savings have to be taken into account.

The condition for allowing old buildings to survive to the new city development is to find for them new functions, which are coherent to the features of the building and with its surrounding, able to totally reintroduce them in the productive circle with a new specific social function.

For retrofitting these industrial buildings in a sustainable way some aspects have to be considered:

- these buildings are normally composed of solid framework, able to bear high loads and for this reason easily adaptable to new compatible functions;
- their envelopes are often in bearing walls (masonry or concrete) able to simultaneously guarantee a durable performance of the framework and a good thermal inertia of the envelope itself; when having a bearing framework structure, the necessity to operate on walls plug for improving their thermal behavior can represent a chance for testing new best energy practices;
- volumes of industrial buildings are generally characterized by a low surface/volume rate: this constitutes a significant element for minimizing energy consumptions;
- industrial spaces typically present out-of-scale dimensions which allow a good level of transformability, also permitting "double envelopes" solutions, oriented to avoid the overloading of the existing structures and to energy retrofit envelopes, without modifying the visual impact from the outside;
- indoor environments of industrial buildings are usually very well lighted by the presence of wide windows both in vertical walls and roofs, where the entry of the zenithal sunlight can generate striking effects;
- generally, inside industrial structures, cavities and technical compartments specifically designed for accommodating technical plants and equipment are present: these spaces can be used for installing new equipment for energy saving.

Furthermore, the evaluation of transformability of existing industrial structures cannot disregard the necessities to:

- pursue levels of safety and security (in terms of structural affordability, durability and fire resistance) which are compatible with the current standards of performance, without totally altering the buildings and its space;

- guarantee a high level of internal comfort, both acoustic and thermal, also fully redesigning the envelope when the original one is considered not adequate to answer the requirements of the current standards of performance.

Despite stakeholders demonstrated interest in retrofitting existing industrial buildings, there are still some difficulties to overcome to make this practice more common. On one side, the complex dynamics of development, as well as *«the need for either public funds or powers, requires public outreach and often involves the provision of public amenities»* [4]. On the other side, there is the necessity to educate societies to recognize, respect and value the industrial heritage. Indeed, the value of these buildings is not only corresponding to their functional and technical components, but is based on its history.

Rediscovering the past and the history of an industrial area allows people to realize the building significance, in an "industrial culture perspective". Yet, it is quite obvious that the public usually more appreciate buildings from a far past rather than ones from a more recent past. Anyway, the role of the restoration of the aged industrial architecture in re-defining shapes of the cities is really important, because each existing building can give its contribution to the conservation and identification of the space, the region and the history.

_ Notes

[1] *ENTRANZE project* (*Policies to Enforce the TRAnsition to Nearly Zero Energy buildings in the EU-27*) is a European project aimed to achieve a fast and strong penetration of nZEB and RES-H/C within the existing national building stocks.

[2], [3], [4] citation from the paper by JEVREMOVIC L., VASIC M., JORDANOVIC M.: *Aesthetics of industrial architecture in the context of industrial buildings conversion.*

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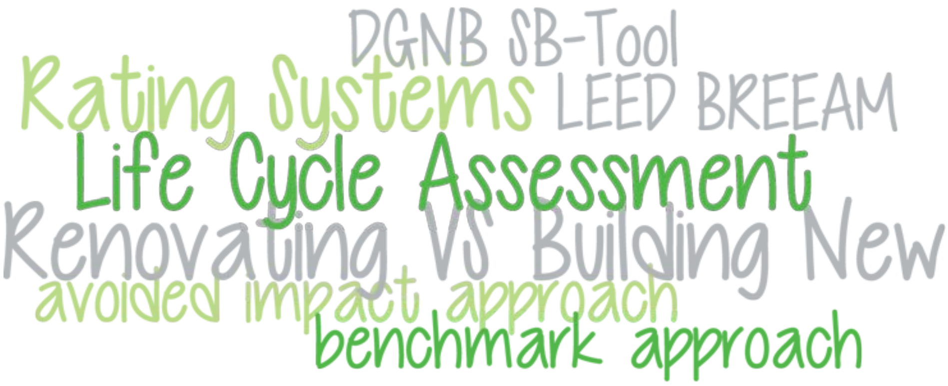
Chapter 2

SUSTAINABILITY ASSESSMENT

The first part of the chapter focuses on the analysis of the two primary methods for evaluating and communicating environmental attributes that relate to buildings: Rating Systems and Life Cycle Assessment, comparing them in terms of advantages and disadvantages and analyzing the forms of integration between these two tools.

In the second part of the chapter the role of existing buildings reuse as strategy for sustainable development is underlined, investigating the different tools for evaluating the environmental performance of renovations and which of them can better rewards their environmental merits. Furthermore, the use of LCA method as tool for objectively estimate the environmental gains coming from a building restoration rather than its demolition and reconstruction is presented.



2.1 _ Assessing sustainability: score methods Vs LCA

2.1.1 Overview

It is well known that construction sector accounts for nearly 40% of the energy consumption of the European Union. Furthermore this sector has a great role in greenhouse gasses emissions, as it is demonstrated by the progressive increase of carbon dioxide rate in the atmosphere. It was estimated that from 1850 to 2000, the carbon dioxide rate increased of the 25% [1] and it could reach the 50% in the decades to come. Focusing the attention on the role of the Italian construction sector, it is possible to observe that its energy consumption in 2007 was equal to the 34% of the national one and its tendency is to further increase.

For this reason, it is necessary to reduce its impact through the construction of less impacting buildings, which should be designed, built and maintained in a more responsible way. At the same time, also people awareness and sensibility on environmental issues related to buildings should be increased, addressing them towards more responsible behaviors.

With the aim to reduce the mentioned negative impacts from the building sector and to help a faster diffusion of “smart” design strategies, the European Union has introduced quite a few policies and regulations starting from 2002, when the first *Energy Performance of Buildings Directive (EPBD) 2002/91/EC* was released with the aim *«to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness»* [2].

Since then, sustainable design and green strategies applied to the building sector have become more and more popular among governments, designers and researchers. In few years, solar passive design and energy performance, insulation thickness increment, plant equipment improvement, renewable resources on site systems have become a trend.

Despite some initial difficulties in spreading the awareness of the importance of energy efficient constructions, the ongoing increasing level of the international requirements, obliged the building sector to achieve the necessary knowledge for building such kind of constructions.

Simultaneously, looking the world tendency, the concept of *“energy efficiency”* quickly moved towards the new concept of *“environmental efficiency”*, modifying and amplifying the concept of sustainable buildings in accordance with the definition of sustainable development, considering the economic, social and environmental aspects. For constructing buildings able to satisfy such features it is important to establish an equilibrated relationship with the environment, conjugating the issues concerning the living quality, the use of materials and resources, the energy consumption, the pollution of the environmental matrixes (water, air, ground).

Because of this wide set of parameters that must be taken into account for designing sustainable constructions there is an evident need to identify the potential environmental gains available with constructing a building. Due to this difficult issue, several tools for assessing building sustainability were developed in every country and most of them are often conflicting with the others. These tools can be split into two main categories: *multi-criteria assessment tools* and *Life Cycle Assessment.*

Both of them are able to evaluate and communicate environmental attributes that relate to buildings, but their approach to the whole building assessment is extremely different.

2.1.2 Building Sustainability Tools

Multi-criteria assessment tools (commonly also known as *Rating Systems - RSs*) are quite young tools, born during the last decade of the last century. They are based on a multi-criteria evaluation according to a framework of environmental indicators, both qualitative and quantitative. They have the triple goal of evaluating, objectively assessing and communicating the environmental quality level achieved by a building.

They are composed of a list of criteria, divided in environmental categories, considering human health and environment (i.e. urban environment, land use, comfort, indoor air quality, energy efficiency, reuse of building waste, adaptability, durability and maintenance). These systems assign a score for each strategy adopted in the project and their sum defines the level of sustainability, on the base of a rating scale.

Usually, RSs award with different weights the quality of the project, the construction site management and the building operation and maintenance.

Due to their simplified structure, they are useful guidelines for building practitioners and for rapidly promoting the sustainable strategies all over the world. Nowadays many building environmental assessment tools are available, such as *BREEAM (UK), DGNB (D), LEED (US), SBTool* (international) and many others.

If on one hand rating systems are good green design guidelines, on the other they address designers to a prescriptive design approach, and not to a performance one, making it farther from innovation and experimentation in technologies. Moreover, in rating systems it is possible to operate in different ways for achieving the same result, by summing and changing design strategies, with a completely different environmental impact, without taking into account that a sum of different types of performance does not correspond to the building global performance.

This defines an *“apparent sustainability”*, giving a final result that is easy to understand, but that comes from several methodological simplification and for that it cannot provide an objective value of the environmental loads generated by the building.

On the basis of these considerations it is possible to affirm that rating systems are an effective tool for the diffusion of sustainable practices in building sector and help designers to meet green design strategies, but at the same time they are not the most adequate tools for evaluating buildings sustainability.

Indeed, the type of indicators used for assessing building environmental performance should be able to provide quantitative and measureable data, which refer to an objective sustainability. *Life Cycle Assessment (LCA)* bases exactly on the use of these indicators, commonly known as *synthetic indicators*, that can analyze the real environmental impact of an intervention during the different stages of its life, *“from cradle to cradle”* or *“from cradle to grave”* (*Figure 2.1*), evaluating the quantity of depleted resources and the amount of emissions to environmental matrices. Only by using synthetic indicators it is possible to estimate the building impacts because they do not suggest design strategies, but calculate and verify the environmental consequences of the design choices.

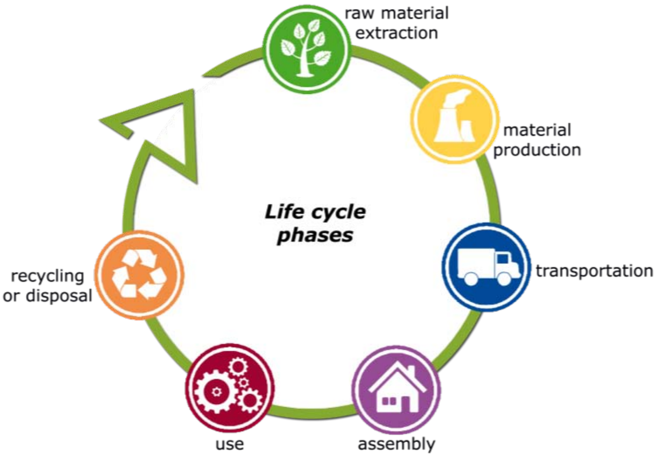


Figure 2.1 _ Life Cycle Assessment phases (raw material extraction, material production, transportation, assembly, use, recycling or final disposal)

Born during Sixties in the industry sector for designing low environmental impact products, LCA methodology started to be applied to the construction sector only in the last years.

Main reference for LCA is the ISO 14040 standard, in which LCA is defined as: «*A technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases. LCA is often employed as an analytical decision support tool*» [3].

As underlined in the SETAC report *"Life cycle Assessment in Building and construction: a state-of-the-art report"*, thanks to the efforts from researchers and from building industry and stakeholders, *«the importance of environment-related product information by means of LCA is broadly recognized, and LCA is considered one of the tools to help achieve sustainability building practices»* [4].

The complexity of buildings has made the application of LCA in the construction sector a distinct working area within the LCA practice. In fact buildings can be considered special products «*since they have a comparatively long life, they undergo changes often (especially offices and other premises), they often have multiple functions, they contain many different components, they are locally produced, they are normally unique, they cause local impact, they are integrated with the infrastructure, system boundaries are not clear, etc*» [5]. This implies that performing a full LCA of a building is not a so simple process like for many other products. Due to the large amount of data required to carry out an LCA, specific applications have been developed to facilitate the use of LCA in the building sector. Nevertheless there are some gaps regarding environmental indicators, easily understandable presentation of LCA results to users, simplification and adaptation of LCA to various purposes (e.g. early design phases).

Only by using synthetic indicators it is possible to estimate the building impacts because they do not suggest design strategies, but calculate and verify the environmental consequences of the design choices. Although this proven scientific validity, LCA method has been rarely adopted for assessing building sustainability, especially because of the presence of barriers and prejudices about it, in particular referred to its complexity, accuracy, costs, poor incentives and low link with the energy certification.

Since their introduction in the construction sector, RSs were preferred by institutions and stakeholders to LCA methodology in light of the higher flexibility and easiness to use, placing in contrast the two methodologies.

With the introduction of the new family of ISO and EN standards (15643 and 16309), tack has been changed and LCA has been progressively integrated into RSs.

2.1.3 Integration between RSs and LCA

Since the launch of ISO/TS 21931:2006 *"Sustainability in building construction – Framework for methods for assessment of environmental performance of construction works"*, the international community has been working for developing a framework for methods of assessment for the environmental performance of buildings, in order to standardize all the assessment methods for buildings environmental performance which have been developed and used worldwide since the early 1990s.

Inevitably life-cycle approach, as standardized methodology, will play a great role in setting performance criteria within methods of assessment of overall environmental performance of buildings.

In light of these evolvements of the international standards, the major part of the most spread RSs, such as the *British protocol BREEAM*, the *German protocol DGNB*, the *international protocol SB-Tool* and the *US protocol LEED*, has been involved in a revision process aimed to introduce LCA-related criteria into their assessment framework. Currently, in all of them it is possible to individuate some criteria clearly inspired to LCA analysis.

BREEAM protocol, launched on the market at the beginning of Nineties, in its last international version (2013) incorporates the majority of environmental performance measures proposed for the evaluation in CEN/TC 350 standards, together with a significant number of social performance and some economic measures:

- *criterion Man 02 _ "Responsible construction practices",*
- *criterion Man 03 _ "Construction site impacts",*
- *criterion Man 05 _ "Life cycle cost and service life planning",*
- *criterion Ene 04 _ "Low and zero carbon technologies",*
- *criterion Ene 05 _ "Energy efficient cold storage",*
- *criterion Mat 01 _ "Life cycle impacts",*
- *criterion Mat 03 _ "Responsible sourcing of materials",*
- *criterion Le 06 _ "Building Footprint".*

Credits Man 02 and Man 03 address to manage construction sites in an environmentally manner in terms of resource use, energy consumption and pollution, while the credit Man 05 has the objective to encourage life cycle costing (LCC) and service life planning in order to improve design, specification and through-life maintenance and operation.

The three criteria Ene 04 and Ene 05, are oriented to reduce carbon dioxide emissions throughout the building usage phase.

For what concerns building material, in the credit Mat 01 and Mat 03 there is a direct reference to the use of construction materials with a low environmental impact (including embodied carbon) over the full life cycle of the building, encouraging the use of EPD certified materials.

The criterion Le 06 aims to promote the most efficient use of a building's footprint by ensuring that *land and material use is optimized across the development*.

In Germany, *DGNB protocol*, was developed since the first edition stressing the attention on the whole building life cycle. In the last version (2012) the first evaluation area of the framework is composed of six criteria, which correspond to the six impact categories of Environmental Product Declarations ("Global Warming Potential", "Ozone Depletion Potential", "Photochemical Ozone Creation Potential", "Acidification Potential", "Eutrophication Potential", "Non-Renewable Primary Energy Demand").

In this RS also a section related to Life Cycle Cost is included, with particular reference to two credits: *"Building Related Life Cycle Costs"* and *"Suitability for the Third-part Use"*, which underlines the importance of reducing costs of management in order to make the building suitable for final users.

At the international level, also *SB-Tool* has been working for the integration of LCA method into its framework.

The five criteria that compose the section *B1 "Total Life Cycle Non-Renewable Energy"* aim to minimize the energy consumption from renewable sources in all life cycle stages. Furthermore, the *section C1 "Greenhouse Gasses Emissions"*, composed of four credits, aims to reduce carbon dioxide emission throughout the whole building life cycle. Other types of impacts and emissions to the atmosphere are considered in the *section C2 "Other Atmospheric Emissions"*. Lastly, the presence of specific credits for the cost evaluation has to be noted: *section F2 "Costs and Economics"* bases on the use of Life Cycle Cost (LCC) method for performing such kind of analysis, considering construction, operational and maintenance cost overall building lifespan.

LEED (Leadership in Energy and Environmental Design) is the most adopted RS in the world. Born in the US in 1993, it is currently under revision and the fourth version of the protocol should be launched within few months. The most significant changes in this new version are that the system is now totally based on a life cycle thinking approach. This is extremely clear looking at the "Material and Resources" area, in which the prescriptive approach adopted in the previous versions is now upgraded to a performance one, proposing new credits in which LCA analysis is required.

In the new proposed *MR credit "Building Product Disclosure and Optimization-Environmental Product Declarations"*, an Environmental Product Declaration

(EPD) or another approved form of reporting LCA-based information is required.

Furthermore, LEED v.4 in the *MR credit "Building Life Cycle Impact Reduction"* asks for a whole building LCA to optimize decisions on structure and envelope, rewarding projects for using less materials while maintaining building function, durability and reducing environmental impacts.

Table 2.1 below shows how LCA is becoming more and more important in RSs, going to overcome criteria related to energy performance reduction. The awareness that materials impact in new buildings can reach the 50% of the overall impact was one of the main drivers in changing RSs structure, introducing LCA parameters. Furthermore LCA-based criteria are able to better consider effective materials impacts, without any prescriptive and benchmark to follow for considering a material as sustainable. Sustainability of materials with LCA criteria is fully measurable, by using indicators, which go beyond the respect of qualitative features.

issues	**Rating Systems (RSs)**			
	BREEAM	**DGNB**	**SB-Tool**	**LEED v.4** pilot version
energy reduction	2 credits	-	5 credits	3 credits
environmental impact using LCA parameters	5 credits	6 credits	9 credits	2 credits
economic analysis using LCC methodology	1 credit	2 credits	4 credits	-

Table 2.1 _ number of life-cycle based criteria into RSs

2.2 _ Assessing sustainability of restoration interventions

2.2.1 The existing buildings role in sustainable development

It is fairly common to see trade and professionals magazine affirm that since *«buildings currently constitute the largest energy-consuming human creation, we must begin to design our buildings more sustainably»* [6]. Anyway, despite of the presence of regulations and knowledge for building energy efficient constructions, *«the slow rate of replacement of existing buildings (between 0.5 and 2% per year) is such that it would be a considerable length of time before they had a significant impact. As emphasized in the 3rd European Minister's Conference on sustainable housing, existing buildings must also be made more sustainable by retrofitting them or ensuring that sustainability is a key consideration in their refurbishment. Improving the energy efficiency of* *existing buildings is one of the most cost-effective ways of meeting the Kyoto climate change commitments*» [7].

This means that building new constructions in a sustainable and virtuous way is not enough: it could be more beneficial retrofitting the existing building stock, that has an incidence of 60% on the European built heritage and of nearly 80% just in Italy. By improving the energetic quality of the 10% of the entire Italian stock it could be possible to achieve a reduction in carbon dioxide emissions equal to 10-11%, quantity that is higher than that one that is possible to reach building new for the next 20 years.

This concept is totally according to the affirmation of Richard Moe, President of the National Trust for Historic Preservation (USA): *«No matter how much green technology is employed in its design and construction, any new building represents a new impact on the environment. The bottom line is that the greenest building is one that already exists»* [8].

In the last years the attention was paid mainly on strategies for a sustainable design of new buildings, omitting the discussion about the importance of improving and re-using existing buildings. Currently the major part of the building stock is used without considering its full potential.

Until now, little has been known about the climate change reductions that might be reached by reusing existing buildings rather than demolishing and replacing them with new constructions. Understanding the environmental value associated with building reuse is one of the fundamental step for increasing communities awareness in building renovations.

There are in fact many reasons to preserve a structure: it may tell an interesting story, serve as tangible link to the past or act as an economic engine within the community. Furthermore, apart from these cultural and economic values, environmental factors may also address to building refurbishment. As communities are learning the importance in reducing greenhouse gas emissions related to energy consumption during the building usage phase, it is increasingly important to understand the potential environmental advantages and disadvantages coming from building reuse and retrofit.

By the way, it is impossible to ignore that the widest part of the Italian building stock is composed of constructions built before 1973, year of the launch of the first energy regulation. Of these buildings, 17,5 millions consume about 200-250 kWh/m^{2}year and other 8,8 millions consume 150 kWh/m^{2}year. These high values of consumption demonstrate how much Italian buildings are lagging behind today's standards of performance.

Studies demonstrate that the least energy efficient structure are those built between 1940-1975. Pre-1940 buildings tend to maximize natural sources of lighting and ventilation and are built considering site, environmental and climate features.

Built for purposes that no longer exist or has changed, existing buildings are often underestimated and people prefer to build new buildings that can better meet the needs of the contemporary society. Anyway this practice is very dangerous because continuing to build new constructions we will have only an increase in buildings number and in territory consumption, do not considering that new buildings of today will be existing buildings of tomorrow.

Generally renovation is more complicated than new construction as different buildings require different solutions, and even more so in protected buildings. Although their low level of performance, these existing buildings can be considered very important from a sustainability perspective and their renovation has several advantages over demolition and reconstruction.

Existing (and ancient) buildings can have an environmental, economic and cultural-social value. As it is well known this meets the definition of sustainability given in Brundtland Report *Our Common Future* (1987), in which it was defined like combination of three different systems: the environmental system, the economic system and the social system.

For what concern existing buildings the environmental value is due to the embodied energy in construction materials and to the land saving, considering that the adaptation of the building stock to meet evolving requirements can reduce the need for new constructions. From an economic point of view, existing buildings are important because they can be driver for urban regeneration and for tourism; furthermore they also have a social-cultural value, because they contribute to the sense of pride and heritage in local communities, transmitting to the people a sense of place and an aesthetic and educational value. Because of all these values it is possible to consider the built heritage like a good example of sustainability. The difficult thing is to prove objectively these affirmations without access to appropriate data and tools.

2.2.2 Rating systems for existing buildings

Despite the large availability of tools for assessing sustainability of buildings, there is a gap for what concerns the development of specific tools for renovation projects. In most cases, tools for new constructions and for renovations are the same; minimizing the beneficial role that existing stock could have in reducing environmental loads.

All the rating systems listed in *Paragraph 2.1.3* do not include in the current last version a specific path for existing buildings, and the tool used for the evaluation of restorations is the same used for new constructions. There are just few credits inside their framework, which take into account benefits of reusing existing buildings.

In DGNB, just the credit *"Use of Existing Structures"* in the *"Socio-cultural and Functional Equity"* section directly regards existing buildings. Also in SB-Tool just one credit refers to existing buildings: it is *"Culture and Heritage"* in the section *"Social, Cultural and Perceptual Aspects".*

For what concerns BREEAM an LEED the situation is quite different. Despite in the current versions (BREEAM International 2013 and LEED 2009 for new Constructions and major Renovations) of the two protocols there are just a few of criteria regarding existing buildings, both the institutions (BRE Global and US GBC) are working for improving their systems.

Traditionally BREEAM has included refurbishment, fit-out and new build assessments as part of the same methodology and scheme as is the case with BREEAM 2008. BRE Global association, next to the BREEAM International framework is developing a specific tool for refurbishment. Currently the scheme *"BRREAM Domestic Refurbishment 2012"* is on the UK market. It has been developed with the aim to help owners and stakeholders in improving the efficiency of the housing stock, in light of the objectives of the Europe 20-20-20 policy. Furthermore, BRE Global is currently developing a new standalone scheme for assessment of non-domestic buildings refurbishment titled *"BREEAM Non Domestic Refurbishment 2014"*. This new version of BREEAM will provide a dedicated scheme for non-domestic refurbishment and fit-out, running alongside BREEAM New Construction and BREEAM In-Use. The *BREEAM Non-Domestic Refurbishment* scheme is targeted to be live in early 2014.

At the same time US GBC is developing LEED v.4, which should be launched within next spring. From the pilot version of the protocol it is possible to observe a clearer reference to existing buildings (historical or not) than in 2009 version. In fact, in *"Material and Resources"* section, the credit *"Building Life Cycle Impact Reduction"* has a specific option for historical buildings, in which the choice to reuse the existing structure rather than demolish and rebuild a new one is rewarded.

About LEED a special concern has to be done. GBC Italia, is currently developing a specific tool for historical buildings. In this new framework a specific consideration is given to existing historical buildings. Using as starting point LEED Italia 2009 for New Construction and Major Renovation and GBC Home, the new protocol *GBC Historic Building Rating System* has been developed (*Figure 2.2*).

Figure 2.2 _ GBC Historic Buildings development

Despite the major part of the evaluation areas remains the same, a new section has been introduced. This section, called *historical value*, bases on the application of sustainability principles to the restoration field: an intervention of restoration/conservation is sustainable when it allows future generations to recognize the same cultural values which can recognize today.
This section includes criteria specifically related to the building investigation phase and to the compatibility of the intervention. Furthermore other evaluation areas have been modified in order to include credits able to better meet aspects related to a restoration project.
Today this RS exists only as pilot version and some case studies have being currently studied, but it seems sure a definitive release of this protocol in the next future. The introduction of such kind of scheme by GBC Italia it is a clear demonstration of the fact that in the Italian context there is the need to operate on the built heritage in a sustainable way.
As described in *Chapter 1,* the largest part of the existing stock need to be renovated and the presence of schemes that can contribute in helping the renovation process in a sustainable way is a key element for addressing the objective of more environmental friendly existing buildings.

2.2.2 LCA for existing buildings

Difficulties in assessing environmental sustainability of building reuse through the use of rating systems can be bypassed using different methods, able to better estimate and proactively manage potential negative impacts of the building practice. Convenience in retrofitting the existing stock can be evaluated quantifying the differences between the environmental impacts of building reuse versus new construction. The handful of studies that explore this topic were mainly developed in North America and US, despite this in most countries demolition and replacement of buildings is a common practice and the opportunity to gain carbon and other environmental savings through building reuse and retrofit remain poorly understood.

A leading tool to perform the comparison between a refurbished building and a new one (and the only tool which have the potential to fully evaluate all sources and types of impact) is Life Cycle Assessment. Thanks to its structure and methodology, LCA allows understanding both advantages and disadvantages of building reuse and retrofitting. Furthermore, the LCA framework enables an in-deep analysis at how buildings variables can affect the decision to reuse buildings versus build new.

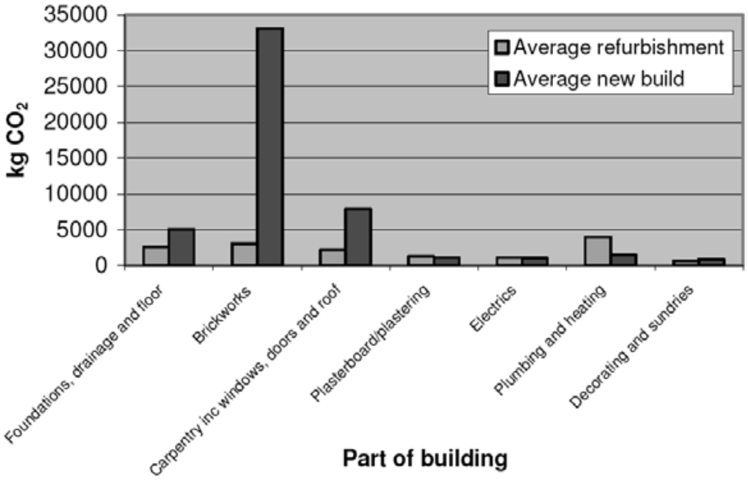
While *«it may seem intuitively obvious that retaining and renovating older buildings has environmental merit, the case is difficult to prove without access to appropriate data and tools»* [9].

First efforts to quantify the environmental value of building reuse in US began in 70s-80s, when some analyses on the calculation of the embodied energy in buildings were performed. The results of these analyses were published in 1979 in a report released by the Advisory Council on Historic Preservation, during the peak of the energy crisis. This study contains formulas developed for measuring the energy need to restore and rehabilitate existing buildings and to demolish and replace them with comparable new constructions. Furthermore the importance to carefully considering aspects affecting the building environment and energy conservation is highlighted.

In recent times, the ATHENA Institute proposed a method for the assessment of the environmental benefits of building reuse. This method is explained Wayne B. Trusty, President of the ATHENA Institute, in a paper of 2004 titled "*Renovating Vs Building New: the Environmental Merits*". In the paper, the author describes two basic approaches that can be taken for this kind of assessment. The first approach consists of building up a profile of the effects associated with demolition, material choices and new construction of specific building elements. Then, these effects can be compared with those one coming from the construction of a new building, including the total demolition of the existing structure. Trusty defines this approach as *"benchmark approach"*, since the new building serves as benchmark for determine the renovation merits. Differently, the second approach is based on the estimation of the environmental impacts avoided by saving and rehabilitating a building. This implies to calculate only the impacts generated by the demolition and construction of building elements. Thus, this approach is called *"avoided impact approach".* This approach considers two different possible scenarios of avoided impacts: the *"minimum avoided impact case"* and the *"maximum avoided impact case"*. The first one considers saving only the structural system of an existing building, demolishing and replacing the rest. In this case, the avoided impacts equal the effects of: *demolishing a structural system + rebuilding a comparable structural system.* In the second case the envelope as well as the structure are saved, with avoided impacts equal to the effects of: *demolishing a structural/envelope system + rebuilding a comparable structural/envelope system.*

The *"benchmark approach"* is more adequate when one or more renovation scenarios is being compared to one or more new construction alternatives. The *"avoided impact approach"* is instead useful when the main objective of the evaluation consists of deciding whether a renovation project gives enough environmental benefits to balance eventual extra monetary costs. In other words *«the extra costs "buy" the environmental gains estimated as avoided impacts»* [10].

The avoided impact approach was used also in a 2008 study by the UK-Empty Home Agencies. This report compares the embodied CO_2 values of six new homes to those resulting from refurbishment of existing old houses, for a 50 years lifespan (*Graph 2.1*). In this way it was found that for a new house nearly 35-50 years are necessary in order to recover all of the carbon dioxide expended during the construction phase, despite the use of efficient operation and maintenance practices.



Graph 2.1 _ comparison of embodied CO_2 values in new and refurbished homes

A further specification of the assessment method can be found in a document of the ATHENA Institute. Written in 2009, the report titled *A Life Cycle Assessment Study of Embodied Effects for Existing Historic Buildings* describes the use of LCA for assessing the environmental impacts of four commercial and mixed-use historic buildings in Canada. Four options for each selected case studies were modeled: the "*renovated building"*; the "*best-renovated building"* (with the best energy performance that could be achieved by an existing building); the "*typical new building*"; and the *"best new building"* (with the best energy performance that could be achieved by a new building). For the *"best-renovated"* option, the team developed a series of measures to improve the energy performance of the older buildings. The *"typical new building"* and *"best new building"* were also modeled. After that, the impacts associated with building retrofit were compared to the impacts associated with new construction, analyzing the primary energy use and global warming potential. The study found that the initial avoided impacts associated with the reuse of the existing buildings ranged from a savings of 185 to 1562 tons of carbon dioxide and between 2,6 million to 43 million MJ of primary energy.

More recently, another American study titled *The Greenest Building: Quantifying the Environmental Value of Building Reuse* performed by the National Trust for Historic Preservation has proposed the use of the same methodology. The study reveals that reusing and retrofitting buildings of equivalent function and size «*can sensibly reduce the negative environmental impact associated with building development*» [11]. Moreover, in the study it is underlined how a new efficient building can take between 10 and 80 years to overcome the environmental impacts associated with its construction.

Thus, building reuse can avoid the need for new constructions and consequently carbon emissions, helping in achieving the carbon-reduction-goals. The report presents a case from Portland (Oregon, USA) in which retrofitting, rather than demolishing and replacing, only 1% of the building stock of the city over the next 10 years, it is possible to achieve an overall reduction of emissions equal to 15% of their county's total CO_2 reduction targets over the next decade. In this scenario it should not be forgotten the importance of material choice. It is clear that this aspect can significantly affect the building impacts during its whole life cycle. It is demonstrated that, «*where building renovation require a huge quantity of materials and those materials are not carefully selected*» [12], the benefits of reusing an existing structure can substantially reduced, even if fully eroded. Consequently, it is necessary to be care during the design phase in order to minimize the environmental loads of building refurbishment, through an accurate planning and an appropriate selection of materials. Anyway, better tools are needed to improve and simplify both design and materials choice processes.

Although it is recognized that LCA is the most important tool for evaluating material choice, it is not yet widespread used in the design process, since it is considered time-consuming and expensive. A more-affordable and simple LCA-based tool could be integrated more easily in the design process, allowing designers to perform analysis on the environmental convenience of building reuse and giving a precious opportunity to minimize impacts associated with constructions.

_ Notes

[1] information based on the paper by Knorr W. *Is the airborne fraction of anthropogenic CO2 emissions increasing?* Published in Geophysical Research Letters, Vol. 36, L21710;

[2] aim of the energy certification, defined in 2002/91/EC: *Energy performance of Buildings Directive;*

[3] definition of LCA methodology from ISO 14040:2006 *"Environmental management - Life cycle assessment - Principles and framework";*

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Chapter 3

LCA IN BUILDING SECTOR: STATE OF THE ART

This chapter describes the development of LCA methodology and it current situation, focusing the attention on the international legal framework on which this type of analysis is based and illustrating different methods and databanks developed all over the world for performing the analysis. Then, it is explained how to use LCA for assessing buildings environmental impact. After this theoretical description, methods and tools selected for carrying out this research are presented, explaining their pros and cons.

3.1 _ LCA: regulations, methods and materials' databanks

3.1.1 Overview

As underlined in the previous chapter, the building sector is the largest contributor of the human activities in the global environmental load. For such reason it also represents the major potential for reducing impacts on the environment, addressed by most environmental policies.

This impacts reduction in the building sector requires appropriate evaluation methods; hence, the current regulatory trends are oriented towards methodologies based on the Life Cycle Thinking approach, because they allow estimating the effects of the different design choices on the environment. In this context, *Life Cycle Assessment* is a fundamental tool for assessing environmental sustainability of buildings.

Developed during the Sixties in the industry sector with the aim to determine the impacts of productive processes, LCA has been recently transferred to the construction sector and used as tool for helping in environmental design. Differently from rating systems, LCA can estimate the potential impacts of buildings in an objective way and, because of this, international standards have been progressively modified, introducing this method into their framework.

Introducing this method inside the international standards on one hand underlines its scientific value and on the other becomes a first attempt to order the fragmented framework of the existing tools. The European Union has been working towards the definition of a regulatory structure aimed to promoting the use of life-cycle approach both for buildings and building products. In 2006, in ISO/TS 21931-1:2006 *"Sustainability in building construction – Framework for methods for assessment of environmental performance of construction works"*, it was highlighted for the first time the need to use a life-cycle based and standardized method for assessing environmental performance of buildings, with the aim to improve quality and comparability of the existing assessment tools.

Two years later CEN TC/350 group *"Sustainability of construction works"* was established in order to actually harmonize the existing tools. The developed (and also under development) CEN/TC 350 standards deal with sustainability of construction works with the final objective to define international common rules to perform a whole evaluation of environmental performance and costs, also including quantifiable aspects concerning human health and comfort.

3.1.2 A brief history of LCA

The first studies on life cycle aspects of products and materials date from the late sixties and early seventies, when concerns over the limitations of raw materials and energy resources stimulated interest in finding ways to cumulatively account for energy use and to plan future resource management. The first full environmental analysis of a product was made by Coca Cola Company in 1969. In this study researchers quantified raw materials, fuels and environmental loadings from the manufacturing processes of different beverage containers in order to determine which of them had the lowest releases.

At Seventies beginning the two studies *The Limits to Growth* (Meadows *et al.,* 1972) and *A Blueprint for Survival* (Goldsmith *et al.,* 1972) stressed the attention on the increasing demand for finite raw materials and energy resources, due to the changes in world populations. In the same period, about a dozen studies were performed to estimate costs and environmental implications of alternative sources of energy. Also other companies in both United States and Europe performed similar comparative life cycle inventory analyses in the early Seventies. At that time, as specific industrial data were not available, most data were collected from publicly-available sources such as government documents or technical papers.

In US, the process of quantifying the resource use and environmental impacts of products became known as a *Resource and Environmental Profile Analysis (REPA)*. Simultaneously a similar inventory approach, later known as the *"Ecobalance"*, was defined in Europe, where a standard research methodology for conducting these studies was developed few years later by the Britannic Ian Boustead, who, after several studies on different materials, published the *Handbook of Industrial Energy Analysis*.

With the formation of public interest groups encouraging industry to ensure the accuracy of information in the public domain and with the Seventies oil crisis in 1973, approximately 15 REPAs were performed between 1970 and 1975. Then, for few years, environmental concerns were abandoned and the attention was mainly paid on issues of hazardous and household waste management. However life cycle inventory analysis continued to be performed and the methodology was improved thanks to the development of some studies, most of which focused on energy requirements. It was only in the mid eighties and early nineties that the interest in environmental assessment by industries, design establishments and retailers actually grew. When solid waste became a worldwide issue in 1988, this methodology again emerged as a tool for analyzing environmental problems and, since the increasing interest in resources scarcity and environmental issues, it was further improved.

At the first SETAC *(Society of Environmental Toxicology and Chemistry)* international workshop in 1990, the term *"life cycle assessment"* was officially coined and two years later at the UN Earth Summit, life cycle assessment methodologies were defined *the most promising new tools for a wide range of environmental tasks*. In 1993 a comprehensive international review of LCA activity, *The LCA Sourcebook* was published.

At the time, LCAs were of limited interest *«outside a very small community of scientists, mostly based in Europe or North America. But then,»* as noted in the Sourcebook, *«their work escaped from the laboratory and into the real world»* [1]. Thus, the need to move beyond the inventory to impact assessment has brought LCA methodology to another step of evolution and the pressure from other environmental organizations to standardize LCA methodology led to the development of the LCA standards. Beginning in 1993, the *International Organization for Standardization* (ISO) tasked a small group of SETAC LCA experts to standardize LCA. Product of this working group, completed by the end of 1997, was the ISO 14040 standard for "*Life cycle assessment – Principles and framework"*. Later, other additional standards were developed and ultimately reviewed in 2006.

In 2002, SETAC and *UNEP (United Nations Environment Programme)* launched an international partnership, known as *Life Cycle Initiative*. In this initiative, three different programs on LCA were defined, with the aim to put life cycle thinking into practice and improve the supporting tools through better data and indicators. The first program, *Life Cycle Management (LCM)*, wanted to create awareness and improves skills of decision-makers by producing information materials, establishing forums for sharing best practice, and carrying out training programs in all parts of the world. The *Life Cycle Inventory (LCI)* program aimed to improve global access to transparent, high quality life cycle data by hosting and facilitating expert groups. The *Life Cycle Impact Assessment (LCIA)* program, instead, was aimed to increase the quality of life cycle indicators by promoting the exchange of views among experts.

A number of LCA-based guidelines and standards have subsequently been developed. In 2012, the European Commission Joint Research Centre's Institute for Environment and Sustainability published the *International Reference Life Cycle Data System Handbook* as part of the European life cycle initiative, with the aim to push and further specify the broader provisions of the ISO standards. According to Jim Fava, one of the fathers of LCA, *«life cycle assessment has become a recognized instrument to assess the ecological burdens and human health impacts connected with the complete life cycle of products, processes and activities, enabling the practitioner to model the entire system from which products are derived or in which processes and activities operate»* [2].

LCA use continues to expand and is now being heavily integrated into green schemes around the world.

3.1.3 Methodological framework

Over the past 20-30 years, life cycle assessment has been used by many organizations and companies either for internal or external use. For the most part, however, the lack of international standards on environmental assessment or life cycle assessment made the results non-comparable and variable.

From Nineties, several organizations - including SETAC (Society of Environmental Toxicology and Chemistry) and ISO (International Standards Organization) - began striving to develop consistency in approach to this emerging field. These efforts produced a number of guidelines and draft standards on different aspects of life cycle assessment, with varying success degrees. The most important result in terms of standardization of the LCA method is ISO 14000 series and in particular ISO 14040:1997 *"Environmental management _ Life Cycle assessment – Principles and framework"* and ISO 14044:1997 "*"Environmental management _ Life Cycle assessment – Requirements and guidelines"*.

In ISO 14040 the LCA framework is described as *«a technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases. LCA is often employed as an analytical decision support tool»* [3]. According to this definition, LCA is a systematic and phased approach, which consists of four main components:

- *Goal and Scope Definition,*
- *Inventory Analysis,*
- *Impact Assessment,*
- *Interpretation.*

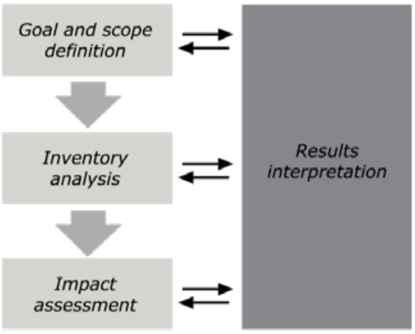


Figure 3.1 _ LCA method scheme

In the first phase *(Goal and Scope Definition)* the product, process or activity to analyze is defined and described, the context in which the assessment is to be made is established and boundaries and environmental effects to be reviewed for the assessment are identified.

