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Scuola di Ingegneria Industriale e dell’Informazione

Master of Science in Management Engineering

Circular Economy in the Construction Industry

Exploration of the role of Circular Economy for achieving carbon neutrality in the construction industry

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Abstract

Climate change is a problem that grieves on the whole world and one of the main causes is the raise of carbon dioxide emissions in the atmosphere. Construction industry is of the sectors that contribute for the large part to such emissions. In 2018 it was accountable for the 38 percent of total carbon emissions. The two main sources of carbon emissions in the life cycle of a building are the manufacturing of materials and the operation and use. First attempts in the construction of Zero Carbon Buildings (ZCBs), building with zero carbon emissions associated, and Zero Energy Buildings (ZEBs), buildings that do not take energy from the grid and satisfy their own demand by producing energy from renewable sources, are happening. This Master of Science thesis examines the possible solutions that reflect the circular economy principles that may be applied to the construction industry in order to reduce the carbon emissions associated. This work is divided in three main parts: in the first one a general overview of ZCBs and ZEBs is provided. In the second part the main circular economy solutions, both at theoretical level and implemented in real case studies, are described. In the last part the main barriers that may hinder their implementation, and drivers that instead may make easier their realization are discussed. Results show that following the circular economy principles is possible to achieve carbon emissions reduction associated to buildings.

Sommario

Il cambiamento climatico è un problema che sta affliggendo l'intero mondo e una delle principali cause è l'aumento delle emissioni di anidride carbonica nell'atmosfera. Il settore edilizio è uno dei principali attori in questo processo, nel 2018 è stato responsabile del 38% delle emissioni totali di anidride carbonica. Le due principali fonti di emissioni nel ciclo vitale di un edificio sono la produzione dei materiali e la fase di abitazione. Primi passi per la riduzione delle emissioni associate a queste fasi sono stati fatti nella forma di Zero Carbon Buildings (ZCBs), edifici che hanno zero emissioni associate, e Zero Energy Buildings (ZEBs), edifici che non prendono energia dalla griglia energetica pubblica, ma la producono in loco e con fonti rinnovabili. Questa tesi esamina le soluzioni relative all'economia circolare applicate nel settore edilizio. Questo lavoro si divide in tre parti: nella prima viene fornita una visione di insieme delle principali definizioni di ZCBs e ZEBs e su quali elementi si focalizzano maggiormente; nella seconda parte sono descritte le principali soluzioni in linea con i principi dell'economia circolare studiate sia solamente a livello teorico sia a livello pratico in reali casi studio; nell'ultima parte sono elencate e discusse le barriere che possono rendere difficile l'implementazione di tali soluzioni e i fattori che invece possono rendere più semplice la loro realizzazione. I risultati mostrano che l'adozione di soluzioni che seguono i principi dell'economia circolare possono ridurre le emissioni di anidride carbonica associate alla costruzione di edifici.

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1 Introduction

This thesis aims to explore the role of circular economy practices in the construction industry and if its implementation can lead to significant reductions for what concern the embodied carbon emissions associated to buildings. The reason behind this study is that construction industry is one of the sectors accountable for large proportion of carbon emissions and energy consumption. In 2018 the 36 percent of global energy consumption was accountable to the building industry and operations, while for what concern carbon emissions, the building industry is responsible of 39 percent of the total [Abergel, Dulac, Hamilton, Jordan, & Pradeep, 2019].

An excessive emission of carbon dioxide has an impact on the whole world, in fact, carbon dioxide is one of the main responsible of climate change. Climate change is a phenomenon caused by the presence of certain gases, called Greenhouse Gases (water vapor, carbon dioxide, methane, nitrous dioxide, and chlorofluorocarbons), that do not allow the heat to leave the Earth's atmosphere, Greenhouse Effect. Among the Greenhouse Gases, the most critical one is carbon dioxide as is a direct consequence of human activities, such as burning of fossil fuels [Nasa, 2020b]. The greenhouse effect, occurs naturally and warms the Earth's surface. However, if the concentration of greenhouse gases increases, it leads to a higher amount of heat trapped inside the Earth's atmosphere causing the rise of temperature. The consequences of the Earth becoming warmer are an increase in the evaporation and precipitation phenomena, making some regions wetter and other dryer; melting of glacier and ice sheets, increasing the level of seas [Nasa, 2020a].

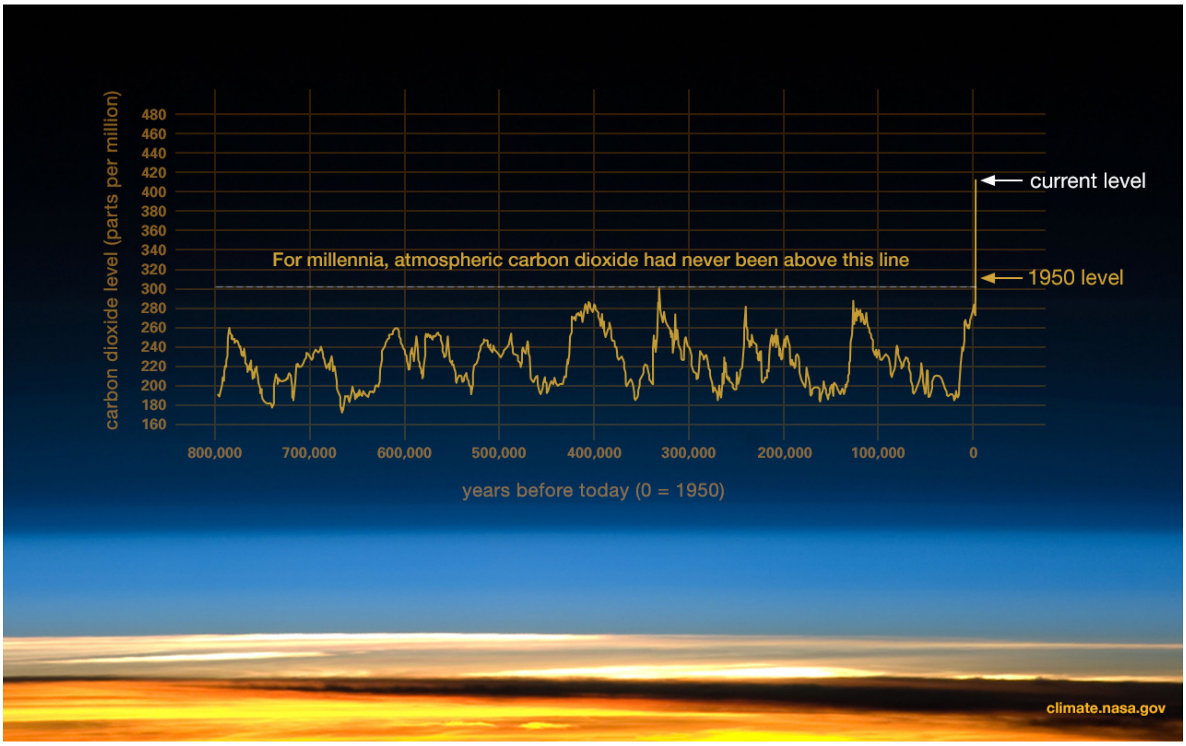


Figure 1: level of carbon dioxide emissions over the years. Source: [Nasa, 2020a]

The construction industry has an important role in the carbon emissions release, and this weight might even increase in the future years. Among the macro-forces that drive the world, there is the urbanization of areas as a direct consequence of the increase of population [Efrat, 2014]. Currently, in the world there are 7.8 billion inhabitants, and the 8 billion milestone is expected to be reached in 2023 and 10 billion in 2056 [Ghosh, 2019]. An increase in population will lead to an expansion of city limits, impacting on the future of mobility, working life and society. A consequence of urbanization is urban sprawl, the spreading of the population of a city over an increasing geographical area [National Geography Society, 2019]. Another phenomenon that is taking place is urban shift, the movement of people from rural areas to the cities. Nowadays, more than half of world population lives in urban areas, 56 percent, and this number is expected to reach 70 percent by 2050 [Chamie, 2020].

The need to reduce CO_2 emissions embedded in building has been widely recognised. Organizations and governments have started to take action in the form of policies. In particular, the European Community, in 2010, has disclosed a directive containing the guidelines the Member States have to follow in order to meet the goals set by the Kyoto Protocol. New buildings have to meet a minimum requirement performance; the methodology to calculate energy performance of a building has to take into account the whole year in order to not be biased by peek of demand such as heating in winter or cooling in summer. The minimum requirements are fixed by the European Commission, but further constraint can be applied by the member states [European Parliament, 2010]. In 2018, the European Commission enacted a further directive, reviewing what has been done since that point and setting new goals according to what has been established in the Paris Agreement of 2015 [European Parliament, 2018]. The Italy's National Energy Strategy (NES) is a set of key targets to be achieved in the medium-long term (2020): alignment with the cost of energy with European Union average, exceed the environmental carbon reduction target established by EU Climate-Energy Package for 2020, increase energy supply security, and boost sustainable economic growth through the development of energy sector. The most important aspect to the strategy is the achievement of energy efficiency [Italian Government, 2013].

For this reason it is crucial to provide the right infrastructures and services in order to solve problems that may arise, such as the supply of materials and energy requirements [Ghosh, 2019]; and understanding these trends is critical for the implementation of The 2030 Agenda of Sustainable Development, since the sustainable development depends strongly on the urban growth's management [United Nation, 2018].

A useful tool that can be employed in the fight against the raise of carbon emissions is circular economy. Circular Economy (CE) is defined by The Ellen MacArthur Foundation as *"a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources"* [Ellen MacArthur Foundation, 2017]

According to Napier (2016) the implementation of CE practices in the construction industry will help to reduce the carbon emissions related to a building, mainly thanks to the use of materials with high embodied energy at the end of their useful life or materials that have low embodied carbon. Also, the end of life a building plays a significant role in the reduction of carbon emissions, a responsible management of waste is a key aspect for the construction of sustainable buildings. A bad management of waste, meaning that construction and demolition waste are still disposed in landfills, will create a harm for the environment and human health. In recent years, the awareness of this problem with the industry has been recognized; elimination of waste is the first practice to prioritize, then minimize waste when possible and then reuse the materials that may become waste [Napier, 2016]

Carbon neutrality is a concept that has already started to attract the action of practitioners. put in practice. There are the first attempts of construction of Zero Carbon Buildings (ZCBs), buildings with zero carbon emissions associated, and Zero Energy Buildings (ZEBs), buildings that have their energy demand covered by renewable source of energy. However, this concept it has not been associated to the circular economy yet, and it might be useful to see how circular economy can improve carbon neutrality, and which circular economy practices are already been in implemented in the construction industry.

The goal of this thesis is to answer the following questions:

- What are the key sources of CO_2 emissions associated with the construction industry?
- What circular economy practices have been implemented in the construction industry?
- How circular economy practices can foster carbon neutrality in construction sector/built environment/building?
- What are the drivers and barriers that affect the implementation of circular economy solutions?

The answer to these questions was found by conducting a literature review on Scopus, by consulting the web site of the most influent consulting companies on the topic, and a case study of L'Innesto based on analysis company reports and an interview.

The thesis has the following structure. Chapter 2 provides an overview of which is the environmental impact of the construction industry and which life cycle stages have more weight in such impact and then the definitions of ZCBs and ZEBs. Chapter 3 is the description of the methodology followed. In Chapter 4 are presented the circular economy solutions that are studied in the literature and they will be grouped according to which life cycle stage they can be implemented. An analysis of case studies found in the literature will be conducted. The analysis of the ARUP project L'Innesto is presented in Chapter 5. Barriers and levers influencing the circular economy practice are discussed in Chapter 6.