In the *Inventory Analysis* input and output are identified and quantified. This phase involves the data collection and the definition of procedures for quantifying sources and environmental releases of the considered product for all life-cycle stages. Input data include energy, water and materials usage; while output data correspond to environmental releases, such as air emissions, solid waste disposal, waste water discharges. Allocation procedures must be also considered when dealing with systems involving multiple products or recycling systems. Furthermore the life-cycle inventory is an iterative process: as data are collected and the system is better defined, new data requirements or limitations may become evident, making necessary implementation of data information and modification of system boundaries.

Purpose of the *Impact Assessment* is providing information on the ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis. This phase can be subdivided into four sub-steps:

1. *category definition*: selecting and defining the environmental categories addressed by the study. The selection should be rather complete and consistent with the goal and scope of the study.
2. *classification:* inventory input and output data are assigned to the defined impact categories. It is a qualitative step based on scientific analysis or an understanding of the relevant environmental processes. All the relevant inventory data are assigned to potential environmental impacts, in so-called “impact categories”.
3. *characterization:* quantification of the contributing substances. The characterization step necessitates the ability to model the categories in terms of standardized indicators. The chosen indicator is used to represent the overall change or loading in the category and it represents the contributions to impact categories in terms of equivalent amounts of emitted reference substance for each impact category.
4. *weighting:* combination of impact categories, through the definition of weights that represent degrees of significance. Weighting often involves ethical or societal value judgments rather than scientific information.

Lastly, the *Interpretation* phase evaluates the results of the inventory analysis and impact assessment with a clear understanding of the uncertainty and the assumptions used to generate the results. Results analysis are normally summarized in a report in which strengths and weaknesses of the performed analysis are explained to non practitioner, in order to make them understandable. Furthermore this stage is useful for proposing changes to the analysis and achieving an improvement of the performance. Often the communication of the results is a difficult process, since this technique of analysis has a low level of accessibility, due to its complexity.

The ISO 14000 family includes also some standards concerning environmental labels and declarations of products or services:

- ISO 14021: *"Environmental labels and declarations. Self-declared environmental claims (Type II environmental labeling)",*
- ISO 14024: *"Environmental labels and declarations. Type I environmental labeling. Principles and procedures",*
- ISO 14025: *"Environmental labels and declarations. Type III environmental declarations. Principles and procedures".*

3.1.4 LCA standards for buildings

If in the last decades the interest of the international scientific community in LCA growth and its application in the industrial sector as well, there are still some difficulties in spreading the method in the building sector. These difficulties are mainly due to the fact that buildings can be considered special products *«since they have a comparatively long life, they undergo changes often (especially offices and other premises), they often have multiple functions, they contain many different components, they are locally produced, they are normally unique, they cause local impact, they are integrated with the infrastructure, system boundaries are not clear, etc»* [4]. When performing a building LCA, different aspects must be taken into account, such as: functional service life time, use and maintenance scenarios, repair and replacement of components, major refurbishment or renovation scenarios for the building and demolition or recycling scenarios. This implies that performing a full LCA of a building is not a simple process. Furthermore, the huge number of aspects to consider can affect LCA studies of buildings, leading to different result and conclusions.

In order to promote and encourage the use of life-cycle methods in construction sector, researchers and regulation bodies have been working for developing standards in which the use of LCA for building assessment is codified and standardized. In particular, ISO/TC 59/17 *"Sustainability in building construction"* launched some standards on sustainability of the built environment, which include various aspects of sustainability (environmental, economic and social) with the aim to define a clearer methodological framework on which basing building life-cycle analysis.

Main products of this working group are:

- ISO 15392:2008: *"Sustainability in building construction - General* *principles”,*

- ISO/TS 21929-1:2006*: “Sustainability in building construction - Sustainability indicators - Part 1: Framework for development of indicators for buildings”,*
- ISO 21930:2007: *“Sustainability in building construction - Environmental declaration of building products”,*
- ISO/TS 21931-1:2006: *“Sustainability in building construction - Framework for methods of assessment for environmental performance of construction works - Part 1: Buildings”.*

ISO 15392:2008 identifies and establishes general principles for sustainability in building construction. It is based on the concept of sustainable development as it applies to the life cycle of buildings and other construction works, from their origin to the end of life. The standard does not provide levels (benchmarks) that can serve as basis for sustainability claims. ISO 15392 defines that sustainable development of construction works brings about the required performance with minimum adverse environmental impact, while encouraging improvements in economic, social (and cultural) aspects at local, regional and global levels.

The Technical Specification ISO/TS 21929-1:2006*: “Sustainability in building construction - Sustainability indicators - Part 1: Framework for development of indicators for buildings”* provides a framework, makes recommendations, and gives guidelines for the development and selection of appropriate sustainability indicators for buildings. The aim of this part of ISO/TS 21929-1:2006 is defining the process that shall be followed when addressing the economic, environmental and social impacts of a building using a common framework and a set of indicators.

These core indicators are given for three levels: *location specific indicators, site-specific indicators* and *building specific indicators*. The indicators consider the environmental, social and economic impacts to the different areas of concern. The main impacts are outlined as follows:

- Environmental: *Impacts to environment and resources*,
- Economical: *Economic value, Productivity,*
- Social: *Health, Satisfaction, Equity, Cultural value,*

ISO 21930:2007: *“Sustainability in building construction - Environmental declaration of building products”* provides principles and requirements for type III environmental declarations (EPD) of building products. The standard contains specifications and requirements for the EPD of building products and provides a framework of indicators and basic requirements for product category rules as defined in ISO 14025 for type III environmental declarations of building products. The standard defines the use of resources and renewable primary energy into the following categories:

- depletion of non-renewable energy resources;

- depletion of non-renewable material resources;
- use of renewable material resources;
- use of renewable primary energy;
- consumption of freshwater.

Framework for the Assessment of Environmental Performance of Building can be found in ISO/TS 21931-1:2006: *"Sustainability in building construction - Framework for methods of assessment for environmental performance of construction works - Part 1: Buildings".* The standard provides a general framework for improving the quality and comparability of methods for assessing the environmental performance of buildings. It identifies and describes issues to be taken into account when using methods of assessment of environmental performance for new or existing building in their design, construction, operation, refurbishment and deconstruction stages. According to this standard following building environmental aspects shall be included in the environmental assessment methods:

- use of resources and renewable primary energy, which shall include
- depletion of non-renewable energy resources (use of fossil energy, etc.),
- depletion of non-renewable material resources,
- use of renewable material resources,
- use of renewable primary energy,
- consumption of freshwater;
- production and segregation of waste to disposal,
- hazardous waste,
- non-hazardous waste.

The scientific validity of life-cycle based methods is recognized also by the European Union. Since 2004 some technical bodies have been working for developing a regulation framework in which LCA plays a great role for building sustainability assessment. In particular the technical committee CEN/TC 350, known as *"Sustainability of construction work",* is currently developing new voluntary standardized methods for assessing sustainability of construction works. The final scope of the working group is to define a harmonized and comprehensive methodology for simultaneously assessing environmental performance, economic costs and building comfort conditions, adopting the same approach.

Thus, the aim of the committee is to unifying the assessment method at the international level, giving the same importance to the three pillars of sustainability (environmental, economic and social equity). Objective of CEN/TC 350 is to define standards and technical reports which can be divided into three main levels, as shown in *Figure 3.2*:

- framework level,
- building level,

- product level.

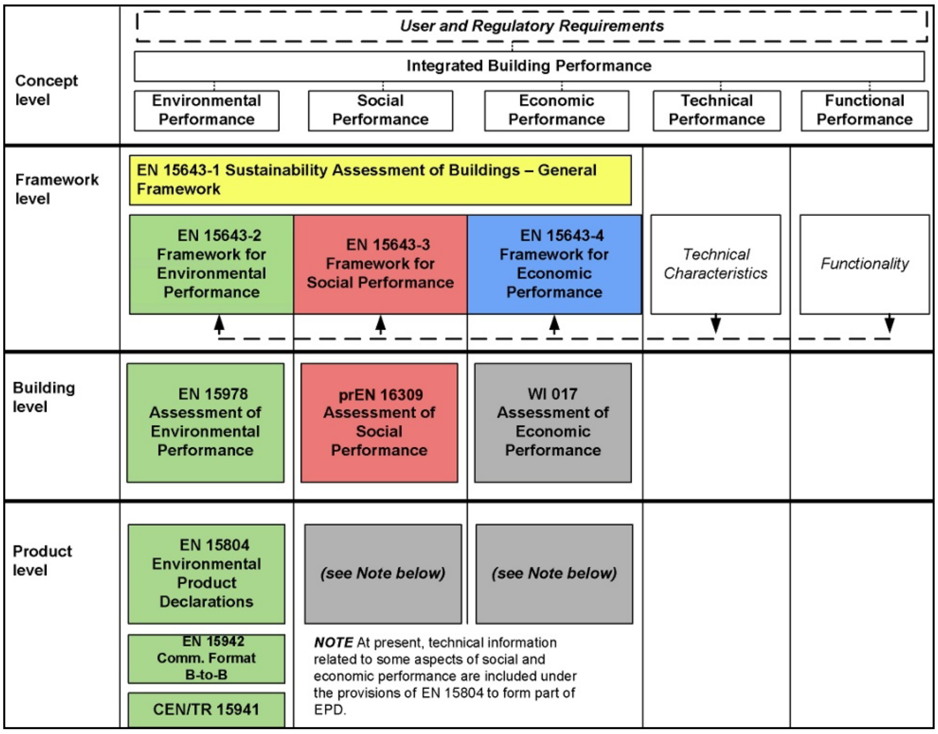


Figure 3.2 _ CEN/TC 350 work plan

For what concerns framework level, the standard EN 15643: *"Sustainability of construction works. Sustainability assessment of buildings"* has been developed. This standard is composed of four different parts, organized as follow:

- EN 15643-1: *"General framework",*
- EN 15643-2: *"Framework for the assessment of environmental performance",*
- EN 15643-3: *"Framework for the assessment of social performance",*
- EN 15643-4: *"Framework for the assessment of economic performance".*

EN 15643-1 provides the general principles and requirements, expressed through a series of standards, for the assessment of buildings in terms of environmental, social and economic performance taking into account technical characteristics and functionality of a building. The assessment will quantify the contribution of the assessed construction works to sustainable construction and sustainable development. The framework can be applied to all buildings types and it is relevant for the assessment of the environmental, social and economic performance of new buildings over their entire life cycle, and of existing buildings over their remaining service life and end of life stage.

EN 15643-2 describes the requirements for the assessment of buildings environmental performance, limiting the dimension of sustainability to the evaluation of environmental impacts and aspects of a building on the local, regional and global environment. This analysis is mainly based on the use of LCA. The third part (EN 15643-3), instead, provides the specific principles and requirements for the assessment of the social performance of buildings, by using SLCA (Social Life-cycle assessment) while the fourth part (EN 15643-4) provides specific principles and requirements for the assessment of the economic performance of buildings, through the use of the LCC (Life-cycle Cost) methodology.

At building level the standards are two:

- EN 15978:2011: *"Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method",*
- EN 16309 (under development): *"Sustainability of construction works - Assessment of social performance of buildings – Methods".*

EN 15978 specifies the calculation method, based on Life Cycle Assessment (LCA) and other quantified environmental information, to assess the environmental performance of a building, and gives the means for reporting and communicating of the assessment outcome. The standard is applicable to new and existing buildings and refurbishment projects. The standard gives:

- the description of the object of assessment;
- the system boundary that applies at the building level;
- the procedure to be used for the inventory analysis;
- the list of indicators and procedures for the calculations of these indicators;
- the requirements for presentation of the results in reporting and communication;
- the requirements for the data necessary for the calculation.

The approach to the assessment covers all stages of the building life cycle and is based on data obtained from Environmental Product Declarations (EPD), their "information modules" (EN 15804) and other information necessary and relevant for carrying out the assessment. The assessment includes all building related construction products, processes and services, used over the life cycle of the building. The interpretation and value judgments of the results of the assessment are not within the scope of this European Standard.

The standard EN 16309, which defines methods for calculating social performance, is still under development.

Considering the product level, there are three standards:

- EN 15804:2012**:** *"Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products",*

- EN 15942: *"Sustainability of construction works - Environmental product declarations - Communication format business-to-business",*
- CEN/TR 15941: *"Sustainability of construction works - Environmental product declarations – Methodology for selection and use of generic data".*

EN 15804:2012 provides core product category rules (PCR) for all construction products and services. It provides a structure to ensure that all Environmental Product Declarations (EPD) are derived, verified and presented in a harmonized way. An EPD communicates verifiable, accurate, non-misleading environmental information for products and their applications, thereby supporting scientifically based, fair choices and stimulating the potential for market driven continuous environmental improvement.

EPD information is expressed in information modules, which allow easy organization and expression of data packages throughout the life cycle of the product. The approach requires that the underlying data should be consistent, reproducible and comparable. This standard provides the means for developing a Type III environmental declaration of construction products and is part of a suite of standards that are intended to assess the sustainability of construction works.

EN 15942 is applicable to all construction products and services related to buildings and construction works. It specifies and describes the communication format for the information defined in EN 15804 for business-to-business communication to ensure a common understanding through consistent communication of information.

This technical report CEN/TR 15941 supports the development of Environmental Product Declarations (EPDs). It assists in using generic data according to the core product category rules (EN 15804) during the preparation of EPD of construction products, processes and services in a consistent way, and also in the application of generic data in the environmental performance assessment of buildings according to EN 15978. The requirements for the use of generic data are described in EN 15804.

The development of these standards confirms the tendency of the international community to adopt life-cycle based assessment methods for buildings. Nevertheless there are still some gaps, which not allow the whole adoption of the explained framework, especially for what concerns the assessment of the social and economic performance. Differently, the evaluation of the building environmental performance is better defined: since it is based on LCA, which has been used for nearly thirty years, it is supported by a well developed existing framework (ISO 14000 family) and also by tools and software able to help in performing such kind of assessment. Due to the large amount of data required to carry out an LCA, specific applications have been developed to facilitate the use of LCA in the building sector.

3.1.5 Databases, calculation methods and tools for LCA

When performing a LCA a huge number of data is needed. Anyway, data collection depends on what type of information we are looking for. According to the needs, it is possible to use average or specific data, modern or aged data, depending on products and the technologies that we are going to study.

The data set used for the LCA has the largest importance for the usefulness of the result in terms of relevancy, accuracy and representativeness. Moreover, it usually is the most time consuming phase of an LCA.

When having all data from producers and manufacturers is difficult, it is possible to use data from *external databases* and literature. Anyway, when information from such sources is used, the transparency of the data must be considered: some databases are totally free of charge, while others are commercial and require a license. Typically the databases contain both gate-to-gate data and cradle to gate data for a number of different processes, products and transportation.

For example, some industry associations have developed and compiled LCI data for their industry. This data is available in the form of reports, but they have also generally been implemented into several LCI databases.

Furthermore, national LCI database projects have been performed in some countries with the aim of collecting LCI data and making them available.

At European Level, the European Commission – *Joint Research Center (JRC)* has constituted an international network for LCI data, named *International Reference Life Cycle Data System* (ILCD).

In 2010, ILCD published the *ILCD handbook – General guide for Life Cycle Assessment*, in which uniform guidelines for making LCA studies were provided, in order to make them more reliable and comparable. The manual consists of a general guidance document and other separate appendixes focusing specific issues. Aim of ILCD is to collect the best practices among existing LCA tools and databases in order to make uniform data collected in different databases.

An overview of available life cycle inventory data resources was compiled in 2006 as part of the work within UNEP/SETAC Life Cycle Initiative.

Some examples of available databases and industry data are illustrated below in *Table 3.1* and *Table 3.2*:

Name	Availability	Language	Data focus (if any)
Australian Life Cycle Inventory Data Project	Free	English	Australia
BUWAL 250	Fee or included with SimaPro	German, English, French	Packaging materials
Canadian Raw Materials Database	Free	English, French	Raw materials
DuboCalc	Upon request	top level in Dutch/underlying	Construction materials
Dutch Input Output	Licence fee	English	Input-output
ecoinvent	Licencefee	English, Japanese, German	Global/Europe/ Switzerland
Eco-Quantum			
EDIP	Licencefee	Danish, English, German	Denmark
Franklin US LCI	Available with SimaPro	English	U.S.A
German Network on Life Cycle Inventory Data	On-going	German, English	Germany
IBO	Free	English, German	
ICE	Free	English	
ITRI Database	Taiwanese, English		
IVAM LCA Data	Licencefee	Chinese, English	Construction, food, waste, etc.
Japan National LCA Project	Fee	Japanese	Japan
Korean LCI	On-going		
LCA Food	Free	English	Food products
SPINE@CPM	Fee	English	-
Cycle Assessment Database (SALCA)	Free with contact	German	Agriculture
Thailand LCI Database Project	Thai,English		
US LCI Database Project	Free withcontact	English	US

Table 3.1 _ examples of available database of materials

Industry organisation	Avail-ability	Product group or sector	Geographic coverage
American Iron and Steel Institute (AISI)	America		
American Plastics Council (APC)	America		
EDP-Norway	Free	Norwegianbusiness (several sectors)	Norway and Europe
European Aluminium Association (EAA)	Aluminium	Europe	
European Copper Institute (ECI)	Free with contact	Copper	Europe
European Federation of Corrugated Board Manufacturers (FEFCO) Groupement Ondulé, European Association of Makers of Corrugated Base Papers (GEO) European Containerboard Organisation (ECO)	Free	Corrugated Board	Europe
International Iron and Steel Institute (IISI)	Freewithcontact	Steel	Global
ISSF International Stainless steel Forum (ISSF)	Free with contact	Stainless steel	Global
KCL (EcoData)	Fee	Pulp and paper	Finnish/Nordic
Nickel Institute	Free with contact	Nickel	Global
PlasticsEurope (formerly APME)	Free	Plastics	Europe
Volvo EPDs	Free	Trucks and busses	Europe

Table 3.2 _ examples of available database of industry data

Of these, the main databases on the market can be considered:

- *The European Reference Life Cycle Data System (ELCD core database)*, developed as an initiative of the European commission through the Joint Research Center and is part of the work with developing the ILCD network (available free of charge).
- *Ecoinvent* is developed and maintained by the Ecoinvent center, where several Swiss research institutes is responsible for collecting and compiling data (commercial, needs licence).
- Some *LCA software and consultancy providers* are developing LCI databases. For example, PE international offers different dedicated database packages in its GaBi software.

It is important to consider that databases are difficult to use outside from the framework of software. Furthermore many of them are available just buying software. Over the years there has been a proliferation of LCA software on the market, able to help designers to design sustainable products. This software can be more or less complex and more or less focused on a type of analysis. There are in fact a lot of tool, which are mainly based on building assessment, which use specific databases for building materials.

Table 3.3 below shows some software, which are actually on the market.

Name	**Availability**	**Language**	**Data focus(if any)**
BEES 3.0	Free with contact	English	Building materials and products
Boustead Model 5.0		Global	
CMLCA 4.2	Licence fee only for commercial use	English	Europe
Ecosoft	Licence fee	English, German	Building materials and products
eiolca.net	Free	English	Input-Output
EMIS	Licence fee	English, German	Global
Environ-mental Impact Estimator	Licence fee	English	Building materials and products
GaBi	Licence fee	English, German, Japanese	Global
GEMIS	Europe		
GREET 1.7	Free	English	Transportation sector, energy sector
IDEMAT 2005		English	Netherlands
KCL-ECO 4.0	Licence fee	English	Global
LCAiT	Licence fee	English	
MIET			
AIST-LCA (JEMAI-LCA)	Licence fee to JEMAI	Japanese	
Regis	Licence fee	English,German, Japanese	Global
Simapro	Licence fee	English, Japanese	Global
TEAM			
Umberto	Licence fee	English, German, Japanese	Europe

Table 3.3 _ examples of available database of industry data

When using calculation software it is important to consider that in each of them LCA is performed according to different Life Cycle Impact Assessment methods. Each method defines groups of environmental impact, called categories. The three more general categories are: resource use, human health and ecological effect. Every category can be divided into sub-indicators, able to give information on different aspects of sustainability.

The list below summarizes some of the most important impact categories, also summarized in *Figure 3.3*:

- *Global warming*

  It is due to the increasing concentration of greenhouse gases in the atmosphere, primarily due to the burning of fossil fuels. Primary greenhouse gases in the Earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous dioxide (N_2O) and ozone (O_3). As IPCC says *«Most of the observed increase in global average temperatures since mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations»* [5]. Consequences are the temperature rising of 1,1 to 6,4 °C, the increase and decrease of rainfall and the sea level rising of 18 to 59 cm.

- *Ozone layer depletion*

  This layer protects the earth surface against ultraviolet radiation of the sun. It is supposed that an increased UV-radiation due to ozone depletion could be dangerous for people and also cause damage to plants. The reduction of the ozone is caused by atomic chlorine and bromine, deriving from CFC compounds (freons) and bromofluorocarbon compounds (halons). In building sector the most important contributor to ozone depletion are refrigerants.

- *Acidification*

  Normally clouds and rainwater have a pH of 5.65. When the pH decreases under this threshold, soil and surface water are acidified. Human activities cause modifications to the normal balance by emitting sulphur dioxide, nitric oxides and ammonia.

  The consequent release of hydrogen chloride leads to acidification, which leads to an accelerated corrosion of metals and causes negative impacts on biodiversity and human health.

- *Eutrophication*

  It is an increase of the concentration of chemical nutrients (containing nitrogen, phosphorous and potassium) in soil, water and air to an extent that alter the natural cycle. It is caused by the use of fertilizers, effluent water drainage, combustion processes, landfill of households waste and water purification slit.

  Eutrophication can have consequences at local, regional and global level. At local level it may lead to the contamination of drinking water, biodiversity reduction and qualitative decrease of food-plants.

  Regionally, it has a negative effect on life in water, since it causes an excessive develop of algae with a consequent reduction of light in the water and an increase of the activity of some bacteria. Thus, fishes and other organisms have difficulties to survive. Globally, eutrophication causes an increase of the emission of N_2O, an important greenhouse gas.

- *Photochemical oxidation (organic compounds)*

It is the presence of chemical substances in the air, such as ozone, peroxyacetylnitrate, nitrogen dioxide (NO2), hydrogen peroxide (H2O2) and other substances with oxidizing properties.

These substances are formed in warm days, when NO_x and non-methane volatile organic compounds are subjected to sunlight. These two types of chemicals are known as “ozone precursors” of photochemical air contamination. since ozone can be considered one of the most harmful substances for humans, plants and materials, its production is a very negative impact. Ozone can lead to respiratory problems, cause a reduction of the stress resistance of crops and also the degradation of some materials.

Furthermore, ozone contributes to global warming. Main responsible of the ozone precursors emissions are traffic, industries and combustion processes; the energy sector and the use of solvents contribute to the emission. Many other volatile organic compounds (VOCs) have negative impacts on human health, including irritation of mucous membranes and long-term toxic reactions.

- *Toxic emissions*

Two types of substances generate toxic emissions: heavy metals and organic emissions. They are spread by air everywhere, but the high rate of concentration is in ground water in highly populated areas.

- *Radioactive effects*

Human kind is continuously exposed to many sources of ionizing radiation: some of them are naturals, while others are the human activity results. Two sources are responsible for the 75% of the total originated by human activity: the first one correspond to medical appliances, while the second one is the inert gas radon emitted from soil and buildings materials.

- *Winter smog (inorganic compounds)*

Air pollution given by the presence in the air of a mix of chemical compounds and fine particles, mainly emitted by the combustion of sulphur-carrying fuels (industry) and fossil fuels (traffic, industry, households).

It can cause respiratory problems, heart complaints and reduced well-being.

- *Carcinogens*

They are substances that contribute to the exacerbation of cancer or increase its possibility of propagation, such as inhaled asbestos, certain dioxins, tobacco smoke, vinyl chloride, formaldehyde and others.

- *Resource depletion*

It occurs when extraction and use of sources is higher than the growth of new ones. Minerals, biotic resources and fresh water have to be distinguished.

- *Land use*

Land use and modifications have a major impact on the biodiversity of the occupied site, but their effect can be extended to regional level.

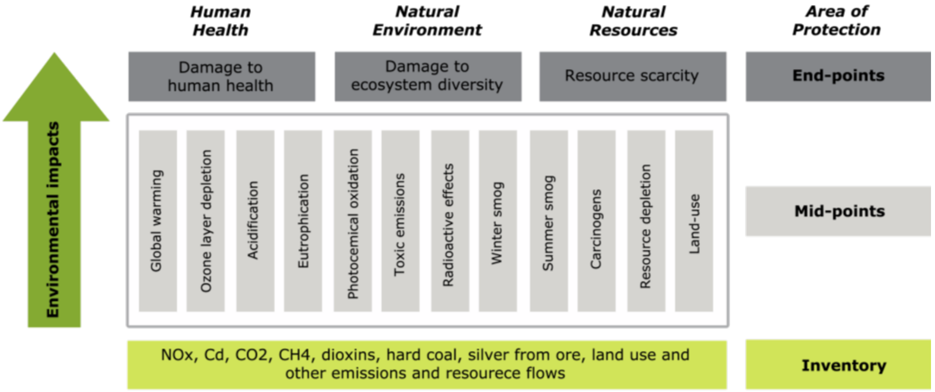


Figure 3.3 _ LCIA phases scheme

Once defined these more spread categories, it is possible to analyze the existing calculation methods. A literature study reveals that in Europe a proliferation of methods is currently in use.

These methods can be differentiated on the basis of their approach: they can use a mid-point or an end-point approach. Mid-point indicators are located in an intermediate position on the cause-effect chain between the LCI data and the damage, while end-point indicators corresponds to the final damage categories. Both of them have merits and limitations: while mid-point indicators are more reliable, they also have minor relevance in helping decision-making process than end-point indicators.

The tables below show a summary of the most used impact assessment methods:

Name	Impact categories	Approach	Origin
CML 2001	Ozone layer depletion (ODP) Human toxicity Fresh water acquatic ecotoxicity Marine acquatic ecotoxicity Terrestrial ecotoxicity Photochemical oxidation Global warming (GWP100) Acidification Abiotic depletion Eutrophication	mid-point	Netherlands

Table 3.4a _ examples of impact assessment methods

Name	Impact categories	Approach	Origin
Eco-Indicator 99	Human health (carcinogens, respiratory inorganics, respiratory organics) Quality of ecosystems (climate change, radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication) Depletion of resources (land use, minerals, fossil fuels)	mid-point and end-point	Netherlands
EPS 2000	Human health Ecosystem production capacity Abiotic stock resource Biodiversity and cultural recreational values	end-point	Sweden
Ecological scarcities	Emissions to air Surface water Ground water and top soil Energy and natural resources Deposited wasre	end-point	Switzerland
EDIP 2003	Global warming (GWP100) Ozone layer depletion (ODP) Acidification Eutrophication Photochemical smog Ecotoxicity water chronic Ecotoxicity water acute Ecotoxicity soil chronic Human toxicity air Human toxicity soil Bulk waste Hazardous waste Radioactive waste Sag/ashes Resources	mid-point	Denmark
Impact 2002+	Human toxicity Acquatic ecotoxicity Terrestrial ecotoxicity	mid-point and end-point	Switzerland
EPD	Non renewable fossil fuels Global warming (GWP100) Acidification Eutrophication Ozone layer depletion (ODP) Photochemical oxidation	mid-point	Netherlands

Table 3.4b _ examples of impact assessment methods

It is possible to make a differentiation within the end-point methods. Some of them express the damage results in eco-points (Eco-Indicator 99, Ecological scarcities 2006), while others in monetary value (e.g. EPS 200). Furthermore, methods like Impact 2002+ and Eco-Indicator 99 merge a mid-point and an end-point approach, linking several mid-point categories with some damage categories in order to combine the mentioned advantages coming from both two approaches.

3.2 _ Selecting databanks and methods for the research

3.2.1 Overview

The debate on LCA methods is still open all over the world. While LCIA phase is not yet standardized, since the huge numbers of developed methods, the inventory phase is uniform everywhere. Anyway, for making life-cycle tools more spread, a common method should be selected and used especially in countries like Italy, in which there is a lack of specific tools as well as material databanks.

Thus, also for what concerns materials it is expected to define a unique database, where all common construction materials with their associated impacts are listed. In fact, as explained before, one of the core aspect in terms of environmental performance is given by the materials role. It is expected that in the next years an increasing number of products will be provided with Environmental Product Declarations (EPD), according to the standard EN 15978, which encourages the use of materials environmental profile.

3.2.2 Selection of software and material databanks

In the previous paragraph the existing LCA software, databanks of materials and LCIA methods were discussed. While in many other European countries LCA practices and tools are quite spread, in Italy they are still unknown and unused.

The lack of a country-specific database constrains to look to foreigner list of materials and products: however, it should be considered that production technologies are not the same everywhere and, for such reason database coming from countries with similar methods of production have to be selected. Once the database to use has been defined, it possible to select also the software. Thus, software in which the chosen database is supported has to be selected.

For what concerns databases two possibilities have been considered for the Italian context, in which the research is performed: the first one is to use the *IBO database* from Austria and the second one to use the Swiss *EcoInvent database*, adapted for the Italian context.

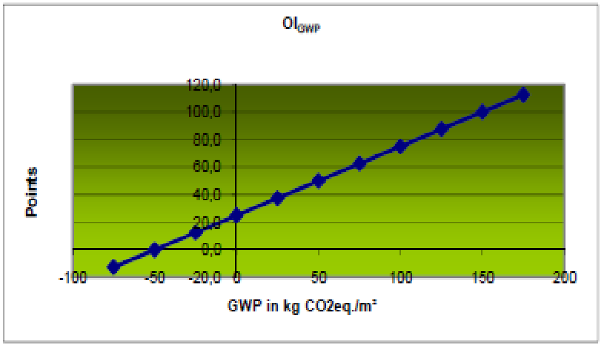
IBO database, developed by the *Austrian Institute for Healthy and Ecological Building,* is composed of a list of nearly 250 construction materials with the associated impacts, expressed in seven categories:

- *Global Warming Potential,*
- *Acidification Potential,*

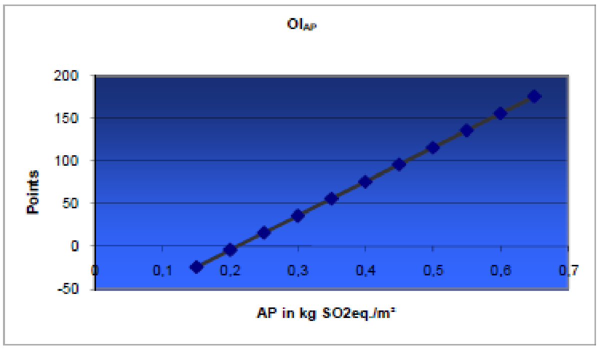
- *Eutrophication Potential,*
- *Ozone Layer Depletion Potential,*
- *Photochemical Oxidation Potential,*
- *Non Renewable Primary Energy,*
- *Renewable Primary Energy.*

This database can be used with the support of a specific simplified software for buildings' assessment, which communicates environmental impacts with a single dimensionless indicator, called OI3.

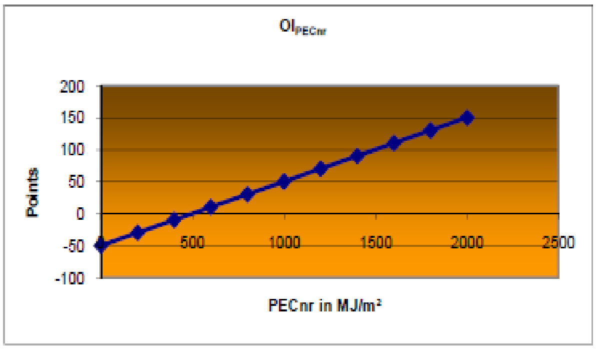
OI3 indicator summarizes the results obtained by the building in the three environmental categories Global Warming Potential, Acidification Potential and Non Renewable Primary Energy, as explained in the IBO document *Guidelines for calculating the OI3 indicators for buildings*.



Graph 3.1 _ calculation procedure for OI_{GWP}



Graph 3.2 _ calculation procedure for OI_{AP}



Graph 3.3 _ calculation procedure for OI_{PECnr}

EcoInvent is the most famous LCA database used in more than 40 countries, worldwide. This database was developed by the Swiss Centre for Life Cycle Inventories, with the aim *«to generate a set of generic uniform and consistent LCI data of high quality, which is valid for Swiss and other European conditions»* [6]. It is a consistent, coherent and transparent LCA dataset, which contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services and transport services.

The database is integrated in many calculation software, of which the most popular are *Gabi* by PE International (Germany) and *SimaPro* by PRè Sustainability Consultant (Netherland).

These software are the most used and common tools for performing a full LCA, especially in European continent, where both are developed.

Nevertheless, they have pros and cons, reported by the Department of Electro-technical Engineering and Energy Technology (ETEC) of the Vrije Universiteit Brussel in the document *LCA software selection* [7]. *Table 3.5* below summarizes the features of the two software:

software	Pros.	Cons.
Gabi	_ good visibility of the process tree	_ no intuitive use _ lack of visibility in the fitting of the running windows _ no modification existence in the event of error in the architecture of the processes
SimaPro	_ intuitive use _ good visibility of the fitting of the running windows _ good visibility of the process tree	_ rigid construction of the software

Table 3.5 _ Pros and cons of Gabi and SimaPro

On the basis of the table above, developed through an interview to the software users, it is possible to affirm that SimaPro resulted more user friendly than Gabi and it also allows to better managing the assessment process. Furthermore it gives the possibility to modify existing calculation methods, developing customized ones. For this reason, it has been decided to use SimaPro for supporting this research.

For what concerns the calculation method to adopt, the EPD method has been selected. This choice was based on the possibility to integrat data from the Ecoinvent database and data from IBO database. While the first dataset can be used with different calculation methods, the second one is composed of data that can be used only with the EPD2008 method.

As explained above, this is a mid-point method, in which environmental impacts are divided in six different impact categories:

- global warming potential,

- acidification potential,
- eutrophication potential,
- ozone layer depletion,
- photochemical oxidation potential,
- non renewable primary energy consumption.

Moreover, the selection of this method also allows integrating the existing materials' databanks with a set of EPD certificates related to specific products. In this way an own database of materials can be constructed, permitting to perform a more realistic estimation of the potential environmental impacts. As explained in *Paragraph 3.1.4,* there is currently a little availability of Environmental Product Declarations on the market, anyway, in light of the future developments of the regulatory framework of CEN/TC 350, it has been chosen to introduce the use of EPDs within this research, in order to promote, when possible, the overcoming of generic databases.

3.2.3 Reliability of the analysis

When performing a LCA, some problems can occur. According to M. Lenzen [8], they are mainly due to data quality, errors in building description or in the estimation of the durability of building components, but also to uncertainties in the impact assessment method.

Clearly, the use of different calculation methods can lead to different results, especially when mid-point and end-point methods were compared. The uncertainty in impact assessment increases for modeling stages towards the end-point, as well-recognized in the international literature.

For example, U. de Haes states that *«in general, definition of an indicator closer to the environmental interventions will result in more certain modeling, but will render the indicator less environmentally relevant»* [9], while L. P. Rosa and others note that *«there is a trade-off among indicators. On the one hand, the indicator should be as close as possible to the actual impacts (of climate change), i.e. damages. On the other hand, it should be calculated with certainty and therefore at the beginning of the cause-effect chain»* [10]. Jolliet et al. defined this situation as *«a dilemma between certainty and completeness»* [11].

The debate around the mid-point end-point relationship was object of the Third UNEP International Workshop, held in 2000 in Brighton (GB) [12]: the summary *Midpoints versus Endpoints: The Sacrifices and Benefits* reports the consensus-reached idea that both midpoint and endpoint level indicators have complimentary merits and limitations. *«Decisions can be made using the midpoint indicators, which are more certain but can have a lower* *relevance for decision support in some cases, or using the endpoint indicators, which were argued to often have a higher relevance but lower certainty»* [13].

However, while SETAC and UNEP Life Cycle Initiative approaches stop quantitative modeling relatively early in the cause-effect chain in order to limit uncertainties, Eco-Indicator try to enhance the relevance of the results by indicating damages through endpoint weighting.

The comparison of mid and end-point approach is also the subject of the *ReCiPe project* funded by the Dutch government [14]. While the ReCiPe project encourages the use of sensitivity analysis, conventional approaches do not deal with error propagation and statistical analysis for decision-making. Despite a high level of quality of LCA results is required, uncertainty analysis is underestimated and performed in few studies, because of the lack of a recognized methodology and little research on this topic.

Uncertainty analysis should be performed in order to illustrate how methodological choices can affect the final results of an LCA: system boundaries definition, allocation methods procedures and data selection are all parameters which influence the analysis outcomes.

Within this research some attempts to reduce the uncertainty of the final results were carried out. For minimizing errors in building descriptions it has been decomposed in hierarchical parts *(element method),* then, the use of peer-reviewed databanks such as EcoInvent and IBO guarantees a good quality of the final results.

Furthermore, the use of EPD2008 mid-point method contributes in reducing uncertainty. As explained above, the more complex is the model, the harder it is to maintain a good level of transparency, which enable a correct results interpretation. As J. C. Bare et al. state, *«the level of transparency associated with midpoint indicators can be considered higher than in endpoint approaches»* [15].

_ Notes

[1] citation from book *The LCA Sourcebook: A European Business - Guide to Life-cycle Assessment*, SustainAbility, 1993;

[2] citation from the workshop report *A Technical Framework for Life-cycle Assessment: Workshop*, held in August 18-23, 1990, Smugglers Notch, Vermont;

[3] definition of LCA methodology from the international standard ISO 14040:1997: *"Life Cycle Assessment – Principles and framework";*

[4] citation from *Life-cycle Assessment in Building and Construction: A State-of-the-art Report*. Research report edited by SETAC, 1993;

[5] citation from the research report of the IPCC *Climate Change 2013 - The Physical Science Basis*, 2013 edition.

[6] citation from *The Ecoinvent Database: Overview and Methodological Framework* by R. FRISCHKNECHT and others, 2005.

[7] data and information from the report *LCA software selection* of the Department of Electrotechnical Engineering and Energy Technology (ETEC) at Vrije Universiteit Brussel, 2007.

[8] from *Uncertainty in Impact and Externality Assessments. Implications for Decision-Making* by LENZEN M., 2006;

[9] citation from *Best available practice regarding impact categories and category indicators in life cycle impact assessment* by DE HAES U. and others, 1999;

[10] citation from *The Brazilian Proposal and its Scientific and Methodological Aspects* by ROSA L. P. and others, 2003;

[11] citation from *Final report of the LCIA Definition study* by O. JOLLIET and others, 2003;

[12] on May 25-26, 2000 in Brighton (England), the third in a series of international workshops organized by UNEP was held. The workshop addressed issues in Life Cycle Impact Assessment (LCIA), providing a forum for experts to discuss midpoint vs. endpoint modeling.

[13], [15] citations from *Midpoints versus Endpoints: The Sacrifices and Benefits* by BARE J. C. and others, 2000;

[14] ReCiPe project was developed by RIVM, CML, PRé Consultants, and Radboud Universiteit Nijmegen with the aim to define a LCIA method which comprises harmonized category indicators at the midpoint and the endpoint level.

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_ List of Figures, Tables and Graphs

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Tables

Graphs

Chapter 4

INTEGRATING LCA, ENERGY PERFORMANCE AND LCC

This chapter is divided into three main parts. The first two paragraphs describe respectively calculation methods for energy performance of buildings and "Life Cycle Cost" analysis, according to the international standards, underlining the necessity to link them to the environmental construction materials impact. Then, an integrated methodology for the assessment of the solutions for building renovation is proposed. This method considers: energy performance, construction and maintenance costs and the OI3 environmental indicator from Austria. Lastly, the project of renovation of an industrial building is analyzed in order to test the developed methodology. The benefit in reusing the existing building has been calculated and also the further benefit coming from other material choices have been considered.

4.1 _ Energy Performance

4.1.1 Overview

The reduction of the primary energy consumption is one of the key objectives in European and International policies, as it is demonstrated by the signature of the Kyoto protocol and by the decision to achieve the 20-20-20 target. It is fairly known that construction industry is a highly active sector all over the world and it can be considered responsible for a high rate of energy consumption, environmental impact and resource depletion produced by developed countries.

In the European Union, buildings cause of roughly 40% of the overall environmental loads: the construction industry consumes 40% of the materials entering the global economy and generates 40–50% of the global output of GHG emissions and the agents of acid rain. For this reason, it is necessary to reduce its impact through the construction of more environmentally responsible buildings. For achieving these ambitious track it is very important to orient the building sector in an appropriate way.

The first step in this direction was the exit of the *Energy Performance of Buildings Directive (EPBD) 2002/91/EC.* Main objective of this Directive was «*to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness*» [1], by applying a minimum requirements on the energy performance of new buildings and existing buildings subjected to major renovation.

In reason of this regulation, in the last years, governments, designers and researchers have been all affected by the trend of sustainable design and green strategies, such as the solar passive design and the improvement of the energy performance. In new buildings strategies for reducing energy consumption started to be regularly applied: the insulation thickness was increased, plant equipment was changed with more efficient ones and systems based on the exploitation of renewable resources for energy production on site started to be used.