2 Zero Energy/Carbon Buildings

2.1 Sources of Carbon Emissions of a Building

In the last years the building and construction sector has seen an increase in both carbon emissions and energy use [Abergel et al., 2019]. In 2017, the 39 percent of carbon emission related to global energy was accountable to the construction industry [World Building Green Council, 2021]. Building emissions are measured taking into account two parameters: operation and use activities (day-to-day energy use, such as heat, cool, power and electricity), known as "operational carbon emissions" and account for the 28 percent; the remaining 11 percent came from construction activities throughout the whole building lifecycle and manufacturing of materials, this emissions are known as "embodied carbon of a building" [Budds, 2019; World Building Green Council, 2021]. Embodied carbon energy is calculated as the amount of carbon dioxide equivalent of the energy and materials used to construct existing building [Foster, 2020].

The final energy use raised from 118 EJ in 2010 to around 128 EJ in 2019 [IEA, 2020]. The electricity used in buildings has seen an increase of 19 percent from 2010 to 2018, equal to more than 6.5 EJ

[Abergel et al., 2019]. While from 2018 to 2019 the increase was equal to around 3.5 EJ. Emissions saw an increase as well, this is the result of the source of the electricity that still include coal as fuel, especially in emerging economies [Abergel et al., 2019].

As can be seen in *figure 2*,in 2018 the 36 percent of global energy consumption was accountable to the building industry and operations, while for what concern carbon emissions, the building industry is responsible of 39 percent of the total [Abergel et al., 2019]. The section “Construction Industry” is the estimated portion of the building industry dedicated to the manufacturing of building materials [Abergel et al., 2019].

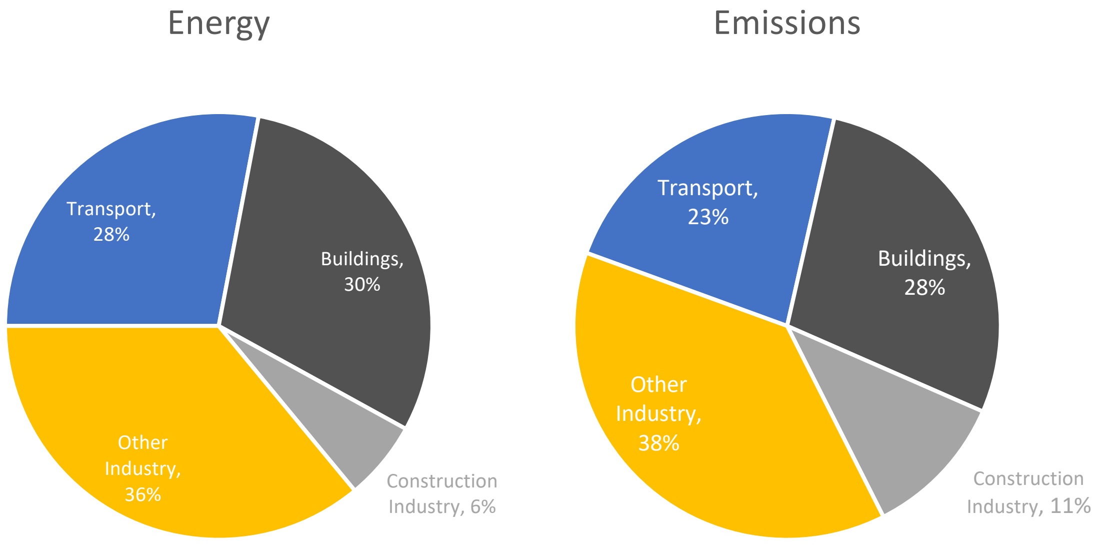


Figure 2: Global share of building final energy and emission. Sources: IEA, World Energy Statistics and Balances (database), www.iea.org/statistics

In order to have a better vision of how the carbon emissions are distributed, it is useful to open the life cycle of a building and investigate each stage.

Manufacturing of Building Materials

In the Manufacturing of Building Materials stage are included the emissions derived from the extraction, production and transportation of raw materials. These emissions are also known as embodied emissions. The emissions generated depend on the nature of the materials employed. Cement and Steel are the materials with the highest share of embodied emissions [Fenner et al., 2018]. Steel-frame buildings are more energy intensive to manufacture than concrete-frame buildings. The production of cement has been estimated to be the main sources of non-energy emissions [Fenner et al., 2018]. It is calculated that the production of 1 tons of cement generates carbon emission around 0.7-0.99 tons of CO2/t, and that cements and cement-related products constitute more than 50 percent of material composition of a building [Orsini & Marrone, 2019].

In their work Fenner et al. found out that the 60-70 percent of embodied emissions of a building in Canada are accounted to the use of bricks, windows, drywall and structural concrete [Fenner et al., 2018].

Also, an important role is played by the sources used to produce the energy required to extract, manufacture and transport raw materials. For these processes is still used energy coming from fossil fuels and is indicated as the major carbon emission factor [Fenner et al., 2018].

Construction

The construction stage comprehends all the activities included from the manufacturing of building materials stage to the operation and use stage.

In this stage, according to Fenner et al. the major source of emissions is related to the use of fossil fuel for heavy equipment and the transportation of building materials [Fenner et al., 2018]. As in the previous stage, more emissions and energy use are associated to cement-frame buildings because of their installation and transportation process, and equipment use.

Emissions associated to the construction stage constitute the 2 percent of the total emissions of the life cycle of a building [Fenner et al., 2018].

Operation and Use

Operation and use stage, along with the manufacturing of building materials, is the stage with the highest embodied emissions associated, and it could be seen as the reflection of users and the current society dependence on fossil fuels to generate electricity.

The cause of the high emissions associated to this stage is the elevated electricity used for space cooling, appliances and hot water. From 2010 to 2018, the demand of electricity for space cooling increased more than 33 percent; in the same years the electricity demand for appliance rose by 18 percent and for water heating by 11 percent. The demand for space heating stayed stable over the years, but it is accountable of one-third of total energy demand in buildings [Abergel et al., 2019].

Another aspect to consider is the consumption of water, because it requires a relevant amount of energy for its sanitization, filtration, and transportation [Fenner et al., 2018].

The result of all these operations led in 2019 to 3 GtCO2 of building carbon emissions associated to the operation and use, a value that has had an increase of 5% with respect the emission in 2010. If also the indirect emissions from the upstream power generation are taken into account, buildings are responsible of 10 GtCO2 [IEA, 2020]. With the term indirect carbon emission are intended emissions related to power generation for electricity and commercial heat [Abergel et al., 2019].

Demolition

The end-of-life phase of a building, as shown in literature, has proven to have a minimal impact of the carbon emissions associated to a building. However, in this phase, the major sources of emissions are associated to the energy used to the demolition machineries and the transportation to landfill [Fenner et al., 2018].

To summarize the findings from this section, the two life cycle stages that are the main source of carbon emission and the most energy demanding are manufacturing of building materials and operation and use. In the first stage greater emissions are generated from different materials such as concrete and steel and their manufacturing and transportation process. In the second one, great emissions are produced from the source used for the electricity generation in order to powerhouse appliances and for inner temperature control.

2.2 The zero-concept

The zero-concept related to buildings dates back to 1940s, but it has seen a growth in use in the last decades. The zero-concept idea is to develop technologies that have zero energy and zero emissions and apply them in zero energy and zero emissions buildings [Santamouris, 2016].

When calculating the carbon and/or energy associated to a building, there are three types which include building-related regulated carbon/energy, such as heating ventilation, and air conditioning (HVAC), or internal lighting, user-related unregulated carbon/energy in the operation and use stage, the appliances installed in the building, and embodied carbon/energy in the other stages of the building [Pan, 2014]. In their work Santamouris identified the relationship between the building industry and local climate change. The implementation of highly efficient Heating, Ventilating, and Air Conditioning (HVAC) systems will help reduce the overall carbon emissions generated by a building. This is particularly true for retrofitting projects, it has been estimated that in 2050 the decarbonisation that can be achieved is in the range of 18 – 73 percent, in case a slow decarbonisation scenario, while if a fast scenario is considered the decarbonisation achieved is in the range of 72 – 91 percent. The shift from fossil fuel-based source of energy to renewable sources will result in lower gas emissions. Proper insulation is important in order to limit the local climate change, it has been demonstrated that in areas where the average summer temperature is higher than 27 degrees Celsius the cooling load is higher, leading the an increase of energy demand and a consequential raise of emissions [Santamouris, 2016].

In the current panorama of Zero Energy Building and Zero Carbon Building there is a fuzziness in the definitions, there a lot of different topics taken into account, but there are few that are redundant in all the papers: Zero Energy Buildings, Zero Carbon Buildings, Net Zero Energy Buildings and Nearly Zero Energy Buildings. The definitions evolved in the time, and as can be seen from *table 1* and table 2, for both ZEBs and ZCBs new definitions are emerging; the most common and used ones are:

Zero Energy Building: Zero energy consumed by a building in its day-by-day operation; a building that has greatly reduced energy loads such that renewable energy can supply the remaining energy needs of the building; 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 [IPEEC Building Energy Efficiency Taskgroup, 2018].

Zero Carbon Building: zero carbon emission release into the environment; a building with zero net energy emissions; a building within its defined system boundaries with net zero carbon emission on an annual basis during the operational stage of this building; the building produces at least as much emissions-free renewable energy as it uses from emissions producing energy sources [Pan, 2014].

However, the zero concept has been difficult to achieve, for this reason related concepts emerged during the years, leaving to ZEBs and ZCBs definitions a more general meaning. The new concepts that emerged and gained more diffusion are the net and nearly concept. With the net concept are considered the emissions released during a set period, usually are calculated on yearly basis, and the emissions absorbed in the same amount of time, and the sum should give the neutrality as result. In the nearly concept the emissions released during the lifetime of the building should be very low, almost near to zero. The same considerations are true for the energy consumption.

Table 1: list of definitions for ZEBs find in the literature

Definition	**Description**	**Reference**
Nearly Zero Energy Building	Very high energy performant building with a very low amount of energy required covered by renewables	[D'Agostino & Mazzarella, 2019]
Net Zero Energy Building	Yearly energy neutral building that delivers as much energy to the grid as it draws back	[D'Agostino & Mazzarella, 2019]
Zero Energy Building	Zero Energy consumed by a building in its day-to-day operation	[D'Agostino & Mazzarella, 2019]
Net Zero Source Energy Building	A building that produces at its location as much energy as it uses in a year, when accounted for at the source	[D'Agostino & Mazzarella, 2019]
Net Zero Site Energy Building	A building that produces at its location as much energy as it uses in a year, when accounted for at the building	[D'Agostino & Mazzarella, 2019]
Net Zero Cost Building	The amount of money the owner pays for the energy consumed is balanced by the money the owner receives for the energy delivered to the grid	[D'Agostino & Mazzarella, 2019]
Nearly Net Energy Building	A building with a national cost optimal energy use greater than zero primary energy	[D'Agostino & Mazzarella, 2019]
Autonomous Zero Energy Building	Stand-alone building that supplies its own energy	[D'Agostino & Mazzarella, 2019]
Energy Plus Building	A building that produces more energy from renewables than the one it imports over a year	[D'Agostino & Mazzarella, 2019]
Photovoltaic Zero Energy Building	A building with a low electricity demand and a photovoltaic system	[D'Agostino & Mazzarella, 2019]
Wind Zero Energy Building	A building with a low electricity demand and an on-site wind turbine	[D'Agostino & Mazzarella, 2019]
Photovoltaic Solar Thermal Heat Pump Zero Energy Building	A building with a low heat and electricity demand, a photovoltaic system in combination with a solar thermal collector, a heat pump and storage	[D'Agostino & Mazzarella, 2019]
Wind Solar Thermal Heat Pump Zero Energy Building	A building with a low heat and electricity demand and a wind turbine in combination with a solar thermal collector, a heat pump and storage	[D'Agostino & Mazzarella, 2019]
EU Nearly Zero Energy Building	A building that has a very high energy performance and the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy form renewable sources produced on-site or nearby [Directive 2010/31EU]	[Bortoluzzi, Pereira de Sousa Lima, Marchant, & Vàxquez Padilla, 2019]

US Net Zero Site Energy	A site ZEB that produces at least as much energy as it uses in a year, when accounted for at the site	[Bortoluzzi et al., 2019]
US Net Zero Source Energy	A source ZEB that produces at least as much energy as it uses in a year, when accounted for at the source	[Bortoluzzi et al., 2019]
US Net Zero Energy Cost	The amount of money that the utility pays the building owner for the energy that the building exports to the grid is at least equal to the amount that the owner pays the utility for the energy services and energy used over the year	[Bortoluzzi et al., 2019]
UK Zero Carbon Building	Zero carbon, including both regulated and unregulated energy, to energy regulated only, neglecting the usage of energy in uncontrolled or unregulated activities	[Bortoluzzi et al., 2019]
Zero Energy Building	A building that has greatly reduce energy loads such that renewable energy can supply the remaining energy needs of the building	[Iyer-Raniga, 2019]
Zero Energy Building	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	[Ascione et al., 2017]
Net Zero Energy Building	Buildings that are connected to the energy utility infrastructure, and the wording “Net” underlines the fact that there is a balance between the energy taken from and supplied back to the energy grid overtime	[Andresen, Wiik, Fufa, & Gustavsen, 2019]

A first consideration that can be drawn is that there is not accordance in the definition neither among different Countries: US have different definitions for ZEBs whether considering site, source of cost; EU has a unique and broad definition; UK instead, for its buildings decided to use a definition that may take or take not into account the energy used for cooking, washing, and electronic entertainment appliances (the “unregulated” energy); Australia do not consider the energy, but the carbon emissions, and provided a definition for ZBCs.