The introduction of a benchmark level of energy consumption made it possible to drastically reduce the energy performance of new buildings. Furthermore, the European Union, for helping a faster diffusion of efficient design strategies all over the continent, has continuously introduced policies and regulation with the aim to reduce negative impacts from the building sector, such as:

- *directive 2005/32/EC on Energy using Products (EuP),*

- *directive 2006/32/EC Energy Saved Directive (ESD) on energy end-use efficiency and energy services,*
- *directive 2009/125/CE on Energy related Products (ErP).*

EPBD directive had a great role also in increasing awareness in some environmental issues. In particular, in the energy certificate the carbon dioxide emissions associated to the energy consumption are identified. Later, this concept was strengthened by the directive *2010/31/EC*, known as "*EPBD recast"*, launched in 2010. In this directive a further reduction of the energy consumption both for new buildings and major renovations is required. All new constructions since 2018 for public and since 2020 for private buildings must be *"nearly Zero Energy Buildings",* with an *«excellent energy performance and a very low or almost zero energy demand, covered in a significant extent from renewable sources»* [2].

But at international level the definition of ZEB is not so clear and shared. The main reference in the literature is Torcellini which says: «*a net zero energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies»* [3]. Moreover, the same author indicates that the definition of Zero Energy Building can be constructed in several ways, depending on the project goals, intentions of the investor, concerns about the climate changes and greenhouse gas emissions or finally the energy costs. Taking into consideration all the above mentioned scenarios Torcellini, et al. distinguish and point out advantages and disadvantages of four most commonly used definitions:

- *Net Zero Site Energy*: a *site ZEB* produces at least as much energy as it uses in a year, when accounted for at the site.
- *Net Zero Source Energy*: a *source ZEB* produces at least as much energy as it uses in year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.
- *Net Zero Energy Costs*: in a *cost ZEB*, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.
- *Net Zero Energy Emissions*: a *net-zero emissions building* (*zero carbon building*) produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

From this general framework an important issue emerges: the acronyms ZEB is combined to two different definitions. This is due to the consideration of the energy produced by renewable sources, thus free energy (zero energy) without greenhouse gasses emissions (zero emission). Performing an energy balance is different from making an emissions one. Furthermore the definition *“zero emissions”* is only related to the carbon dioxide emissions, forgetting that there are many other types of pollutant substances and gasses.

In particular, in this ZEB definition, a whole life cycle approach is totally absent, without taking into account that, especially in buildings with a low energy consumption, the amount of energy spent for construction has the same order of magnitude respect to the energy generated during the utilization stage. The lowest the energy in the usage stage, the highest the energy percentage spent for construction is; in some cases, the embodied energy can be the prevalent contribution to the environmental impacts.

At the same way, also the evaluation of greenhouse gasses emission is underestimated: a building cannot be considered *“carbon neutral”* because it uses renewable energy sources: it is necessary to take into account also the impacts generated by the production of plants and equipments which allow to use such kind of resources. Furthermore, for having a more complete scenario on the environmental impacts generated by a building, the analysis should be extended to all typologies of emissions.

From this analysis a total lack of a whole life-cycle approach, able to evaluate energy and emissions respectively used and generated by constructive elements and plants designed for achieving the “zero energy” target. A whole life-cycle balance can underline if technological designed solution are adequate or less. It is possible that strategies oriented to improve the energy efficiency during the building use can cause an increase of the impacts during the other stages of its life-cycle (raw materials extraction, materials production, transportation, operation and maintenance or final disposal). Under this perspective, extending the system boundaries to the entire life-cycle instead of limiting it to the mere usage phase, can be considered as the most appropriate choice in order to drive towards the construction of buildings not only with a low energy consumption, but with a low environmental impact. Thus, literature definitions normally do not include the used energy and the generated emissions for the building construction (embodied energy and embodied carbon in construction materials due to their production, transportation and assembly phases), maintenance (related to materials durability) and end of life (depending on the end of life scenario: disposal, recycling, reuse).

In the last years several studies demonstrated that the energy spent for building construction is not negligible, especially in case of low consumption buildings. Sartori and Hestnes underline how the 30% of the total amount of energy spent during the building life cycle is stored in construction materials; the lowest is the energy need during use, the highest is the necessity to consider the building in a whole life cycle perspective. In these cases, energy for constructing, maintaining and disposing buildings can be higher than that one consumed during the building use. It follows the importance of using a life cycle balance, that can better evaluate design choices for reducing the energy production of buildings not only during the usage stage, but also through the other stage of their service life (extraction and production processes, transportation, maintenance, end of life). By the way, choosing adequate solutions and materials during the design phase becomes one of the most appropriate strategies for reducing the global energy balance.

4.1.2 Integrating Energy performance and LCA

One of the main fields in which LCA can be applied is the energy certification sector. *«Some studies have been performed in order to find out the proportion of embodied energy in materials used and life cycle assessed. This can vary between 9 and 46% of the overall energy used in the building lifespan when dealing with low energy consumption buildings and between 2 and 38% in conventional buildings»* [4]. This wide range of values is mainly due to the type of materials: selecting environmentally friendly materials improves the LCA results of a building. Changing high embodied energy materials (such as reinforced concrete) with alternative materials (such as hollow concrete blocks) can lead to an energy saving in the order of 20%. Also the use of recyclable materials allows a reduction which could reach 30% for what concerns energy and 18% in terms of greenhouse gasses emissions. In some materials, such as steel or aluminum, the use of recycled material can allow to save more than 50% in embodied energy. Thus, the most efficient is the building in use, the highest is the quantity of energy used for its materials production.

In their study I. Z. Bribián, A. A. Usón, S. Scarpellini proposed a simplified method for integrating LCA method into energy certificate. The study, focused on the Spanish system of certification, aims to define a complementary method for performing energy performance assessment with a LCA approach. The authors underline how both embodied energy and CO_2 emissions of the building materials are not considered as it happens in the most part of European certification schemes. The simplified methodology is based on the introduction of LCA data in building energy certificate, only considering aspects related to product stage (raw material supply, transportation, manufacturing) and use stage (operational energy use), as illustrated in *Figure 4.1* below:

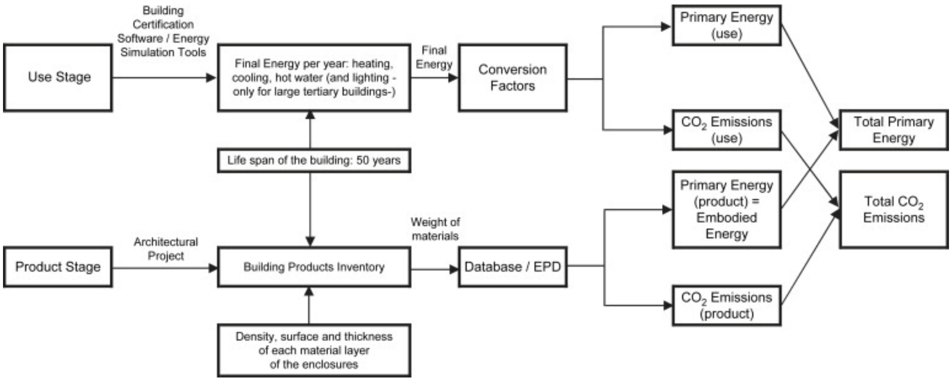
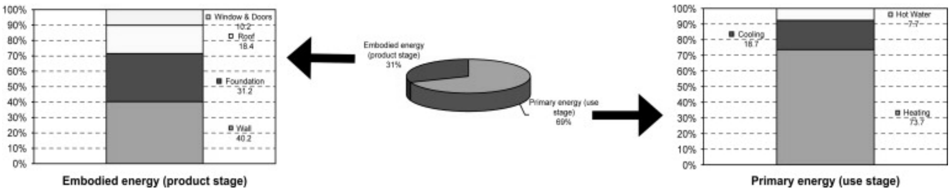


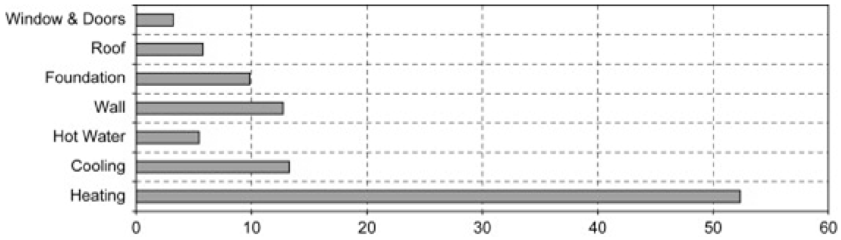
Figure 4.1 _ simplified LCA method in energy certification system

Applying this methodology to a case study of a residential building in Spain it was found that the embodied energy (approximately 170 MWh) represents 31% of the total energy requirement during the building's lifespan. This energy is ignored in the building certification (*Graph 4.1*).



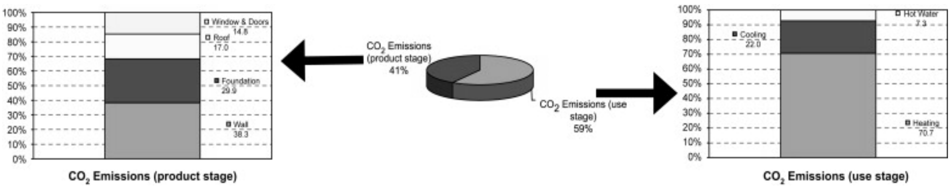
Graph 4.1 _ embodied and primary energy

In *Graph 4.2* below, causes of the energy consumption are illustrated: the main energy consumption is heating, but the second is the building materials, which represent 61% of the heating consumption.



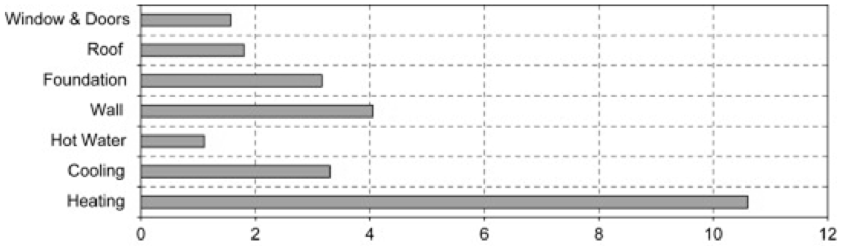
Graph 4.2 _ energy per habitable m^2

For what concerns carbon dioxide emissions, the rate of CO$_2$ embodied in construction materials represent 41% of the total emissions during the building lifespan (*Graph 4.3*).



Graph 4.3 _ embodied carbon and carbon dioxide emissions

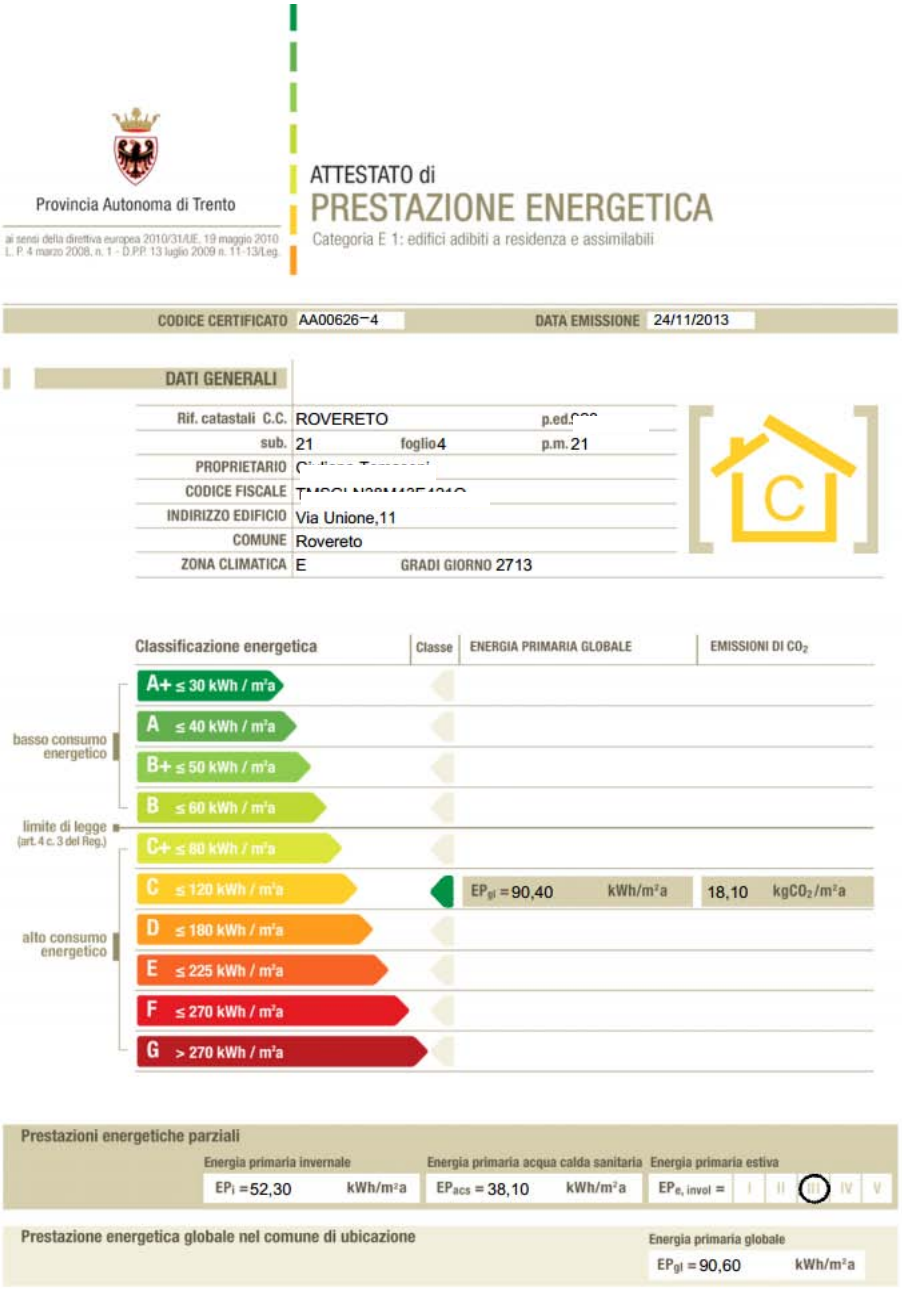
In this case, materials produce almost the same level of emissions as heating, as shown in *Graph 4.4*:



Graph 4.4 _ carbon dioxide emissions per habitable m^2

Starting from this results it was demonstrated that, for the selected case study, the cumulative primary energy related to the usage stage will be equal to the embodied energy of construction materials in 23 years, while for CO_2 emissions, 35 years are needed.

On the basis of this Spanish study, further analysis were performed on how integrating LCA methods with energy performance calculation. In order to evaluate the environmental convenience of design choices, the methodology proposed by the authors I. Z. Bribián, A. A. Usón, S. Scarpellini has been applied to the Italian case study of the Autonomous province of Trento (Italy). This Province has its own specific regulation and software for assessing building energy performance, which differs from those used at national level. The proposed work aims to overcome common difficulties associated with LCA, defining a specific relation with the energy certificate, through the development of an “extended certificate”, in which non renewable energy consumption and carbon dioxide emissions, both in use and construction phase, are estimated. Software and calculation tools used for estimating energy performance are based on a standardized evaluation of winter and DHW consumptions (asset rating) using a quasi-steady method. Main references for this calculation are the technical standards UNI/TS 11300:2008 – *Part 1: “Energy performance of buildings. Evaluation of energy need for space heating and cooling”* and *Part 2: “Energy performance of buildings. Evaluation of primary energy need and of system efficiencies for space heating and domestic hot water production”*. Also the spreadsheet adopted in the province of Trento basis on these standards (*Figure 4.2*).



Provincia Autonoma di Trento

ai sensi della direttiva europea 2010/31/UE, 19 maggio 2010
L. P. 4 marzo 2008, n. 1 - D.P.P. 13 luglio 2009 n. 11-13/Leg.

ATTESTATO di
PRESTAZIONE ENERGETICA
Categoria E 1: edifici adibiti a residenza e assimilabili

CODICE CERTIFICATO AA00626−4 DATA EMISSIONE 24/11/2013

DATI GENERALI

Rif. catastali C.C.	ROVERETO		p.ed. [redacted]
sub.	21	foglio 4	p.m. 21
PROPRIETARIO	[redacted]		
CODICE FISCALE	[redacted]		
INDIRIZZO EDIFICIO	Via Unione,11		
COMUNE	Rovereto		
ZONA CLIMATICA	E	GRADI GIORNO 2713	

C

	Classificazione energetica	Classe	ENERGIA PRIMARIA GLOBALE	EMISSIONI DI CO_2
basso consumo energetico	A+ ≤ 30 kWh / m²a			
	A ≤ 40 kWh / m²a			
	B+ ≤ 50 kWh / m²a			
	B ≤ 60 kWh / m²a			
limite di legge (art. 4 c. 3 del Reg.)	C+ ≤ 80 kWh / m²a			
alto consumo energetico	C ≤ 120 kWh / m²a	◀	EP_{gl} = 90,40 kWh/m²a	18,10 $kgCO_2/m^2a$
	D ≤ 180 kWh / m²a			
	E ≤ 225 kWh / m²a			
	F ≤ 270 kWh / m²a			
	G > 270 kWh / m²a			

Prestazioni energetiche parziali

Energia primaria invernale	Energia primaria acqua calda sanitaria	Energia primaria estiva
EP_i = 52,30 kWh/m²a	EP_{acs} = 38,10 kWh/m²a	$EP_{e,\ invol}$ = I II [✓ III] IV V

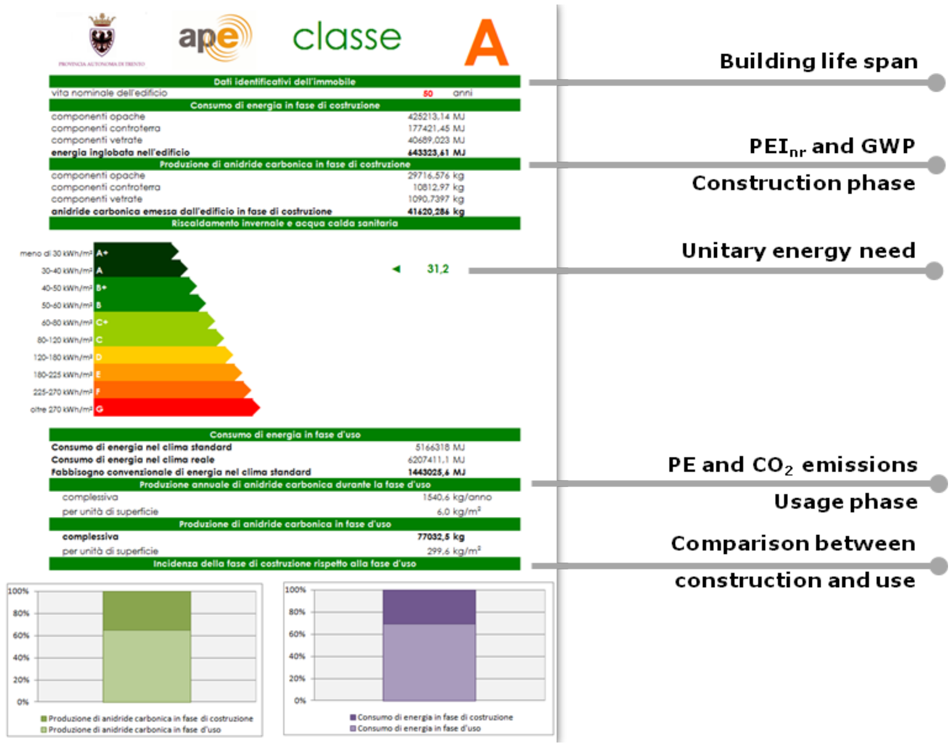
Prestazione energetica globale nel comune di ubicazione

Energia primaria globale
EP_{gl} = 90,60 kWh/m²a

Figure 4.2 _ energy certificate of the Province of Trento

For introducing life-cycle parameters in the calculation procedure, the excel sheet was modified and environmental data for materials were added in it. Thus, a list of 250 materials with their corresponding values of GWP an PEI_{nr} has been introduced into the spreadsheet.

Since in Italy there is no database of materials for LCA analysis, data of the Austrian database IBO have been used for implementing the calculation tool, which is able to automatically calculate embodied energy and carbon dioxide related to construction phase. Furthermore it can compare CO_2 and energy for construction phase with the same parameters for usage stage, in order to understand the incidence of the construction phase considering a life-span of fifty years, as shown in *Figure 4.3*.



Dati identificativi dell'immobile	
vita nominale dell'edificio	50 anni
Consumo di energia in fase di costruzione	
componenti opache	425213,14 MJ
componenti controterra	177421,45 MJ
componenti vetrate	40689,023 MJ
energia inglobata nell'edificio	**643323,61 MJ**
Produzione di anidride carbonica in fase di costruzione	
componenti opache	29716,576 kg
componenti controterra	10812,97 kg
componenti vetrate	1090,7397 kg
anidride carbonica emessa dall'edificio in fase di costruzione	**41620,286 kg**
Riscaldamento invernale e acqua calda sanitaria	
Consumo di energia in fase d'uso	
Consumo di energia nel clima standard	5166318 MJ
Consumo di energia nel clima reale	6207411,1 MJ
Fabbisogno convenzionale di energia nel clima standard	**1443025,6 MJ**
Produzione annuale di anidride carbonica durante la fase d'uso	
complessiva	1540,6 kg/anno
per unità di superficie	6,0 kg/m²
Produzione di anidride carbonica in fase d'uso	
complessiva	**77032,5 kg**
per unità di superficie	299,6 kg/m²
Incidenza della fase di costruzione rispetto alla fase d'uso	

Figure 4.3 _ modified energy certificate of the Province of Trento

Modifications on the sheet have been tested on a case study of a low energy dethatched house, giving the following results: the construction phase accounts for nearly 40% of the energy consumption and for 42% of the carbon dioxide emissions. However, once demonstrated the high impact of the construction phase in the building life-cycle, it was interested to investigate which is the limit of the convenience in building energy efficient constructions.

For such reason, multiple scenarios of envelope have been hypothesized, considering the same composition of the constructive elements, but changing the insulation materials thickness (and in some cases also the density). Thus the U-values of the building components have been changed, in order to understand the relation between building envelope and environmental impact and to estimate how much the insulation level contributes in modifying environmental performance.

Nine different alternative buildings configurations have been simulated, using mineral fiber as main insulation material for walls and roofs. The configurations are characterized by average U-values between 0,107 and 0,265 W/m^{2}K (*Table 4.1*).

constructive elemnt	**surface**	**U0**	**U1**	**U2**	**U3**	**U4**	**U5**	**U6**	**U7**	**U8**
	m^2	W/m^{2}K	W/m^{2}K	W/m^{2}K	W/m^{2}K	W/m^{2}K	W/m^{2}K	W/m^{2}K	W/m^{2}K	W/m^{2}K
wall 1	301,3	0,259	0,226	0,201	0,154	0,143	0,128	0,117	0,104	0,095
wall 2	63,78	0,236	0,208	0,187	0,146	0,135	0,122	0,112	0,1	0,092
wall 3	30,53	0,237	0,212	0,212	0,192	0,175	0,161	0,161	0,149	0,13
roof	161,43	0,259	0,229	0,229	0,206	0,171	0,146	0,127	0,12	0,112
groundfloor	145,75	0,302	0,262	0,262	0,232	0,208	0,188	0,158	0,137	0,128
total surface	702,79	**U0 m**	**U1 m**	**U2 m**	**U3 m**	**U4 m**	**U5 m**	**U6 ma**	**U7 m**	**U8 m**
		0,265	0,232	0,219	0,183	0,164	0,145	0,129	0,116	0,107

Table 4.1 _ envelope configurations

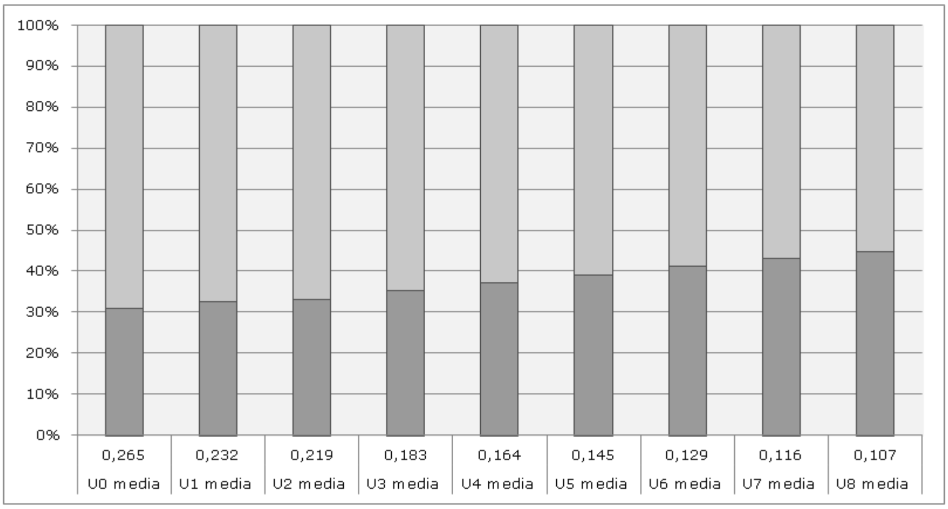
Performing the LC analysis of each designed solution according to the developed method, the following results in terms of primary energy and carbon dioxide emissions have been obtained:

U-value		**Primary Energy (MJ)**			**CO2 emissions (kg CO_2 eq.)**		
W/m2K		**embodied EP**	**EP use**	**EP total**	**embodied CO2**	**CO2 use**	**CO2 total**
U0 m	0,265	643323,61	1443025,61	**2086349,21**	41620,29	77032,48	**118652,77**
U1 m	0,232	676399,18	1405752,68	**2082151,87**	43534,14	74987,37	**118521,51**
U2 m	0,219	687592,35	1389454,27	**2077046,62**	44321,98	74093,10	**118415,08**
U3 m	0,183	727914,99	1346607,11	**2074522,10**	46309,45	71742,14	**118051,58**
U4 m	0,164	775458,23	1323505,73	**2098963,96**	48696,94	70474,60	**119171,54**
U5 m	0,145	830450,09	1302505,65	**2132955,74**	51336,38	69322,35	**120658,73**
U6 m	0,129	894951,86	1284261,29	**2179213,15**	54230,96	68321,31	**122552,27**
U7 m	0,116	958911,44	1264889,15	**2223800,58**	56815,05	67258,39	**124073,43**
U8 m	0,107	1015002,96	1253314,02	**2268316,99**	57097,13	66623,28	**123720,41**

Table 4.2 _ results of the analysis of the nine envelope configurations

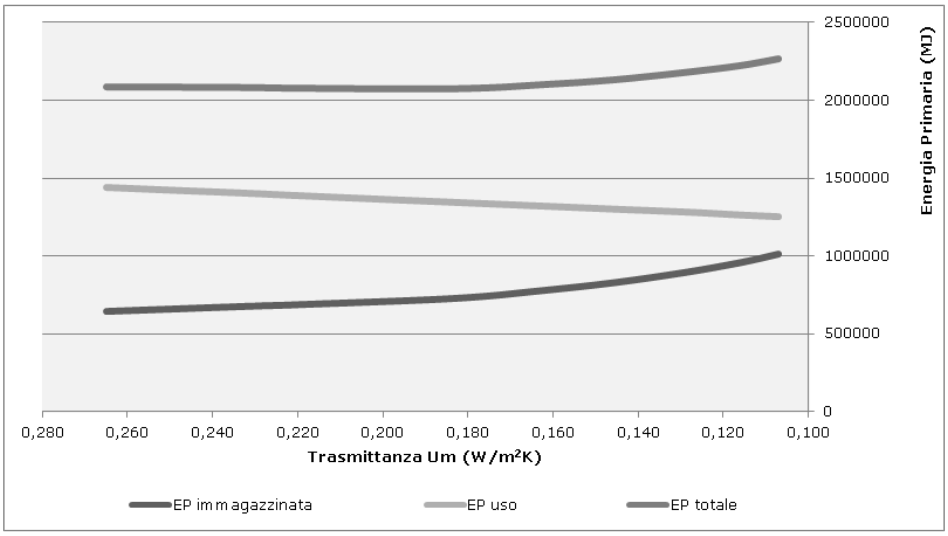
How it is possible to observe in *Table 4.2* above, both values of embodied primary energy and embodied carbon increase when the average U-value (U_m) decreases, while values associated to the usage phase decrease. However, the most important aspects to underline are:

- the percentage of embodied energy in construction materials in energy efficient buildings can reach 50% of the total energy used during the whole building life-cycle, as shown in *Graph 4.5*;

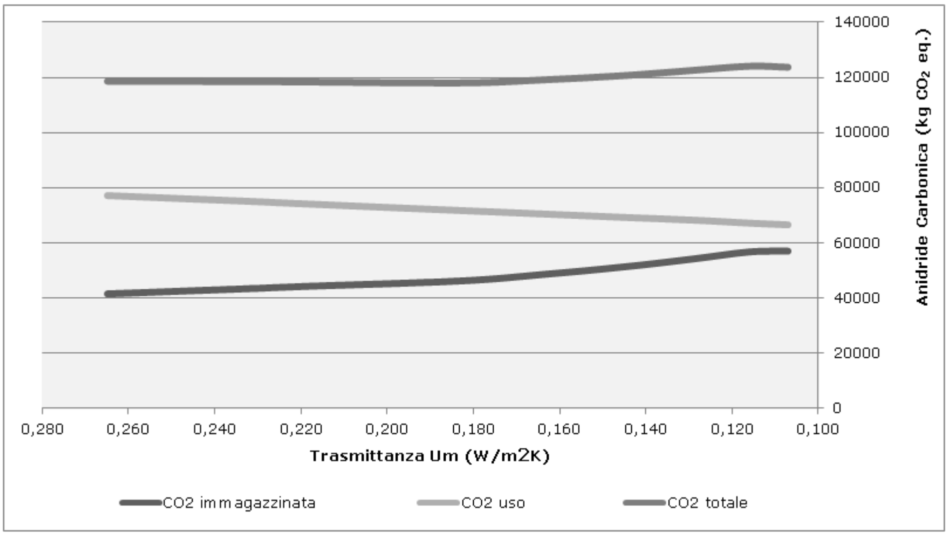


Graph 4.5 _ percentages of carbon dioxide during construction and use

- the little reduction of the total energy and total carbon in the range of U-values between U_{0m} (0,265 W/m^2K) and U_{3m} (0,183 W/m^2K). For U-values smaller than U_{3m}, the total results of both parameters tend to considerably increase, as illustrated in *Graph 4.6* (Primary Energy) and *Graph 4.7* (Carbon Dioxide).



Graph 4.6 _ primary energy flows



Graph 4.7 _ carbon dioxide flows

These two last graphs highlight the fact that a building with a high energy efficiency is not synonymous of low environmental impact: super-insulation can lead to the generation of negative impacts on the environment.

Designers almost know the importance of building constructions with a minimum energy requirement and also technologies for doing it, and stakeholders as well. However, the concept of *"whole building sustainability"* should be introduced inside the design process. In this way the energy certificate could become a more complete tool, able to better meet the issues of sustainable design.

4.2 _ LCC methodology

4.2.1 Overview of the method

Life cycle costing analysis (LCC) is a method able to give information of a product about most total costs over the whole life cycle. In building sector LCC is used for evaluating the economic performance of a building over its entire life, balancing initial monetary investment with the long-term expense of owning and operating the building.

According to *WBDG* – Whole Building Design Guide, scope of LCC is to estimate «*the overall costs of project alternatives and to select the design that ensures the facility will provide the lowest overall cost of ownership consistent with its quality and function*» [5]. Thus, the most important task of LCC is to determine the economic effects of buildings design alternatives. When performing such kind of analysis there are a lot of costs to take into account associated to the different building phases, which can be divided as follow:

- initial costs: purchase, acquisition, construction costs;
- fuel costs;
- operation, maintenance, and repair costs;
- replacement costs;
- residual values: resale or salvage values or disposal costs;
- finance charges: loan interest payments;
- non-monetary benefits or costs [6].

Viewed over a 30 year period, initial building costs account for approximately just 2% of the total, while operations and maintenance costs equal 6%, and personnel costs equal 92%.

Using LCC methodology is useful for designers and decision makers for selecting the most cost effective measures over the whole building life cycle.

4.2.2 Integrating LCC and LCA

History of LCC is older than that of LCA. These two methods base on different foundations: LCA was born in the field of industrial design, while LCC comes from system engineering. In *Environmental Life Cycle Costing*, David Hunkeler describes the diffusion of

LCC methodology. Although this tool started to be commonly used in United States only in Nineties for verifying operational and maintenance costs of tractors, it saw its true beginning in the Sixties, when the US Department of Defense started to adopt LCC for assessing the economic costs of purchasing, operating and maintaining high-cost military equipment, during their whole lifespan. In the last decade of the last century some academic studies on LCC were performed, which contributed to develop a standardized methodology.
LCC became a common tool in public sector for the evaluation of the investments both in constructions and infrastructures. Furthermore, several studies from researchers addressed to find a relation between LCC and LCA in order to make it possible to simultaneously verify economic benefits of environmental design during the entire lifespan of a product. Thus, the method was progressively better defined, according to the principles of life-cycle management and life-cycle thinking. Since their beginning there was little integration between LCA and LCC, because of their methodological differences.

As illustrated in *Table 4.3* below, since LCC and LCA are tools aimed to provide answers to very different questions, these differences are evident in their scope and method. While Life Cycle Assessment evaluates the environmental performance of alternative products in the most holistic way as possible, Life Cycle Cost compares the cost-effectiveness of alternative investments or business. Despite these differences, in the last years, several studied (Norris 2001, Hunkeler and Rebitzer 2003, Klöpffer 2008) recognized the effectiveness of using LCC as supporting tool for environmental assessment.

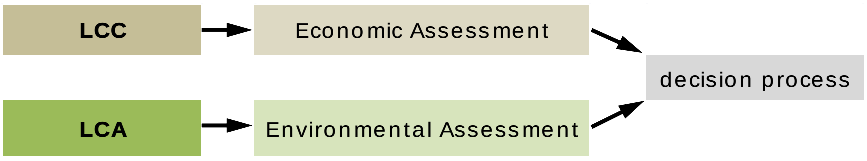
issues	**Tool / Method**	
	Life Cycle Assessment (LCA)	**Life Cycle Costing (LCC)**
Purpose	Compare **relative environmental performance** of alternative product systems for meeting the same end-use function.	Determine **cost-effectiveness** of alternative investments and business decisions.
Activities which are considered part of the Life-Cycle	All **processes** related to the product life cycle, **from cradle to grave.**	Activities causing **direct costs** or benefits to the decision maker **during the economic life of the investment**.
Flows considered	**Emissions of pollutants and depletion of resources.**	**Cost and benefit monetary flows**
Units for tracking flows	**Different units of measure**: mass and energy; volume and other physical units.	**Monetary units** (e.g., dollars, euro, etc.).
Time treatment and scope	Impact assessment addresses a fixed time dring which environmental demages are calculated.	Present valuing of costs and benefits with a specific time horizon scope.

Table 4.3 _ differences between LCA and LCC

In *Environmental Life Cycle Costing: a code of practice*, published by SETAC in 2011, the society defines guidelines for evaluating the economic aspect of the sustainability assessment of a product. In this code, three years of effort by the SETAC-Europe Working Group on Life-Cycle Costing have been summarized. Aim of the code is to give practical indications for performing a LCC in a complementary way with LCA, according to its four-phases structure. In this perspective LCC is characterized, like LCA, in four phases. At first, in *economic goal and scope definition* system boundaries and aspects to consider in the analysis are selected; in *economic life-cycle inventory* a data set of the materials used in the project and of their associated costs are defined. Normally, drawing up a consistent data set for an economic assessment can be challenging, since data usually come from several sources. As written in the editorial of the SETAC code of practice *«allocation is the process of assigning costs to particular cost objects, and has been a contentious topic in both LCC and LCA literature (Schaltegger and Burrit 2000; Curran 2007)»* [7].

For what concerns life-cycle impact assessment, LCC does not have a similar economic phase, because in LCC the same unit of measure characterizes all data. For this reason there is no need for characterization or weighting of inventory data. The aggregation of all data costs provides the final value of the economic impact. Procedures for the interpretation and communication of the results are the same of those for an LCA.

This similarity is fundamental for properly integrating these two tools, but for doing so it is necessary to find a feasible way for incorporating them together, allowing to perform an economic and environmental assessment (*Graph 4.8*).



Graph 4.8 _ decision-making process using LCC and LCA

Since they are both life-cycle based tools, LCA and LCC can be thought with the same cradle to grave approach and the same time horizon (*Figure 4.4*).

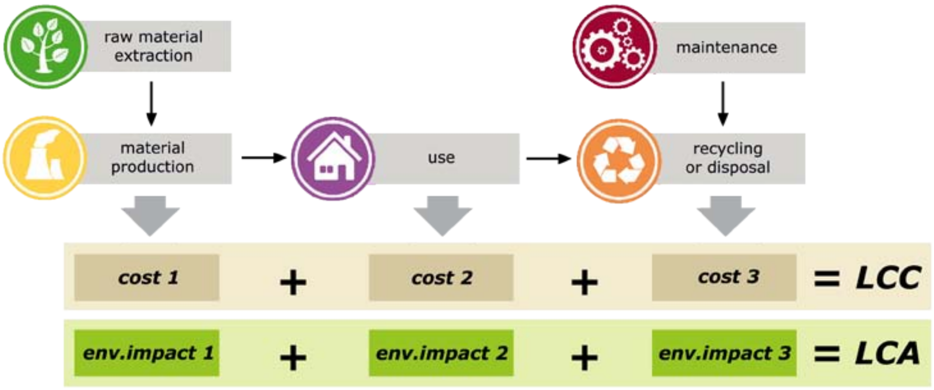


Figure 4.4 _ integration between LCA and LCC

However, differently from LCA, which is a top-down method, LCC is a bottom-up method. This means that for performing an LCA it is necessary to split the final product in different smaller components, while for performing an LCC the total sum of single components has to be done.

According to O. Tupamaki, one way to integrate them together is to convert LCA impacts to cost, using the following equation:

LCC = Capital investment + NPV [(use and maintenance) + (operating cost) + (repairs+ rehabilitation) + (salvage value) + (environmental LCA factors) + (occupational LCA factors) + (location LCA factors)]

where NPV is Net Present Value.

In this equation, environmental factors refer to all the environmental impacts from materials and activities during the entire building life cycle.

Another way to combine the two tools has been proposed by H. A. Boussabaine and R. J. Kirkham in their publication *Whole Life Cycle Costing – Risk and risk Responses*, in which the importance of incorporating *"eco-costs"* into LCA analysis for assisting environmental performance and investments are highlighted. With the term eco-costs, the two authors mean «*both direct and indirect costs of the LCA, impacts caused by the building asset, product, process, etc. in its entire life-cycle*» [8].

The use of eco-costs can assist in evaluating eco-design alternatives and can help in reducing the overall building cost through environmental and economic responsible decisions. The eco-costs include the following specific costs, all-attributable to the process of the building life-cycle:

- *cost of controlling atmospheric emissions;*
- *cost of resources (e.g. energy and water consumptions) used in the extraction and production of product;*
- *cost of waste disposal;*
- *cost of waste treatment including solid and other wastes;*
- *cost of eco-taxes;*
- *cost of pollution rehabilitation measures;*
- *cost of environmental management.*

For concluding, the integration between LCA and LCC can be a market-driver factor for the improvement of the environmental issues creating «*business benefits not only to the client and society but also to the construction industry stakeholders who are now under increasing pressure to deliver quality sustainable design*» [9].

4.3 _ Integrated approach for buildings renovation

4.3.1 Overview

In the two previous paragraphs of this thesis some proposals of integrating life-cycle assessment methodology with the energy certificate and life-cycle costing analysis have been discussed.
The shift from energy efficiency to whole sustainability requires further step of integration. For such reason also the economic aspect has to be taken into account when assessing building sustainability.

Despite the high level of knowledge in how to build energetically efficient buildings, the Italian context is affected by many difficulties in this specific sector. This is primarily due to the people fear to spend too much money for building low impact constructions or for improving the quality of the existing estate. Hence, a whole evaluation of the building behavior during its entire life cycle, considering the costs for construction and use, compared with the return of the investments and to the building environmental profile, is a good method for educating people to sustainable buildings. The use of Life Cycle Cost (LCC) methodology can demonstrate that sometimes saving money during construction is not the best solution for reducing the operating expenses and at the same time for saving the environment.

Clearly, LCA, Energy Certificate and LCC not only differ widely in their respective advantages and shortcomings, but also complement each other. Therefore combining these tools, or part of them, may be an appropriate strategy for successfully assessing buildings impact.