Despite this variety of definitions, it can be seen that all of them have some points in common. For what regard ZEB definition these points are: high energy performance, low demand of energy, and use of renewable sources of energy to meet the demand. For what concern ZCB are: production in loco of energy, use of renewable source of energy, the evaluation of the building is done considering greenhouse gas equivalent instead of energy consumed. Another aspect to consider is that fact that for both definitions, since the total neutrality cannot be achieved, new definitions have been presented. The “Nearly Zero” definitions are dedicated to those buildings that have a low impact almost proximal to zero. The “Net Zero” ones are dedicated to those buildings that can achieve neutrality over a year, but only as a balance between energy consumed, and energy produced, or carbon emissions generated, and carbon emissions avoided.

Table 2: list of definitions for ZCBs find in the literature

Definition	**Description**	**Reference**
Zero Emission Building	Zero carbon emission released into the environment	[D'Agostino & Mazzarella, 2019]
Australia Zero Carbon Building	A zero-carbon building is one that has carbon emissions from the operation of building-incorporated services such as thermal envelope (and associated heating and cooling demand), water heater, appliances, shared infrastructure, and installed renewable energy generation. Zero Energy Building must meet specified standards for energy efficiency and on-site generation.	[Bortoluzzi et al., 2019]
Net Zero Energy Emission	A net zero energy emission building produces at least as much emissions-free renewable energy as it uses from emissions-producing sources	[Ascione et al., 2017]
Zero Carbon Building	A building with zero net energy emission	[Iyer-Raniga, 2019]
Zero Carbon Building	A building with its defined system boundaries with net zero carbon emissions on an annual basis during the operational stage of this building. The system boundaries should be defined in terms of technical components of the definition within relevant contexts	[Pan & Pan, 2019]
Net Zero Emission Building	The balance is measured in terms of greenhouse gas equivalent emissions during the lifetime of a building, instead of energy demand and generation.	[Andresen et al., 2019]

Once ZCBs and ZEBs are defined, it is possible to draw some conclusions about their hierarchy. The definition of ZCBs is the most generic one and it comprehends all the other definitions. One level below, there are the definitions of ZEBs and Net ZCBs, since both are more specific on what needs to be considered. The third level of definitions is related only on ZEBs, since it contains even more specific definitions that are based on which technology is adopted. The results of this hierarchy are shown in *figure 3*.

In *figure 4* and *figure 5* are shown the ideal concept of a ZEBs and ZCBs respectively.

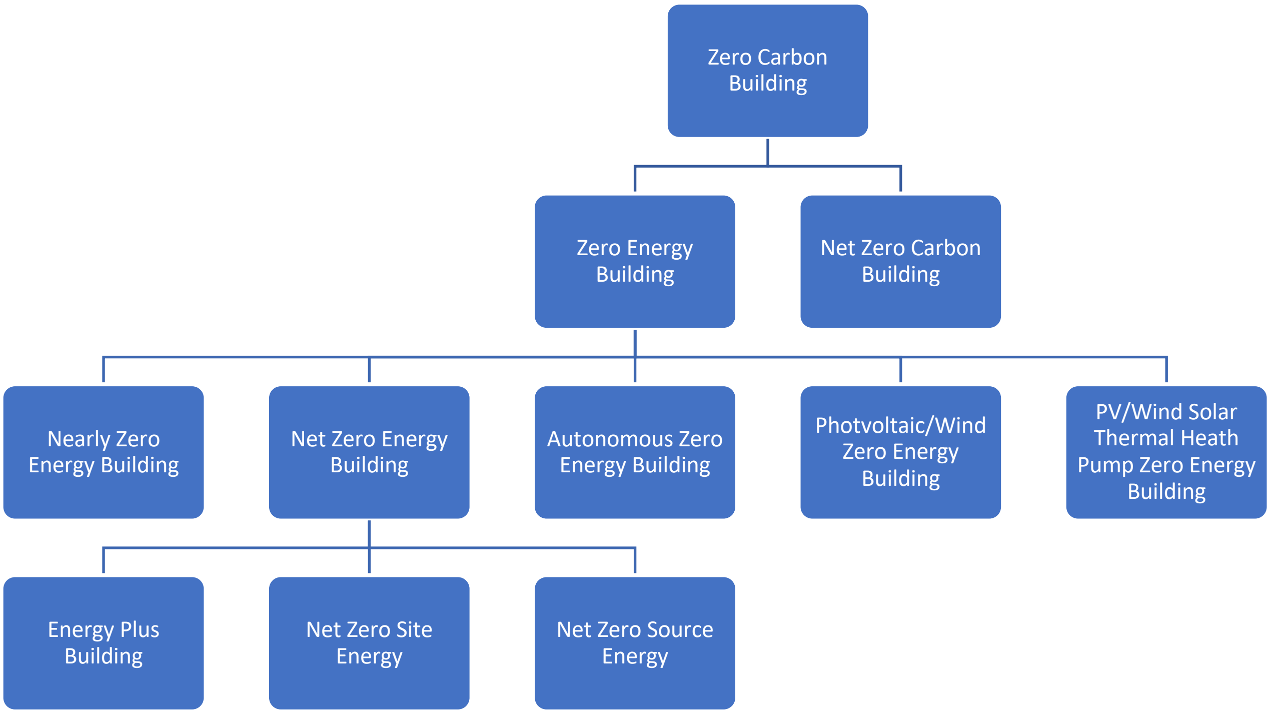


Figure 3: Hierarchy of definitions

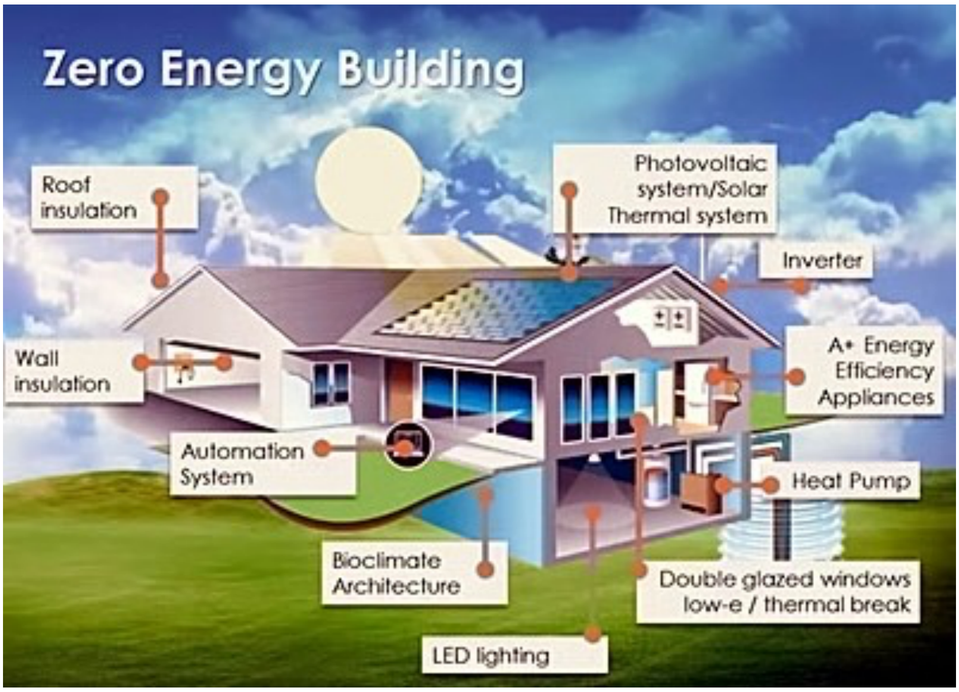


Figure 4: Design of a Zero Energy Building – source: [Awad, 2018]

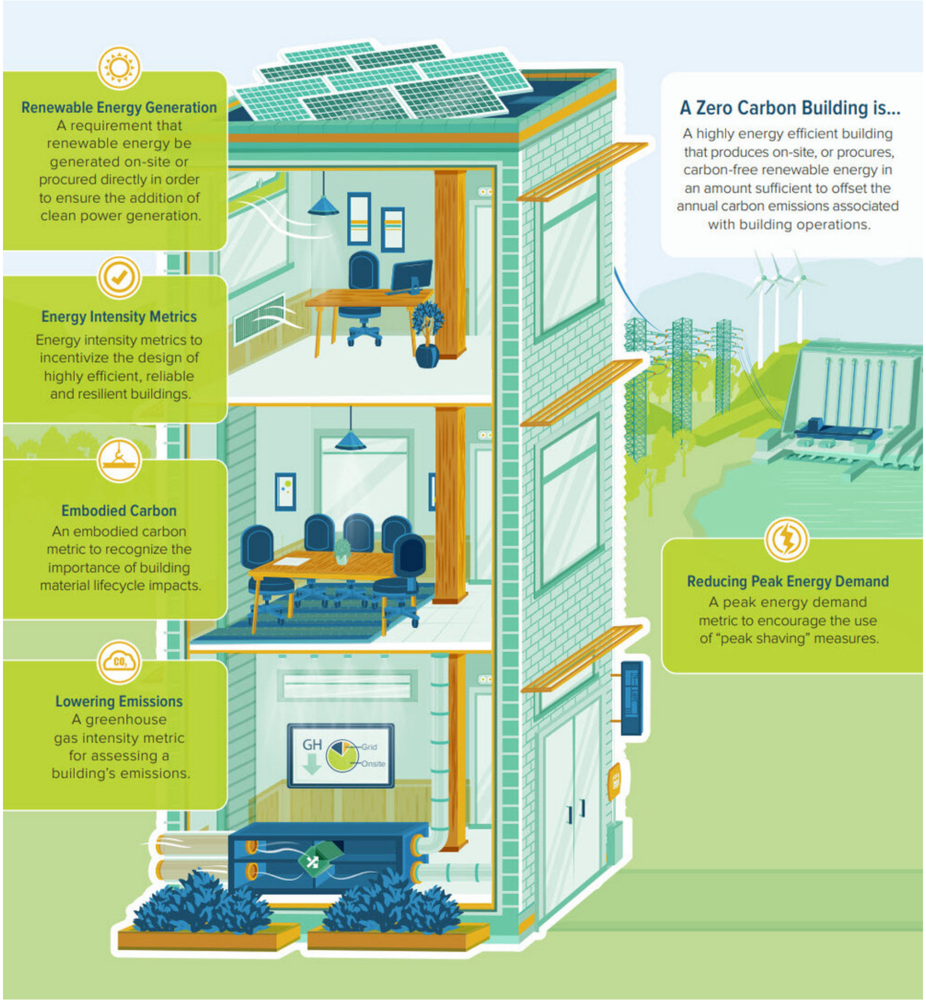


Figure 5: Design of a Zero Carbon Building - -source: [TMD STUDIO LTD, 2020]

3 Literature Review of CE-related practices in the Build Environment

3.1 Methodology

The research questions that this thesis aims to answer are:

- How circular economy practices can foster carbon neutrality?
- What are the drivers and barriers of Zero Energy Building and Zero Carbon Building?