4.3.2 Methodology outline

The modification of the calculation sheet for energy performance of the province of Trento is a practical example on how to combine LCA and energy performance. As underlined in the previous paragraph, also the integration of life-cycle cost method in an assessment tool is important, since it allows evaluating in a more complete way the effective sustainability of constructions.
However, for what concerns environmental performance, considering only the primary energy content and the global warming potential means underestimating the importance of the other environmental impacts. Thus, some more parameters have to be considered for better evaluating environmental damages. According to the selected method of LCIA, six different categories of impacts should be evaluated. Anyway, having four additional parameters to consider can generate difficulties during the

assessment process. Furthermore LCC analysis and energy performance are both expressed with single indicators, which are respectively cost and energy consumption. In order to make the analysis easier also environmental performance should be expressed using the same approach: using the eco-indicator OI3 defined by IBO institute it is possible to summarize three of the six EPD parameters in a single indicator, able to give a synthetic information about the building environmental quality. In this way values related to energy performance, environmental performance and economic cost can easily related one to each other.

The analysis can be performed both at the building and the component level. At the component level it allows to select the best design solution for optimizing the single building element, while the analysis carried out at the building level allows comparing the whole building performance.

In case of a building element the parameters to consider are: the costs for construction and maintenance, the OI3 index and the U-value of the selected functional unit. When assessing the whole building the parameters to evaluate are: the whole energy performance (kWh/m^{2}year or kWh/m^{3}year), the OI3 index of the building and the whole building life cycle cost.

Some further considerations have to be done regarding the evaluation of the building costs. Because of the high number of required parameters, performing a full LCC is a difficult task; however considering only the most important phases of the building lifespan, the analysis can be simplified. Thus, within the research, the following costs have been included in the analysis:

- *construction costs*: cost of building materials and components;
- *maintenance and replacement costs*: cost for guaranteeing a good position of the building, changing its parts when necessary, considering a 50 years lifespan;
- *operational costs*: costs due to the building use, such as energy consumption for heating and cooling.

By adopting these assumptions, this assessment method can be easily applied by designers to carry out an overall simplified sustainability assessment, but however able to provide a comprehensive analysis.

4.3.3 A first test on a case study: the Oleificio Costa

The analyzed case study is a disused mill, known as *Oleificio Costa,* built at the beginning of the XX century in Rovereto (Trento, Italy). Original function of the building was the production of olive oil. The proximity to the Leno creek, allowed the building to use the water flow for producing part of the needed electrical energy through a water-mill.

The oil production required the construction of a heavy structure, able to bear high loads.

The building is composed of a massive concrete framework, silos of big sizes and internal stars and corridors, which define a wide and complex space, typical of industrial buildings of the period. Used until the beginning of Nineties, the building was then left to an abandoned state because of its functional obsolescence (*Figure 4.5*).

Figure 4.5 _ two pictures of the Oleificio Costa (Rovereto, Italy)

Twenty years later (2008) a private investor bought the forsaken mill, deciding to make it the headquarter of his construction company.

After nearly one hundred years from the building construction, the new owner found the structure still in a good position.

Despite of the bad condition of external and internal finishes, concrete framework and walls were still able to bear loads, especially considering that the new destination of use of the building would cause lower solicitations to the structure than the original one.

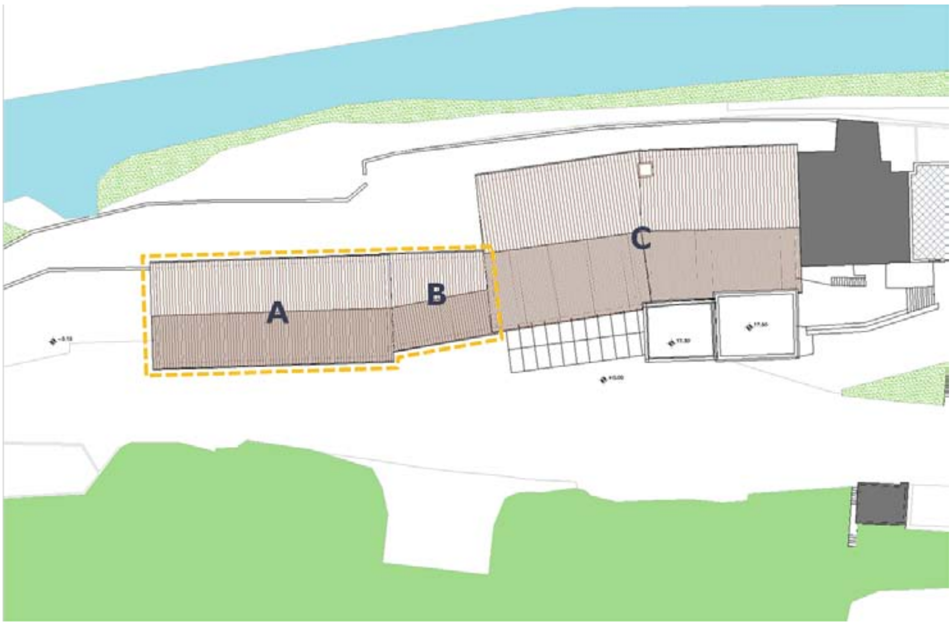


Figure 4.6 _ plan of the Oleificio Costa (Rovereto, Italy)

Due to its historic value, the building was partially subjected to heritage restrictions, but the cultural heritage department permitted some modifications and selective demolitions to the structure. Thus, the renovation project foresaw the demolition of a silo built later respect to the building and the wooden roof remake. However the building was not fully restored: ground and underground levels of the block C *(Figure 4.6)* were simply cleaned from molds and debris for being respectively used as exhibition spaces and storage.

Figure 4.7_ ground floor spaces before and after cleaning

Main scope of the intervention was the retrofitting of the first and second levels of the blocks A and B *(Figure 4.6)*, areas occupied by the enterprise offices. The project, developed in 2008 and built the following year, aimed to enhance the energy performance of this building portion, through the improvement of the existing envelope.

Before the construction works, the energy demand of the zone was higher than 250 kWh/m^2 and the energy retrofitting project had the ambitious track to reduce this value to 20 kWh/m^2, in order to classify the building as an A energy class with the KlimaHaus standard [10]. To obtain this improvement, the existing envelope had to be totally insulated from the inside (according to the previous mentioned heritage restrictions), while the roof covering and all the windows were changed.

Figure 4.8 _ plan of the 1st floor of the Oleificio Costa (Rovereto, Italy)

Figure 4.9 _ plan of the 2nd floor of the Oleificio Costa (Rovereto, Italy)

The building portion object of the intervention (yellow dotted line in *Figure 4.8* and *Figure 4.9*) is characterized by a gross volume equal to 2472 m^3 and a heated surface of 430 m^2. It corresponds to the first nucleus of the building, with an original envelope composed of stone walls 60 cm thick and intermediate floors and roofs partially in concrete and partially in wooden beams, as illustrated in *Figure 4.10* and *Figure 4.11*.

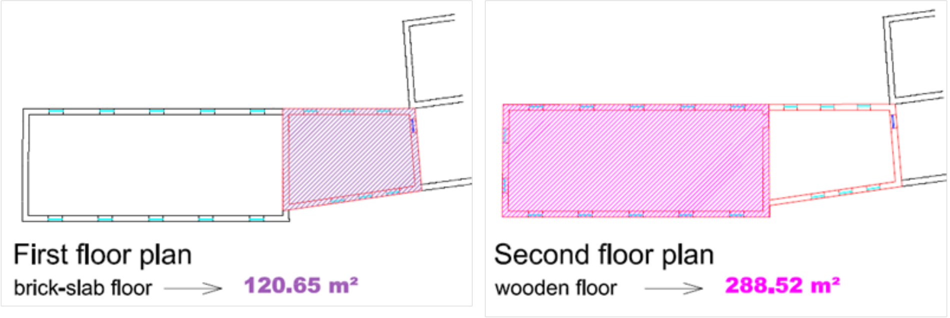


Figure 4.10 _ schematic plans of the 1st and 2nd floors

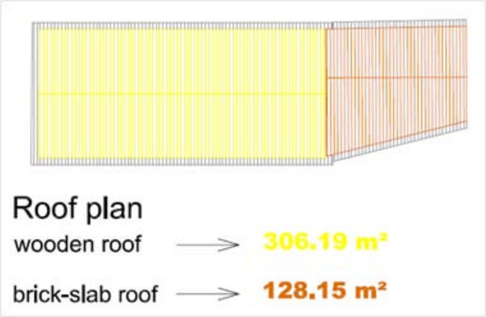


Figure 4.11 _ schematic plan of the roof

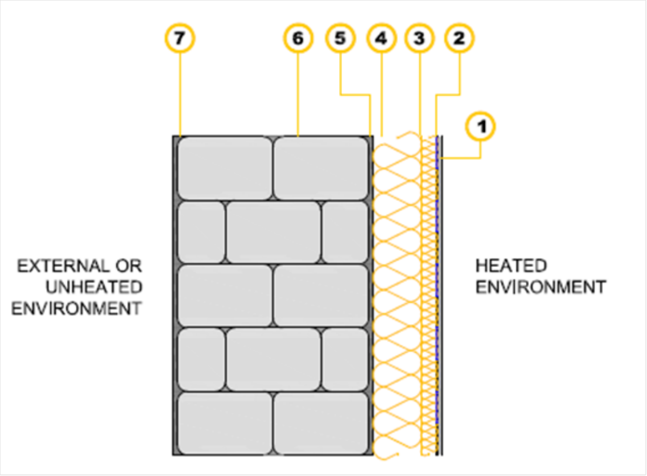
For what concerns retrofitting strategies, the designer chose to use rock wool as main insulation material for walls and floors, while for the new roof covering decided to adopt two layers of insulation: the first one, internal, in glass wool and the other one in wood fiber, in order to increase the thermal shift of the element, thanks to the high thermal capacity of this material. In this way all the retrofitted elements could achieve an U-value lower than 0,2 W/m^{2}K (*Table 4.4*).

Element description	Thickness [m]	Surface [m^2]	U-value before [W/m^2K]	U-value after [W/m^2K]
External masonry walls	0,62	472,15	2	0,17
Internal masonry walls	0,62	108,65	2	0,17
Brick slab floor	0,3	120,65	1,25	0,131
Wood floor	/	288,52	1,8	0,157
Brick slab roof	0,3	128,15	1,4	0,194
Wood roof	/	306,19	1,8	0,135
Windows	/	85,38	3,3	1,4
	Total energy demand		**18,6**	**kWh/m^2year**

Table 4.4 _ summary of U-values and surfaces

Figure 4.12 _ roof covering substitution

How the building subassemblies were retrofitted is shown in figures below, from *Figure 4.13* to *Figure 4.17*.

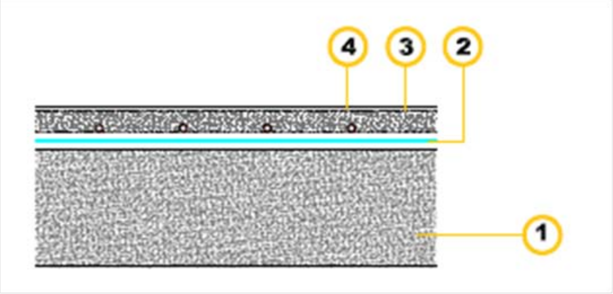


Layers

1 _ plasterboard
2 _ vapor barrier
3 _ ***mineral fiber 19 cm***
4 _ existing plaster
5 _ stone wall
6 _ new plaster

Thickness [m]	Surface [m^2]	U-value before [W/m^2K]	U-value after [W/m^2K]
0.62	472.15	2	0.17
0.62	108.65	2	0.17

Figure 4.13 _ external and internal bearing wall



Layers

1 _ brick-slab floor 20+8 cm

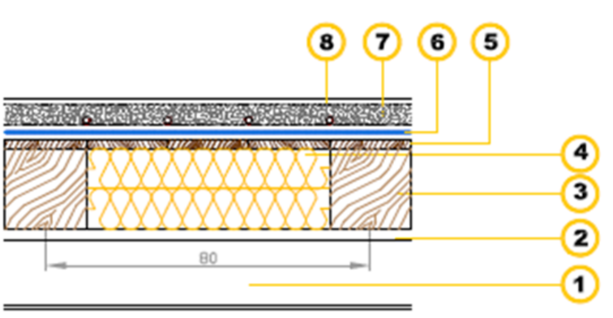
2 _ XPS 4 cm

3 _ concrete screed

4 _ resin floor

Thickness [m]	Surface [m²]	U-value before [W/m²K]	U-value after [W/m²K]
0.3	120.65	1.25	0.131

Figure 4.14 _ intermediate concrete floor



Layers

1 _ plasterboard with VB

2 _ mineral fiber 15 cm

3 _ brick-slab floor 18 cm

4 _ XPS 4 cm

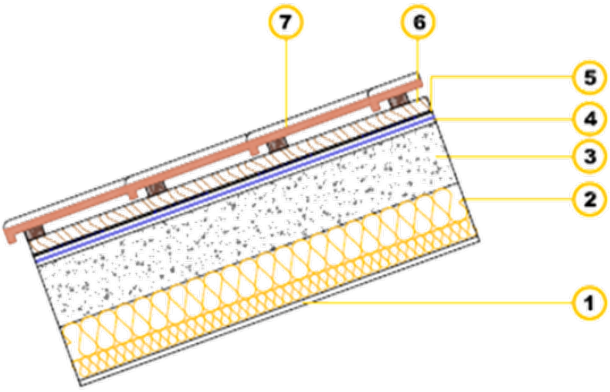
5 _ waterproof sheath

6 _ roofing slats

7 _ Portuguese tiles

Thickness [m]	Surface [m²]	U-value before [W/m²K]	U-value after [W/m²K]
/	288.52	1.8	0.157

Figure 4.15 _ intermediate wooden floor



Layers

1 _ plasterboard with VB

2 _ mineral fiber 15 cm

3 _ brick-slab floor 18 cm

4 _ XPS 4 cm

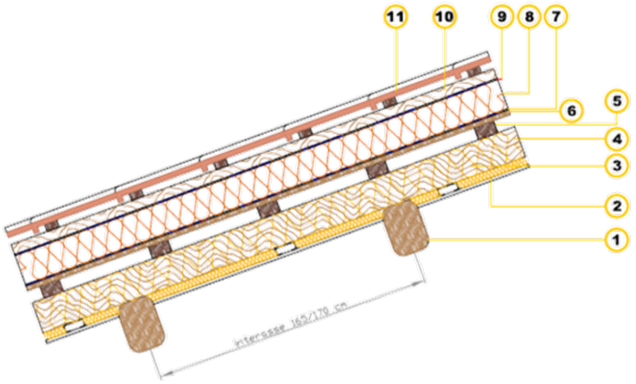
5 _ waterproof sheath

6 _ roofing slats

7 _ Portuguese tiles

Thickness [m]	Surface [m²]	U-value before [W/m²K]	U-value after [W/m²K]
0.3	128.15	1.4	0.194

Figure 4.16 _ concrete roof



Layers

1 _ wooden beams
2 _ plasterboard with VB
3 _ wooden slats
4 _ mineral fiber 15 cm
5 _ wooden slats
6 _ wooden deck
7 _ vapor brake
8 _ wood fiber 12 cm
9 _ waterproof sheath
10 _ wooden slats
11 _ Portuguese tiles

Thickness [m]	**Surface [m²]**	**U-value before [W/m²K]**	**U-value after [W/m²K]**
/	306.19	1.8	0.135

Figure 4.17 _ wooden roof

It has to be underlined that, due to the good position of the structure, it was possible to maintain all the structural elements (walls, floors and roofs structures), only reinforcing roof wooden beams with tie-beams.

Common feature of the retrofitting intervention was the use of materials able to ensure at the same time a good insulation capacity and a minimized economic cost.

This project has been analyzed as case study in order to understand:

- the environmental convenience in restoring Vs demolishing and building new;
- how the selection of more environmental friendly materials can affect construction costs;
- how it is possible to select effective construction alternatives without increasing the global cost of the investment;
- how to define a relation between the three typologies of assessment explained in the previous paragraphs: *energy performance, life cycle cost* and *life cycle assessment*.

In the analysis only the building portion occupied by the offices has been considered, due to the data availability about the amount of materials, costs and the presence of a more detailed project (KlimaHaus documentation).

At first it has been evaluated the whole environmental impact due to the project of renovation by using LCA. The impacts calculation has been performed by using data from IBO databank from Austria, considering new materials for insulation, restoration of internal and external finishes, roof coverings, fixtures. Based on EPD method, the LCA analysis related to the construction phase has given the following results (*Table 4.5*):

building components	**GWP**	**POCP**	**AP**	**EP**	**ODP**	**PE nr**
	kg CO2 eq.	kg C2H2	kg SO2 eq.	kg PO4--- eq	kg CFC-11 eq	MJ
external wall	13687,46	28,83	71,12	11,03	6,78E-04	187914,85
inner walls	3256,64	6,96	17,05	2,64	1,60E-04	44761,43
concrete floor	4725,84	9,67	24,21	3,44	1,83E-04	72186,42
wooden roof	24783,30	23,02	240,53	20,91	2,62E-03	852415,68
concrete roof	14134,32	7,40	80,59	6,19	8,35E-04	301567,83
wooden floor	46224,53	20,54	58,93	8,49	5,06E-04	190844,05
windows	3115,19	2,02	23,85	2,29	1,57E-04	75168,30
velux	365,40	0,18	2,19	0,20	2,78E-05	6283,83
Total	110292,68	98,63	518,48	55,19	5,17E-03	1731142,40

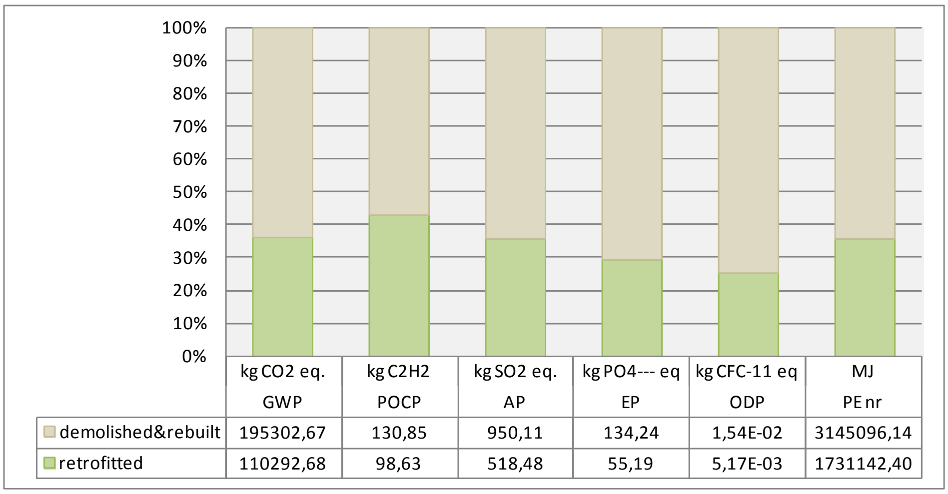
Table 4.5 _ LCA of the retrofitted building

Otherwise, supposing to demolish the existing structure and build a new one with similar technology and equal surfaces, the LCA analysis for the construction phase has resulted as follow (*Table 4.6*):

building components	**GWP**	**POCP**	**AP**	**EP**	**ODP**	**PE nr**
	kg CO2 eq.	kg C2H2	kg SO2 eq.	kg PO4--- eq	kg CFC-11 eq	MJ
demolition	1107,39	5,85	3,33	0,86	1,15E-03	96694,05
external wall	83538,90	44,38	378,24	68,28	7,36E-03	1117188,45
inner walls	19330,68	10,54	87,73	15,82	1,70E-03	258603,59
concrete floor	9122,40	11,14	37,88	5,02	5,18E-04	135770,36
wooden roof	21398,69	24,64	249,71	22,63	2,71E-03	874038,06
concrete roof	17469,94	8,52	90,96	7,38	1,09E-03	349808,21
wooden floor	39854,08	23,58	76,21	11,75	6,83E-04	231541,30
windows	3115,19	2,02	23,85	2,29	1,57E-04	75168,30
velux	365,40	0,18	2,19	0,20	2,78E-05	6283,83
Total	195302,67	130,85	950,11	134,24	1,54E-02	3145096,14

Table 4.6 _ LCA of a new similar building

Using this new building as benchmark (see *paragraph 2.2.2*), it is possible to compare results of the two analysis shown in *Table 4.5* and *Table 4.6* in order to understand if there are benefits in restoring the building and which is their estimated amount. *Graph 4.9* clearly illustrates the environmental savings deriving from the renovation:



	kg CO2 eq. GWP	kg C2H2 POCP	kg SO2 eq. AP	kg PO4--- eq EP	kg CFC-11 eq ODP	MJ PE nr
demolished&rebuilt	195302,67	130,85	950,11	134,24	1,54E-02	3145096,14
🟩 retrofitted	110292,68	98,63	518,48	55,19	5,17E-03	1731142,40

Graph 4.9 _retrofitting Vs demolishing and rebuilding

Table 4.7 shows that the impacts of the retrofitted building are lower in all six categories, with an average saving higher than 47%.

buildings	**GWP**	**POCP**	**AP**	**EP**	**ODP**	**PE nr**
	kg CO2 eq.	kg C2H2	kg SO2 eq.	kg PO4--- eq	kg CFC-11 eq	MJ
retrofitted	110292,68	98,63	518,48	55,19	5,17E-03	1731142,40
demolished&rebuilt	195302,67	130,85	950,11	134,24	1,54E-02	3145096,14
savings percentage	43,53%	24,62%	45,43%	58,89%	66,46%	44,96%

Table 4.7_ environmental savings of retrofitting

This difference is mainly due to the possibility to reuse the existing concrete structure and walls, which have a high value of embodied carbon and energy, because of their mass. Thus, the construction of a new building results as inconvenient and it is preferable to restore the existing building, as it was effectively done.

After established the convenience in restoring the building, the attention was paid on estimating in which way the environmental impact of the intervention could have been further reduced using different materials for the insulation of the existing envelope and for fixtures. Thus, other materials scenarios have been simulated: in all cases PVC windows have been substituted with wooden windows, while different alternatives in terms of types and thickness of insulation materials have been hypothesized. They have been considered two solutions in which the thickness of the insulation layers is equal to that one designed in the original project and other two solutions in which the equal parameter is the U-value of building components (in order to achieve the same energy performance of the building). These four scenarios have been applied to all the building subassemblies illustrated before (from *Figure 4.13* to *Figure 4.17*). Four different parameters characterizing these building elements have been compared:

- thickness of the insulation layers,
- U-values,
- construction cost,
- environmental performance (LCA).

Because of the complexity of LCA results, which are composed of six different typologies of impact with different units, the use of a single dimensionless indicator able to summarize the environmental impacts has been preferred. Hence, in this work, the OI3 indicator has been used. This indicator has been calculated for one square meter of each structure taking into account: non-renewable primary energy content (PEInr), global warming potential (GWP) and acidification potential (AP) as reported by *IBO-Guidelines to calculating the OI3 indicators for buildings* (see *Paragraph 3.2.2*).

Table 4.8 below shows how U-values, costs and OI3 indicators vary for the different hypothesis of insulation materials in case of maintaining the thickness of the benchmark design.

building components	insulation layer	thickness cm	U-value W/m^{2}K	Cost €/m^2	Eco Index OI3
external wall	mineral wool	19	0,167	72,3	-1
	wood fiber		0,201	124,4	-19
	hemp fiber		0,172	81,3	-17
internal wall	mineral wool	19	0,165	51,8	-3
	wood fiber		0,198	103,9	-21
	hemp fiber		0,177	60,3	-20
concrete floor	mineral wool	20	0,131	141,6	13
	wood fiber		0,152	196,5	-5
	hemp fiber		0,139	147,6	-3
wooden floor	mineral wool	18	0,157	153,8	36
	wood fiber		0,179	199,8	23
	hemp fiber		0,165	156,7	25
concrete roof	mineral wool	14	0,194	110,9	19
	wood fiber		0,188	139,7	7
	hemp fiber		0,188	122,9	8
wooden roof	mineral wool	18	0,135	114,7	39
	wood fiber		0,132	151,7	28
	hemp fiber		0,132	130,2	30

Table 4.8 _ U-value, cost and eco-index for different structures insulated with different materials, considering the same insulation thickness

Then, it has been hypothesized to maintain the U-values calculated for the benchmark design. Thus, the thicknesses of insulation materials necessary to guarantee that performance have been calculated and also related costs and environmental impacts, again summarized with the OI3 indicator. *Table 4.9* shows the results of these calculations:

building components	insulation layer	U-value W/m^{2}K	thickness cm	Cost €/m^2	Eco Index OI3
external wall	mineral wool	0,167	19	72,3	-1
	wood fiber		24	142,1	-16
	hemp fiber		20	84,3	-16
internal wall	mineral wool	0,165	19	51,8	-3
	wood fiber		23	134,15	-20
	hemp fiber		20	63,83	-19
concrete floor	mineral wool	0,131	20	141,6	13
	wood fiber		25	226,9	-2
	hemp fiber		22	150,6	-2
wooden floor	mineral wool	0,157	18	153,8	36
	wood fiber		22	226,2	25
	hemp fiber		20	159,7	26
concrete roof	mineral wool	0,194	14	110,9	19
	wood fiber		13	137,7	6
	hemp fiber		13	121,9	7
wooden roof	mineral wool	0,135	18	114,7	39
	wood fiber		17	150,2	28
	hemp fiber		17	129,2	29

Table 4.9 _ thickness, cost and eco-index for different structures insulated with different materials, considering the same U-value

Putting together the calculated information about the different configurations, five different buildings hypothesis have been obtained:

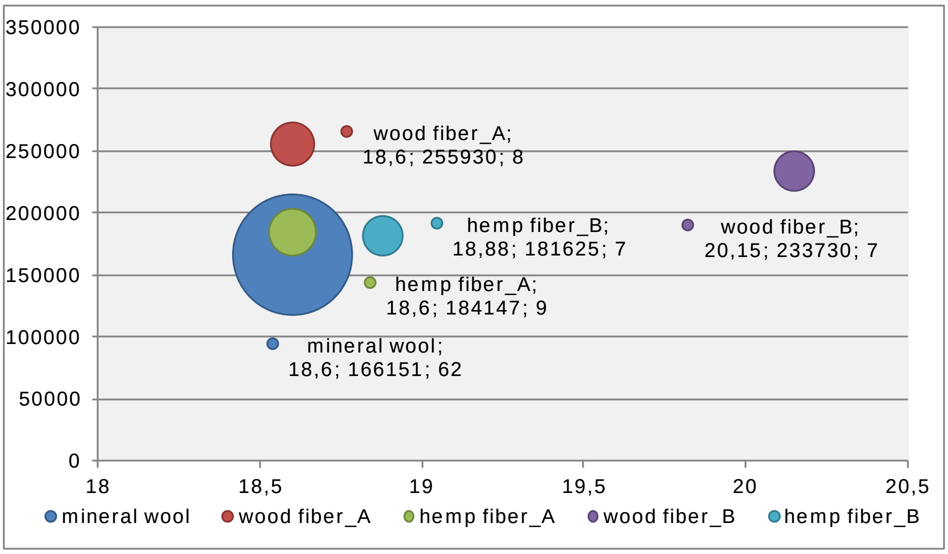
1. *mineral wool:* mineral wool insulation with PVC fixtures (benchmark);
2. *wood fiber*_A: wood fiber insulation with wooden fixtures and fixed U-value
3. *wood fiber_B:* wood fiber insulation with wooden fixtures and fixed insulation thickness;
4. *hemp fiber*_A: hemp fiber insulation with wooden fixtures and fixed U-value
5. *hemp fiber_B:* hemp fiber insulation with wooden fixtures and fixed insulation thickness,

giving the following results in terms of energy performance, construction costs and environmental impact:

building hypothesis	energy performance KWh/m^{2}year	cost €	Eco Index OI3
mineral wool	18,6	166151	62
wood fiber_A	18,6	255930	8
hemp fiber_A	18,6	184147	9
wood fiber_B	20,15	233730	7
hemp fiber_B	18,88	181625	7

Table 4.10 _ building energy performance, cost and environmental performance

These three calculated parameters can be related through the use of a simple bubbles diagram. In *Graph 4.10*, on the x-axis there is the primary energy for the winter season (EPi), while on the y-axis there is the construction cost of the retrofitting intervention. Furthermore, each bubble has a different diameter depending on the eco-index OI3. The largest is the diameter, the more impacting is the intervention.



Graph 4.10 _ bubble diagram representing environmental performance, costs and energy performance

Analyzing in detail the bubble diagram it is possible to observe that the built solution, with mineral wool insulation, is the cheapest one with a cost of 166150 € and it is also the best one from the energy consumption point of view; nevertheless, the corresponding bubble has the largest diameter of all, thus it is the most impacting solution. Instead, considering the solution with wood fiber as main insulation material, it is possible to observe that it is not convenient from the economic and energetic point of view, despite its low environmental impact. In fact, for achieving the same energetic performance of the "mineral wool solution" it is necessary to spend about 256000 €, with an increment of the 54% of the investment.

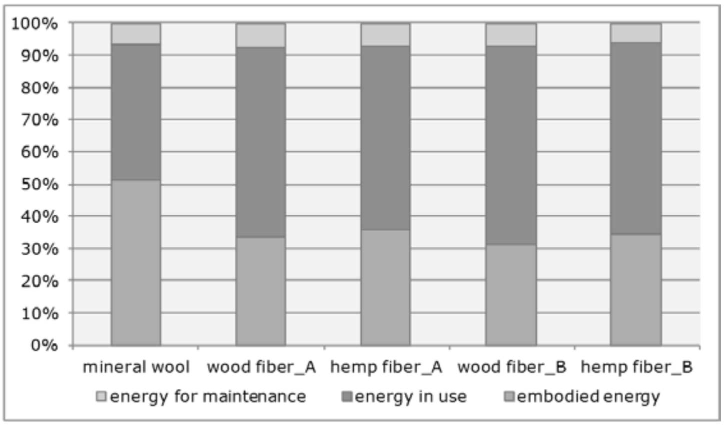
Instead, the use of the hemp fiber allows to obtain nearly the same energy performance (from 18,6 kWh/m^2 year to 18,88 kWh/m^{2}year) without increasing the insulation thickness. Moreover the environmental impact of this solution is equal to that one obtained using wood fiber, but with a lower cost: nearly 181600 €, with a difference of 15500 €, corresponding to 10% of the global investment on the construction.

Some more considerations can be done looking at the whole building lifespan. For what concerns environmental impacts, in *Table 4.11* below it is possible to observe an analysis on building energy and carbon dioxide emission. The *mineral wool solution* is the most impacting: the amount of embodied energy and embodied carbon in construction materials is nearly doubled respect to the other solutions, while values of embodied carbon are nearly tripled.

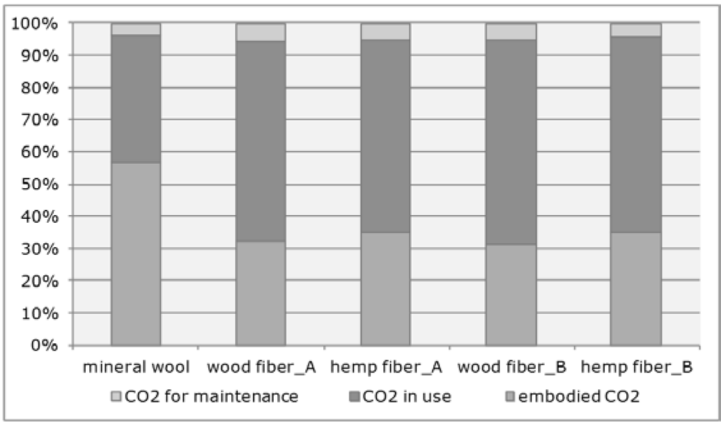
	costruction		**maintenance**		**usage**	
building hypothesis	embodied energy	embodied CO2	energy for maintenance	CO2 for maintenance	energy in use	CO2 in use
	MJ	kg	MJ	kg	MJ	kg
mineral wool	1731142,40	110292,68	225844,78	7812,49	1439640	76300,92
wood fiber_A	821886,23	39624,87	182942,38	6977,26	1439640	76300,92
hemp fiber_A	903221,97	44998,35	183007,97	6980,32	1439640	76300,92
wood fiber_B	792723,87	40487,78	182942,38	6977,26	1559610	82659,33
hemp fiber_B	859435,33	44790,24	159084,76	5894,50	1461312	77449,54

Table 4.11 _ energy and CO_2 of the five building hypothesis

In *mineral wool solution* the highest environmental loads come from the construction phase, while the value associated to the energy consumption for the building use is lower. In the other four solutions construction phase impact account on average for 35% of the total building energy consumption. The same happens when considering carbon dioxide emissions, as it is shown in the two histograms below, *Graph 4.12* and *Graph 4.13*. The contribution of maintenance phase is very little (lower than 10% for energy and than 5% for carbon dioxide).



Graph 4.11 _ energy in different building phases



Graph 4.12 _ carbon dioxide in different building phases

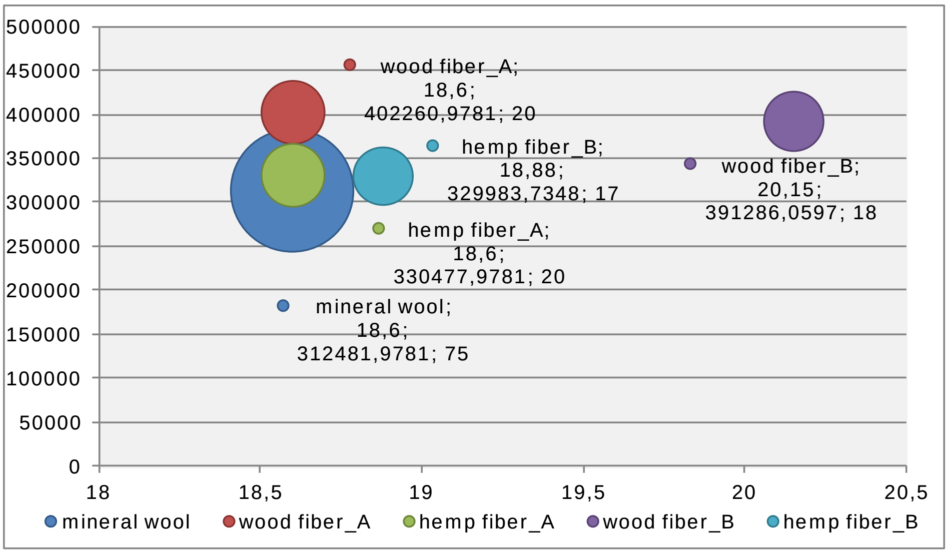
These big differences between the designed and the hypothesized solutions are mainly due to the fully absence of natural materials and to the selection of PVC fixtures. Mineral wool requires high level of energy for being transformed from rock to insulation material, while in the case of natural materials the process is easier and less energy consumer. Furthermore, the use of PVC windows increases the overall building impact. Because of its production, PVC is very impacting and a low rate of recycling of this material does not help in reducing its embodied energy. On the other hand, these materials with a complex productive cycle have lower costs and therefore they are more attractive both for builders and owners.

Extending the comparison of the five solutions in a 50 years perspective the cost difference between *mineral wool solution* and *hemp fiber_B solution* is reduced from 9% to 5,6%, because of the cost monetization and because of operation of maintenance in the two solutions are the same and for such reason they have a higher economic impact in the benchmark building.

building hypothesis	energy performance KWh/m^2year	cost €	Eco Index OI3
mineral wool	18,6	312481,978	75
wood fiber_A	18,6	402260,978	20
hemp fiber_A	18,6	330477,978	20
wood fiber_B	20,15	391286,06	18
hemp fiber_B	18,88	329983,735	17

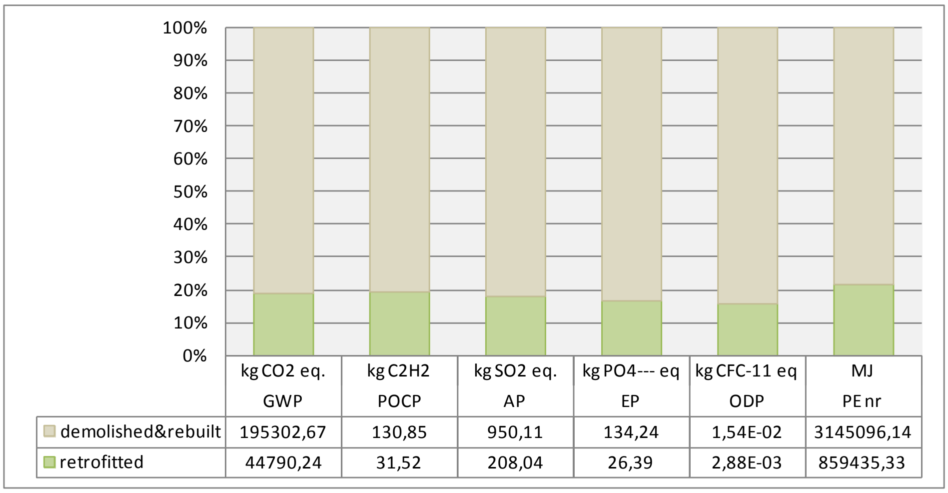
Table 4.12 _ comparison in a 50-years perspective

The bubbles diagram contributes in underlining that in a 50-years period, the *hemp fiber_B solution* is that one with the lowest environmental impact.



Graph 4.13 _ bubble diagram for a 50-years perspective

At this point, it is interesting to compare the most environmental friendly retrofitting alternative with the construction of a new building, as made before. The histogram *Graph 4.14* below shows a further reduction of the impact due to the building renovation respect to the designed mineral wool solution.



	kg CO2 eq. GWP	kg C2H2 POCP	kg SO2 eq. AP	kg PO4--- eq EP	kg CFC-11 eq ODP	MJ PE nr
▨ demolished&rebuilt	195302,67	130,85	950,11	134,24	1,54E-02	3145096,14
🟩 retrofitted	44790,24	31,52	208,04	26,39	2,88E-03	859435,33

Graph 4.14 _ best retrofitting Vs demolishing & building new

From this comparison it resulted an environmental savings percentage of 77%, as shown in *Table 4.13*.

buildings	**GWP**	**POCP**	**AP**	**EP**	**ODP**	**PE nr**
	kg CO2 eq.	kg C2H2	kg SO2 eq.	kg PO4--- eq	kg CFC-11 eq	MJ
best retrofitting	44790,24	31,52	208,04	26,39	2,88E-03	859435,33
demolished&rebuilt	195302,67	130,85	950,11	134,24	1,54E-02	3145096,14
savings percentage	77,07%	75,91%	78,10%	80,34%	81,31%	72,67%

Table 4.13 _environmental savings of the best retrofitting alternative

This demonstrates not only the effectiveness in reusing existing structures, but also the importance in materials selection. Choosing materials with lower impacts is an excellent strategy to further reduce the energy consumption of buildings and the best ally in doing it is the use of Life Cycle Assessment. The use of economic assessment and energy performance is also important for be aware of the choice.

Actually, when comparing different design alternatives it is difficult to select one of them: some alternatives can be better from energy point of view, others can better meet economic aspects and others can have low environmental impact. Currently, the preferred parameter for preferring a design solution to another is the cost. The integrated use of these parameters allows easily selecting strategies and designing solutions, which can result convenient in more than one aspect.

As demonstrated in this analysis, it is possible to design sustainable interventions also using materials at medium and low price, considering in the right perspective the difference of investment.

_ Notes

[1] citation from the directive of the European Union 2002/91/EC *Energy Performance of Buildings Directive* (EPBD);

[2] citation from the directive of the European Union 2010/311/EC *Energy Performance of Buildings Directive Recast* (EPBD II);

[3] citation from *Zero Energy Buildings: A Critical Look at the Definition* by TORCELLINI P., PLESS S., DERU M.;

[4] citation from *Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification* by BRIBIÁN Z., USÓN A. A., SCARPELLINI S.*;*

[5], [6] citations from *Life-Cycle Cost Analysis* by FULLER S. in *WBDG* – Whole Building Design Guide http://www.wbdg.org/resources/lcca.php;

[7] citation from *Environmental Life Cycle Costing: A Code of Practice* edited by SETAC in 2011;

[8] definition of eco-costs from *Whole Life Cycle Costing – Risk and risk Responses* by BOUSSABAINE H. A., KIRKHAM R. J.;

[9] citation from the research *Integration of LCA and LCC for decision making in sustainable building industry* by GUOGUO L.;

[10] KlimaHaus standard is a voluntary standard of energy certification, mandatory in the province of Bolzano (Italy). Among the goals of KlimaHaus is to fuse thrift with comfort and lastingness. The KlimaHaus categories provide an instant estimate of a building's energy consumption.

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Chapter 5

BUILDINGS DE-CONSTRUCTABILITY AND ADAPTABILITY

This chapter focuses on analyzing buildings constructability and adaptability. Because of the fast contemporary changes in lifestyle and technologies our buildings are required to have the inbuilt capacity to be adapted over time to changes of use. Thus, the concept of "design for de-construction" is investigated, defining best practices for designing buildings adopting this strategy. Furthermore, how to adopt the core concepts of the design for de-construction (flexibility and adaptability) in restoring the existing estate is explained.

5.1 _ Design for Deconstruction (DfD)

5.1.1 Overview

Today, construction and demolition waste is an emerging concern in building sector. During the 1990s, in most European countries construction and demolition (C&D) waste generation has risen due to the rapid growth of towns and cities. Although now the activity has entered in a phase of decline, due to the change of the economic situation, the waste stream from construction has been identified as a the main waste stream by the EU, since it constitutes approximately 49% of the total waste produced each year in European Union. Of this quantity, only 8% comes from new constructions, while 92% comes from demolition and renovation. As explained in the previous chapters, the existing building stock is aged and it has an evident need to be remodeled and renovated. This means that a huge number of C&D will be generated during the renovation process. However, buildings that will be restored, «*replaced or newly constructed can either be sources of waste or potentially reused if the materials from existing buildings are recovered. New buildings have the opportunity to be designed for reclamation of their respective materials for the next generation of buildings*» [1].

Design for de-construction (DfD) is a way of thinking a building in order to maximize its flexibility, ensuring the possibility to disassembly it after becoming obsolete. Main goal of design for deconstruction is to design elements that can be easily disassembled, allowing them to be reused, reducing the need for new materials and minimizing energy costs.

Thus, design for deconstruction is an environmentally responsible approach to design and accounts for the future deconstruction of a building.

5.1.2 Benefits and challenges in DfD

While the term "Design for Deconstruction" is new, the DfD movement saw its beginning in the latter XX century, with the foundation of the *open building* [2] movement by N. J. Habakren and the writings of S. Brand on *adaptive architecture* [3].

The open building concept implies the notion of uncomplicated structures that lend themselves to flexibility and change of use during the course of time. A key feature of open buildings is the separation of *"fit-out"* from structure, skin and services, where the term fit out identifies all the elements characterizing a specific destination of use of a building without being necessary for its basic functions. The better the fit-out separation, the more adaptable the building is. Differently, the concept of adaptive architecture refers to the capacity of a building to be used for multiple uses and in multiple ways over its lifespan. Over a building lifetime changes are inevitable and the highest the building capacity to be adaptable to new needs and expectations of its occupants, the longest and most efficient will be the building use, due to its capability to respond to changes at lower costs.

Wheatear open and adaptable building concepts take into account only construction, operation, maintenance and repair stages, DfD concept goes beyond, considering the whole building life-cycle, including major adaptations or eventual whole-building removal from the building site.

To understand the issues of DfD, it is primary to understand the challenges of the deconstruction process. Many products sent to the landfills have a recyclability value, which can produce a profit from the demolition process. With the growth in importance of the salvage market also buildings have to be designed for being easily recycled. Thus it is required that today buildings *«can be broken able down into salvageable and reusable components rather than demolished at the end of their useful life»* [4]. In this scenario, according to B. K. Fishbein, buildings designed for deconstruction will have the greatest value.

In accordance to A. Chini materials end-of-life can have five different outcomes. In order of environmental preference they are: *up-cycling, reusing, recycling, down-cycling* and *land filling*. Up-cycling happens when the new use of a material has a higher value than the previous. Reuse is when a material is used again with the same function or also with another, but without any modification; while recycling aims to preserve only the resource, and for being used the product has to be transformed and requires energy input. Down-cycling refers to the degradation of a material value before its reuse: it will be reused, but with another function of lower value and with a shorter life-span. Finally, sending materials to the landfill is at the same time the most chosen and the least preferable alternative.

The use of DfD encourages different end-of-life outcomes rather than landfill disposal as explained by P. Crawther in his *“recycling hierarchy”* scheme. As shown in *Figure 5.1* below, Crawther orders four options of end-of-life scenarios (*reuse, remanufacture, recycle* and *maintenance*) in terms of convenience, clarifying that DfD is more effective when reuse is preferred to recycle, which requires further environmental and economic costs.

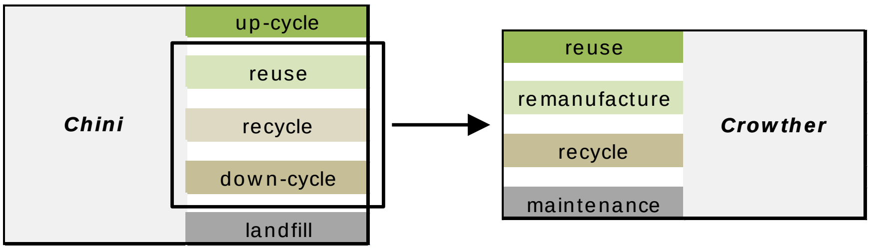

Figure 5.1 _ Chini and Crowther’s metrics

DfD also induce some positive changes in terms of sustainability, which can be assessed within the Triple Bottom Line perspective, considering environmental, economic and social issues.

The main effect of DfD on the environment is the reduction of pressure on landfill sites, as in this way C&D wastes are sensibly reduced. Furthermore a strategic building disassembly increases its reuse potential and reduces demand for new raw materials and natural resources, minimizing pollution. The reuse of building products contributes in avoiding the manufacture of new materials, reducing carbon dioxide emissions generated during the production stage and, if done locally, it minimizes the energy of transportation.

The second Bottom Line aspect is economy. Some DfD studies have demonstrated that in a long time perspective deconstruction is cheaper than demolition because by adopting DfD strategies it is possible to increase the building use or adaptation, minimizing renovation costs. Designing replaceable and easily accessible elements, building parts can easily be replaced without costly renovations and also reducing landfill-use costs.

For the society, the third participant of the Triple Bottom Line, deconstruction is a delicate task when compared to demolition. DfD requires specific skills and many hours of work to complete and this is the reason because at present this practice is not yet popular. However, A. Chini and S. Bruening stated that the acceptance of DfD as common construction method will create ten jobs for every landfill and demolition job, sensibly reducing the unemployment rate in building sector. Summarizing, according to T. Olson, *«the concept of DfD is to make deconstruction more attractive than demolition, and this translates directly to the speed of deconstruction, because in the field decisions are based on finances first, with the environment and society taking a distant back seat»* [5].

Despite all these significant benefits, DfD has some limitations as well. In *Implementing Deconstruction in the United States. Overview of Deconstruction in Selected Countries,* Kibert identifies nine challenges that DfD meets: *«existing buildings are not designed for dismantling, building components are not designed for deconstruction, deconstruction tools most times do not exist, demolition disposal costs are low, deconstruction takes substantially more time, building codes do not address component reuse, costs are unknown in deconstruction, lack of broad standardized industry practices, and the hazardous material, economic, and environmental benefits are not well known and understood»* [6].

At first, market acceptance is the most important challenge to overcome. Usually both designer and builders are diffident to change well known and proved products and methods. On one hand used building materials may often be perceived as having lower quality than their new equivalents, while, on the other, difficulties associated to the design for deconstruction can affect the interest in this type of design. It requires more time from the beginning, since DfD needs to be implemented from the preliminary design stage, in order to have a good coordination between all parts involved in the project and to be effectively integrated in each design phase. But also the deconstruction phase is more complicated and longer than demolition, as explained by Kibert.

Furthermore, transportation has to be limited, preferring the local use of disassembled materials (same site or a nearby site).

According to Olson *«these barriers are best confronted with knowledge, which would alleviate the perception of risk that is associated with using salvaged materials in new construction. For this to occur, standards for recertification and code acceptance will be required; with public interest and involvement will come pressure to solve some of the more technical issues facing DfD»* [7].

5.1.3 Construction and Deconstruction

The goal of Design for Deconstruction (DfD) is to *«increase resource and economic efficiency and reduce pollution impacts in the adaptation of and eventual removal of buildings, and to recover components and materials for reuse, re-manufacturing and recycling»* [8].

Crowther individuate a link between the build-ability and deconstruct-ability of a building: if a building is designed for being quickly and efficiently built, it will also be consistent with many principles of DfD. If constructability analysis during building design helps in simplifying the construction process, at the same way it can help during the deconstruction phase.

Many constructability principles used for simplifying the construction process (such as prefabrication, modularization, simplification of connections and building systems) can be actually used to simplify the process for building disassembly. Identifying constructability and simplified disassembly principles reduces installation costs and the time required for deconstruction. However, introducing constructability concepts and practices in the initial design of a building increase the life-cycle efforts of sustainable design, sustainable construction and deconstruction efforts. The efficiency of DfD can be increased through the introduction of design elements able to limit efforts related to disassembly and reduce the hours of labor for deconstruction.

Implementing DfD strategies can be easier thinking the building in terms of layers. In his book *How Buildings Learn*, S. Brand specifies a method for thinking about the building as a composition of layers, instead of seeing it as a monolithic object. Considering the building as a sum of parts, it is possible to observe that these layers have different life spans and for this reason have to be thought as separated and independent systems. Some layers have a very long lifespan, nearly permanent, while others need to be changed more frequently. Understanding the different durability of each layer is a key issue for planning future changes in a building.

The most part of construction waste comes from ordinary operations of replacement and maintenance of components or renovations, envelope and plants upgrading, spatial changes within the building; hence S. Brand recommends to design buildings in which the layers with a shorter life-cycle are positioned closer to the surface (both inner surface and exterior surface), making them simply accessible and removable, without causing damage to the permanent layers.

Figure 5.2 illustrates two different approaches to building decomposition by layers. On the left side, Duffy and Honey divides the building in four layers: *shell, services, scenery* and *sets*. The shell includes foundations and structure and has a 50-years lifespan. With services, technical plants (electrical, hydraulic, HVAC, lifts) are intended with an assigned lifespan of 15 years. Scenery coincides with partitions and furniture, with a life-cycle of 5-7 years, while sets identify those movable items, which have weekly or daily layouts. In the same graph, on the right side the layers decomposition of Brand is shown. It uses six categories: *site, structure, shell, skin, services, space plan* and *stuff*. Site is the ground on which the building is located and is permanent, structure has a very long life time between 30 and 300 years; building envelope, called skin by Brand, has 20 years lifespan because of maintenance issues and upgrading in aesthetic and technology. Services have the same definition given by Duffy and Honey, but with a different lifespan, which is between 5 and 15 years. Space plan and stuff coincide respectively with the Duffy's definitions of scenery and sets and have the same life time expectancy as well.

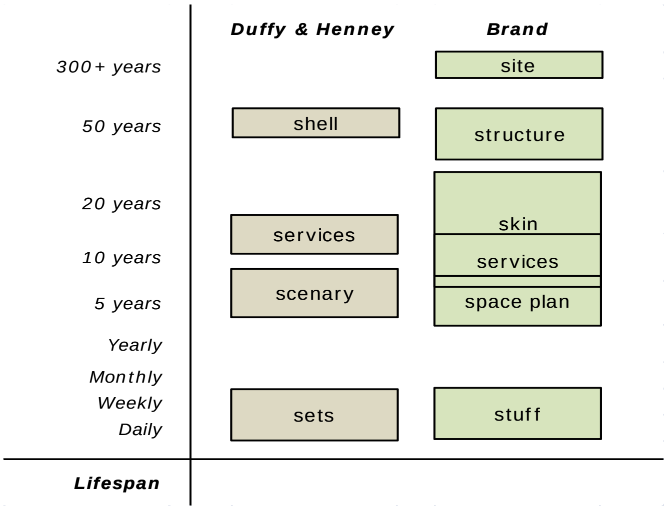

Figure 5.2 _ building layers decomposition

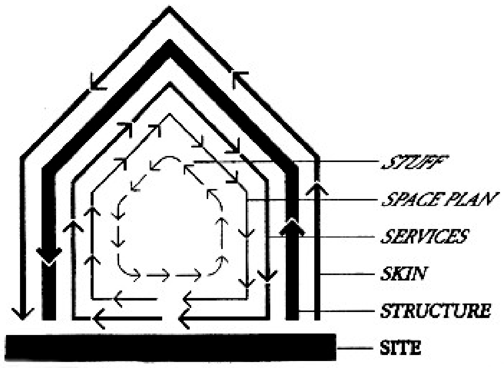

Figure 5.3 _ Brand's six layers

5.1.4 DfD principles

The most important DfD principle is to *"keep it simple".* Reducing the quantity of materials and elements used makes a building project less complicated and requires less labor to deconstruct it in the future.

Some basic principles/strategies were illustrated by B. Guy in his guide *Design for Disassembly in the Built Environment*, for helping design team to achieve DfD goals. These principles are:

1. *Design for flexibility and adaptability over the time;*
2. *Document materials and methods for deconstruction;*
3. *Specify materials and products with good reuse or recycling potential;*
4. *Design connections that are accessible;*
5. *Minimize or eliminate chemical connections;*
6. *Simplify and standardize connection details;*
7. *Separate mechanical, electrical and plumbing (MEP) systems;*
8. *Design to the worker and labor of separation;*
9. *Simplicity of structure and form;*
10. *Safe deconstruction.*

In *Table 5.1* below DfD principles and strategies for practically applying them on construction site are explained.

DfD principles	***DfD strategies***
1. Design for flexibility and adaptability over the time. *Planning for change and differing occupancy patterns can ensure a longer life of the structure.*	→ design a flexible spatial configuration; → design multiuse space to allow for flexible programming; → order extra materials or spare parts in small amounts in order to facilitate replacement of components.

2. Document materials and methods for deconstruction*, in order to facilitate disassembly after the useful life on site of the building.*	→ documenting materials and methods of construction and developing a deconstruction plan will facilitate deconstruction efforts years later, when the useful life of the structure will be concluded. → the deconstruction plan have to include: _ *as built* drawings labeling connections and materials; _ list of all materials of the project, including manufacturer contacts and warranties; _ specifics on finishes and materials chemistries; _ specifics on connections and on how to deconstruct them; _ information on hidden layers and materials; _ copies of the deconstruction plan should be given to the owner, designers, builders ant to everyone involved in the project.
3. Specify materials and products with good reuse or recycling potential. *When specifying materials for DfD, plan the possible reuse of materials before thinking their recycle (see Crowther's metric).*	→ avoid composite materials unless they are reusable in whole form; → design using standard sizes of materials; → specify simple products, not complicated assemblies which can reduce the possibility of reuse or recycling; → if a component is not reusable, it should be recyclable.
4. Design connections that are accessible. *Visually, physically and easily accessible connections will increase efficiency and avoid requirements for expensive equipment or extensive.*	→ components should be easily accessible for disassembly and for the operations of repair and replacement.
5. Minimize or eliminate chemical connections. *Chemical connections can make materials difficult to separate and recycle. Too many types of connection can increase*	→ chemical connections such as adhesives, sealants, mortar and welds can make materials difficult to separate and recycle; → chemical connections can increase the risk to destroy materials during the

deconstruction time and require too many tools.	deconstruction phase; → use of bolted, screwed or nailed connections can ease disassembly.
6. Simplify and standardize connection details*. Using standard and limited palettes of connectors will decrease tool needs, and time and effort to switch between them.*	→ simple and standardized structural connections can enhance the assembly and disassembly process; → simplified, modular connections can require as few as one bolt and no welding for installation, easing the construction process; → simple and standard connections facilitate the ease of disassembly and full recovery of reusable materials.
7. Separate mechanical, electrical and plumbing (MEP) systems. *Independent MEP systems make it easier to separate components and materials for repair, replacement, reuse and recycling.*	→ separating distribution systems (ductwork, wiring, communication cables, etc.) in non-structural walls can allow for selective demolition of these low-value components; → simplified designs reduce oversized components, avoid unnecessary transitions; → separate plenum zones for each distribution system facilitate separation during deconstruction.
8. Design to the worker and labor of separation. *Human-scale components or conversely attuning to ease of removal by standard mechanical equipment will decrease labor intensity and increase the ability to incorporate a variety of skill levels.*	→ designing human-scale components allows to reduce workers labor; → designing elements which can be easily disassembled through the use of common mechanical equipment and tools; → assigning to each worker appropriate tasks , commeasurable to his ability; in this way individual specific skills can be highlighted.
9. Simplicity of structure and form. *Simple open-span structural systems, simple forms, and standard dimensional grids will allow for ease of construction and deconstruction in increments.*	→ design for the minimum amount of building materials and equipment necessary; → reducing the number and size of building components lowers first costs, minimizes resource consumption and expedites the deconstruction or future retrofit process.

10. Safe deconstruction. *Allowing for movement and safety of workers, equipment and site access, and ease of materials flow will make renovation and disassembly more economical and reduce risk.*	→ design to reduce or eliminate safety hazards and the use of potentially hazardous materials; → eliminate or alter design elements that require potentially dangerous/ hazardous construction and deconstruction activities.

Table 5.1 _ DfD principles and strategies

5.1.5 Introducing DfD in sustainable design

According to R. Cole, of all the current models for understanding, assessing, and reducing the environmental consequences of our actions, LCA is perhaps the most useful. LCA tools have a proven validity in estimating environmental consequences of human actions. When performing a LCA, all of the inputs and outputs in the life of a product are identified.

Usually resources are extracted from the environment and then manufactured, causing environmental loads in terms of emissions and wastes. After used, those products are land filled into the environment. This means that at any stage of the life cycle correspond a number of possible environmental impacts. In order to understand how to reduce these negative environmental impacts several authors developed some form of simplified models.

Traditional models are based on a two-axis diagram that plot environmental resources against the life stages of the system or product, allowing to observe and analyze all environmental impacts. However, this type of model does not offer strategies for dealing with the unwanted impacts and furthermore it is unable to show the place and role of design for disassembly within the overall life of environmentally sustainable construction.

Differently, the model proposed by C. J. Kibert bases on a three axis diagram: environmental resources, life cycle stages and sustainability principles. His model can graphically illustrate the number of issues of sustainable construction, also including deconstruction phase.

«Kibert's model shows that there is a time and place for the design of a building to maximize resource reuse for materials in the future. This is to say that this model has identified a place for design for disassembly» [9]

Thus, combining the axis of strategies of sustainable construction, with the two axes of life cycle and impact categories, a simple conceptual model is produced. Kibert's strategies are: *maximize resource reuse, use renewable or* *recyclable resources, protect the natural environment, create a healthy, non-toxic environment, pursue quality in creating the built environment.*

His stages in time are: *development, planning, design, construction, operation* and *deconstruction*. His impact categories are simply divided into the resource categories of: *energy, water, materials* and *land*. The model, then, is represented as three radiating axes (*Figure 5.4)*.

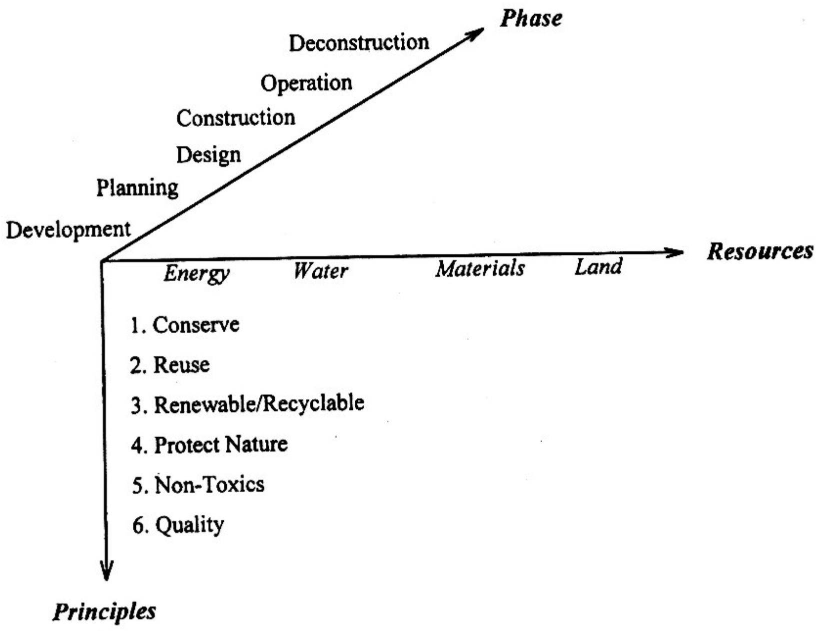

Figure 5.4 _ three-axis model by C. Kibert.

This model assists in an understanding of why to design for disassembly and it can be used as a design tool. However, it may be more helpful to consider the model, not as three axes, but as a three dimensional stack of *"boxes"* (*Figure 5.5*). For each strategy, time stage, and resource, there is a box. In each box there is a collection of issues that need to be addressed, and a collection of theories and principles for addressing them. Theories and principles will obviously not be limited to just one box; some issues will cover large numbers of boxes, as well some strategies for dealing with them.

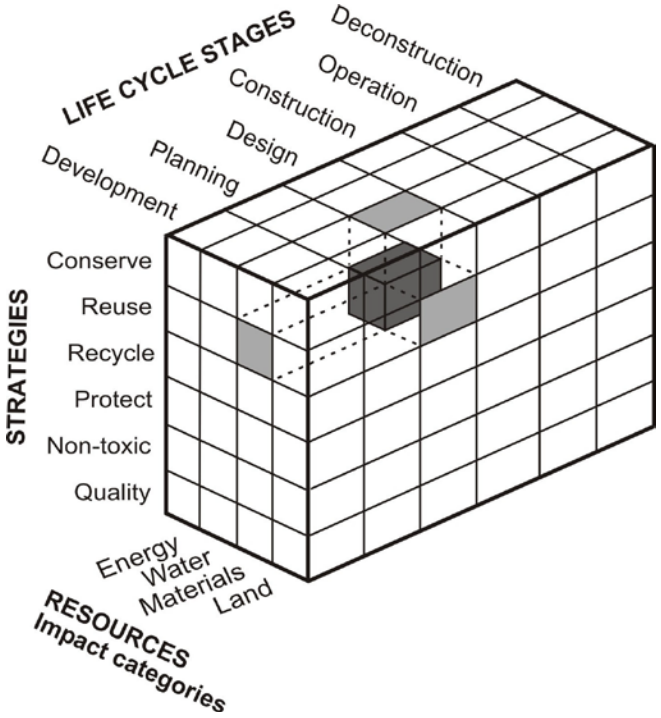

Figure 5.5 _ boxes model by C. Kibert

5.1.6 DfD and C2C approach

Ten design principles illustrated in the previous *Paragraph 5.1.4* aim to a unique scope: turning waste into resources. As explained in this chapter, the typical construction flow is linear *(Figure 5.6, left):* resources are used and eventually discarded with minimal thought of re-cycling or reuse. DfD approach is instead based on a *"closed loop"* flow *(Figure 5.6, right)*, which goes against the traditional linear approach.

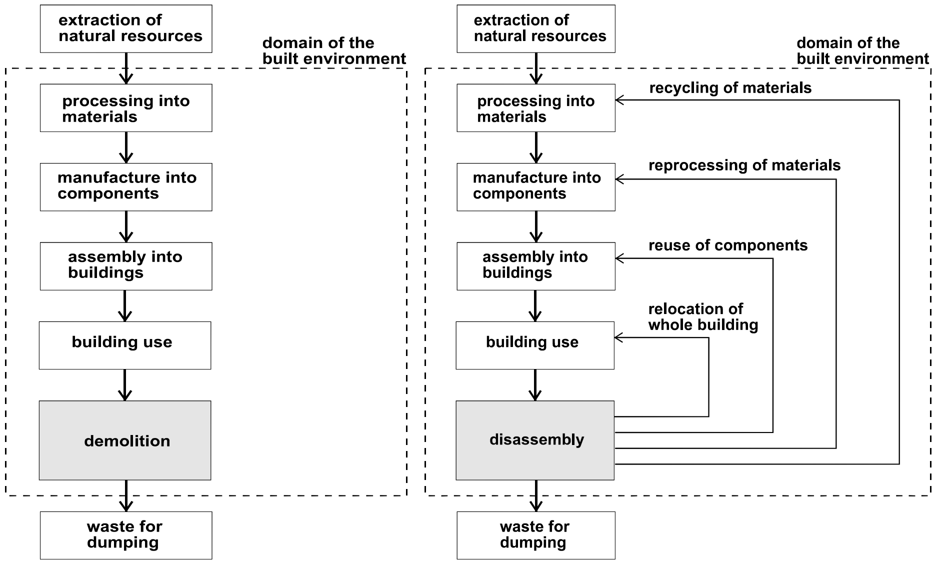

Figure 5.6 _ linear flow of materials Vs "closed-loop" flow

This circular approach is also the base of the *"regenerative design"* or *"cradle to cradle",* also known as C2C. C2C approach promotes material recycling as a loop "cradle back to cradle", in direct contrast to the "cradle to grave" model, in which *«material flows are formed without any conscious consideration of protecting resources»* [10]. Rather than attempt to reduce the linear material flows and current production methods, C2C promotes their redesign into continuous cycles and flows, encouraging a positive vision of the future. It reframes design as a beneficial, regenerative force, called *eco-effective* abandoning the standard approach of minimizing the harm we inflict, called *eco-efficiency* (*Figure 5.7* and *Figure 5.8*).

Figure 5.7 _ eco-effectiveness Vs eco-efficiency

The concept bases on these three main design-principles:

1. *Waste = Food. Everything is a nutriment for something else.*
2. *Celebrate diversity. Species, cultural, and innovation diversity.*
3. *Use current solar income. Energy that can be renewed as it is used.*

Although for the moment these principles applies only to the products within the building, they represents a shift towards awareness of the material flows that go into a building construction. Expanding them to include an entire building design is in fact the final objective of Design for Deconstruction.

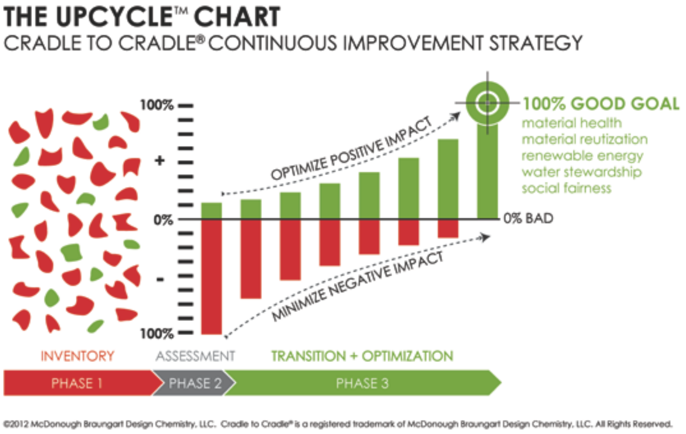

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Figure 5.8 _ eco-efficiency and eco-effectiveness in C2C improvement strategy

5.2 _ DfD and renovations

5.2.1 Overview

Traditionally, many builders worked supposing that their buildings will never have significant changes. But the test of time denied this assumption and the fast contemporary changes in lifestyle and technologies require buildings with the inbuilt capacity to adapt over time to changing uses.

Since much of the existing building stock will still be in use for another 100 years and considering that buildings constructed today will continue to account for the decades to come, introducing the concept of adaptability in contemporary design strategy is a priority. The key principles of the adaptable design are: *independence, flexibility, convertibility.* Designing or renovating a building using these strategies enables buildings to be stabilized and make them able to accommodate new technologies. In addition, it allows for changes in the spatial organization and in the life-styles of building occupants, reducing whole life cycle costs, demolition waste and impacts on the environment.

«If overall "sustainable development" necessitates an increase in the reuse and recycling of urban land and first generation suburbs, the trends towards renovation and rebuilding to use existing land and infrastructure will only increase. It is clearly important to address the decisions made in the design and construction of buildings that will mitigate the waste that will be generated from building removals in 21st century and beyond» [11].

5.2.2 Evaluating buildings adaptability

In *Chapter 1* the importance of retrofitting the existing building stock has been discussed. The question is: which is the link between existing buildings and design for deconstruction? The answer to this question can be found in the concept of adaptability.

Adaptability refers to the building capacity to accommodate substantial changes. Changes are unavoidable in each aspect of the world, from the society to the economy and the most adaptable the building, the longest will be its service life and the highest its capacity to meet the changed needs and expectations of the users.

Nowadays few buildings exist which have been intentionally designed for adaptability. For such reason the largest part of the existing stock is vulnerable to the time flow. However, there is the possibility to improve buildings adaptability performance in at least three way, outlined below.

- *More efficient use of space.* Adaptable buildings use the same amount of space and materials more efficiently on average over their entire life-cycle.
- *Increased longevity.* Adaptability helps in extending the total building lifespan. Most buildings are abandoned because of their technological obsolescence and not because their structural deterioration.
- *Improved operation performance.* Adaptability allows the building to be easily subject to changes as new technologies become available. An adaptable building benefit from technological renovation sooner and at lower costs.

For understanding if a building has adaptability features, it is necessary to determine if the *key principles of adaptability* developed by CMHC were adopted:

- *independence:* integrate systems or layers which can be removed or upgraded without affecting the performance of connected systems;
- *upgradability:* choose systems and components that anticipate and can accommodate potential increased performance requirements;
- *lifetime compatibility:* maximize durability of structural materials without mixing components with different life spans;
- *record keeping:* ensuring the availability of the building information for the future.

Thus, the connection between DfD and adaptability is cleary demonstrated by these principles, which are commons to both design approaches.

Currently, there are just three types of buildings, which can meet adaptability principles: commercial buildings, industrial buildings and warehouses.

These typologies are all characterized by big sizes and flexible internal partitions, which enable the disassembly of non-structural components.

However, commercial buildings are quite new and currently do not yet need for renovation, while, as illustrated in *Chapter 1*, there are a lot of existing industrial buildings or warehouses that actually need.

Since these buildings are good candidate to be rehabilitated and because of the importance to design adopting deconstruction principles, the necessity to apply design for deconstruction to renovation projects emerge.

_ Notes

[1] citation from Symonds LTD report *Construction and demolition waste management practices, and their economic impacts;*

[2] J. Habraken first articulated the principles of open building in his book *Supports: An Alternative to Mass Housing*, published in 1961;

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Chapter 6

SELECTION OF SUSTAINABLE STRATEGIES USING MCA

This chapter focuses on the development of an integrated approach to sustainable renovations. First of all it is explained how to define indicators of environmental performance, economic costs, energy performance, benefit in reuse and reversibility. After that, it is presented a method based on the use of MCA (multi-criteria analysis) for relating together these indicators, in order to have one comprehensive indicator able to give a synthetic information about the sustainability of the intervention.

For testing and validating the developed method, the project of restoration of an industrial building of Sixties has been designed. Different envelope solutions have been hypothesized and compared adopting the developed method, in order to choose the best one. Moreover, a simple tool (spreadsheet) allowing calculating the indicator of sustainable renovation is presented.

6.1 _ Indicator for Sustainable Renovation

6.1.1 Brief summary

The previous chapters investigated a plurality of sustainability issues. The dissertation started with the necessity to value the existing building stock through efficient interventions of renovation, especially considering those forsaken constructions, which were subjected to a fast aging process, like industrial buildings. However, nowadays every construction activity has to face environmental problems and resources scarcity. Thus, not only new constructions, but also retrofitted buildings have to be designed in order to reduce the overall impacts of the construction sector.

What is difficult is how to evaluate sustainability of interventions of restoration.

While for new buildings several standards and guidelines for sustainability were developed, the discussion on how retrofitting in a sustainable way the existing buildings has been fully omitted for many years. Only in the last period the intrinsic sustainability value of the existing built stock has started to be appreciated (especially in North America and UK) and dedicated standards and protocols for restoration have been developed. Nevetheless, these standards cannot be considered as the best tool for understanding benefits in restoring existing buildings, but can only give guidelines on how enhance their environmental quality. Thus, the support of more specific tool is required: according to the international research, LCA has been selected as the most appropriate method for assessing environmental savings from building restoration.

Despite 50 years of life, LCA is a quite young tool in building sector and there is an intense research activity on this topic all over the world. Difficulties in performing life-cycle analysis are mainly due to a proliferation of methods, materials databanks and software for the assessment of the environmental performance.

When carrying out this type of analysis, these aspects have to be deeply investigated and well characterized, selecting materials databanks according to the productive technology of the country in which the analysis is performed and a method able to give results in an appropriate way. Using Environmental Product Declarations (EPDs) rather than average materials from databases can be a strategy for making the analysis more reliable and also building performance can be expressed in the same form, dividing the environmental impacts in the same categories that are in EPDs. For this reason many of the existing software use or include the EPD calculation method.

Since a building life-cycle is divided in phases, it is important to understand which is their impact during the whole building lifespan. Traditionally, the most impacting phase was the use, but nowadays the construction of energy efficient buildings has caused an increase of the impacts related to the construction phase, reducing those coming from the use stage. This means that in new buildings the amount of energy and carbon embodied in construction materials can be equal to the amount of energy consumption and carbon dioxide emissions of the building in a 50 years lifespan.

Several studies demonstrated the importance of selecting materials with a low environmental impact, in order to minimize consumptions associated to the construction phase. Hence, the integration of LCA with the energy certificate is a first step towards this direction and it can be applied both to new and existing buildings.

Nevertheless, sustainability does not correspond to environmental performance; sustainability is a wider concept in which other two aspects are involved: economy and society.

Until now, the economic aspect has been the main driving factor in construction sector: builders prefer saving money during constructions, reducing the building quality components for maximizing their profit rather than finding a good cost and quality rate. For what concerns social aspects, retrofitting the existing building has a great social value due to the possibility to reintroduce such structures within the city, recognizing their symbolic value and giving them a new role.

A further social value to these retrofitted buildings can be given by the possibility to easily modify and adapt them to the changing needs of the society, avoiding the risk of a new future abandon. Used buildings are also well-liked and this increase their possibility to be well-maintained over the years.

The evaluation of the economic and social aspects is important in a life-cycle perspective. For considering the whole building cost it is necessary to perform a cost analysis with LCC method, while for increasing easiness in maintenance and building adaptability strategies of DfD should be adopted.

From this brief overview five different parameters to consider when assessing sustainability of retrofitting design solutions emerge:

- *convenience in restoring,*
- *environmental performance,*
- *energy performance,*
- *economic cost,*
- *adaptability potential.*

6.1.2 Combining parameters by using MCA

The question is: how to relate together these five parameters? As seen in the previous chapters, there are many possibilities to relate different parameters, also when they have different dimensions.

In *Paragraph 4.1.2* it has been possible to relate and compare building embodied energy and energy in use by a histogram, in which the percentage amounts of the two types of energy have been compared.

Instead, in *Paragraph 4.3.3* it has been necessary to assume another method to relate each other the three considered parameters (OI3, cost and PE). Thus, it has been decided to adopt a bubbles diagram representation, which can easily represent comparison characterized by the presence of three parameters.

Now, the possibility to integrate five parameters is discussed. Therefore, both histograms and bubbles diagrams cannot help in summarizing the results for making the comparison easier. In this case there is the necessity to resort to others methodologies.

The biggest problem consists of the fact that each one of the parameters mentioned in the previous paragraph totally differ one from each other: characterized by different units of measurement, some of them are qualitative, while others are quantitative; some are easily calculable, while others are more complex.

A widely recognized instrument which allows to relate several criteria having different units is *multi-criteria analysis (MCA)*. This tool is used in decision-making process to evaluate a problem by giving an order of preference for multiple alternatives on the basis of different criteria. The greatest strength of this tool is the possibility to use criteria with their own dimensions. Thus, the increased number of parameters to consider in the analysis requires a simplified way in which communicating results and the definition of a *"sustainability index"* able to summarize all these issues in a single value is the way.

The need for a single indicator leaded to the inclusion of MCA inside the thesis framework, because thanks to this method it is possible to develop a tool which can be applied by designers, builders or other stakeholders to carry out a comprehensive assessment of an intervention of restoration. This has been done combining the main calculation methods and tools explained in this thesis: calculation of the energy performance, LCA, LCC and other qualitative aspects concerning DfD strategies.

As explained above, some parameters are more complex than others, thus there is the need to accurately define them.

- *Convenience in restoring.* In *Paragraph 2.2.2* the benchmark approach for assessing environmental savings of building restoration has been illustrated. This method bases on the use of LCA for evaluating convenience in restoring, comparing the LCA of the retrofitted building with that one of the construction of a new building with the same features, after the demolition of the existing one. The LCA is performed according to the EPD method and for such reason, from the comparison, six different percentage values will result (see *Table 4.7*):

  $$X_{environmental\ saving} = \frac{(X_{demolished\&rebuilt} - X_{retrofitted})}{X_{demolished\&rebuilt}}$$

  where X corresponds to the six life-cycle parameters: GWP, AP, EP, POCP, ODP, PEI_{nr}.

  Averaging these percentage values of environmental savings (or further impacts, when the value is negative) a single dimensionless rate representing the convenience in restoring will result.

- *Environmental performance.* In *Paragraph 4.3.3* the assessment of the environmental impact has been performed by calculating LCA parameters and summarizing them in the OI3 indicator according to *IBO guidelines for calculating OI3 index.* However, this indicator does not fully represent LCA results, because it is based only on three parameters (GWP, AP, PEI_{nr}).

  Calculating LCA with the EPD method we have to face with six parameters with different units of measurement. Currently, there are no comprehensive indicators which summarize these six parameters. Thus, the proposal is to combine LCA results calculated with the EPD method into a single index by using MCA.

  As underlined by B.G. Herman and others the combination of LCA and MCA has already been researched and published by Benoit and Rousseaux, *«who compare the suitability of several outranking methods for aggregating LCA impact categories and by Pineda-Henson and others, who let an expert panel assign weights to impact categories»* [1].

  In this case the definition of a weighting system has been based on an international literature review and an interview to stakeholders and researchers in building and environmental engineering, who were asked to assign a point from 1 to 6 to each environmental category.

  Table 6.1 below shows the results of these investigation:

source	**GWP**	**AP**	**EP**	**ODP**	**POCP**	**PEI_{nr}**
Italian literature	4	3	3	2	1	5
Austrian literature	2	2	1	1	1	2
German literature	3	2	2	1	1	3
Netherlands literature	5	3	3	2	1	5
Canadian literature	3	1	1	2	1	3
US literature	4	3	2	1	1	4
literature average value	3,5	2,3	2,0	1,5	1,0	3,7
person interviewed 1	3	2	2	2	1	3
person interviewed 2	5	2	2	3	1	4
person interviewed 3	4	3	2	1	1	5
person interviewed 4	6	4	2	3	1	5
person interviewed 5	5	2	3	4	1	6
person interviewed 6	3	3	2	2	1	4
person interviewed 7	4	3	3	2	1	4
person interviewed 8	5	4	3	2	1	5
person interviewed 9	5	3	4	2	1	6
person interviewed 10	5	3	3	2	1	5
person interviewed 11	5	3	3	2	1	5
person interviewed 12	5	4	3	2	1	6
interview average value	4,6	3,0	2,7	2,3	1,0	4,8
personal opinion	4,0	3,0	3,0	2,0	1,0	5,0
rounded number	4,0	2,8	2,6	1,9	1,0	4,5
	4	**3**	**3**	**2**	**1**	**5**

Table 6.1 _ literature review and interview results

For obtaining the value associated to each parameter, the average literature values and average interviews values have been calculated and then averaged with the researcher opinion. From the weighting process, values reported in *Table 6.2* have resulted.

source	**GWP**	**AP**	**EP**	**ODP**	**POCP**	**PEI_{nr}**
rounded number	4	3	3	2	1	5
total	18					
weights	**0,222**	**0,167**	**0,167**	**0,111**	**0,056**	**0,278**

Table 6.2 _ weighting system

Applying the normalization and weighting process to LCA results a dimensionless value between 0 and 1 will result. The highest this value, the lowest the environmental impact of the constructive solution is. Clearly, this combination of LCA and MCA can cause loss of information due to the data aggregation, however the weighting of mid-point impact categories and the calculation of one comprehensive dimensionless indicator is the most important strength of this combination.

- *Energy performance.* As energy performance, in the first case study in *Paragraph 4.3.3* we considered only energy consumed for heating in winter season. This choice has been based on the fact that the information of the Oleificio Costa were limited to such kind of consumption.

Since in this case we are going to analyze a designed building, it is preferable to include in the study energy for heating, cooling and lighting, using data from dynamic simulation. The unit of measure of this parameter is the energy consumption per surface unit (KWh/m^{2}year).

- *Economic cost.* For the evaluation of the whole cost of a building the best tool to use is LCC, as illustrated in *Chapter 4.2.* Clearly, this calculation implies a large amount of information and also some assumptions and simplification. For such reason, costs considered in performing a LCC are: capital investment, cost for use and maintenance, operational cost and cost for repairs. Costs for rehabilitation and disposal have been not included in the analysis, because they can be intended as part of a future restoration project.

  Cost analysis allows to determine the entire cost of the building in terms of money and, since we are in the European Economic Union, it will be calculated in Euros (€).
- *Adaptability potential.* This parameter attempts to give an indicator of the easiness in deconstructing the building. Adaptability increases the building life-time and an adaptable project allows for easier changes in spatial organization and life-styles of building occupants, reducing whole life cycle costs, demolition waste and impacts on the environment.

  Assessing the adaptability level of a project is a difficult track: it is inexpressible with existing parameters and for such reason two qualitative sub-parameters have been defined. The possibility to easily disassembly a building element depends on how it is built. Constructive technology is the main element affecting the possibility to deconstruct a building.

  In those buildings in which wet or mixed construction systems are used there is a little (if none) possibility to deconstruct. Otherwise, when dry construction systems are used, the building disassembly is a more simple process.

  On the other hand also the type of connection between components affect the opportunity to disassembly. Connectors choice plays a great role in determining the possibility to disassembly a product.