In order to find the answer to these questions a literature review on *Scopus* has been conducted.

The first step was the search of *Circular Economy* applied to the Construction Industry. A very high number of papers was found, so to shrink the number of elements, different criteria were selected:

- Years.
- Language.
- Type of document.
- Keywords selected:
    - Building/Buildings

- Architectural Design
- Construction Industry
- Environmental Impact
- Energy Efficiency
- Sustainability

The year was limited from 2010 and 2020; the number of papers comprehended from 2010 and 2020 was the 90% of the totality, which is reasonable number to conduct a research with. In addition, this is a field that is continuously evolving, and the risk of selecting old papers was to consider technologies or practices that now may be obsolete.

The type of document selected are article, book chapter and review, while the language has been limited to only English articles, since all the major results in the scientific field are published in this language, all the search criteria are summarized in *table 3*.

The research on *Scopus* was the followings:

TITLE-ABS-KEY (*"CIRCULAR ECONOMY"* AND (*"CONSTRUCTION INDUSTRY"* OR *"CONSTRUCTION SECTOR* OR *"BUILDING INDUSTRY"* OR *"BUILDING SECTOR" OR "BUILD ENVIRONMENT"*)) AND (LIMIT-TO (PUBYEAR , *2021*) OR LIMIT-TO (PUBYEAR , *2020*) OR LIMIT-TO (PUBYEAR , *2019*) OR LIMIT-TO (PUBYEAR , *2018*) OR LIMIT-TO (PUBYEAR , *2017*) OR LIMIT-TO (PUBYEAR , *2016*) OR LIMIT-TO (PUBYEAR , *2015*) OR LIMIT-TO (PUBYEAR , *2014*) OR LIMIT-TO (PUBYEAR , *2013*) OR LIMIT-TO (PUBYEAR , *2012*) OR LIMIT-TO (PUBYEAR , *2011*)) AND (LIMIT-TO (DOCTYPE , *"ar"*) OR LIMIT-TO (DOCTYPE , *"re"*) OR LIMIT-TO (DOCTYPE , *"ch"*)) AND (LIMIT-TO (LANGUAGE , *"English"*))

The string *"CIRCULAR ECONOMY" AND ("CONSTRUCTION INDUSTRY" OR "CONSTRUCTION SECTOR" OR "BUILDING INDUSTRY" OR "BUILDING SECTOR")* was used because of the multiplicity synonyms for both construction and industry and to be sure that no relevant work was left out from the research.

In parallel to the search on *Scopus*, a more traditional research was conducted on the internet about the work of the major consultant companies (*Accenture, Deloitte and McKinsey*) on the circular economy applied to the construction industry. No relevant papers were found.

A total number of 173 papers was found. All the important information, such as year of publication, title, abstract and author keyword, of the papers from *Scopus* have been saved into a database on *Excel*.

The literature review for this section was conducted in November 2019, but since this topic is becoming more and more relevant, it is more likely that conducting the same research eventually will lead to more results.

A preliminary selection based on the abstract was conducted in order to evaluate whether or not the paper was relevant for the scope of the work. Of these, 71 papers were excluded. The main reasons of exclusion were the following:

- the world building was not intended as edifice, but as a verb, to build something.
- the circular economy aspect was not addressed

- physical and mechanical properties of materials
- the focus of the study was at city level
- identification of indicators
- implementation of different practices or technologies not related to the circular economy

The next step was to go through each paper to ensure its availability and that the information was relevant for the purpose of this work. 24 papers were excluded because of their impossibility to be downloaded, even with the access provided by the Politecnico of Milano. 13 more papers, instead, were excluded because the information reported addressed the circular economy topic only in a superficial way and did not help answering any of the research questions.

A further division is made among the relevant papers: papers that address their scope in a theoretical way and case studies; the first category comprehends 40 papers, the second one 25, for a total of 65 papers. The flowchart of selection process is described in *figure 6*.

Table 3: search parameters

Search Parameter	**Decision Driver**
Limit the search starting from 2010	2010 was the threshold for the minimum number of total papers that should be considered
Included all the papers that address at least one of these approaches: • Theoretical study of a technology or practice • Case study of a practical implementation of a technology or practice • Barriers to circular economy • Sources of carbon emissions	The aim of this thesis is to understand the differences between the technology and practices in the theoretical framework and the ones that are actually put in practices
Inclusion of all possible synonyms	The word “building” has different synonyms, and the same is true for “industry”, they all have been included in the search, in order to not lose important data

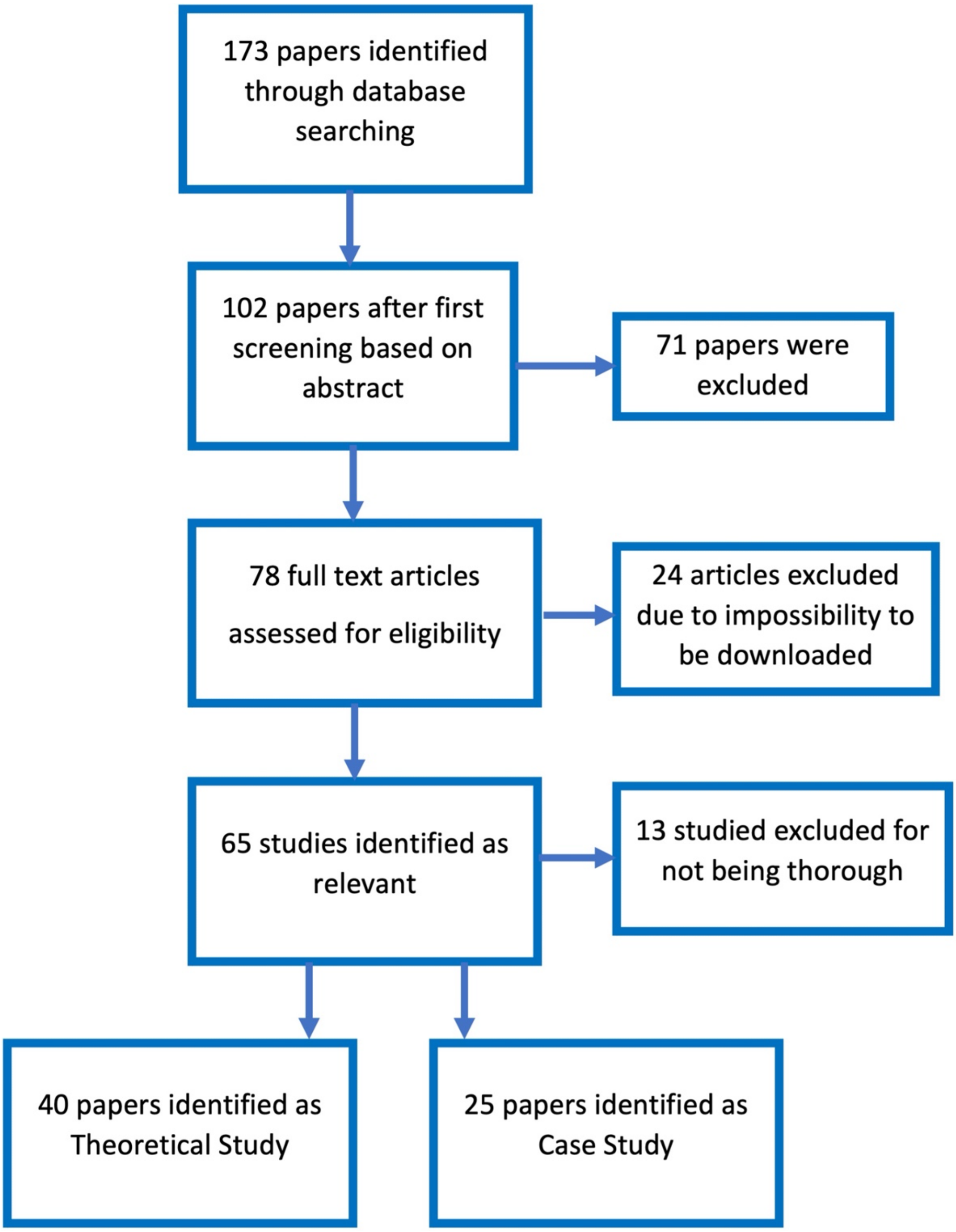


Figure 6: flowchart explaining the decision process

3.2 Literature Analysis Framework

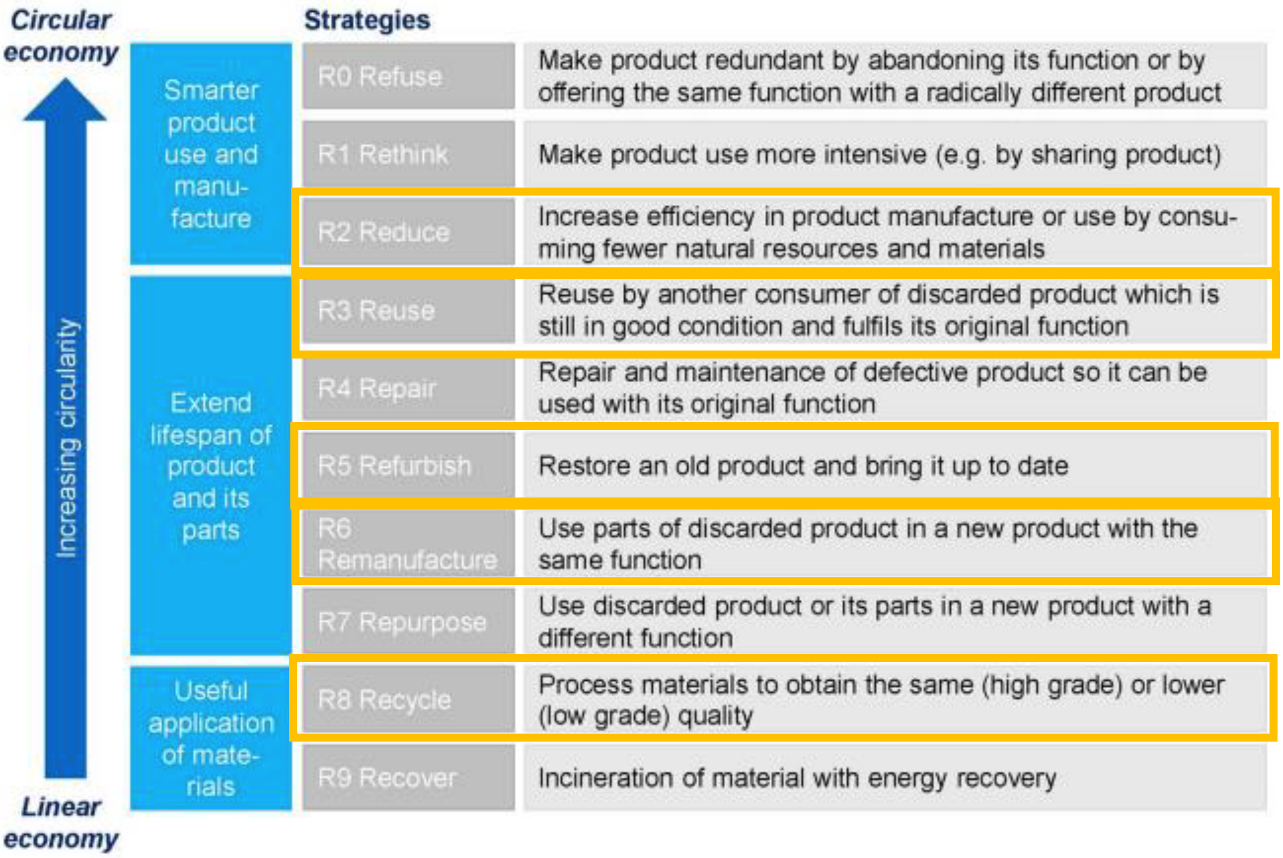
Once the final number of papers has been defined, the last step was to extract all the relevant information from the articles regarding which CE technologies and practices are being studied in the literature. With the terms "technology" are intended all the equipment and tools installed in a building (i.e., photovoltaic panels, systems to produce energy on site, …), while with the term "practice" are intended all the procedures put in practice (i.e. reduction of materials used, …) in order to reduce the carbon emissions produced during the construction of a building. Then, the practices and technologies were categorised against the following dimensions: lifecycle stages, type of resources, and CE strategy. Each dimension is explained in the following paragraphs.