  The method of connection determines if a product can be disassembled using a destructive or non-destructive approach: however, if the final aim is to minimize waste and to recover and re-use materials, non-destructive disassembly is the only option. This *«requires the use of connectors that are easy to unfasten»* [2]

There are some research efforts on reversibility of connections. Sonnenberg M. (2001) classified connectors in five main groups: *discrete fasteners, integral attachments adhesive bonding, energy bonding* and *other connectors*, while Kondo Y. et al. (2003) experimentally analyzed the reversibility and disassembly of connections, grouping them on the basis of their reversibility level. More recently, Calkins M. gave an evaluation of connection alternatives analyzing advantages and disadvantages of each type of them.

Table 6.3.a, Table 6.3.b and Table 6.3.c below summarize the point of view of these three authors:

M. Sonnenberg (2001)			
Type of connection	***Joining portion***	***Dismantled component***	***Possibility of reuse***
Discrete fasteners	screw, bolts, nuts, washers, springs, bundlers, etc.	they are indipendent from the parts to be merged together	they can be removed and reused depending on their condition
Integral attachments	locators, locks, compliant, snap-fits, etc.	they are integrated into the product	they make easier the disassembly process
Adhesive bonding	chemical connections, glue, resin, etc.	they join parts with different types of glues, etc.	they may complicate the disassembly process
Energy bonding	soldering, blazing, welding, moulding, etc.	the joint is melted or plasticized in order to form a bond	they may complicate the disassembly process
Other connectors	all types of connectors not included in the other groups		

Table 6.3.a _ groups of connectors by Sonnenberg M.

Y. Kondo et al. (2003)			
Type of connection	***Joining portion***	***Dismantled component***	***Possibility of reuse***
Shelf board	no deformation	no deformation	very good
Male/female joint	partly deformation	some deformation	good
Plug socket	no deformation	no deformation	very good
Joining with wire	deformation	partly deformation	normal
Snap fitting	some deformation	some deformation	normal
Screw	partly deformation	partly deformation	good
Adhesive reagent	deformation	deformation	bad
Adhesive double coated tape	destructive	deformation	bad
Soldering/welding	destructive	destructive	bad

Table 6.3.b _ comparison of reversibility on various practical connections by Kondo Y.

M.Calkins (2012)		
Type of connection	***Advantages***	***Disadvantages***
screw fixing	_ easily removable	_ limited reuse of hole and screws; _ cost
bolt fixing	_ strong; _ can be reused a number of tim	_ can seize up, making removal difficult; _ cost
nail fixing	_ speed of construction; _ cost	_ difficult to remove; _ removal usually destroys a key of element
friction	_ keeps construction element whole during removal	_ poor choice of fixings; _ structurally weaker.
mortar	_ can be made to variety of strenghts	_ mostly cannot be reused, unless clay or lime; _ strenght of mix often overspecified, making it difficult to separate bonded layers
resin bonding	_ strong and efficient; _ deal with awkward joints	_ virtually impossible to separate bonded layers; _ resin cannot be easily recycled or reuse
adhesives	_ variety of strenghts available to suit task	_ adhesives cannot be recycled or reused, many are also impossible to separate
riveted fixing	_ speed of connection	_ difficult to remove without destroy a key area of element

Table 6.3.c _ evaluation of connection alternatives for deconstruction by Calkins M.

Despite the three authors divide connectors in different ways, all of them identifies three main categories: *irreversible, partially reversible* and *reversible connections*.

The first group include those connections which cannot be disassembled or which can disassembled only damaging the product, such as welding, adhesives, resin bonding, mortar, etc. Partially reversible connectors includes wire joints, snap fittings, screw, etc. Lastly, reversible connections are those using merging shapes and shelf board.

Once defined these three main categories, it has been possible to determine an objective way for estimating the adaptability of the construction alternative.

Thus, according to what explained above, the two selected significant and objectively evaluable parameters are: the construction type (dry construction system, wet traditional systems or mixed systems), and the type of connection between different layers or parts composing the building (reversible, partially reversible, irreversible).

Table 6.4 shows how type of construction systems and type of connections have been considered in defining a single score representing the reversibility/adaptability of the intervention, while *Table 6.5* summarizes types of connections and points corresponding to the three categories identified above.

Construction type	features	points
Dry construction	_ prefabricated elements _ minimal/none use of water _ timber/metal _ light constructions	1
Wet construction	_ on-site elements _ use of water _ concrete/mortar/plaster _ massive constructions	0
Mixed construction	_ combination of dry and wet elements	0,5

Table 6.4 _ assignment of points for construction systems

Type of connection	connectors	points
Reversible	_ merging shapes _ shelf board	3
Partially reversible	_ wire joints _ snap fittings _ screw	2
Irreversible	_ welding _ mortar _ resin bonding _ adhesives	1

Table 6.5 _ assignment of points for type of connections

The possibility to easily disassembly the building element is expressed by multiplying the point corresponding to the construction type with that one associated to the connection type. The final point will be between 0 and 3. The highest the value, the best the easiness of disassembly is.

At this point the five indicators to link through the use of MCA have been defined, but it is necessary to specify how using this set of parameters for comparing alternative constructive solutions.

Since the five parameters have different units of measurement they have to be normalized. Convenience in restoring and environmental performance are yet between 0 and 1, thus it possible to use them without applying any further normalization. Differently, the adaptability potential has to be normalized by using a maximization formula:

$$\textbf{\textit{maximization:}}\ Mij^* = Mij / M\max$$

while economic cost and energy performance have to be normalized with a minimization formula:

$$\textbf{\textit{minimization:}}\ Mij^* = M\min / Mij$$

In this way the best performance in each category correspond to the highest calculated value between 0 and 1.

After that, the five values can be weighted according to a rating scale.

However, because each project has different needs it has been avoided to establish a fixed scale; in this way in each project it is possible to give a different weight to the involved parameters. For example, in some cases the economic aspect is more important than the environmental one, or the possibility to easily disassembly building components has a great role in the evaluation process, while achieving high value of energy efficiency is less fundamental; or all of them can be important at the same way. The introduction of a flexible weighting system allows designers, stakeholders and decision-makers to manage the alternatives comparison, giving more points to a parameter rather than to another.

The final comprehensive single indicator is obtained by using the following formula:

$$\boldsymbol{RE-GREEN\ indicator} =$$
$$\boldsymbol{A * CONVindex + B * ENVindex + C * ECOindex + D * PEindex + E * DfDindex}$$

where:

- 0 < *RE-GREEN indicator* ≤ 1 express the whole convenience in selecting a constructive alternative or another according to the selected weighting system;
- A, B, C, D, E are variable parameters defined by the decision-makers;
- 0 < *CONVindex* ≤ 1 is the percentage of convenience in restoring Vs demolishing and building new;
- 0 < *ENVindex* ≤ 1 is the summury of LCA analysis;
- 0 < *ECOindex* ≤ 1 is the minimized cost;
- 0 < *PEindex* ≤ 1 is the minimized primary energy consumed by the building;
- 0 < *DfDindex* ≤ 1 is the maximized value of adaptability potential.

6.2 _ Application of the method to a case study

6.2.1 Case study description

For testing the new combination presented in the previous paragraph, it has been applied to an illustrative case study. The selected case study is a Sixties' forsaken warehouse located in the suburbs of Udine (Italy).

The building is divided into two blocks with two different vaulted roofs, covering a total area of 574 m^2 on a unique level. The average height of the roof is 6,70 m. The vertical structures are in prefabricated concrete, ground floor is in concrete, while roof beams are in steel. External walls are in concrete blocks of 20 cm thickness, while hollow flat blocks covers the roof beams.

Figure 6.1 _ external and internal view of the building selected as case study

This building is currently used both as exhibition space and store. It is internally divided into two main areas with a temporary partition wall.

A building model has been drawn in order to evaluate the building energy need in terms of *regulated (non-process) energy* [3].

To build this model data supplied by the company owner of the building have been used, both in terms of dimensions and materials. In order to define thermal parameters of materials, due to the lack of specific data, *UNI 10351 standard – Construction materials. Thermal conductivity and water vapor penetrability* has been used, also considering materials aging process.

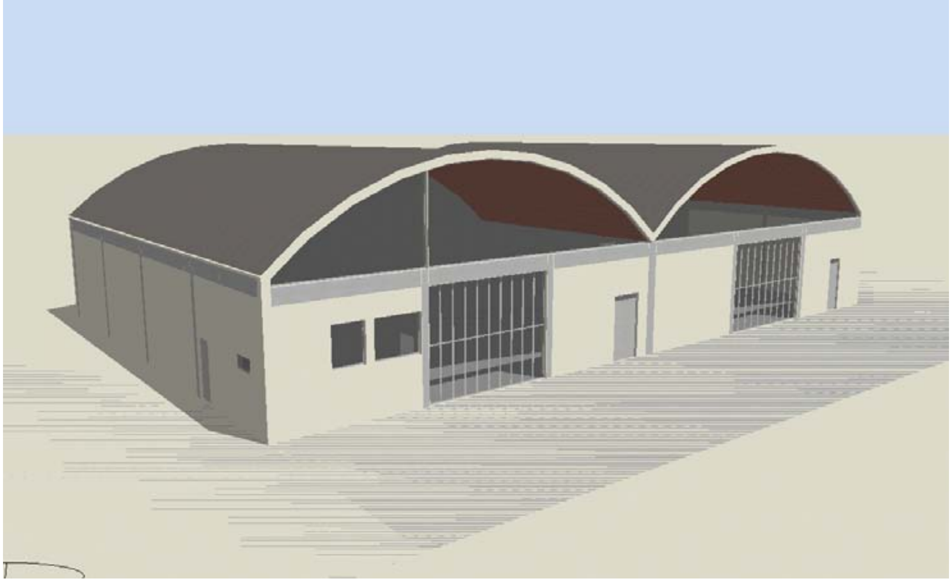


Figure 6.2 _ building model drawn with Design Builder

Thus energy consumption for heating, cooling, lighting and domestic hot water has been included in the analysis. In its current position, the energy simulation of the building has given the following results of energy need:

primary energy			
envelope energy need	*heating*	30,55	kWh/m^{3}year
	cooling	11,57	kWh/m^{3}year
other energy needs	*lighting*	8,42	kWh/m^{3}year
	ACS	0	kWh/m^{3}year
total		50,536996	kWh/m^{3}year

Table 6.6 _ building regulated energy need

The external envelope has a calculated energy demand for heating equal to 30,55 kWh/m^{3}year. This value is very high, because of the threshold fixed by the Italian standard for the climate zone of Udine is 14 kWh/m^{3}year.

This means that there is the necessity to well insulate the existing envelope for reducing the consumption from the current value of consumption to a value lower than 14 kWh/m^{3}year (corresponding to the Italian C class). Furthermore, also the energy consumptions for cooling and lighting have to be reduced in order to meet the new regulation requirements.

6.2.2 Architectural project definition

More than upgrading the building to the current standards of performance, the project of retrofitting is aimed to convert the building in an office, defining an interesting space from the architectural point of view. Nevertheless, the commitment required to restore the building maximizing the use of the inner space, reducing its energy demand and operational costs by using low environmental impact materials. In order to take full advantage of the building size, it has been decided to lower the level 0 of nearly 150 cm and dividing the total height of the construction into three different levels.

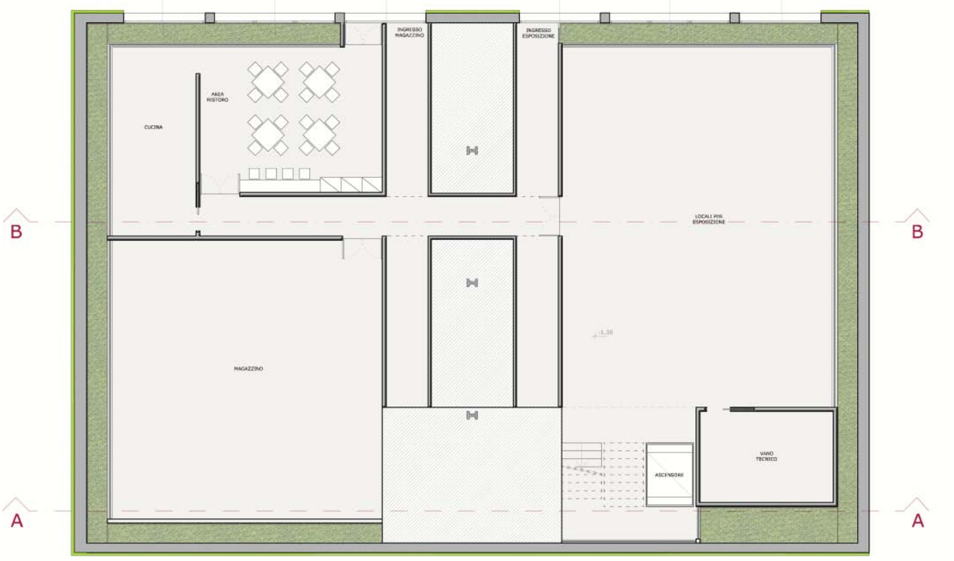


Figure 6.3.a _ underground level

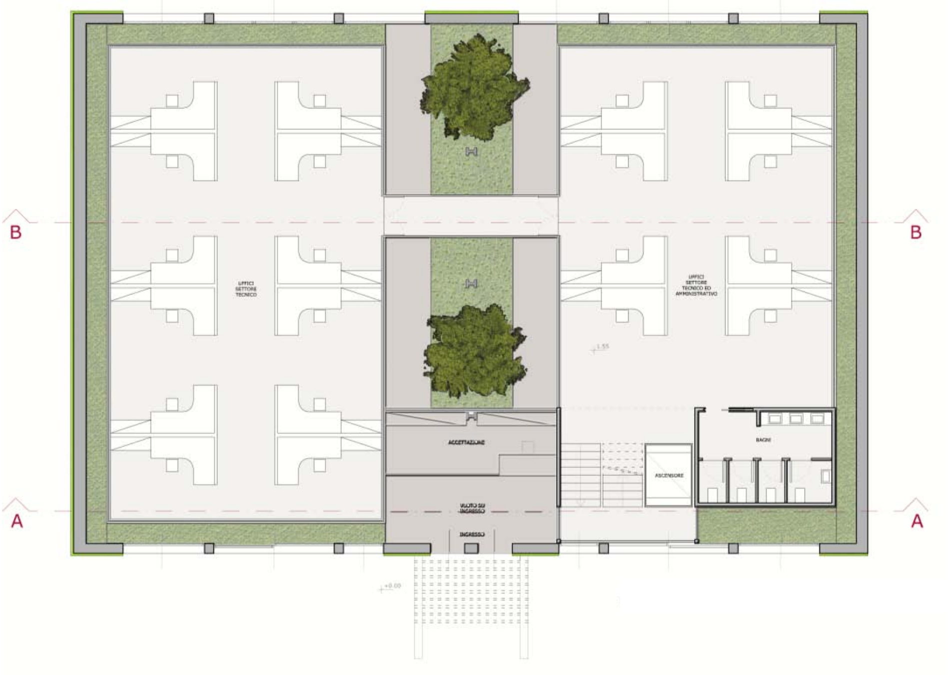


Figure 6.3.b _ first level

Figure 6.3.c _ second level

Building entrance is located at ground level in the same place respect to the original building configuration. There, a reception has been designed, from where it is possible to go upstairs or downstairs by using stairs or lift.

Downstairs, at underground level, there are on the right side an exhibition space and a technical room, while on the left side a storage and a small kitchen and break area are. Going again upstairs to the first floor both on right and left side open-space offices are located. Toilets are on the right side and a walkway allows occupants to cross the building from a part to another. At the second level on the left side a toilet, a small waiting area and a conference room are, while the left side is occupied by the secretary's office, a meeting room and the manager's office.

The division of the building in levels is well visible in vertical sections. In *Figure 6.4.a* the glazed walkway colligating the two buildings sides and cutting the roof surface, at the second level, is clearly visible.

Figure 6.4.b shows the opening of new skylights in the roof, which allow the light entering and lighting the second building level.

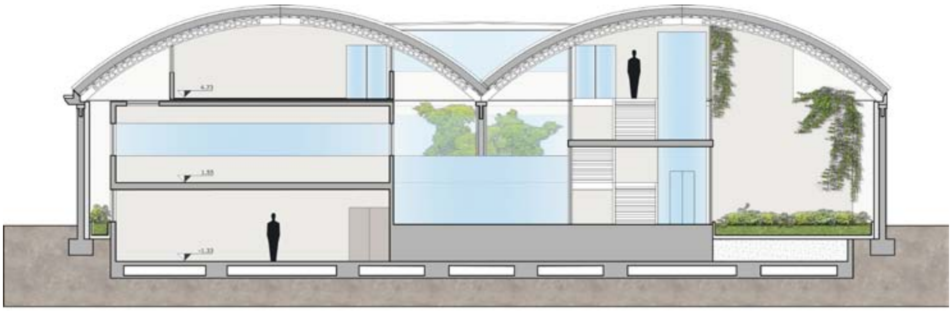


Figure 6.4.a _ section AA

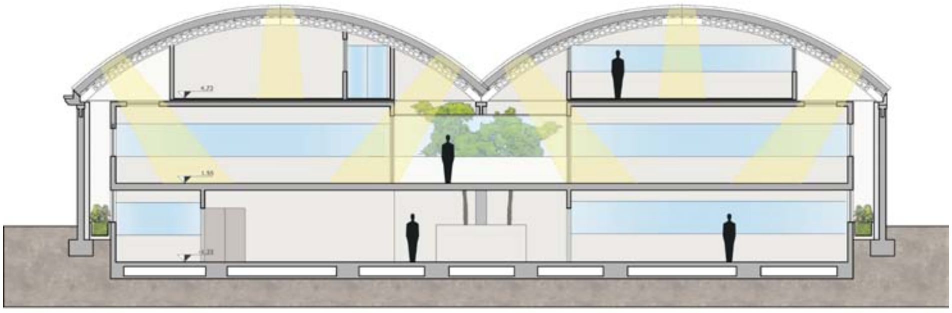


Figure 6.4.b_ section BB

The presence of green elements inside the building is one of the main aspects characterizing the project. In the middle of the underground level, where there are the three pillars bearing loads from the roof, two small trees have been planted.

Furthermore, always at underground level, along all the perimeter a stripe of grass runs, defining a vacuum space useful for allowing hot air to rise up until the roof for going out from the roof windows. Climbing ivies go down from horizontal planes, greening building facades.

All inner rooms at first and second level open on the double height space, allowing visitors and occupants to watch down the trees. Also the two walkways connecting right and left sides of the building overlook this space and especially that one at the first floor is like a balcony on the underground level.

Figure 6.5.a _ schematic volumetric model of the building from the entrance

Figure 6.5.b_ schematic volumetric model of the building from the back

6.2.3 Technical solutions proposal

Once defined the inner spatial organization of the building, the main problem has been how to upgrade the existing envelope in order to meet new standards of regulation and sustainability issues. Building envelope improvements with insulation is the most common approach, yet decision-making plays an important role in determining the most appropriate envelope retrofit strategy.

There are two primary methods for insulating a building, on the inside or outside and both solutions offer several advantages.

An interior retrofit can be done year-round; it does not require the removal of exterior cladding and reduce distances to property boundaries; it is mandatory when a building is partially protected by cultural heritage department. This kind of intervention is quite disruptive, so it is more frequent to add insulation from the exterior. An exterior insulation can provide a continuous and airtight insulation around the house without affecting interior finishes and reducing room sizes. The continuous insulation and air barrier systems help keep the house structure at a more uniform temperature, which improves its durability and performance. Furthermore, an exterior retrofit provides an opportunity to improve the appearance of the building.

The most common insulation method is ETICS (External Thermal Insulation Composite Systems). It consists in bringing up insulation panels, covering them with reinforced priming material and a plaster coating. It is also possible to insulate existing walls from outside with a ventilated façade system. In this case insulation is brought up between laths or other substructure, fixed with mounting system and then covered by various cladding types.

Otherwise, when there is the need to operate on a building with an internal insulation, it is required to build a new inner structure put against the existing walls, bringing up insulation between new laths and then covering with plasterboard or other types of board.

However, when it is difficult to operate on the existing structure and the building object of the retrofitting is composed of a single empty space, it is possible to adopt another strategy of retrofitting. This strategy is known as *"envelope within an envelope"* [4]. A project in which the envelope within an envelope concept is applied can have many benefits, such as:

- necessity to only insulate internal envelopes;
- the external envelope is not subjected to modifications;
- cost reduction;
- inner modules can be designed in modern way;
- zoned/targeted lighting, cooling and heating are possible.

The inner structure/building has to be totally independent from the existing one, thus, the emptiest the space, the easiest designing this kind of intervention is. Until now this approach was mainly tested on the existing barns of the Alpine region, but the spatial features of the case study building have made it a good candidate for applying this method.

Thus, for the warehouse, six main building retrofitting solutions have been hypothesized: two with an external insulation (*ETICS* and *ventilated facades*), two with an inner insulation (*metallic substructure* and *wooden substructure*) and other two solutions by using the envelope within an envelope concept (*timber-framed panels* and *cross-laminated panels*).

For each of these six solutions several alternative insulation materials have been tested, in order to understand their insulating capability, costs, environmental impact and recyclability potential.

Table 6.7 below summarizes the full set of the proposed constructive solutions, defining which kind of insulation materials and reinforcing inner structural elements have been used for each envelope configuration.

retrofitting method		**sinthetic insulation**	**mineral insulation**	**natural insulation**	**notes**
outside insulation	*ETICS*	EPS XPS	rockwool -	wooden fiber -	structural reinforcing elements in steel
	ventilated facades	EPS XPS	rockwool -	wooden fiber -	structural reinforcing elements in steel
inner insulation	*metallic substructure*	-	rockwool glasswool -	cellulose hemp fiber wooden fiber	structural reinforcing elements in steel
	wooden substructure	-	rockwool glasswool -	cellulose hemp fiber wooden fiber	structural reinforcing elements in wood
envelope within an envelope	*timber-framed panels*	-	rockwool glasswool -	cellulose hemp fiber wooden fiber	structural reinforcing elements in wood
	cross laminated panels	-	rockwool glasswool -	cellulose hemp fiber wooden fiber	structural reinforcing elements in wood

Table 6.7 _ tested building configurations

This means that 28 different retrofitting alternatives have been tested: 8 for the outside insulation, 10 for the inner insulation and 10 for the envelope within an envelope.

However, for better explain the developed methodology it has been decided to report the full calculation only for four solutions (from *Figure 6.6.a* to *Figure 6.9*):

- *ETICS (External Thermal Insulation Composite System)*: EPS has been used as main insulation materials for walls, mineral fiber has been used on the roofs and XPS panels for the ground floor;

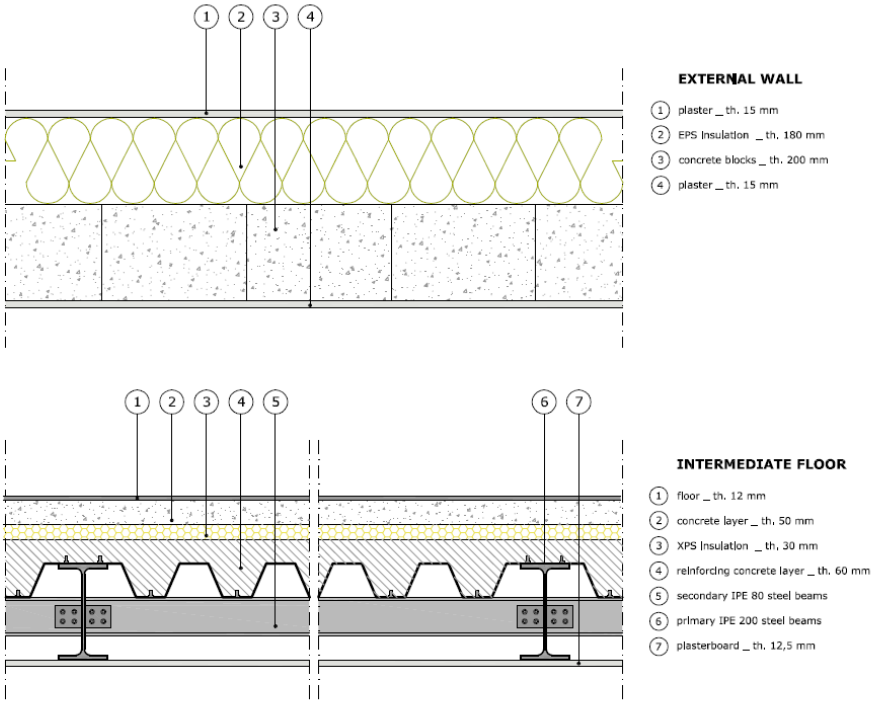


Figure 6.6.a _ ETICS construction details

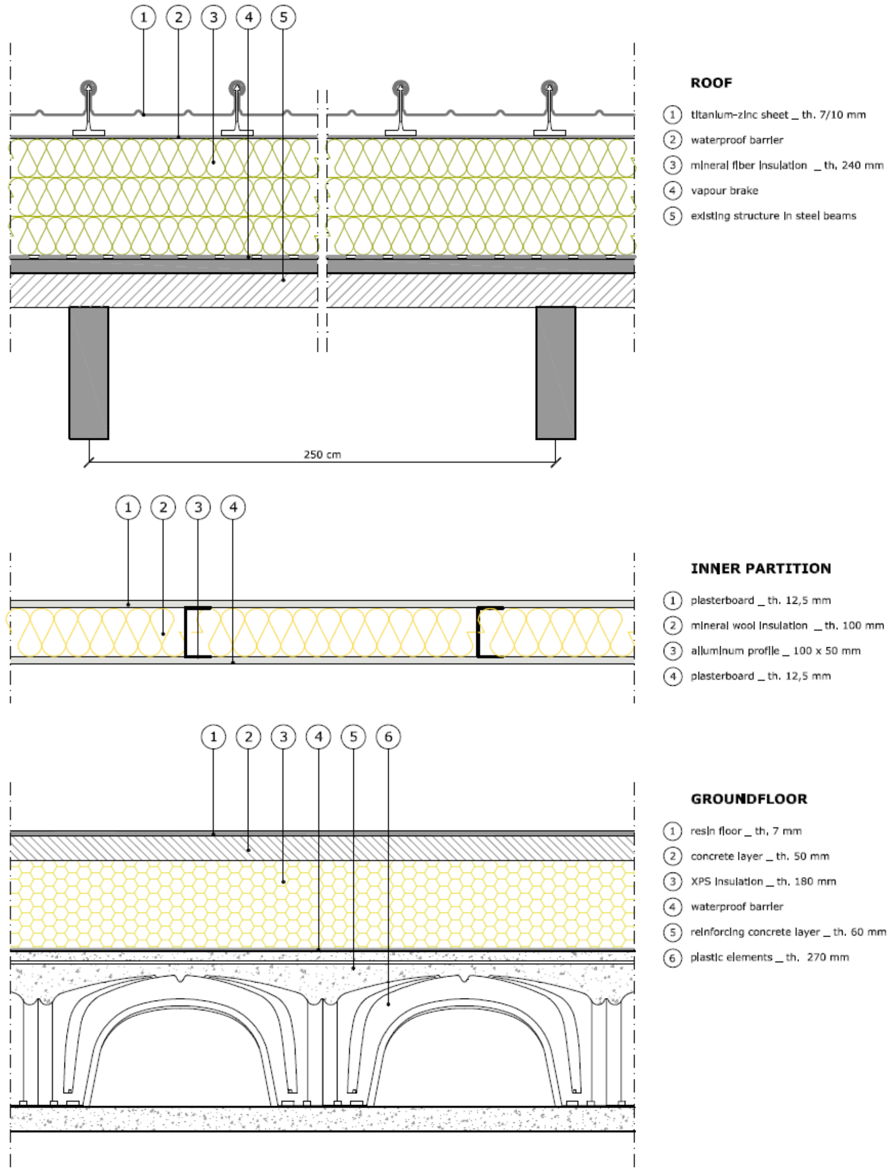


Figure 6.6.b _ ETICS construction details

- *ITI (Inner Thermal Insulation)*: metallic substructure with glass-wool panels both for walls and roofs and XPS panels for the ground floor insulation;

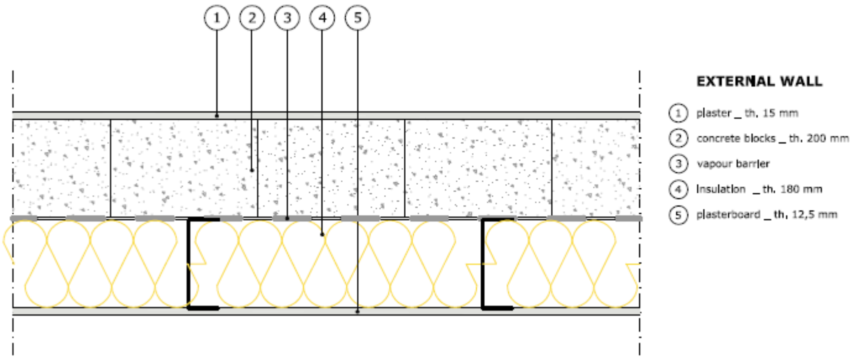


Figure 6.7.a _ ITI construction details

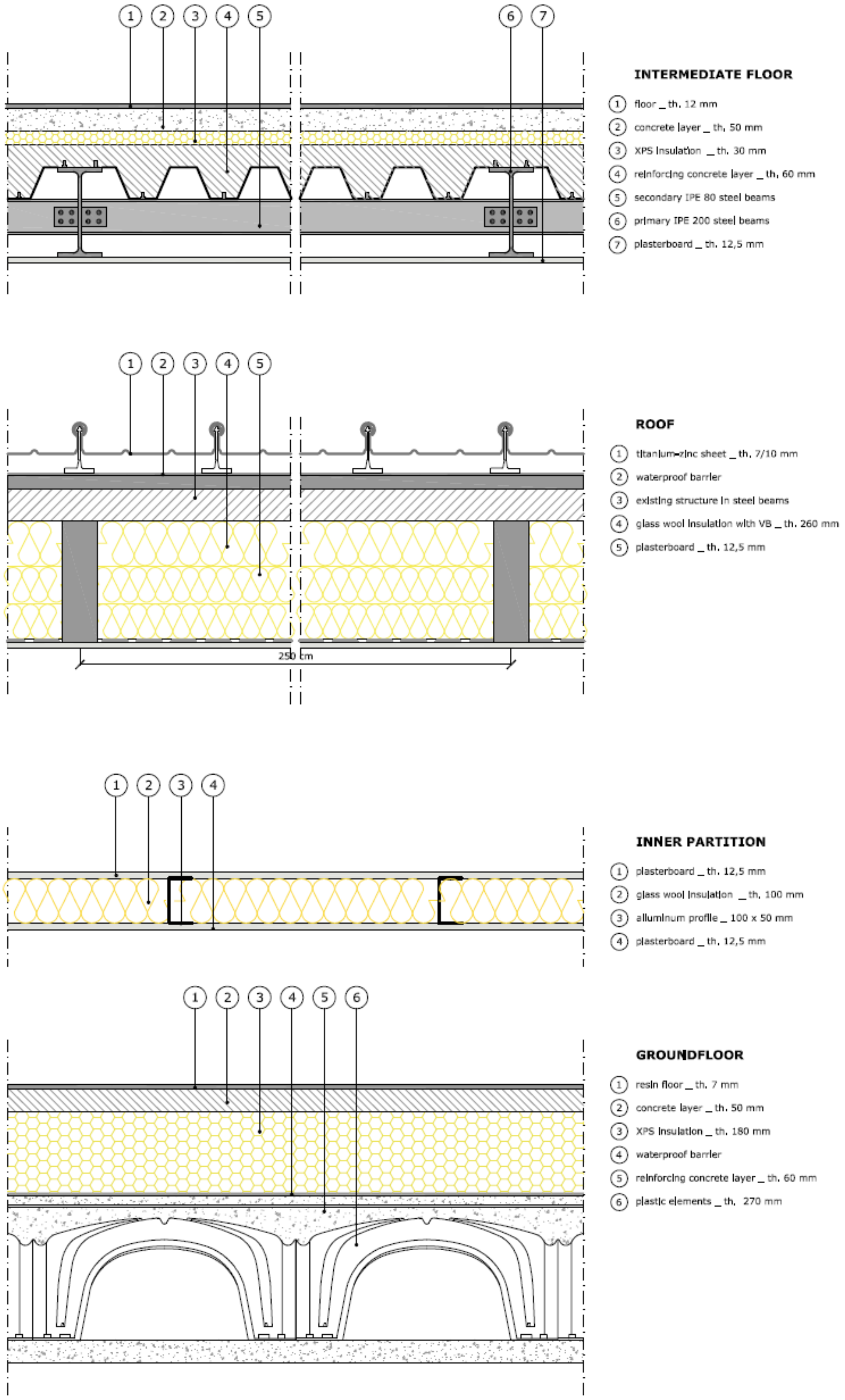
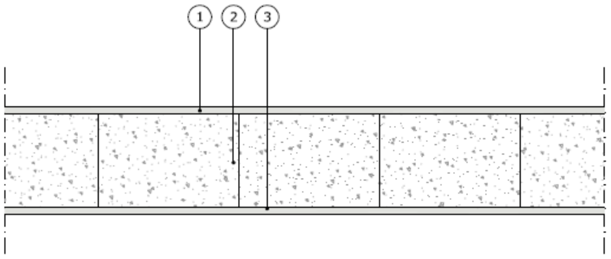


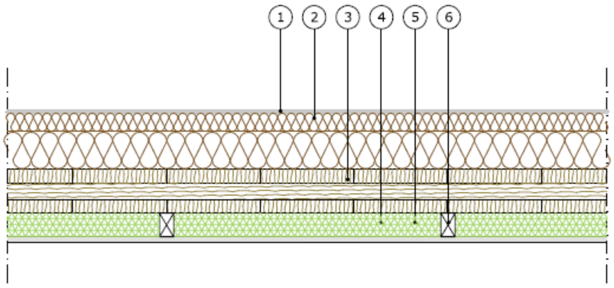
Figure 6.7.b _ ITI construction details

- *EWE-1 (Envelope Within an Envelope)*: the new envelope isconstituted by X-lam panels insulated with a wood fiber ETICS and hemp fiber in gaps for plants. The ground floor is always insulated with XPS panels;



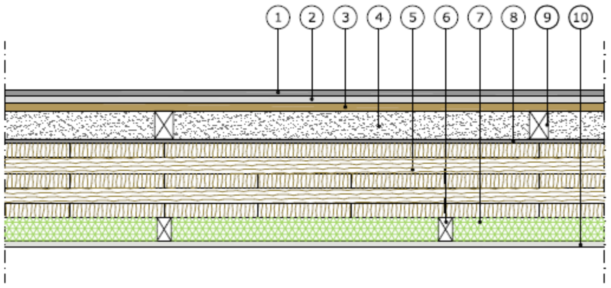
EXTERNAL WALL

① plaster _ th. 15 mm
② concrete blocks _ th. 200 mm
③ plasterboard _ th. 12,5 mm



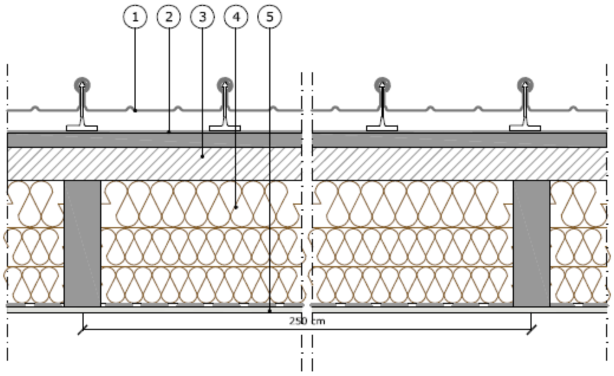
EWE WALL

① plaster _ th. 5 mm
② insulation _ th. 120 mm
③ X-lam _ th. 94 mm
④ plants gap _ th. 50 mm
⑤ plasterboard _ th. 12,5 mm
⑥ laths _ sec. 30 x 50 mm



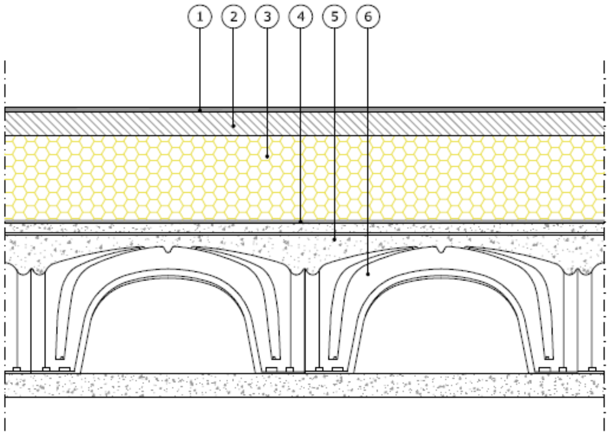
EWE WALL

① wooden floor _ th. 12 mm
② fiberboard _ th. 15 mm
③ OSB panel _ th. 18 mm
④ perlite layer _ 60 mm
⑤ X-lam _ th. 158 mm
⑥ plants gap saturated with hemp fiber _ th. 50 mm
⑦ laths _ sec. 30 x 50 mm
⑧ acoustic insulation _ th. 10 mm
⑨ laths _ sec. 40 x 60 mm
⑩ plasterboard _ th. 12,5 mm



ROOF

① titanium-zinc sheet _ th. 7/10 mm
② waterproof barrier
③ existing structure in steel beams
④ wood fiber insulation with vapour brake _ th. 260 mm
⑤ plasterboard _ th. 12,5 mm



GROUNDFLOOR

① resin floor _ th. 7 mm
② concrete layer _ th. 50 mm
③ XPS insulation _ th. 180 mm
④ waterproof barrier
⑤ reinforcing concrete layer _ th. 60 mm
⑥ plastic elements _ th. 270 mm

Figure 6.8 _ EWE-1 construction details

- *EWE-2 (Envelope Within an Envelope)*: the new envelope is constituted by timber-framed panels insulated with cellulose flakes and hemp fiber in gaps for plants. The ground floor is always insulated with XPS panels.

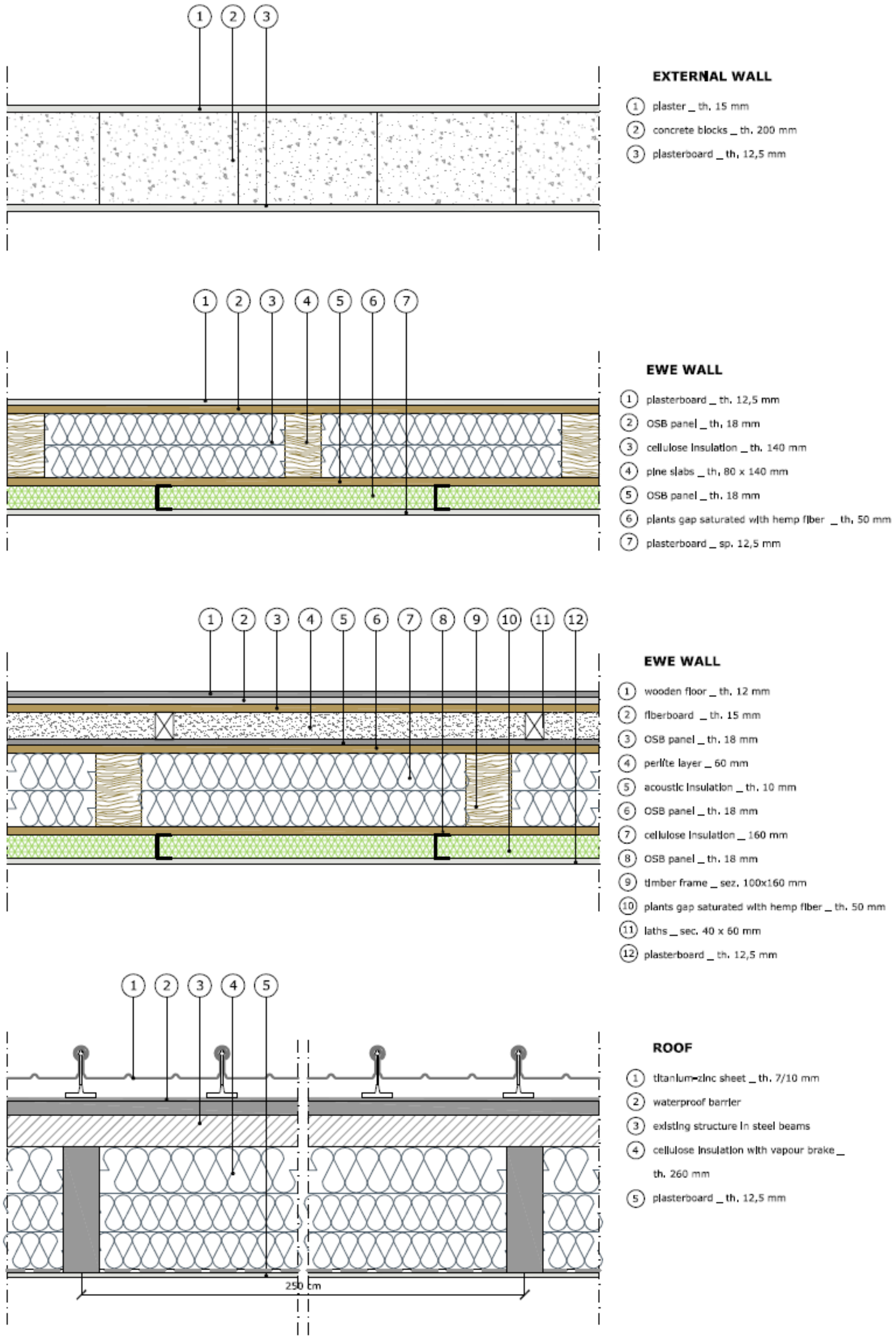


Figure 6.9.a _ EWE-2 construction details

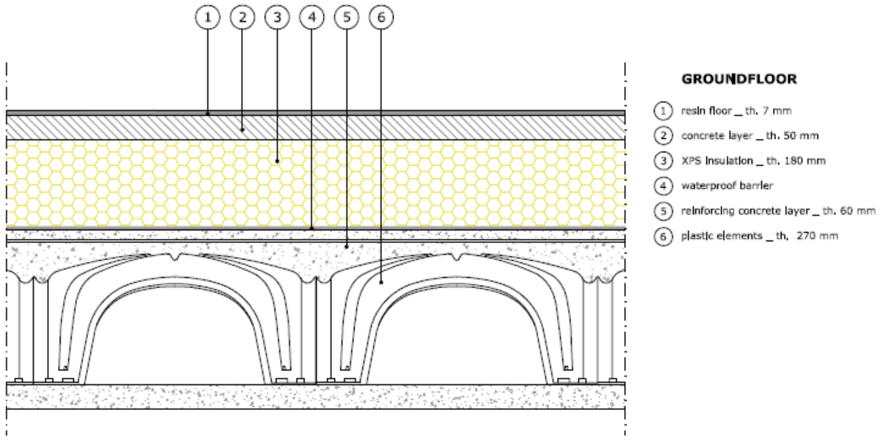


Figure 6.9.b _ EWE-2 construction details

These four different hypothesis have been selected in the set of the 28 proposed scenarios for different reasons. ETICS and ITI solutions are the most common retrofitting strategies, as explained above. Thus it is interesting to see their differences and understanding how them can be evaluated in a pair wise comparison. The introduction of the envelope within an envelope retrofitting strategy is a way of changing the traditional retrofitting practices and to compare the two most spread technologies in the field of wooden constructions.