The first dimension is the life cycle stage(s) for which a practice/technology is applicable. The life cycle stages division is based on the work of Huovila, Iyer-Raniga, & Maity (2019). They identified 6 stages (manufacturing of building materials, design, construction, operation and use, renovation, and end-of-life), which were discussed in chapter 2. It is important to consider this dimension to see which are the stages that are currently investigated more, because each life cycle stage has a different impact on the amount of emissions released by a building.

The second dimension consists in the resources taken in consideration by the papers, the resources are grouped in three categories: energy, materials and water. For energy is intended the energy that is used to perform any activity during each of life cycle stage described above; materials are all the physical resources involved in the construction process; while for water is intended all the water consumed during the construction or tearing down of the building or during its use. The importance of this dimension is due to the fact that the manufacturing of building materials is one of the two most polluting life cycle stages, and it is useful to investigate solutions that might reduce the amount of carbon emissions associated to this stage.

The third dimension is the CE strategies. The implementation of circular economy practices relies on the 9R model presented in *figure 7*, but for what concern the scope of this thesis and the interest of construction industry the circular economy practices considered are less (*figure 7*, yellow squares). The reasons behind the elimination of the other strategies are the following:

- Refuse: unfortunately, the function of buildings cannot be abandoned, especially for what concern residential ones.
- Rethink: a more intensive use of buildings is more difficult to achieve than other products such as cars, mainly due to their function and time of use, However, a small step has been done in this direction with the renting of spaces that act as office.
- Repair: the repair of a building is a small intervention and does not have the same impact of the repair other products. The strategies of refurbishment and remanufacturing are considered more suitable for buildings.
- Repurpose: after conducting the literature review, it emerged that wastes coming from the construction industry do not find place in the manufacturing of materials different than building components.
- Recovery: the incineration of building components with the aim of recovering energy is a more difficult process than recovering energy from other objects,



	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Figure 7: circular economy principles [Kirchherr, Reike, & Hekkert, 2017]

Seen from the perspective of buildings the circular economy practices can be defined as follow:

- Reduce: increase of efficiency of the manufacturing of materials in order to reduce the waste generated and to consume less materials in the process. Efficiency has to be pursued in all life cycle stages of a building.
- Reuse: reuse of a discarded building component, either structural or internal, that is still in good condition and there is no need of remanufacturing it.
- Refurbish: restoration of an old building with the purpose to bring it up to date.
- Remanufacture: similar to reuse, but components are not in pristine conditions and need to be remanufactured before reuse.
- Recycle: process through which is possible to obtain an object with same or lower quality, this process can involve the use materials coming from different sectors.

This division has been made in order to understand what CE practices and technologies have been applied in the construction industry, in which categories is put more effort and in which ones there is still room for improvement.

3.3. Literature review results

Looking at the data gathered, some information can be drawn. First, it is worth showing that the number of articles that are published on *Scopus* every year. As can be seen from *figure 7,* the number of papers on *Scopus* is increasing over the years, this means that the circular economy practices in the construction industry is a topic that is gaining more and more interest.

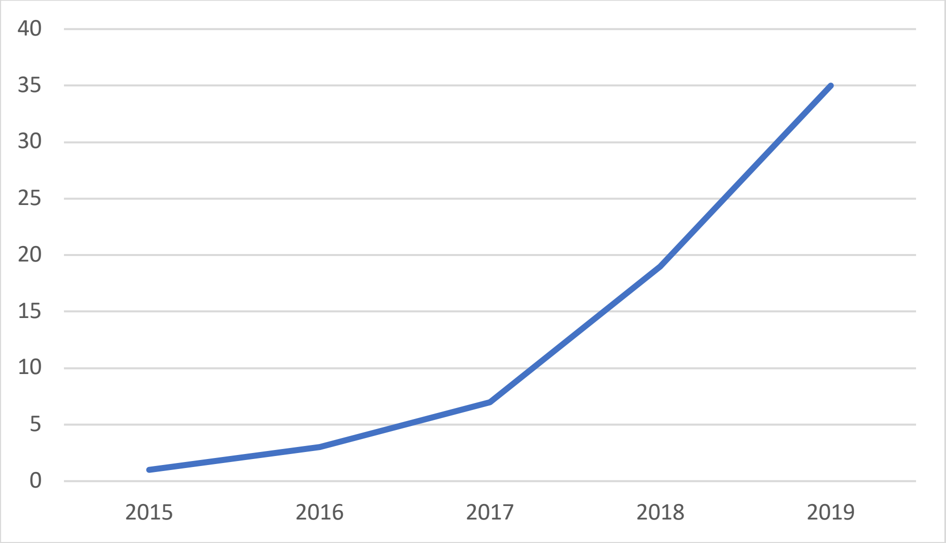


Figure 8: Number of Papers over the years

For what concern the division of the resources used, as can be seen from *figure 8*, almost the totality of paper is addressing the circular economy topic in the building industry from a material perspective, while only one study is addressing it from the point of view of the use of water. The explanation of this distribution is quite simple, since the construction of buildings is very materials demanding, while water is not as much important.

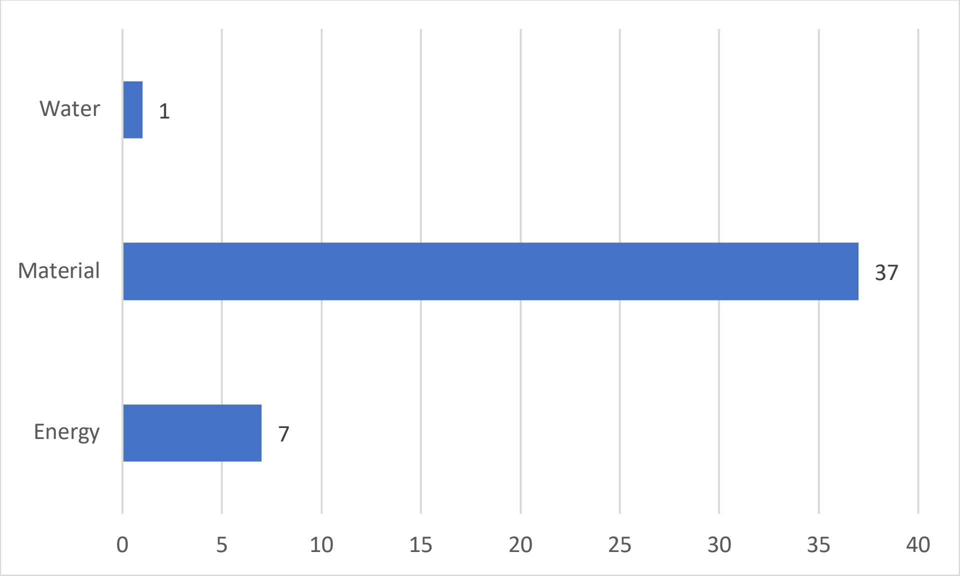


Figure 9: Number of papers per resource

The same consideration done for the resources used is also true for the life cycle stages. As previously stated, buildings are resources demanding, for this reason more than half of the life cycle stages tackled by the article's focus are the demolition and the manufacturing of the materials phase.

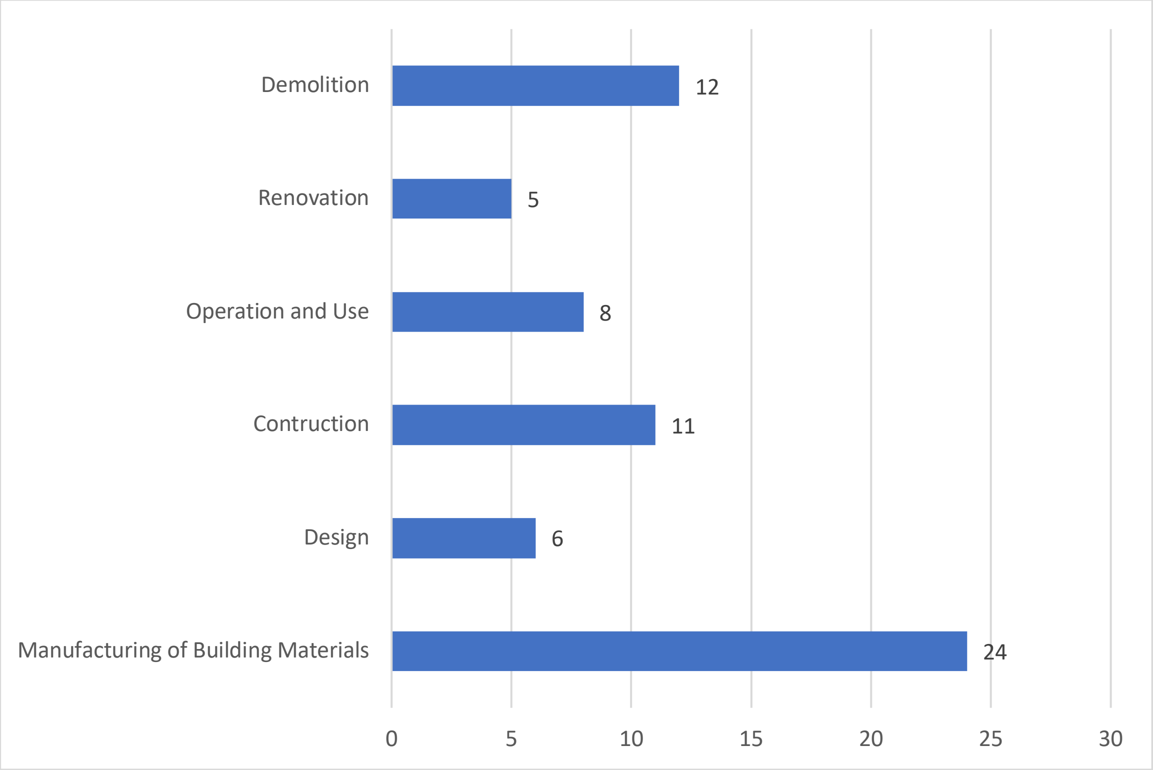


Figure 10: Number of Papers per Life Cycle Stage

The total number of resources is greater than the total number of papers, that is because a study may work on more resource at the same time, same for what concern the life cycle stages.

The practices and technologies found in the literature review were clustered within each life cycle stage and the result is shown in *table 4* and *table 5*.