Nevertheless, after the exploitation of the developed methodology through these four alternatives, a final summary including all the tested solutions will be provided.

6.2.4 Comparing solutions by using MCA

Objective of the analysis is defining which kind of envelope alternative better meets sustainability issues on the basis of the previous considerations (*Figure 6.10*).

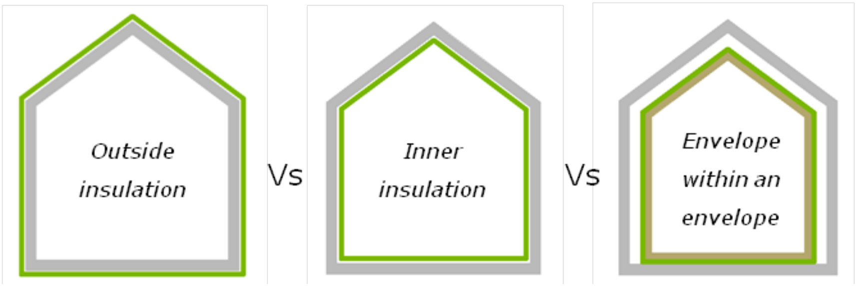


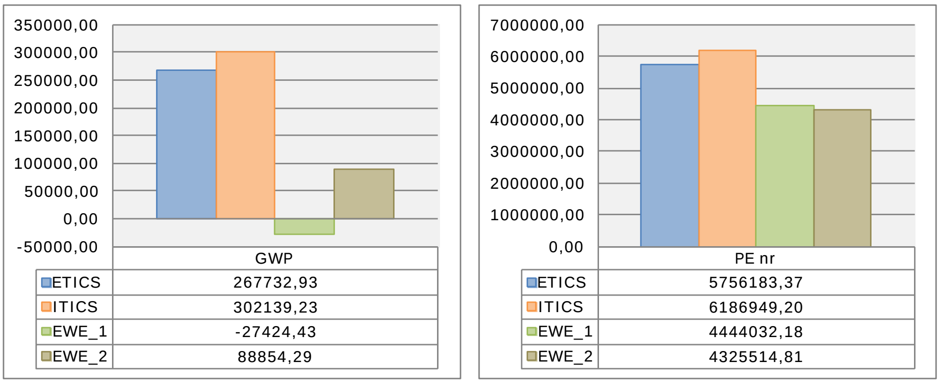
Figure 6.10 _ alternative configurations comparison

As explained above, the first assessed parameter has been environmental impact. Using a combination of the Ecoinvent and IBO databases and including in the analysis also some data from EPDs, the LCA of each alternative has been calculated, giving the following results (*Table 6.8*):

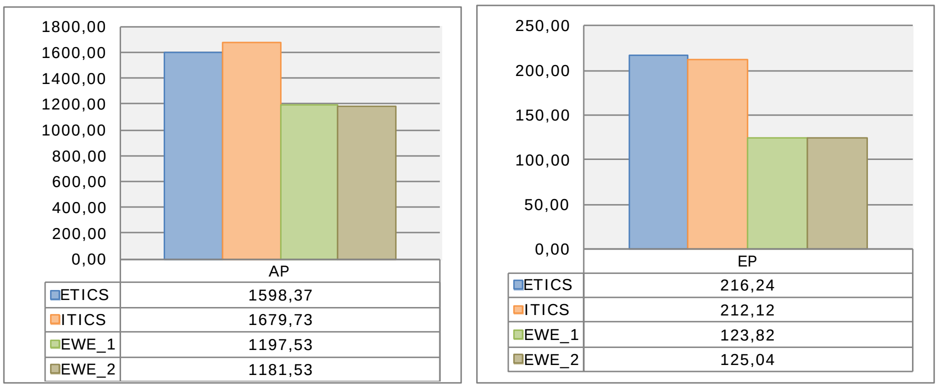
enevelope hypothesis	**GWP**	**POCP**	**AP**	**EP**	**ODP**	**PE nr**
	kg CO2 eq.	kg C2H2	kg SO2 eq.	kg PO4--- eq	kg CFC-11 eq	MJ
ETICS	267732,93	263,51	1598,37	216,24	0,0138	5756183,37
ITICS	302139,23	239,63	1679,73	212,12	0,0166	6186949,20
EWE_1	-27424,43	163,10	1197,53	123,82	0,0115	4444032,18
EWE_2	88854,29	167,37	1181,53	125,04	0,01	4325514,81

Table 6.8 _ LCA results

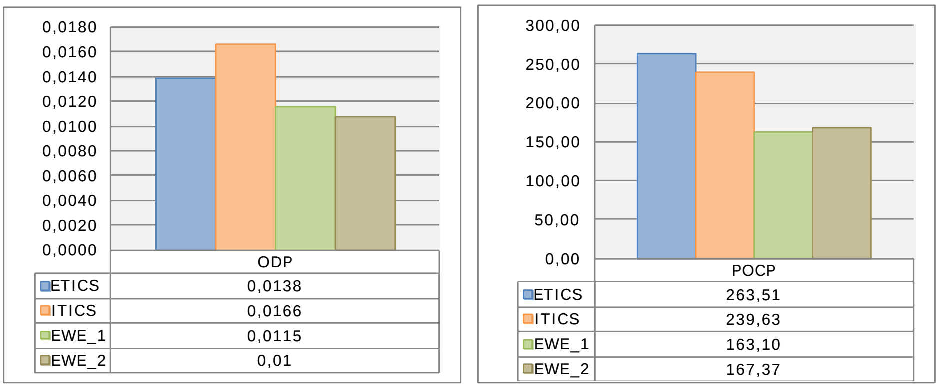
The same values are also represented in the histograms below (*Graph 6.1*, *Graph 6.2* and *Graph 6*.3):



Graph 6.1 _ LCA results for GWP and PEnr



Graph 6.2 _ LCA results for AP and EP



Graph 6.3 _ LCA results for ODP and POCP

From this diagrams it is possible to observe a similarity between ITI and ETICS and between EWE-1 and EWE-2. The major difference between the two last options is visible in GWP diagram (*Graph 6.1*). Here the GWP value for EWE-1 is negative. This is due to the fact that the structural parts of wall is built in cross laminated timber panels, using EPD data. Values of GWP reported in this EPD are negative, because they consider the biotic contribution that wood gives to the environment storing carbon dioxide during its service life. Furthermore LCA of a new building has been performed in order to quantify benefits in restoring. For calculating the environmental impact of this new building energy for demolition has been estimated and considered. After that, the new benchmark building has been compared with the four hypothesized envelope solutions, in order to individuate that one allowing the major average environmental savings. Results of this assessment are reported in *Table 6.9* below.

envelope hypothesis	**GWP**	**POCP**	**AP**	**EP**	**ODP**	**PE nr**	**average environmental savings**
	kg CO_2 eq.	kg C_2H_2	kg SO_2 eq.	kg PO_4--- eq	kg CFC-11 eq	MJ	%
demolishing & rebuilding	284059,00	276,09	1638,61	222,20	0,017	6043951,00	-
ETICS	267732,93	263,51	1598,37	216,24	0,014	5756183,37	6,2%
ITI	302139,23	239,63	1679,73	212,12	0,017	6186949,20	1,1%
EWE-1	-27424,43	163,10	1197,53	123,82	0,012	4444032,18	46,5%
EWE-2	88854,29	167,37	1181,53	125,04	0,011	4325514,81	40,6%

Table 6.9 _ retrofitting Vs demolishing and building new

In this way the first parameter for the final assessment has been obtained. Analyzing the results, it is possible to observe that the highest percentage of benefits in retrofitting the existing building corresponds to EWE-1 and is equal to 46,5%, which is followed by EWE-2. For what concerns the other two envelope alternatives, retrofitting produces a little benefit.

LCA have been also used for defining a parameter able to summarize all environmental categories in a single value. Thus, as explained in *Paragraph 6.1.2*, MCA has been applied to LCA results. All calculated value were normalized by using the *minimization formula* (*Table 6.10*)*:*

envelope hypothesis	**results**	**GWP**	**POCP**	**AP**	**EP**	**ODP**	**PE nr**
		kg CO_2 eq.	kg C_2H_2	kg SO_2 eq.	kg PO_4--- eq	kg CFC-11 eq	MJ
ETICS	*total*	267732,93	263,51	1598,37	216,24	0,01	5756183,37
	normalized	-0,10	0,62	0,74	0,57	0,78	0,75
ITI	*total*	302139,23	239,63	1679,73	212,12	0,02	6186949,20
	normalized	-0,09	0,68	0,70	0,58	0,65	0,70
EWE_1	*total*	-27424,43	163,10	1197,53	123,82	0,01	4444032,18
	normalized	1,00	1,00	0,99	1,00	0,93	0,97
EWE_2	*total*	88854,29	167,37	1181,53	125,04	0,01	4325514,81
	normalized	-0,31	0,97	1,00	0,99	1,00	1,00

Table 6.10 _ LCA values normalization

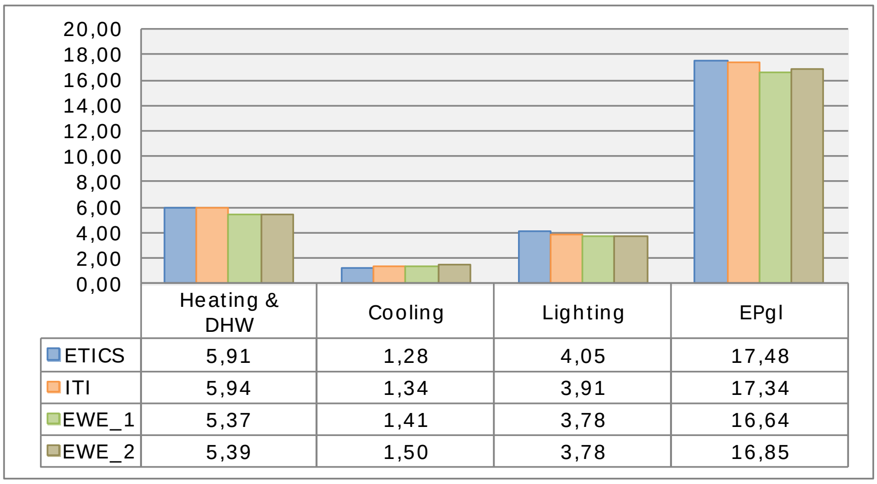
After that, these results were weighted according to the weighting system illustrated in *Table 6.2*, giving the following outputs of environmental performance parameters (*Table 6.11*):

envelope hypothesis	**LCA indicator**
ETICS	0,525
ITI	0,498
EWE_1	0,982
EWE_2	0,706

Table 6.11 _ LCA single scores

Then, the energy performance of each hypothesized solution have been estimated, performing four different dynamic simulations with Design Builder. All the building hypothesis have been designed with the same plant: a boiler for heating and chiller units for cooling, with VMC. Also energy for lighting has been calculated. After their estimation, electrical energy contribution were converted to primary energy using the Italian conversion factor for the electrical greed, multiplying electricity values per 2,17.

From these simulations the following energy performances for the four building configurations were obtained (*Graph 6.4*):



	Heating & DHW	Cooling	Lighting	EPgl
🟦 ETICS	5,91	1,28	4,05	17,48
🟧 ITI	5,94	1,34	3,91	17,34
🟩 EWE_1	5,37	1,41	3,78	16,64
🟫 EWE_2	5,39	1,50	3,78	16,85

Graph 6.4 _ building configurations Energy Performance

In *Graph 6.4* it is clearly visible the similarity between the different configurations in terms of energy performance. This is because energy efficiency has been a driving-concept in this work and each building envelope configuration has been designed in order to achieve this goal.

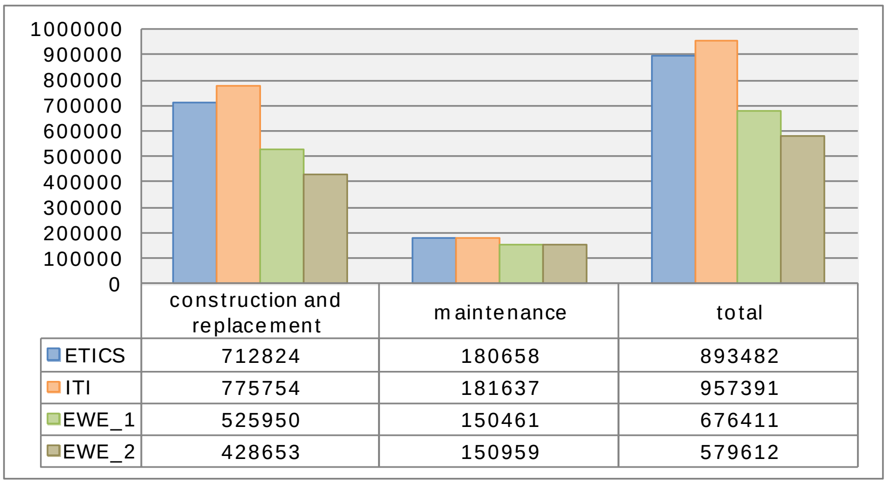
However, while the ETICS and ITI hypothesis are more consumer, the two EWE hypothesis have a lower energy consumption. This is due to the presence of some unheated spaces (non included in the new envelope) inside the building and to the fact that the new inner envelope is not in direct contact with the outside, thus energy losses are further reduced respect to the other two solutions. The normalization process of these energy performance values, conducted by using again the *minimization formula,* have leaded to the results in *Table 6.12* below:

envelope hypothesis	**results**	**EPgl**
ETICS	*total*	17,48
	normalized	0,95
ITI	*total*	17,34
	normalized	0,96
EWE_1	*total*	16,64
	normalized	1,00
EWE_2	*total*	16,85
	normalized	0,99

Table 6.12 _ total and normalized EP values

The following step of the analysis has been the evaluation of the whole building cost in a life-cycle perspective.

Thus, construction costs and cost for components replacement in a 50 years lifespan have been calculated. Furthermore costs related to the building maintenance (energy-related costs) have been included, on the basis of what explained in *Paragraph 6.1.2.*



	construction and replacement	maintenance	total
🟦 ETICS	712824	180658	893482
🟧 ITI	775754	181637	957391
🟩 EWE_1	525950	150461	676411
🟫 EWE_2	428653	150959	579612

Graph 6.5 _ building configurations cost

As it is shown in the histogram *Graph 6.5* above, the whole cost for EWE-2 configuration is the lowest one. Indeed, if we compare this solution with EWE-1 it is possible to observe a cost reduction equal to 18,5%. Furthermore, the largest part of the cost saving (14,3%) is in construction phase because of timber-framed panels technology is less expensive than X-lam panels technology. For what concerns the maintenance phase this two solutions are nearly the same: the fact that these two envelope hypothesis are designed inside the existing envelope contributes in reducing energy-related costs and also need for components substitution.

The higher costs of ETICS and ITI solutions are due to the major surface to retrofit and insulate and, as consequence, to the higher costs required for simple maintenance operation or replacements. Moreover, since the energy need of this two building solutions is higher than the two EWE envelope hypothesis, also their energy-related costs are higher.

EWE-2 solution resulted as the most convenient under the economic aspect: compared to ETICS, the costs reduction is equal to 35,1%, while compared to ITI, the saving is 39,5%.

The normalization process with the *minimization formula* applied to these values have given the results reported in *Table 6.13*:

envelope hypothesis	***results***	**cost**
ETICS	*total*	893481,74
	normalized	0,65
ITI	*total*	957390,68
	normalized	0,61
EWE_1	*total*	676410,80
	normalized	0,86
EWE_2	*total*	579611,88
	normalized	1,00

Table 6.13 _ total and normalized cost values

Lastly, de-constructability aspects for the proposed solutions have been evaluated.

ETICS is characterized by a wet traditional construction system, in which elements and layers are mainly connected in an irreversible way, using primers and sealants. Only inner partitions have been designed in order to guarantee an easy disassembly process.

ITI, instead, better meets DfD principles. External walls are insulated with a dry construction system and also inner partitions and roof can be constructed using the same technology. However, intermediate floors have been designed with a mixed construction type (presence of wet concrete layer).

The two EWE retrofitting hypothesis are very similar in terms of DfD possibilities. Despite their construction technology is different they both use dry construction systems and partially reversible connections with metallic connectors. In all cases the ground floor has been designed in the same way, in concrete with an insulating layer in XPS in order to well answer to eventual humidity problems. It has to be reminded that for the assessment of the connection system, it has been considered the prevalent type of connection in each building subassembly.

Table 6.14 below summarizes the evaluation of the DfD index for each designed element, obtained by multiplying the score associated to the construction type to that one associated to the connection system, and then summing the results.

envelope hypothesis		vertical walls	groundfloor	intermediate floor	roof	inner partions	**total**
ETICS	construction system	0	0	0,5	1	1	**5**
	connection system	1	1	2	2	2	
	DfD index	**0**	**0**	**1**	**2**	**2**	
ITI	construction system	1	0	0,5	1	1	**7**
	connection system	2	1	2	2	2	
	DfD index	**2**	**0**	**1**	**2**	**2**	
EWE_1	construction system	1	0	1	1	1	**8**
	connection system	2	1	2	2	2	
	DfD index	**2**	**0**	**2**	**2**	**2**	
EWE_2	construction system	1	0	1	1	1	**8**
	connection system	2	1	2	2	2	
	DfD index	**2**	**0**	**2**	**2**	**2**	

Table 6.14 _ DfD index for the four constructive solutions

Normalizing the total score obtained by each building configuration with the *maximization formula*, the following results have been obtained (*Table 6.15*):

envelope hypothesis	***results***	**DfD**
ETICS	*total*	5,00
	normalized	0,63
ITI	*total*	7,00
	normalized	0,88
EWE_1	*total*	8,00
	normalized	1,00
EWE_2	*total*	8,00
	normalized	1,00

Table 6.15 _ total and normalized DfD indexes

At this point, all the necessary indicators have been calculated: each design solution is characterized by five values, summarized in *Table 6.16* below:

enevelope hypothesis	**Convenience indicator**	**LCA indicator**	**EP indicator**	**Cost indicator**	**DfD indicator**
ETICS	0,06	0,525	0,952	0,649	0,625
ITI	0,01	0,498	0,965	0,605	0,875
EWE_1	0,46	0,982	1,000	0,857	1,000
EWE_2	0,41	0,706	0,987	1,000	1,000

Table 6.16 _ indicators for the four hypothesized constructive solutions

6.2.5 Results comparison

What has to be done now is weighting the five values corresponding to each designed solution. In *Paragraph 6.1.2* it has been underlined that this MCA evaluation method does not provide a fixed weighting system.

This is because, in this way, decisions can be taken according to the needs of each stakeholder or figure involved in the project. Thus, for defining the best design solution it is necessary to decide which is the perspective under which assign weights to parameters. Three main actors have been identified: *clients, technicians* and *final users*.

Client’s needs can vary depending on the case: he could be a private citizen or coincide with a public authority. Obviously these two stakeholders have different requirements, expectations and investment possibilities. In the last years the tendency of the public sector has been oriented towards sustainable design, in light to promote best practices in building sector and to highlight the sensibility to environmental concerns. Moreover, a great importance has been given to the redevelopment of forsaken built areas.

Thus, currently for the public client, it is very important to give to the citizens an example on how building new constructions and managing the existing stock, optimizing environmental attributes of buildings. On the other hand, private clients approach differently to sustainability issues. In private sector there is still little awareness on sustainability; however, the last period have seen an increase of the interest in energy performance, due to the progressive diffusion on the construction market of energy efficient buildings, as required by the current European and national standards.

For what concerns the technicians perspective, two sub-views have been identified: the first one corresponds to the designer, while the second one is that one of the builder or general contractor. Usually designer, during the design-phase, proposes a project that meets client’s requirements. When the design process is based on an integrated approach, the design team is composed of more than one designer, and the different aspects of the project have to be analyzed in the same way. Thinking in terms of builders and general contractors, the approach to the project is quite far from optimizing all the building qualities: usually these actors put more attention on economic issues, often overlooking environmental aspects and respecting minimum standards of performance. However final users, as written above, in the last years have started to be more responsible and aware of energy concerns. Thus, builders, because of market requirements, have been obliged to build energy efficient constructions, improving the average quality level of their buildings. The economic crisis strongly contributed in reducing the building market, causing the close of many construction companies. But the crisis has also been one of the driving factors in increasing people awareness: if efficient and high quality buildings require a major investment cost for purchasing, they also allow to reduce maintenance costs during their lifespan. This have forced builders to enhance energy efficiency and constructive qualities of their buildings in order to be market competitive.

Lastly, final users perspective has been investigated. As explained above, building quality and energy efficiency are fundamental parameters for building occupants. In addition to these features also maintenance plays a fundamental role. Two different things contribute in simplifying the maintenance process: firstly the maintenance cost and then the easiness of maintenance. Since the maintenance cost is given by energy-related costs, cost for building operations and replacement of components, a reduced energy need and the use of materials requiring few maintenance operations are excellent strategies for minimizing cost. Furthermore, designing the building in order to make easier the process of maintenance, using easily replaceable materials and components, helps to enhance the easiness of maintenance. This means that a final user has interest in having an energy efficient building, with a low cost of maintenance and at the same time able to guarantee simplicity in maintenance operations.

On the basis of these considerations, five different “stakeholders” weighting systems have been developed, using a score-scale from 1 to 5 (*Table 6.17*):

stakeholders perspective	**Convenience indicator**	**LCA indicator**	**EP indicator**	**Cost indicator**	**DfD indicator**	**Total score**
Public Authority	4	5	5	2	4	20
Private Client	1	1	4	5	2	13
Builder	1	1	4	5	1	12
Designer	4	4	5	5	4	22
Final users	1	1	5	5	5	17

Table 6.17 _ weighting systems on the basis of different stakeholders perspectives

Furthermore, other three more general weighting systems have been developed, depending on the choice to optimize the whole building sustainability, or only the environmental or economic sustainability of the project. For the whole building sustainability weighting system, all the parameters have been considered in the same way; for what concerns environmental sustainability, 5 points have been assigned to those indicators more related to environmental aspects, 3 points have been assigned to the EP indicator and 1 point to the Cost indicator. Instead, for optimizing economic issues, 5 points have been assigned to the Cost indicator, 3 points to the EP indicator and DfD indicator and only 1 point to environmental indicators (*Table 6.18*):

sustainability perspective	**Convenience indicator**	**LCA indicator**	**EP indicator**	**Cost indicator**	**DfD indicator**	**Total score**
Whole	5	5	5	5	5	25
Environmental	5	5	3	1	5	19
Economic	1	1	3	5	3	13

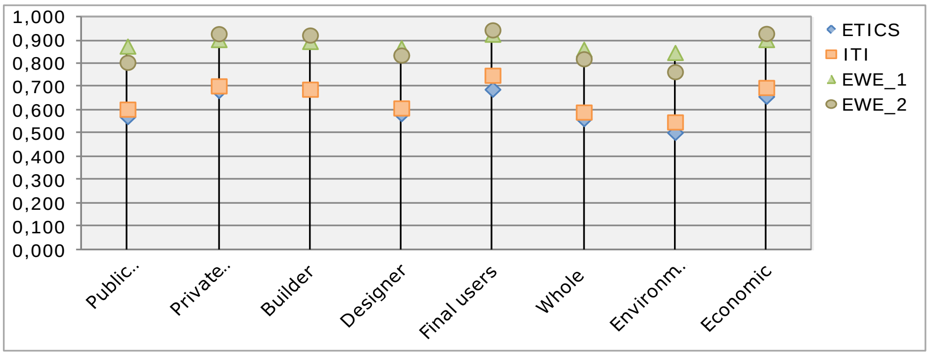
Table 6.18 _ weighting systems on the basis of sustainability perspectives

Applying the eight developed weighting systems to the four building alternatives, the following values for the global indicator, called RE-GREEN indicator, have been obtained (*Table 6.19*):

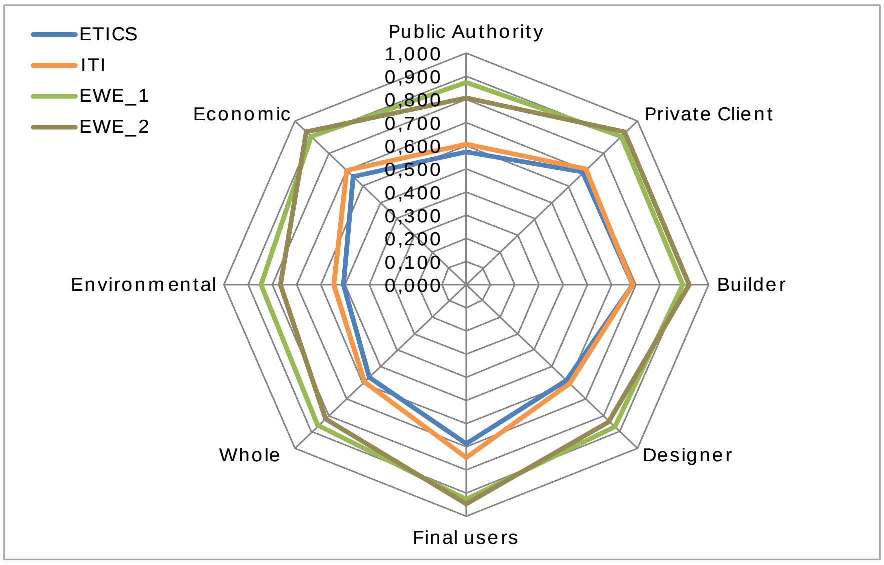
stakeholders perspective	**RE-GREEN indicator**				
	ETICS	*ITI*	*EWE_1*	*EWE_2*	*selected*
Public Authority	0,571	0,603	**0,874**	0,805	**0,874**
Private Client	0,684	0,703	0,902	**0,928**	**0,928**
Builder	0,689	0,689	0,894	**0,922**	**0,922**
Designer	0,584	0,608	**0,867**	0,836	**0,867**
Final users	0,689	0,749	0,925	**0,944**	**0,944**
Whole	0,562	0,591	**0,861**	0,820	**0,861**
Environmental	0,503	0,548	**0,847**	0,764	**0,847**
Economic	0,659	0,697	0,902	**0,929**	**0,929**

Table 6.19 _ results comparison

Looking at the data above, some considerations have to be outlined. In the set of the four proposed alternatives, for each weighting system both ETICS and ITI have never been resulted as the best retrofitting solution. Instead, the two EWE solutions obtained higher scores, due to their general better performances (*Graph 6.6* and *Graph 6.7*).



Graph 6.6 _ RE-GREEN indicator for building configurations



Graph 6.7 _ radar graph of the RE-GREEN indicators

When EWE-1 resulted as the best design solution for meeting stakeholder requirements, it can be attributed to the fact that this design solutions in characterized by the best environmental performance and the highest environmental benefits in restoring. When to result as the best design alternative it is EWE-2 the reason can be found in its lower cost.

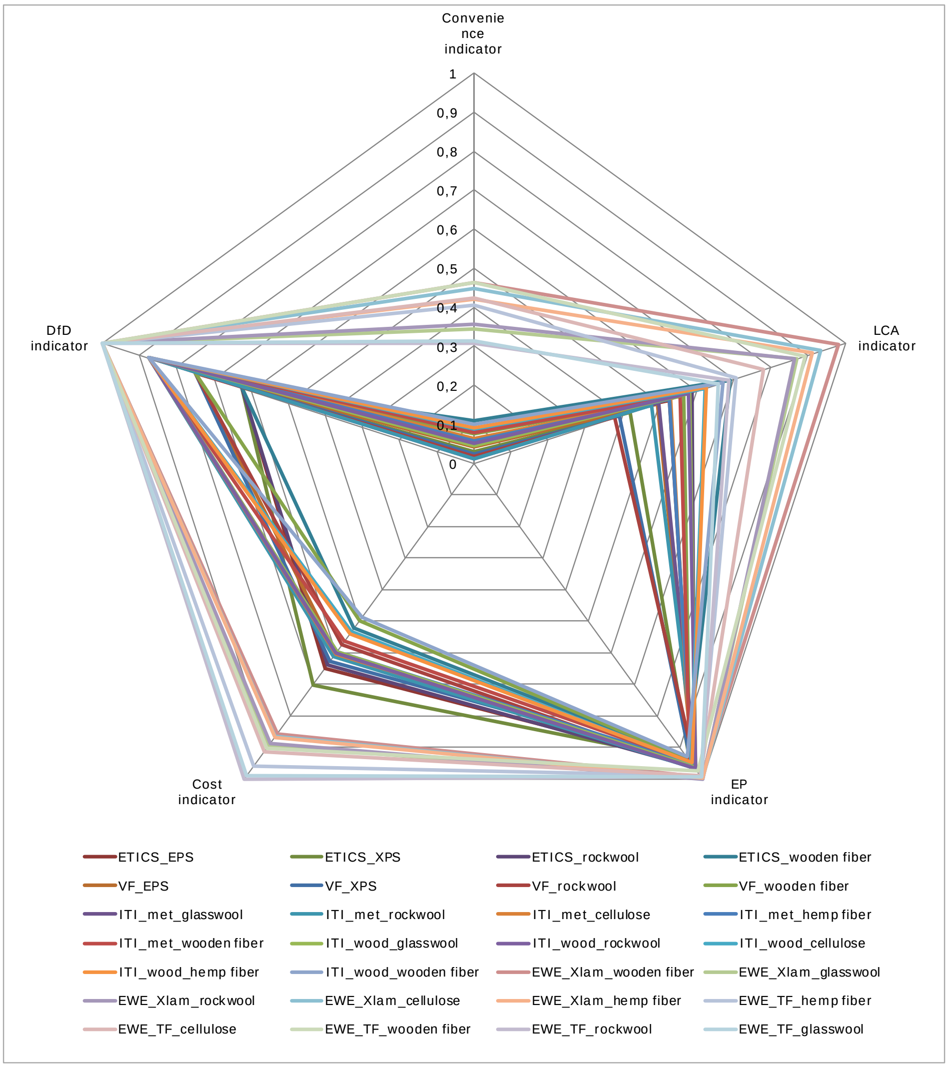
This result underlines the effectiveness from both environmental and economic point of view of the envelope within an envelope method for retrofitting existing buildings.

Actually, as mentioned in *Paragraph 6.2.3*, the full research investigated and compared 28 different design alternatives. Looking at the values obtained from this extended comparison the validity of the envelope within an envelope technique emerges with major strength.

Table 6.20 below reports the values of the five indicators for each proposed solution, while in *Graph 6.7* the same values are illustrated in a radar diagram, for allowing to immediately graphically individuate which solutions are characterized by higher scores:

enevelope hypothesis	**Convenience indicator**	**LCA indicator**	**EP indicator**	**Cost indicator**	**DfD indicator**
ETICS_EPS	0,062	0,525	0,952	0,649	0,625
ETICS_XPS	0,029	0,421	0,938	0,702	0,625
ETICS_rockwool	0,082	0,587	0,961	0,638	0,625
ETICS_wooden fiber	0,108	0,691	0,931	0,521	0,625
VF_EPS	0,043	0,495	0,958	0,601	0,750
VF_XPS	0,025	0,391	0,945	0,627	0,750
VF_rockwool	0,017	0,379	0,967	0,574	0,750
VF_wooden fiber	0,077	0,564	0,939	0,499	0,750
ITI_met_glasswool	0,011	0,498	0,965	0,605	0,875
ITI_met_rockwool	0,012	0,477	0,966	0,612	0,875
ITI_met_cellulose	0,064	0,531	0,948	0,603	0,875
ITI_met_hemp fiber	0,058	0,528	0,951	0,598	0,875
ITI_met_wooden fiber	0,078	0,557	0,942	0,563	0,875
ITI_wood_glasswool	0,045	0,580	0,964	0,597	0,875
ITI_wood_rockwool	0,051	0,578	0,965	0,601	0,875
ITI_wood_cellulose	0,088	0,624	0,947	0,534	0,875
ITI_wood_hemp fiber	0,092	0,627	0,949	0,541	0,875
ITI_wood_wooden fiber	0,099	0,671	0,929	0,487	0,875
EWE_Xlam_wooden fiber	0,465	0,982	0,993	0,857	1,000
EWE_Xlam_glasswool	0,345	0,871	0,998	0,893	1,000
EWE_Xlam_rockwool	0,357	0,864	1,000	0,887	1,000
EWE_Xlam_cellulose	0,449	0,934	0,995	0,864	1,000
EWE_Xlam_hemp fiber	0,421	0,912	0,996	0,867	1,000
EWE_TF_hemp fiber	0,406	0,706	0,987	0,957	1,000
EWE_TF_cellulose	0,423	0,779	0,988	0,913	1,000
EWE_TF_wooden fiber	0,463	0,891	0,975	0,902	1,000
EWE_TF_rockwool	0,309	0,686	0,991	1,000	1,000
EWE_TF_glasswool	0,313	0,658	0,993	0,988	1,000

Table 6.20 _ indicators values



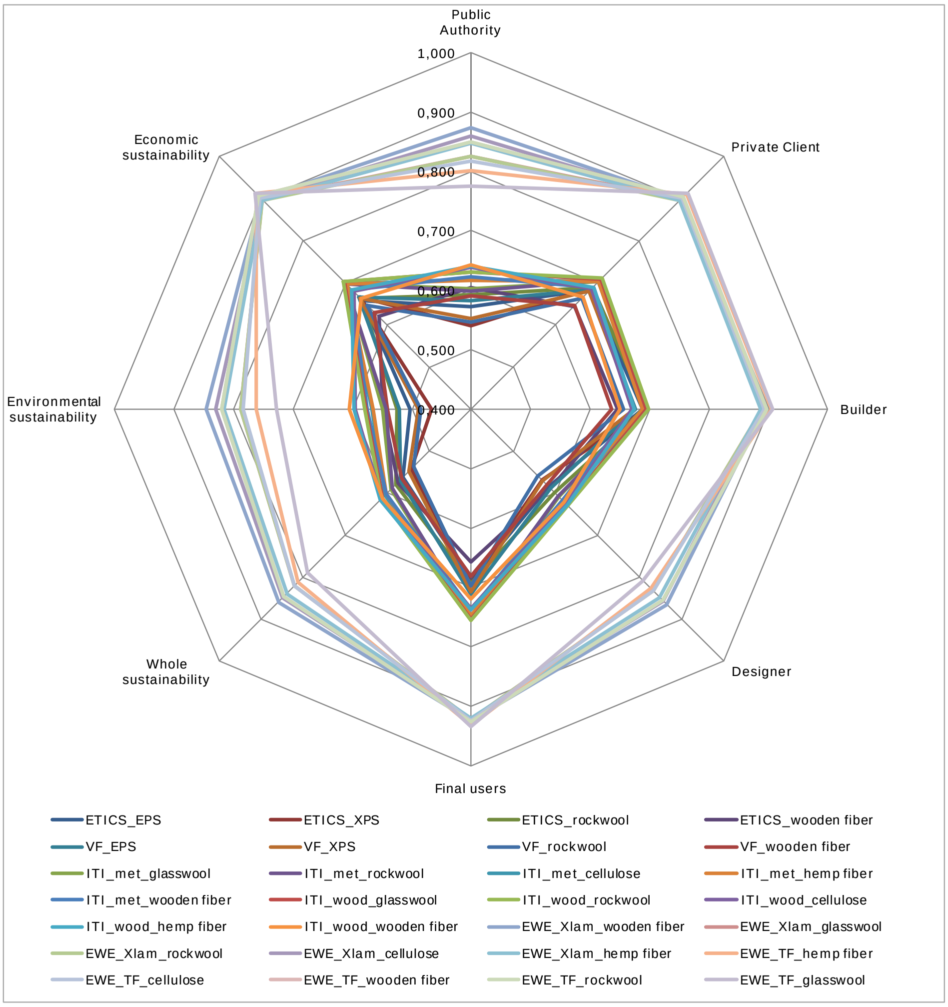
Graph 6.8 _ graphic representation of the indicators values

All these values have then been weighted according to the eight weighting systems proposed above, for understanding which could be the best solution under each perspective.

The final results of the RE-GREEN indicator are in *Table 6.21.* Here the worst values for each decisional perspective are identified in red, while the best values are identified in green. For what concerns the worst solutions, it is possible to observe a variety of the results: for two decision-makers the worst solution is *ETICS-XPS*, in three cases the worst solution coincides with *ETICS-wooden fiber*, in two cases it is individuated in *VF-rockwool* and in one perspective the worst design alternative is *VF-wooden fiber*. On the other hand, in terms of best solution, from the comparison only two design alternatives have been selected as the best: in four perspectives it resulted *EWE-Xlam-wooden fiber*, while in the other four perspectives the resulting alternative has been *EWE-TF-rockwool*. The same results have been shown through a radar representation in *Graph 6.9.*

enevelope hypothesis	*Public Authority*	*Private Client*	*Builder*	*Designer*	*Final users*	*Whole sustainability*	*Environmental sustainability*	*Economic sustainability*
ETICS_EPS	0,571	0,684	0,689	0,584	0,689	0,562	0,503	0,659
ETICS_XPS	**0,541**	0,689	0,695	0,568	0,693	0,543	**0,468**	0,665
ETICS_rockwool	0,592	0,689	0,694	0,599	0,693	0,579	0,526	0,663
ETICS_wooden fiber	0,604	**0,644**	0,646	0,589	**0,658**	0,575	0,549	**0,621**
VF_EPS	0,582	0,683	0,677	0,589	0,711	0,569	0,522	0,667
VF_XPS	0,552	0,679	0,673	0,569	0,707	0,548	0,489	0,664
VF_rockwool	0,547	0,664	0,657	**0,559**	0,697	**0,537**	0,484	0,647
VF_wooden fiber	0,591	0,646	**0,637**	0,580	0,681	0,566	0,541	0,631
ITI_met_glasswool	0,603	0,703	0,689	0,608	0,749	0,591	0,548	0,697
ITI_met_rockwool	0,599	0,705	0,691	0,607	0,750	0,588	0,544	0,698
ITI_met_cellulose	0,618	0,704	0,690	0,620	0,749	0,604	0,568	0,698
ITI_met_hemp fiber	0,616	0,702	0,688	0,618	0,747	0,602	0,566	0,696
ITI_met_wooden fiber	0,622	0,690	0,674	0,617	0,737	0,603	0,576	0,685
ITI_wood_glasswool	0,630	0,709	0,695	0,628	0,753	0,612	0,578	0,702
ITI_wood_rockwool	0,631	0,711	0,697	0,629	0,755	0,614	0,580	0,704
ITI_wood_cellulose	0,639	0,686	0,670	0,625	0,735	0,614	0,595	0,681
ITI_wood_hemp fiber	0,642	0,690	0,675	0,628	0,738	0,617	0,598	0,684
ITI_wood_wooden fiber	0,643	0,667	0,650	0,621	0,719	0,612	0,605	0,663
EWE_Xlam_wooden fiber	**0,872**	0,900	0,892	**0,865**	0,923	**0,859**	**0,846**	0,901
EWE_Xlam_glasswool	0,826	0,898	0,889	0,833	0,922	0,821	0,788	0,898
EWE_Xlam_rockwool	0,826	0,897	0,888	0,833	0,921	0,822	0,789	0,897
EWE_Xlam_cellulose	0,858	0,899	0,890	0,856	0,922	0,848	0,830	0,899
EWE_Xlam_hemp fiber	0,848	0,896	0,888	0,848	0,920	0,839	0,817	0,897
EWE_TF_hemp fiber	0,800	0,911	0,904	0,826	0,931	0,811	0,762	0,912
EWE_TF_cellulose	0,818	0,901	0,893	0,832	0,924	0,821	0,784	0,902
EWE_TF_wooden fiber	0,849	0,905	0,897	0,855	0,926	0,846	0,821	0,907
EWE_TF_rockwool	0,781	**0,920**	**0,913**	0,815	**0,938**	0,797	0,734	**0,921**
EWE_TF_glasswool	0,774	0,914	0,907	0,809	0,934	0,790	0,727	0,915

Table 6.21 _ RE-GREEN indicator values



Graph 6.9 _ graphic representation of the RE-GREEN indicator values

Thanks to these two representations, some main aspects can be highlighted:

- the fact that only two alternatives result as the best ones it is due to their environmental and economic performance. When the weighting system considers more relevant the environment-related aspects, *EWE-Xlam-wooden fiber* results as the best alternative, while when a higher score it is assigned to cost-related parameters to result as the best design alternative is *EWE-TF-rockwool.*
- The indicators of the traditional design alternatives (outside insulation and inner insulation) are grouped together in a range of values between 0,468 and 0,753. Instead values associated to the envelope within an envelope retrofitting alternatives constitute another group of values, in which RE-GREEN indicators are between 0,727 and 0,938.
- The results confirm what has been described in *Paragraph 6.2.3*, giving an objectivity to the features characterizing an envelope within an envelope, which has an average better performance respect to the traditional techniques. This underlines the effectiveness of the choice to use this design strategy for retrofitting a building characterized by big dimension and inner space totally free from structural elements.
- The decision-makers role and the used weighting system can strongly modify the results of the analysis, affecting them with subjective values.
- However, the application of a weighting system to the five indicators has a primary role in simplifying the process of comparison among different solutions, because at the increasing of the design alternatives number, the complexity of the evaluation process increases too. Having the possibility to compare with a single indicator a so huge number of parameters becomes fundamental in order to make it easier the process of selection of the best design choices.