Table 4: CE practices and strategies mentioned in conceptual Studies

Manufacturing of Building Materials	**Design**	**Construction**	**Operation and Use**	**Renovation**	**Demolition**
Reuse of Water	Design for X	Material Passport	HVAC (Heating, Ventilation and Air Conditioning)	Adaptive reuse	Design for Disassembly
Use of different materials	BIM (building Information Model)	Prefabricated elements	Renewable sources of energy	Substitution of old elements with newer ones	Modular Building
Recovery of materials from waste	Modular Buildings		Use of batteries coming from EVs		Material Passport
	Virtualization		Green Façades		
	Material Passport				

Table 5: CE practices and strategies mentioned in Case Studies

Manufacturing of Building Materials	Design	Construction	Operation and Use	Renovation	Demolition
Use of Different Materials	Design for X	Demountable Walls	Renewable sources of energy	Reuse of materials	Collection of reusable building components
Recycle and Reuse of materials	Reduction of spatial needs		Green roofs	Reuse of existing buildings	Design for disassembly
	Modular Buildings				Management of waste at local level
					Demountable Walls

As can be seen from *Table 4* and *Table 5*, different solutions may act on more than one stage, meaning that with a single solution is possible to address the carbon emissions released during different stages.

In the next table for all the solution founded are indicated which circular economy strategy they refer to, which resource they address, in which Life Cycle Stage can be applied, and how relevant to reaching carbon neutrality each practice is.

Table 6: circular economy practice and relevance to decarbonisation of each solution

Solution	CE Strategy	Material/Energy/Water	LC stage	Relevance to carbon neutrality [1]
Reuse of Water	Reuse	Water	Manufacturing of Building Materials	***
Use of different materials	Reuse Recycle Remanufacture	Material	Manufacturing of Building Materials	***
Recycle and Reuse of materials	Reuse Recycle	Material	Manufacturing of Building Materials	***
Recovery of materials from waste	Reuse Recycle	Material	Manufacturing of Building	***

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[1] The number of * indicate the relevance to carbon neutrality, * = low relevance, ** = medium relevance, *** = strong relevance

			Materials, Demolition	
Design for X	Reduce Reuse	Material	Design	**
Virtualization	Reduce	Material	Design	*
Modular Buildings	Reduce Reuse	Material	Design, Demolition	*
BIM (building Information Model)	Reduce	Material	Design, Demolition	*
Material Passport	Reuse Recycle	Material	Design, Demolition	*
Prefabricated elements	Reduce Reuse	Material	Design, Demolition	**
Demountable Walls	Reduce Reuse	Material	Design, Demolition	**
HVAC (Heating, Ventilation and Air Conditioning)	Reduce	Energy	Operation and Use	***
Renewable sources of energy	Reduce	Energy	Operation and Use	**
Green Façades	Reduce	Water	Operation and Use	**
Green roofs	Reduce	Energy	Operation and Use	**
Adaptive reuse	Reduce Reuse	Material, Energy	Operation and Use, Demolition	***
Substitution of old elements with newer ones	Refurbish	Material, Energy	Renovation	***
Reuse of existing buildings	Refurbish	Material	Demolition	***
Collection of reusable building components	Reuse Remanufacture	Material	Demolition	**
Management of waste at local level	Reduce Recycle	Material	Demolition	**

In the paragraphs below each section will be commented superficially, while each technology or practice will be presented deeply in the next chapter.

Manufacturing of Building Materials

In this section the technology and practices have two objectives: either they aim at reusing materials coming from waste in order to reduce the amount of virgin materials extracted, or they want to substitute the current materials employed in the construction of building with materials that have a lower amount of carbon emissions embedded. From the literature two approaches emerged, technologies and practices that address the circular economy within the construction industry and others that try to tackle the circular economy by using by-products from other sector, such as paper industry. The most common CE strategies on this stage focus on the recycle of construction and demolition waste, the finding of suitable secondary materials that have a low of carbon emissions associated, or the reuse of secondary materials coming from different sectors.

Design

In this stage, the building and all its characteristics are designed. From the literature emerged that buildings are now designed with different scope in mind, such as design for disassembly, in order to be easily dismantled, or design for recycling, in order to recycle the majority of materials used, and so on. Modularity is an aspect that is becoming more and more popular, modular buildings can be dismantled easily, but they can also be expanded without effort.

Construction

The technologies and practices in this section aim at reducing the amount of waste generated during the construction of a building. Additionally, buildings can be seen as material banks, so it is important to keep track of the amount of materials used in order to make easier the demolition phase. The most common solution in this stage is the use of material passport that allows the materials present in the building to be easily identified and reused and recycled.

Operation and Use

This phase is the one that takes the majority of the life cycle of the building. In this stage the focus is aimed at optimizing the energy used during the occupation of the inhabitants. Renewable energy sources are preferred over fossil fuels, and high energy efficient technology are installed. Also, strategies focusing at compensating the embodied carbon emissions of the building are rising. The most common practice is the installation of high efficient heating and air conditioning systems, in order to increase the energy efficiency of the building a reducing the demand of energy.

Renovation

In this phase older buildings are brought back to new life, thanks to the substitution of obsolete materials to more efficient ones and the implementation of newer technologies. Newer materials may come from freshly manufactured materials or from demolished buildings. In this stage all the previous solutions are considered, the renovation of the structure is conducted with the use of sustainable materials, the insulation is efficient, and the supply of energy comes from renewable sources.

Demolition

The demolition phase is the end of life of a building, in this phase a building is teared down in order to make space for other infrastructures. Management of waste at local level is crucial; the technologies and practices in this stage focus on finding the optimal strategy to recover materials that will require the minimum amount of work in order to be put back into flow. The most common solutions contemplate the deconstruction of the building while preserving the value of materials in order to reduce the eventual manufacture process before being reused.

4 Relevance of Circular Economy practices for Carbon Neutrality

4.1 Approaches to implement circular economy

In this section all the papers identified as relevant at the end of literature review are analysed in a deeper way, showing which are the area in which is possible to achieve carbon emissions savings. They have been categorized according to the life cycle they were thought for, and for each solution, after its description, is indicated in a qualitative or, if possible, quantitative way the reduction of emissions.

4.1.1 Manufacturing of building materials

As previously stated, the manufacturing of building materials is one of the main sources of carbon emissions, mainly because of the production of concrete. In order to make up for these emissions in the literature are studied different solutions to make the concrete a more sustainable material, by limiting the extraction of virgin raw materials. This is primarily done by implementing environmental friend materials, such as natural and renewable materials, or by implementing materials coming from waste both from construction industry and other sectors that otherwise would be disposed in a landfill.

Nußholz et al. in their work identied the main factors that influcence the carbon savings related to the manufacturing of building materials: geographic proximity to the site of production is significant, also the ratio of substutution (the amount of concrete aggregates that are replaced with secondary materials) is crucial as well. For C&DW that can be reintroducted in the supply chain the recycling rate is the key factor for carbon emissions savings [Nußholz, Nygaard Rasmussen, & Milios, 2019].

Concrete is produced by mixing together, cement, aggregates, and water. CE solutions in the manufacturing focus mainly on the reduction of emissions associated to the production of water and aggregates. While, for what concern the use of low carbon embodied materials, the main substitute is timber.

4.1.1.1 Reuse of water

Along with cement and sand, water is one of key components in the preparation of concrete mix. In order to produce strong and lasting concrete, water has to have a low level of impurities, so water types such as drinking water are good to be used in mixes. To avoid the use of potable water in the construction industry, Magro et al. evaluated the use of electrodialytic technology to purify water and eventually use it in the construction industry. Electrodialytic technology is the application of low-level current density to water in order to remove both organic and inorganic contaminants in sewage sludge from wastewater treatment plants [Magro, Paz-Garcia, Ottosen, Mateus, & Ribeiro, 2019].

The aim of this technology is to clean wastewater from impurities in order to later use it to produce cements for the building industry.

In the work made by Magro et al. it is shown that after the Electrodialytic process, the anions removed were comprehended in a range between 85 and 99.7 percent and that the optimal results are achieved within 6 hours [Magro et al., 2019].

Once the water has been purified its effect on cement paste was studied. In order to see if water obtained from this process can be effectively used in the cement manufacturing process, different characteristics needed to be analysed: setting time and workability, flexural strength, compressive strength and morphology.

Findings from the work of Magro et al. show that cements obtained from water purified by Electrodialytic technology have a high workability and compressive strength, and results are reported in *figure 10*, meaning that cements manufactured with water after an Electrodialytic treatment can be implemented on a large scale. In their work, different waters were analysed: after 6h, 12h and 24h of Electrodialytic treatment, and from results it is shown that after 6h of treatment water can still achieve acceptable mechanical properties, this means that there is no need to use more energy for the longer treatments [Magro et al., 2019].

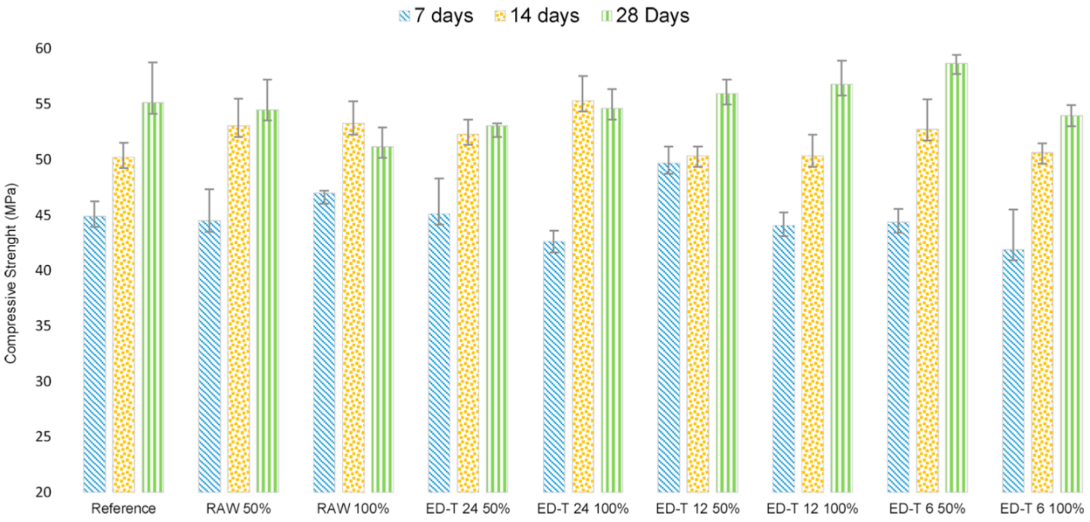

Figure 11: Compressive strength of age 7, 14 and 28 days using: tap water (reference), raw effluent (50 and 100% replacement) and effluent with Electrodialytic treatment (6, 12 and 24h – 50% and 100% replacement)

4.1.1.2 Use of different materials

Construction and Demolition Waste

The first line of action is to close the loop within the building sector by reusing, recycling and remanufacturing construction and demolition waste (C&DW). The C&DW can be divided into three categories: inert waste, non-inert waste and contaminated waste [Ghisellini, Ji, Liu, & Ulgiati, 2018]

Inert waste includes concrete, blocks and mortars and are the majority of C&DW, in China inert waste represent the 85 percent of total C&DW. They are the main source of materials in order to produce aggregates; it is estimated that for each ton of C&DW it can be produced up to a ton of 0.9 ton of recycled aggregates [Ghisellini et al., 2018].

The generation of C&DW is affected by internal and external factors; internal factors are age, category, geometrical characteristics, structure and construction technologies; external factors are population growth, GDP growth, legislation, and technology development of construction and demolition activities [Ghisellini et al., 2018].

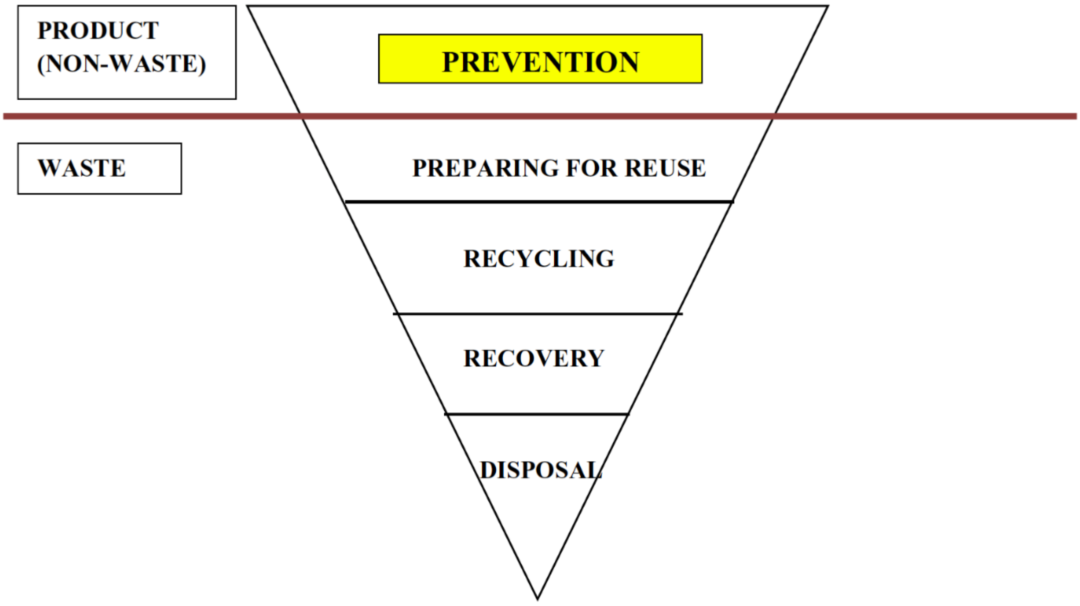

Figure 12: Waste management strategies hierarchy. Source: European Commission 2016: http://ec.europa.eu/environment/waste/framework/.

The techniques of sustainability in C&DW follow the waste hierarchy as showed in *figure 11*. The best practice to pursue is preventing the generation of waste in first place; reuse is preferred over recycling because it does not require energy for further manufacturing of materials. If neither of these two options is suitable the recovery of thermal energy is preferred over disposal in landfill.

The use of C&DW has a double effect: first it helps in reducing the emissions and energy use, second it reduces the amount of waste that goes to landfill. The implementation of C&DW in the manufacturing of building materials process has also economic benefits since it reduces the cost of the disposal of the waste [Orsini & Marrone, 2019].

Along with the reuse and implementation of materials coming from within the building industry, several studies are examining the application of materials coming from industries different from construction. New materials created from C&DW are called recycle aggregates [López-Uceda et al., 2018].

Timber

Timber is currently largely used in the construction industry, it is estimated that its usage is within the range of 2.4-4.0 tonnes per capita; however, in some countries the timber harvested is greater than the forest stock production [Rose et al., 2018]. The use of timber is preferred because in the initial phases, which are also the most critical ones, it emits less carbon emissions with respect concrete and steel. An additional benefit is that during its life cycle, before it is harvested to produce building materials, it subtracts carbon dioxide from the atmosphere thanks to photosynthesis. For this reason, timber is considered a “carbon sink” and it acts like a carbon storage [Robati, Oldfield, Nezhad, Carmichael, & Kuru, 2021].

The use of cross laminated timber in construction industry is growing, and this trend will grow exponentially in the future years. In their work D’Amico et al. analysed the use of hybrid cross laminated timber, a cross laminated timber slab with a steel reinforcement, as a substitute material of the most common steel and concrete. They estimated that within with the use of only steel frame structure buildings the carbon emissions released in the atmosphere will be in the range of 171-303 Mt of CO_2e. If the construction industry will shift towards more sustainable choices like the hybrid cross laminated timber, the level of carbon emissions released will be significant lower. In their scenario the carbon emissions released by the use of timber will be in the range of 142-229 Mt of CO_2e, that in mean value terms is a reduction of 22 percent [D’Amico, Pomponi, & Hart, 2021]

In order to avoid further extraction of new timber and to minimize waste produced, reuse of timber coming from building demolition (secondary timber) is strongly recommended. Preparation of cross-laminated secondary timber is as equal as possible to manufacturing process of cross-laminated timber. An adhesive is used to glue together the lamellae and panels, and a machinery is used to cut the boards [Rose et al., 2018]. Once the cross-laminated secondary timber is manufactured, the load on the three axes of a cubic specimen of 85mm per edge was tested. The results showed no differences from the reference values, although stiffness may be affected by the aging of crosswise lamellae, for this reason Rose et al. suggested in their work that for the construction industry projects a combination of both secondary and primary timber has to be nurtured [Rose et al., 2018].

Robati et al. in their work evaluated the savings associated to alternative materials for the production of buildings. The base scenario was a residential building, with some space dedicated to retail and offices. The total embodied carbon emissions are 32.446 tCO_2e. In the scenario that evaluated the savings associated to the use of timber as main component; due to the height of the building, the wood structure is reinforced with a core made of concrete. However, it emerged that this scenario had a total of 28.208 tCO_2e, which results in a 13 percent less embodied carbon emissions associated with respect the base scenario. The results showed that the use of timber is not only better from an environmental point of view, but it actual more convenient from an economical point of view, in fact the base scenario has a total capital cost of 63.56 mln AUD, while the timber one has a total capital cost of 60.7 mln AUD [Robati et al., 2021].

4.2.2.2 Materials outside the building sector

With the scope of reducing the carbon emissions related to the manufacturing of cement, several substitute materials are taken into account. The main candidates as substitutes are by-products coming from different industries [Orsini & Marrone, 2019]. These materials are: coal fly ash, a by-product of combustion of pulverized in thermoelectric plants; silica fume, a by-product of metallic silicon and iron-silicon alloys; granulated slag, a by-product of cast iron production process [Orsini & Marrone, 2019].

In order to evaluate if a material is a suitable substitute in the concrete mix some physical properties have to be evaluated.

Setting time is defined as: *"specific time required for concrete or mortar to change from liquid state to a solid state, where the surface becomes sufficiently rigid to withstand a defined amount of pressure"* [Magro et al., 2019].

Workability is defined as: *"a property that directly impacts strength, quality, appearance, and the cost of labour operations; can be divided into three categories (low, medium and high), describing the ability to mix, place, consolidate and finish with minimal loss of homogeneity a mortar preparation"* [Magro et al., 2019].

Flexural strength is *"the ability of a beam or slab to resist failure bending"* and it is a mechanical property [Magro et al., 2019].

Orsini and Marrone in their article pointed out also some risks related to the implementation of substitute materials: possible lower performance with respect of already-tested materials, the lack of knowledge in the production process, and the possible new emissions related to the implementation of activators [Orsini & Marrone, 2019].

Another possible solution studied by Orsini and Marrone is the use of natural materials from the agricultural sector, wood, wool, and hemp. The advantages of using these materials are the ability to absorb part of the carbon during the whole life cycle, the local availability and low cost of the production process. The problems with these materials are slightly lower performances and lack of knowledge in the production process [Orsini & Marrone, 2019].

Steelwork dust

Steelwork dust is a by-product generated during the fusion of scrap and it is mainly composed by heavy metals such as Zn, Pb, Fe or Cd, for this reason it is classified as "hazardous" waste [Lozano-Lunar, Barbudo, Fernández, & Jiménez, 2020].

Approximately the 70 percent of steelwork dust goes to landfill after being treated with cement-based materials in order to prevent heavy metals mobility. In their work Lozano-Lunar er al. highlighted a use of steelwork dust as a substitute of aggregate in the production of concrete [Lozano-Lunar et al., 2020].

The addition of steelwork dust to the mortar mix increased the workability time, but the presence of Zn increased the hydration time. For what concern compressive strength, all mortars with steelwork dust showed a greater compressive strength than classic mix mortars leading to an improvement of mechanical behaviour [Lozano-Lunar et al., 2020].

Considering the fact that steelwork dust is classified as "hazardous waste", an important aspect to consider is leaching behaviour. Among all the test run, whose value are reported in *figure 12*, only the mix containing the highest concentration of steelwork dust (1600g) is classified as "hazardous waste" since it slightly exceeded the limit of leachability for Pb. While all the other mixes (400g and 800g) registered values between the limits [Lozano-Lunar et al., 2020].

Lozano-Lunar et al. concluded their work classifying the mortars as viable for their implementation as secondary raw materials in the construction industry and that further investigation about the leachability of Pb should be conducted [Lozano-Lunar et al., 2020].

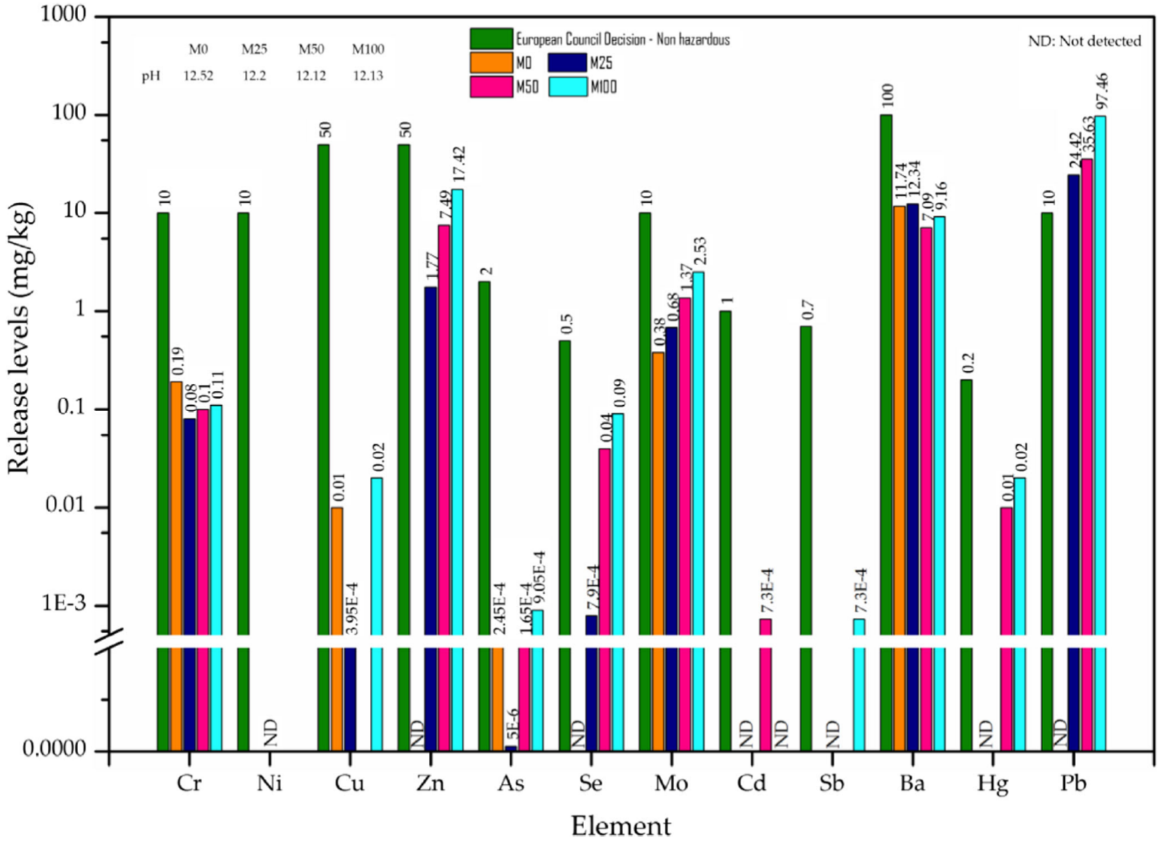

Figure 13: Release level of elements in mortars in accordance with UNE-EN 12457-4 (AENOR 2017) [Lozano-Lunar et al., 2020]

Sugar

In their study Gopinath et al. reviewed the possible uses of sugar industry wastes, in particular they studied the possible application on burnt cane trash and bagasse ash from cogeneration boilers [Gopinath, Bahurudeen, Appari, & Nanthagopalan, 2018].