6.3 _ A simplified tool for performing MCA comparison

6.3.1 _ Overview

The methodology presented in this chapter consider several aspects: it is required to carry out LCA, to evaluate energy consumptions and to perform a whole life cycle cost. This could be considered quite complex by stakeholders, due to the huge number of required data and professional skills, which are still less spread in construction sector.

Thus, in the following paragraph, a simplified Excel spreadsheet which can help in performing this analysis is illustrated, in order to allow technicians to apply MCA to the comparison of their project alternatives, requiring less data, time and expert knowledge, but still able to provide a comprehensive analysis.

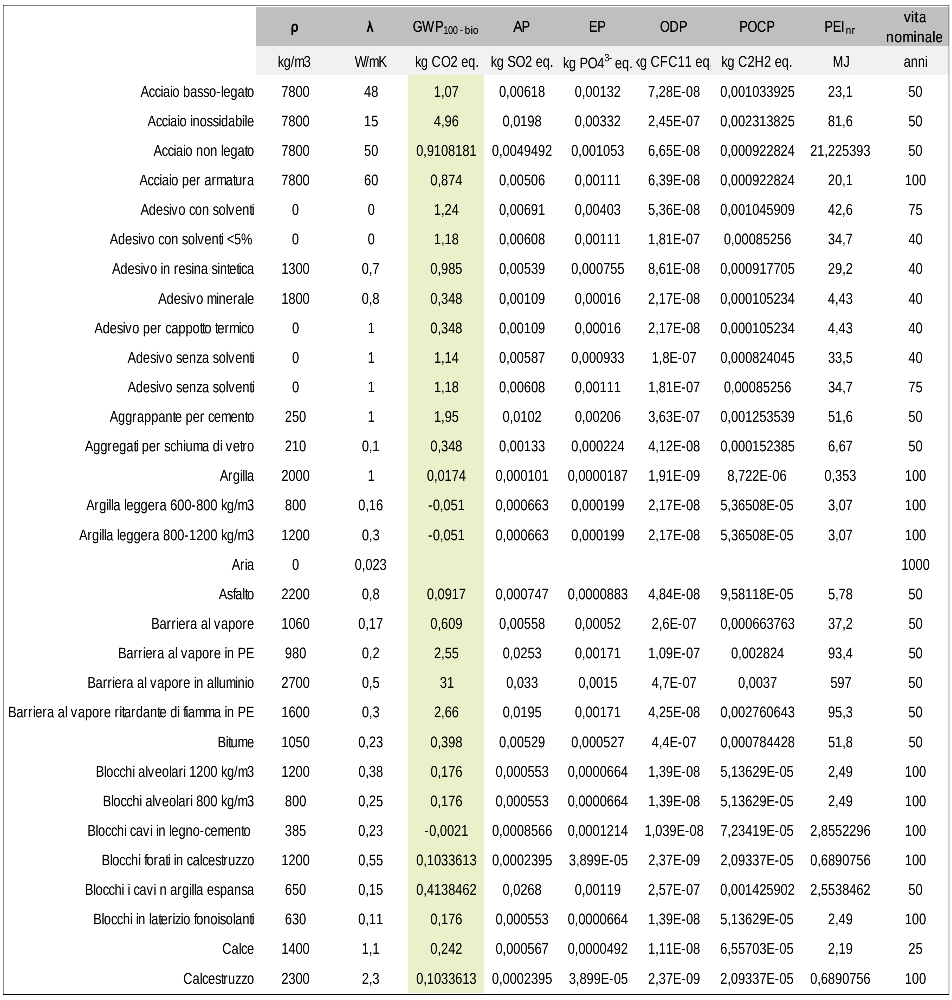
6.3.2 _ RE-GREEN tool

The tool proposed in this paragraph allow stakeholders to perform a simplified comparative analysis of their project, comparing five different alternative design strategies.

The tool is composed of eight sheets, organized as follow:

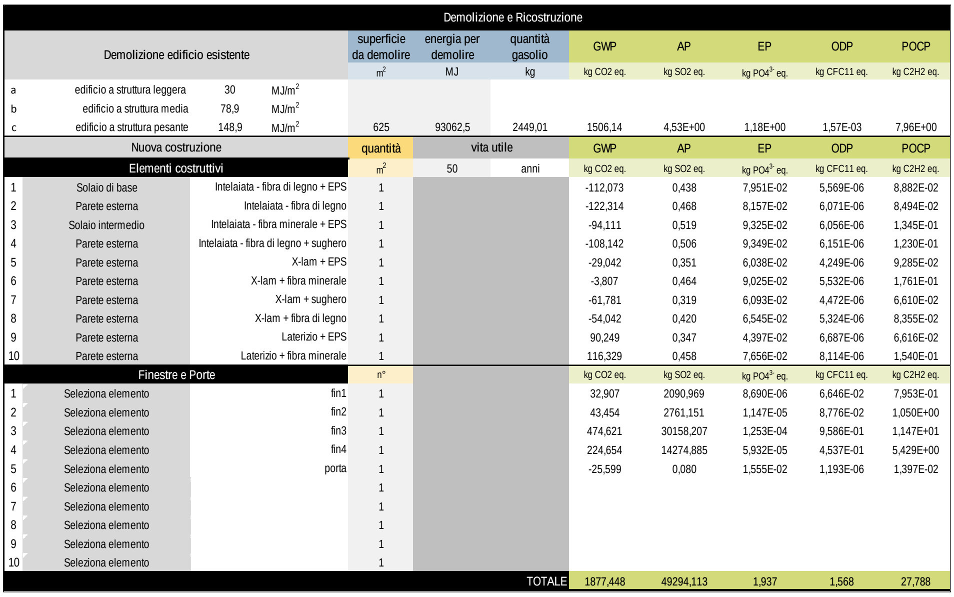
- *Sheet 1: materials DB*. In this sheet data of the open source IBO database and some EPDs data (especially for wood-based material) have been organized, in order to build an user-friendly database, which can be editable and implementable by the user.
- *Sheet 2: LCA for demolishing and rebuilding a new building.* Here it is possible to perform a simplified LCA analysis, which can evaluate the energy need for demolishing the building and the environmental impact due to the construction of a new building.
- *Sheets 3-4-5-6-7: building retrofitting hypothesis.* In this five sheets it is possible to evaluate the environmental impact, the cost, the adaptability potential and the energy performance of five alternative constructive solutions. These sheets are structured in order to perform a simplified LCA analysis, considering construction and replacement of components during the building lifespan, a simplified energy performance calculation for heating, according to the simplified method of the UNI-TS 1300 part 1, and a simplified LCC, which considers construction costs, replacement costs and cost for heating during the winter season for the whole lifespan perspective. Also the DfD indicator is calculated in these sheets.
- *Sheet 8: Buildings summary and comparison.* In this last sheet the five indicators calculated for the different building hypothesis are summarized. Here, it is possible to select the more adequate weighting system for calculating the RE-GREEN indicator and defining the best design alternative to adopt, according to the stakeholders needs.

Below, some screenshots of the RE-GREEN tool are illustrated, in order to show how the tool is built and structured (from *Figure 6.11* to *Figure 6.14*).



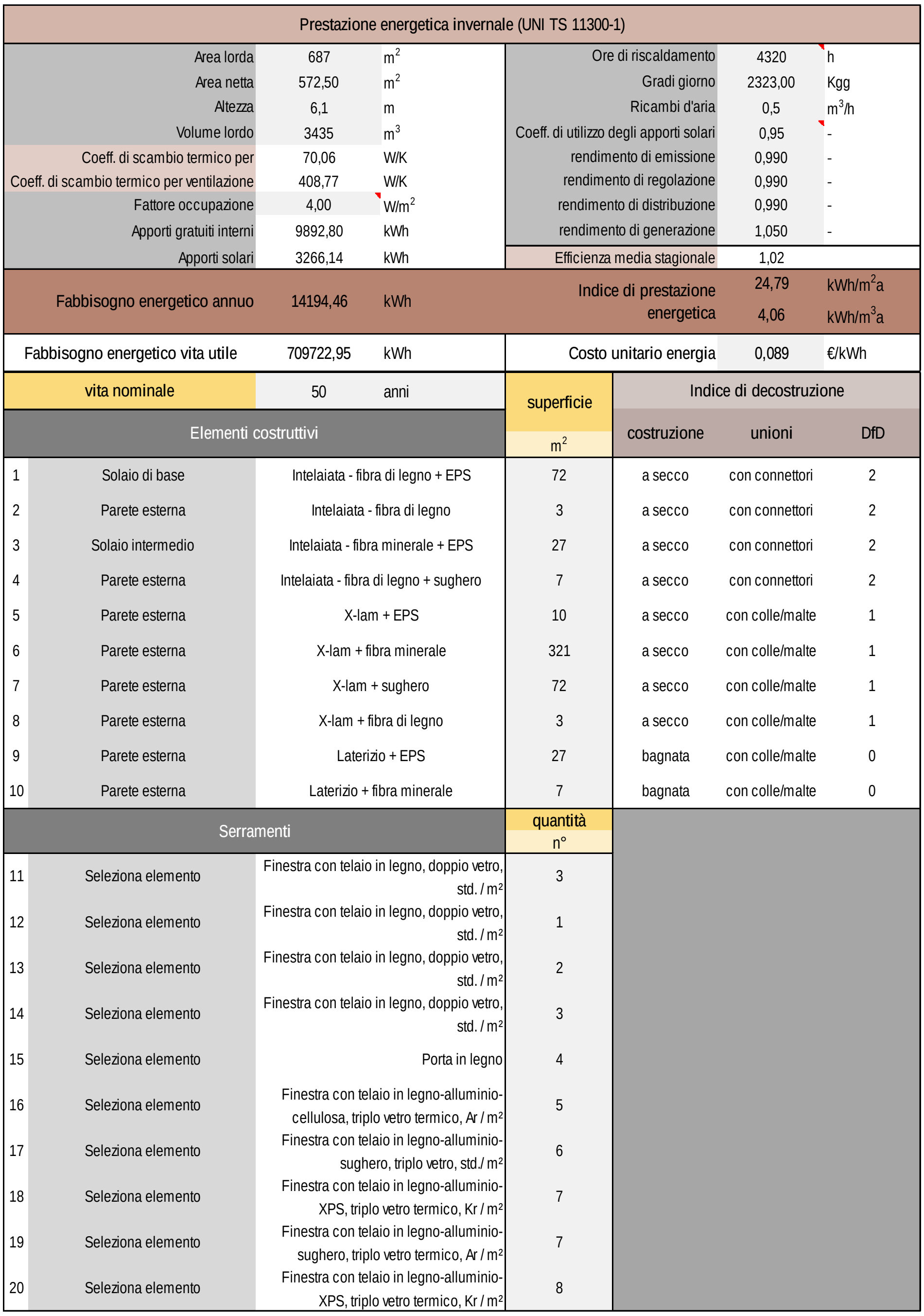
	ρ	λ	$GWP_{100-bio}$	AP	EP	ODP	POCP	PEI_{nr}	vita nominale
	kg/m3	W/mK	kg CO2 eq.	kg SO2 eq.	kg $PO4^{3-}$ eq.	kg CFC11 eq.	kg C2H2 eq.	MJ	anni
Acciaio basso-legato	7800	48	1,07	0,00618	0,00132	7,28E-08	0,001033925	23,1	50
Acciaio inossidabile	7800	15	4,96	0,0198	0,00332	2,45E-07	0,002313825	81,6	50
Acciaio non legato	7800	50	0,9108181	0,0049492	0,001053	6,65E-08	0,000922824	21,225393	50
Acciaio per armatura	7800	60	0,874	0,00506	0,00111	6,39E-08	0,000922824	20,1	100
Adesivo con solventi	0	0	1,24	0,00691	0,00403	5,36E-08	0,001045909	42,6	75
Adesivo con solventi <5%	0	0	1,18	0,00608	0,00111	1,81E-07	0,00085256	34,7	40
Adesivo in resina sintetica	1300	0,7	0,985	0,00539	0,000755	8,61E-08	0,000917705	29,2	40
Adesivo minerale	1800	0,8	0,348	0,00109	0,00016	2,17E-08	0,000105234	4,43	40
Adesivo per cappotto termico	0	1	0,348	0,00109	0,00016	2,17E-08	0,000105234	4,43	40
Adesivo senza solventi	0	1	1,14	0,00587	0,000933	1,8E-07	0,000824045	33,5	40
Adesivo senza solventi	0	1	1,18	0,00608	0,00111	1,81E-07	0,00085256	34,7	75
Aggrappante per cemento	250	1	1,95	0,0102	0,00206	3,63E-07	0,001253539	51,6	50
Aggregati per schiuma di vetro	210	0,1	0,348	0,00133	0,000224	4,12E-08	0,000152385	6,67	50
Argilla	2000	1	0,0174	0,000101	0,0000187	1,91E-09	8,722E-06	0,353	100
Argilla leggera 600-800 kg/m3	800	0,16	-0,051	0,000663	0,000199	2,17E-08	5,36508E-05	3,07	100
Argilla leggera 800-1200 kg/m3	1200	0,3	-0,051	0,000663	0,000199	2,17E-08	5,36508E-05	3,07	100
Aria	0	0,023							1000
Asfalto	2200	0,8	0,0917	0,000747	0,0000883	4,84E-08	9,58118E-05	5,78	50
Barriera al vapore	1060	0,17	0,609	0,00558	0,00052	2,6E-07	0,000663763	37,2	50
Barriera al vapore in PE	980	0,2	2,55	0,0253	0,00171	1,09E-07	0,002824	93,4	50
Barriera al vapore in alluminio	2700	0,5	31	0,033	0,0015	4,7E-07	0,0037	597	50
Barriera al vapore ritardante di fiamma in PE	1600	0,3	2,66	0,0195	0,00171	4,25E-08	0,002760643	95,3	50
Bitume	1050	0,23	0,398	0,00529	0,000527	4,4E-07	0,000784428	51,8	50
Blocchi alveolari 1200 kg/m3	1200	0,38	0,176	0,000553	0,0000664	1,39E-08	5,13629E-05	2,49	100
Blocchi alveolari 800 kg/m3	800	0,25	0,176	0,000553	0,0000664	1,39E-08	5,13629E-05	2,49	100
Blocchi cavi in legno-cemento	385	0,23	-0,0021	0,0008566	0,0001214	1,039E-08	7,23419E-05	2,8552296	100
Blocchi forati in calcestruzzo	1200	0,55	0,1033613	0,0002395	3,899E-05	2,37E-09	2,09337E-05	0,6890756	100
Blocchi i cavi n argilla espansa	650	0,15	0,4138462	0,0268	0,00119	2,57E-07	0,001425902	2,5538462	50
Blocchi in laterizio fonoisolanti	630	0,11	0,176	0,000553	0,0000664	1,39E-08	5,13629E-05	2,49	100
Calce	1400	1,1	0,242	0,000567	0,0000492	1,11E-08	6,55703E-05	2,19	25
Calcestruzzo	2300	2,3	0,1033613	0,0002395	3,899E-05	2,37E-09	2,09337E-05	0,6890756	100

Figure 6.11 _ materials DB sheet



Demolizione e Ricostruzione										
Demolizione edificio esistente			superficie da demolire	energia per demolire	quantità gasolio	GWP	AP	EP	ODP	POCP
			m^2	MJ	kg	kg CO2 eq.	kg SO2 eq.	kg $PO4^{3-}$ eq.	kg CFC11 eq.	kg C2H2 eq.
a	edificio a struttura leggera	30 MJ/m^2								
b	edificio a struttura media	78,9 MJ/m^2								
c	edificio a struttura pesante	148,9 MJ/m^2	625	93062,5	2449,01	1506,14	4,53E+00	1,18E+00	1,57E-03	7,96E+00
Nuova costruzione			quantità	vita utile		GWP	AP	EP	ODP	POCP
Elementi costruttivi			m^2	50	anni	kg CO2 eq.	kg SO2 eq.	kg $PO4^{3-}$ eq.	kg CFC11 eq.	kg C2H2 eq.
1	Solaio di base	Intelaiata - fibra di legno + EPS	1			-112,073	0,438	7,951E-02	5,569E-06	8,882E-02
2	Parete esterna	Intelaiata - fibra di legno	1			-122,314	0,468	8,157E-02	6,071E-06	8,494E-02
3	Solaio intermedio	Intelaiata - fibra minerale + EPS	1			-94,111	0,519	9,325E-02	6,056E-06	1,345E-01
4	Parete esterna	Intelaiata - fibra di legno + sughero	1			-108,142	0,506	9,349E-02	6,151E-06	1,230E-01
5	Parete esterna	X-lam + EPS	1			-29,042	0,351	6,038E-02	4,249E-06	9,285E-02
6	Parete esterna	X-lam + fibra minerale	1			-3,807	0,464	9,025E-02	5,532E-06	1,761E-01
7	Parete esterna	X-lam + sughero	1			-61,781	0,319	6,093E-02	4,472E-06	6,610E-02
8	Parete esterna	X-lam + fibra di legno	1			-54,042	0,420	6,545E-02	5,324E-06	8,355E-02
9	Parete esterna	Laterizio + EPS	1			90,249	0,347	4,397E-02	6,687E-06	6,616E-02
10	Parete esterna	Laterizio + fibra minerale	1			116,329	0,458	7,656E-02	8,114E-06	1,540E-01
Finestre e Porte			n°			kg CO2 eq.	kg SO2 eq.	kg $PO4^{3-}$ eq.	kg CFC11 eq.	kg C2H2 eq.
1	Seleziona elemento	fin1	1			32,907	2090,969	8,690E-06	6,646E-02	7,953E-01
2	Seleziona elemento	fin2	1			43,454	2761,151	1,147E-05	8,776E-02	1,050E+00
3	Seleziona elemento	fin3	1			474,621	30158,207	1,253E-04	9,586E-01	1,147E+01
4	Seleziona elemento	fin4	1			224,654	14274,885	5,932E-05	4,537E-01	5,429E+00
5	Seleziona elemento	porta	1			-25,599	0,080	1,555E-02	1,193E-06	1,397E-02
6	Seleziona elemento		1							
7	Seleziona elemento		1							
8	Seleziona elemento		1							
9	Seleziona elemento		1							
10	Seleziona elemento		1							
					TOTALE	1877,448	49294,113	1,937	1,568	27,788

Figure 6.12 _ sheet for calculating LCA for demolishing and building new



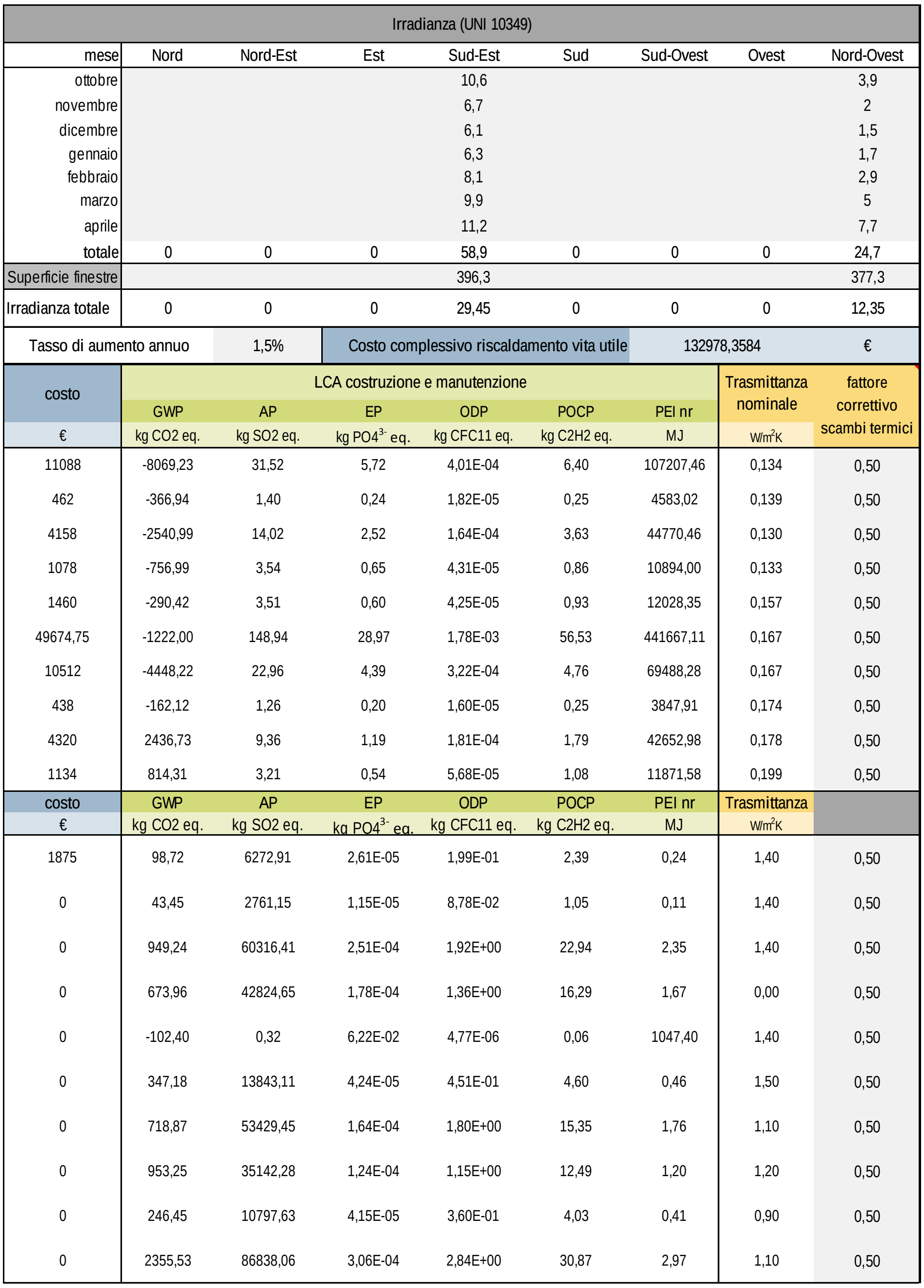
Prestazione energetica invernale (UNI TS 11300-1)

Area lorda	687	m²	Ore di riscaldamento	4320	h
Area netta	572,50	m²	Gradi giorno	2323,00	Kgg
Altezza	6,1	m	Ricambi d'aria	0,5	m³/h
Volume lordo	3435	m³	Coeff. di utilizzo degli apporti solari	0,95	-
Coeff. di scambio termico per	70,06	W/K	rendimento di emissione	0,990	-
Coeff. di scambio termico per ventilazione	408,77	W/K	rendimento di regolazione	0,990	-
Fattore occupazione	4,00	W/m²	rendimento di distribuzione	0,990	-
Apporti gratuiti interni	9892,80	kWh	rendimento di generazione	1,050	-
Apporti solari	3266,14	kWh	Efficienza media stagionale	1,02	
Fabbisogno energetico annuo	14194,46	kWh	Indice di prestazione energetica	24,79 4,06	kWh/m²a kWh/m³a
Fabbisogno energetico vita utile	709722,95	kWh	Costo unitario energia	0,089	€/kWh
vita nominale	50	anni			

Elementi costruttivi			superficie m²	Indice di decostruzione costruzione	unioni	DfD
1	Solaio di base	Intelaiata - fibra di legno + EPS	72	a secco	con connettori	2
2	Parete esterna	Intelaiata - fibra di legno	3	a secco	con connettori	2
3	Solaio intermedio	Intelaiata - fibra minerale + EPS	27	a secco	con connettori	2
4	Parete esterna	Intelaiata - fibra di legno + sughero	7	a secco	con connettori	2
5	Parete esterna	X-lam + EPS	10	a secco	con colle/malte	1
6	Parete esterna	X-lam + fibra minerale	321	a secco	con colle/malte	1
7	Parete esterna	X-lam + sughero	72	a secco	con colle/malte	1
8	Parete esterna	X-lam + fibra di legno	3	a secco	con colle/malte	1
9	Parete esterna	Laterizio + EPS	27	bagnata	con colle/malte	0
10	Parete esterna	Laterizio + fibra minerale	7	bagnata	con colle/malte	0

Serramenti			quantità n°
11	Seleziona elemento	Finestra con telaio in legno, doppio vetro, std. / m²	3
12	Seleziona elemento	Finestra con telaio in legno, doppio vetro, std. / m²	1
13	Seleziona elemento	Finestra con telaio in legno, doppio vetro, std. / m²	2
14	Seleziona elemento	Finestra con telaio in legno, doppio vetro, std. / m²	3
15	Seleziona elemento	Porta in legno	4
16	Seleziona elemento	Finestra con telaio in legno-alluminio-cellulosa, triplo vetro termico, Ar / m²	5
17	Seleziona elemento	Finestra con telaio in legno-alluminio-sughero, triplo vetro, std./ m²	6
18	Seleziona elemento	Finestra con telaio in legno-alluminio-XPS, triplo vetro termico, Kr / m²	7
19	Seleziona elemento	Finestra con telaio in legno-alluminio-sughero, triplo vetro termico, Ar / m²	7
20	Seleziona elemento	Finestra con telaio in legno-alluminio-XPS, triplo vetro termico, Kr / m²	8

Figure 6.13.a _ sheet for assessing indicators of the different building alternatives



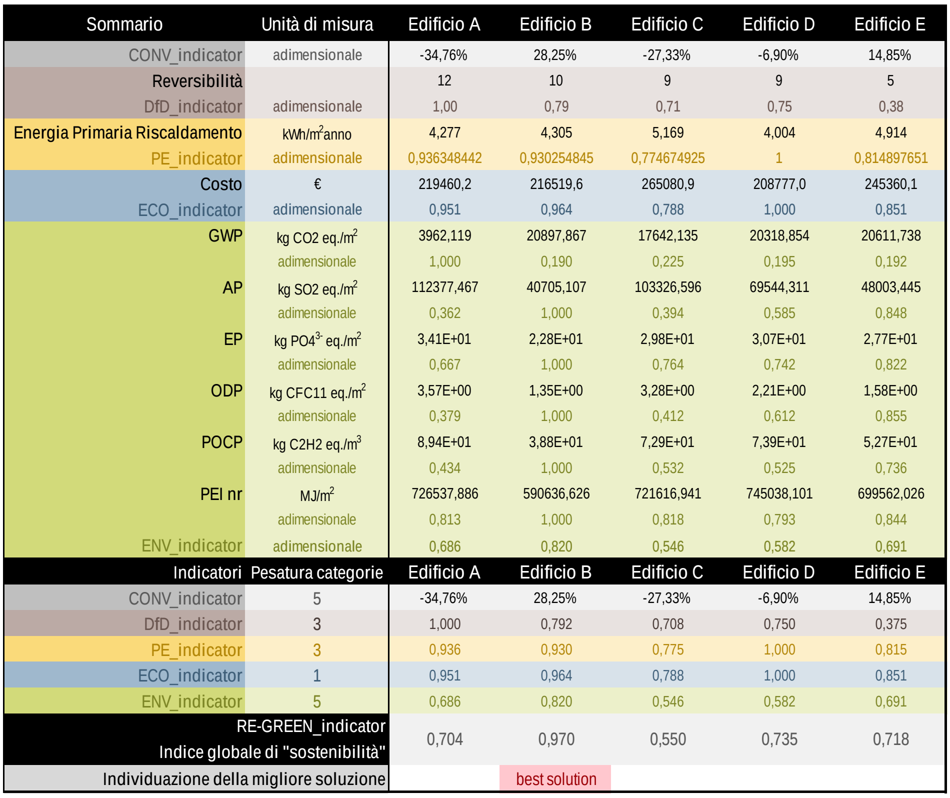
Irradianza (UNI 10349)								
mese	Nord	Nord-Est	Est	Sud-Est	Sud	Sud-Ovest	Ovest	Nord-Ovest
ottobre				10,6				3,9
novembre				6,7				2
dicembre				6,1				1,5
gennaio				6,3				1,7
febbraio				8,1				2,9
marzo				9,9				5
aprile				11,2				7,7
totale	0	0	0	58,9	0	0	0	24,7
Superficie finestre				396,3				377,3
Irradianza totale	0	0	0	29,45	0	0	0	12,35

Tasso di aumento annuo	1,5%	Costo complessivo riscaldamento vita utile	132978,3584	€

costo	LCA costruzione e manutenzione						Trasmittanza nominale	fattore correttivo scambi termici
	GWP	AP	EP	ODP	POCP	PEI nr		
€	kg CO2 eq.	kg SO2 eq.	kg PO4^{3-} eq.	kg CFC11 eq.	kg C2H2 eq.	MJ	W/m^{2}K	
11088	-8069,23	31,52	5,72	4,01E-04	6,40	107207,46	0,134	0,50
462	-366,94	1,40	0,24	1,82E-05	0,25	4583,02	0,139	0,50
4158	-2540,99	14,02	2,52	1,64E-04	3,63	44770,46	0,130	0,50
1078	-756,99	3,54	0,65	4,31E-05	0,86	10894,00	0,133	0,50
1460	-290,42	3,51	0,60	4,25E-05	0,93	12028,35	0,157	0,50
49674,75	-1222,00	148,94	28,97	1,78E-03	56,53	441667,11	0,167	0,50
10512	-4448,22	22,96	4,39	3,22E-04	4,76	69488,28	0,167	0,50
438	-162,12	1,26	0,20	1,60E-05	0,25	3847,91	0,174	0,50
4320	2436,73	9,36	1,19	1,81E-04	1,79	42652,98	0,178	0,50
1134	814,31	3,21	0,54	5,68E-05	1,08	11871,58	0,199	0,50

costo	GWP	AP	EP	ODP	POCP	PEI nr	Trasmittanza	
€	kg CO2 eq.	kg SO2 eq.	kg PO4^{3-} eq.	kg CFC11 eq.	kg C2H2 eq.	MJ	W/m^{2}K	
1875	98,72	6272,91	2,61E-05	1,99E-01	2,39	0,24	1,40	0,50
0	43,45	2761,15	1,15E-05	8,78E-02	1,05	0,11	1,40	0,50
0	949,24	60316,41	2,51E-04	1,92E+00	22,94	2,35	1,40	0,50
0	673,96	42824,65	1,78E-04	1,36E+00	16,29	1,67	0,00	0,50
0	-102,40	0,32	6,22E-02	4,77E-06	0,06	1047,40	1,40	0,50
0	347,18	13843,11	4,24E-05	4,51E-01	4,60	0,46	1,50	0,50
0	718,87	53429,45	1,64E-04	1,80E+00	15,35	1,76	1,10	0,50
0	953,25	35142,28	1,24E-04	1,15E+00	12,49	1,20	1,20	0,50
0	246,45	10797,63	4,15E-05	3,60E-01	4,03	0,41	0,90	0,50
0	2355,53	86838,06	3,06E-04	2,84E+00	30,87	2,97	1,10	0,50

Figure 6.13.b _ sheet for assessing indicators of the different building alternatives



Sommario	Unità di misura	Edificio A	Edificio B	Edificio C	Edificio D	Edificio E
CONV_indicator	adimensionale	-34,76%	28,25%	-27,33%	-6,90%	14,85%
Reversibilità		12	10	9	9	5
DfD_indicator	adimensionale	1,00	0,79	0,71	0,75	0,38
Energia Primaria Riscaldamento	kWh/m^{2}anno	4,277	4,305	5,169	4,004	4,914
PE_indicator	adimensionale	0,936348442	0,930254845	0,774674925	1	0,814897651
Costo	€	219460,2	216519,6	265080,9	208777,0	245360,1
ECO_indicator	adimensionale	0,951	0,964	0,788	1,000	0,851
GWP	kg CO2 eq./m^2	3962,119	20897,867	17642,135	20318,854	20611,738
	adimensionale	1,000	0,190	0,225	0,195	0,192
AP	kg SO2 eq./m^2	112377,467	40705,107	103326,596	69544,311	48003,445
	adimensionale	0,362	1,000	0,394	0,585	0,848
EP	kg PO4^{3-} eq./m^2	3,41E+01	2,28E+01	2,98E+01	3,07E+01	2,77E+01
	adimensionale	0,667	1,000	0,764	0,742	0,822
ODP	kg CFC11 eq./m^2	3,57E+00	1,35E+00	3,28E+00	2,21E+00	1,58E+00
	adimensionale	0,379	1,000	0,412	0,612	0,855
POCP	kg C2H2 eq./m^3	8,94E+01	3,88E+01	7,29E+01	7,39E+01	5,27E+01
	adimensionale	0,434	1,000	0,532	0,525	0,736
PEI nr	MJ/m^2	726537,886	590636,626	721616,941	745038,101	699562,026
	adimensionale	0,813	1,000	0,818	0,793	0,844
ENV_indicator	adimensionale	0,686	0,820	0,546	0,582	0,691
Indicatori	**Pesatura categorie**	**Edificio A**	**Edificio B**	**Edificio C**	**Edificio D**	**Edificio E**
CONV_indicator	5	-34,76%	28,25%	-27,33%	-6,90%	14,85%
DfD_indicator	3	1,000	0,792	0,708	0,750	0,375
PE_indicator	3	0,936	0,930	0,775	1,000	0,815
ECO_indicator	1	0,951	0,964	0,788	1,000	0,851
ENV_indicator	5	0,686	0,820	0,546	0,582	0,691
RE-GREEN_indicator Indice globale di "sostenibilità"		0,704	0,970	0,550	0,735	0,718
Individuazione della migliore soluzione			best solution			

Figure 6.14 _ RE-GREEN indicator sheet

_ Notes

[1] citation from the paper by HERMANN B. G. *"Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators"*;

[2] citation from the paper by GUNGOR A. *"Evaluation of connection types in design for disassembly (DfD) using analytic network process"*;

[3] according to ASHRAE std. 90.1/2010 regulated (non-process) energy includes lighting, heating, ventilation and air conditioning (HVAC) and service water heating for domestic or space heating purposes;

[4] *"Envelope within an envelope"* concept was explained by FRATTARI A. and LAWRENCE D. in the paper "*Envelope within an envelope: an FM approach to adaptive re-use of redundant barns".*

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- ZAVADSKAS E. K., LIIAS R., TURSKIS Z., 2008. *"Multi-attribute decision-making methods for assessment of quality in bridges and road construction: state of the art surveys"*, in The Baltic Journal of Road and Bridge Engineering, Vol. 3, issue 3, pp. 152-160.

_ List of Figures, Tables and Graphs

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CONCLUSION

The idea of this thesis was inspired by the increasing proliferation of tools for the assessment of buildings environmental sustainability (Rating Systems), which are based on providing guidelines and suggesting best practices for designing buildings with a minimized environmental impact. Often tools for new constructions and for renovations are the same, but the renovation process is more complicated than new construction. Moreover, the Rating Systems are not able to communicate the beneficial role that existing stock could have in reducing environmental loads, because of their prescriptive approach.

Thus, in the thesis synthetic indicators and *life-cycle tools* have been proposed as alternative methods to RSs, investigating their pros and cons and how they can be used for assessing environmental benefits in restoring existing buildings. The suitability of the life-cycle methods has been confirmed both by literature review and cases studies analysis and also the effectiveness, on average, in retrofitting rather than demolishing and rebuilding was demonstrated.

Because of their proven validity, life-cycle tools have been integrated together, with the aim to define a *comparative methodology* for the assessment of interventions of restoration, able to take into account apart from the environmental concerns (Life Cycle Assessment), the energy (energy performance) and economic aspects (Life Cycle Costing) in a whole building lifespan perspective. The developed method allows to individuate in a set of alternative design proposals, the best retrofitting solutions according to the decision-makers needs.

The process of comparison of the alternatives is made easier by the RE-GREEN indicator, a single dimension-less value of between 0 and 1, in which five building aspects are summarized: *environmental convenience in restoring, environmental performance, energy performance, whole building cost* and *easiness of adaptability over the building lifespan.*

The application of the developed methodology to a case study emphasized how the use of a multi-criteria approach is useful for comparing different design alternatives, especially when there is a huge number of parameters involved in the analysis, all characterized by different units of measurement. By using the developed method, the assessment of nearly 30 alternatives retrofitting hypothesis according to the life-cycle thinking principles could have been easily conducted.

Another interesting aspect that has emerged from this analysis is the effectiveness in using the *“envelope within an envelope”* strategy, that resulted as the most convenient. This is due to the fact that the analysis focused on the retrofitting of big sizes buildings, characterized by empty inner spaces (in this case an industrial building and a warehouse, but it can also be a commercial space).

Due to the complexity of the topics and the huge number of required data, carrying out this research has been possible only thanks to the integrated use of several specific software and expert knowledge. Because of this, some simplifications have been introduced in this work, still without affecting the reliability of the research, which can be considered a *“methodological research”.*

However, in the future, the developed and adopted multi-criteria methodology can be implemented introducing in the analysis some aspects that in this phase have been omitted.

Because of the “theoretical” nature of the project, a specific provenience of materials has not been identified. In carrying out LCAs, materials from databanks have been mainly used, using some specific EPDs data for making the analysis more reliable. For this reason it has been decided to do not consider the transportation contribution in performing the environmental assessment, but in the future or in case of a true project, for which materials information are available, also this aspect can be introduced and analyzed.

For the same reason also the assessment of the social impact could not be fully performed. For carrying out a Social Life Cycle Analysis (SLCA), there is the necessity to involve in the design many actors, but because for the moment this project cannot be effectively built, there are actually no stakeholders to face up. Thus, this kind of assessment it is postponed to future times.

However, in the thesis the social aspect has been considered in two ways: at first recognizing the value of retrofitting the existing stock as social and cultural element of a community, and then introducing different weighting systems representing the different actors involved in the construction process.

This research has been based on forsaken industrial buildings and warehouse. Further research can be carried out by applying the RE-GREEN indicator to other building types as well as residential buildings or public buildings. Surely construction methods, specifications and impacts on the environment will be different from industrial buildings and this may provide different results and best practices to adopt.

Furthermore, the RE-GREEN indicator can be extended to other parameters and modified to accomplish the ultimate goal of promoting and improving sustainable practices in construction. A possible improvement of this work could be the introduction of Cradle-to-Cradle (C2C) certified building materials in the analysis: in this way LCA and easiness of adaptability (DfD indicator) will be accounted as a single aspect.

The RE-GREEN indicator can be used as the basis for benchmarking buildings allowing decisions to be made to improve the quality of the built environment. The indicator can help in making better decisions as environmental issues are successfully measured and incorporated into the decision-making methodology.

Therefore, in order to make this work more accessible to designers, builders or other stakeholders, and to spread the developed method, a simplified Excel spreadsheet (RE-GREEN tool) based on the proposed methodology but requiring less detailed data and specific skills, has been elaborated. The tool can compare five alternative building solutions, calculating their RE-GREEN indicator and providing the best alternative under different stakeholders perspective. The RE-GREEN indicator provides an opportunity for stakeholder’s participation in the decision-making process and this can be of primary importance in improving the overall quality of the built environment.

ACKNOWLEDGMENTS

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