This possible uses of wastes coming from agro-based industries are the ideal solution for both sectors: currently, the disposal of these residues is a huge concern and their implementation as a replacement in mortar mix would offset part of carbon emissions and it will extract their maximum potential [Gopinath et al., 2018].

Cements manufactured with by-products of sugar industry are reported to have a setting time within the range of acceptability, even though it is slightly higher that the average. This is due to the fact that the sugarcane bagasse contains some juice when it leaves the mill, an additional reason for the longer setting time is that the cellular structure of sugarcane bagasse ash has a high demand for water [Gopinath et al., 2018].

For what concern workability, the replacement with sugarcane bagasse ashes resulted in a reduction of workability, due to the water absorbability, and required the addition of super plasticizer in order to counter that effect [Gopinath et al., 2018].

Along with these benefits, there is one main problem: cements factories and sugar plants are not proximal to each other, this means that the carbon emissions related to the extraction of raw materials for the cement production and compensated by the use of by-products of sugar industry may be nullified by the emissions derived by the transportation of these materials.

Cork

Cork is a natural product usually used to close bottles of wine and champagne. The cork industry can be divided into two types: white cork, generally used in the food sector, and black cork, used in non-food sectors such as the construction [Sierra-Pérez, García-Pérez, Blanc, Boschmonart-Rives, & Gabarrell, 2018]. Black cork in the construction industry is used typically for insulating and flooring purposes. Its application as thermal insulator replaces materials such as polystyrene, extruded polystyrene, foam, fibre glass, mineral wool that have an inorganic and non-renewable origin [Sierra-Pérez et al., 2018].

The environmental assessment conducted in the literature shows that the manufacturing of the insulation boards is where the majority of carbon emissions are concentrated. This is due to the high quantity of energy required to increase the temperature necessary to form the boards. The sustainability of cork derives from its high carbon storage capacity acquired during its cultivation, because part of carbon fixed in the trees is transferred to the cork materials. It is calculated, considering a cradle to gate approach, that the production of the final boards has a final balance of -2.88kg of CO2. Also, the use of cork instead of less sustainable materials helps in mitigating the carbon emissions generate during the manufacturing process [Sierra-Pérez et al., 2018].

Cork is a suitable substitute for traditional insulation materials, for what concern the physical characteristics, but not from an economical point of view. As studied by Sierra-Pérez et al., the cork boards come to the market with a price that is almost double than competitor materials. Also, the capacity of oak forest to produce this material and keep up with the demand for the construction industry has to be considered [Sierra-Pérez et al., 2018].

Hempcrete

Hemp production generates by-products, such as non-eatable oils, unusable fibre in the textile industry and hard hemp, that may find a use in the construction industry. Fibres of hemp can be used for both insulation and reinforcement for plastic or prefabricated materials. Hard hemp is used for insulating production thanks to its lightweight and porosity, but also as insulating materials in closed double walls. Bricks made with hemp are used in self-supporting walls or surfaces with vibro-compression [Aversa et al., 2019].

Aversa et al. conducted tests on four types of concrete considering a cradle-to-gate scenario: hempcrete wall system, AAC wall system (blocks made with cellular concrete), expanded clay wall system (lightweight concrete and expanded clay), and masonry bricks wall system. The results are summarized in *figure 13*; it emerged that hempcrete blocks are a sustainable solution to the needs of buildings. The benefits related are high energy savings, thanks to their better performances as thermal insulating materials, and sustainability of materials due to their natural origin. They also perform similarly to blocks made with traditional materials, while remaining very comparable to concrete wall for what concern size and shape [Aversa et al., 2019].

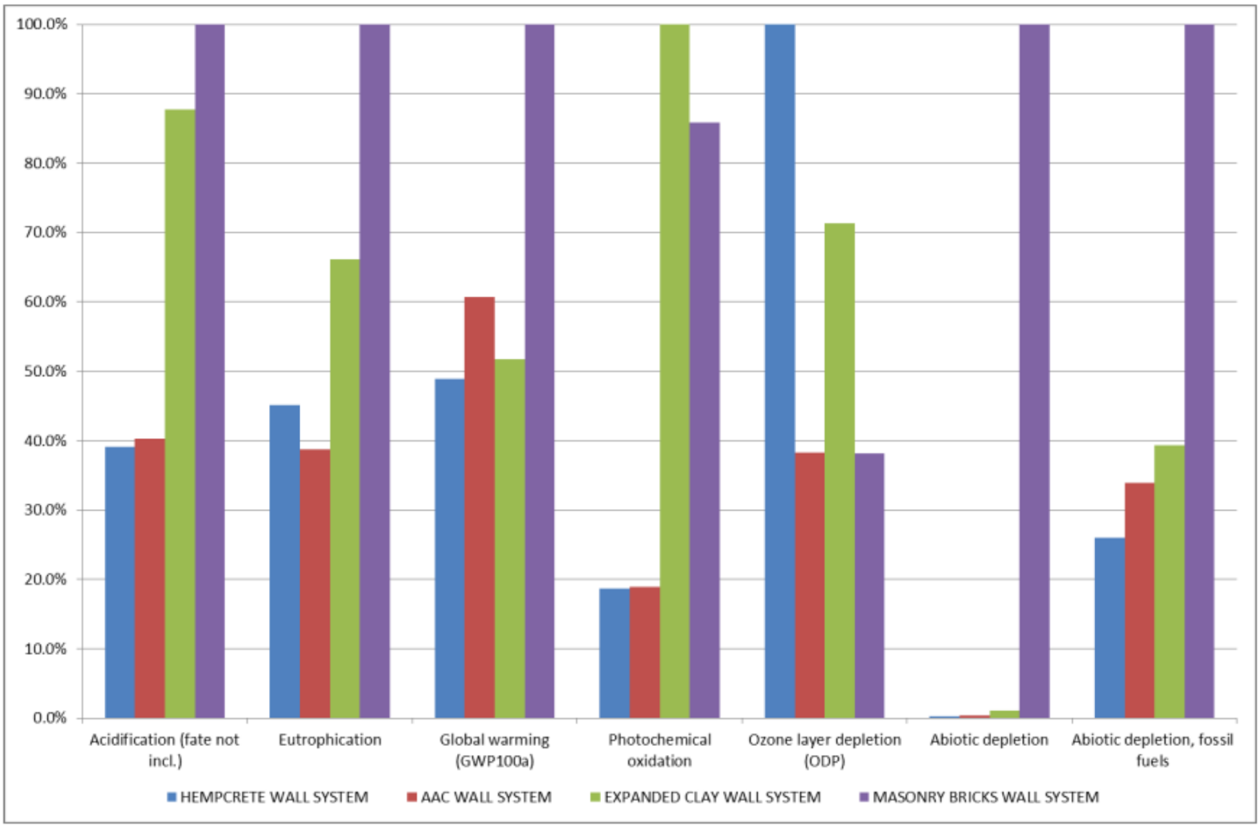

Figure 14: impacts related to the four categories of walls assemblies

Sewage Sludge

Possible substitute materials in cement mix can be recovered from sewage sludge. One of the materials that can be extracted from sewage sludge is cellulose; the amount of cellulose that can be extracted by sewage sludge is linked on the amount of toilet paper consumed. This consumption is related to the degree of urbanization, sewage infrastructure and waste transport of the city and it may be variable amount [Palmieri et al., 2019].

According to the work presented by Palmieri er al., cellulose fibres have a positive effect of the concrete mix for what concern physical properties such as lightweight and flexural strength [Palmieri et al., 2019].

The addition of cellulose fibres to the mix reduced the workability of the mortars, but the overall workability stayed within the boundaries of acceptance. A high presence of cellulose fibres in the mortars caused the formation of pores that lead to an increase of porosity causing a reduction of density, for this reason Palmieri et al. stated that it is better to avoid excessive addition of cellulose fibres to the mix and recommend staying below 20 percent. The presence of cellulose fibres tough led to an increase of flexural strength [Palmieri et al., 2019].

In order to produce 1 ton of mortar with 5 percent of cellulose fibres, it is necessary to use 7.80kg of pure fibres, 6.18kg of fibres coming from newspaper and 5.82kg of fibres coming from wastewater. It has been calculated that from the waste of a medium wastewater treatment plant could be produced from 102 to 356 sacks of pre-mixed mortar daily, whereas a large wastewater treatment plant could produce from 305 to 1069 sacks of pre-mixed mortars per day [Palmieri et al., 2019]. On average a small-medium company that produce cement products generates 800 sack of pre-mixed mortars of 25kg each, this means that a large wastewater treatment plant possibly can fully supply the daily production of a small medium company.

If no other possible treatments can be done to sewage sludge, they are sent to an incinerator for combustion in order to recover thermal energy. The by-product generated is called sewage sludge ash whose composition may vary depending on the origin of wastewater, but the main components are SiO_2, CaO, Al_2O_3, Fe_2O_3, MgO, and P_2O_5 [Smol, Kulczycka, Henclik, Gorazda, & Wzorek, 2015].

Sewage sludge ash can find application in the building industry as components of the mixture for cement production, bearing component of raw material in the production of bricks and ceramic tiles, substitute for sand in the construction of roads [Smol et al., 2015].

In the literature two mixture for mortars were studied: one with sewage sludge ash content of 15 percent and the other with content at 30 percent. The mortars with the mixture at 15 percent showed physical properties such as compressive strength similar to normal mixture, while the mortars with mixture at 30 percent showed a slight decrease of workability due to water absorption by the sewage sludge content, but still within the limits of acceptability. Also, thermal damage caused to the building by the presence of fire decreased thanks to the presence of calcium silicate that strengthen the cement [Smol et al., 2015].

As previously said, sewage sludge ash can be also used to manufacture bricks, and differently from cements, the amount of sludge ash that can be incorporated can be up to 40 percent of total weight. Brick manufactured with sludge ash presented improved physical characteristics compared to traditional composition [Minunno, O'Grady, Morrison, Gruner, & Colling, 2018].

Several benefits are associated to the use of sewage sludge ashes in the construction industry: reduction of cost of landfill, reduction of possible leaching of liquid constituents, reduction of energy consumption related to the transformation of wastes into raw materials [Smol et al., 2015].

According to different authors sludge ash waste can replace up to 20 percent of raw materials necessary to manufacture cements [Smol et al., 2015].

Paper-Pulp

In the paper-pulp industry two common solid waste that are disposed in landfills are lime slaker grit and biomass fly ash. The European community has recently discouraged such practice due to the high risk of water and soil contamination. Since they do not contain an high amount of organic components or hazardous elements, the solution found is their employment as aggregates in the preparation of mortar mix in the construction industry [Saeli et al., 2019].

In the work presented by Saeli et al. three different mix were tested: only grits, sand and grits, and only sand as a benchmark. In the results presented, the mix containing only grits presented a slight increase in the setting time due to availability of free water that makes the paste more fluid. The main issue is the insufficient workability, but this is a parameter that can be adjusted with the adoption of specific chemicals. However, this does not prevent the application of grits mix in the construction industry [Saeli et al., 2019].

4.1.2 Design

4.1.2.1 Design for X

The design of a building is the preliminary step in its life cycle, for this reason in this phase it is important that the design team chose the optimal solution for the reduction and limitation of emissions during the whole lifetime, especially in those phases that are critical under this aspect. It is important to define key sustainable goals and establish different targets that alternative solutions can accomplish [Andrade, Araújo, Castro, & Bragana, 2019].

According to Castro et al. there are three main areas designer can focus on: design for change, design for resource efficiency, and use of materials with low-embodied carbon [Castro & Pasanen, 2019].

Design for change is intended as the design of interior space plan, services and the building skin, elements that will face a change in the near future to adapt to the users' needs. The design of these elements focuses more on easy disassembly and material recovery [Castro & Pasanen, 2019].

Design for resource efficiency is the design for materials with long service life such as floor slabs, structural frames; the aim is to minimize the amount of materials used in the production and also the amount of materials that will be part of the building [Castro & Pasanen, 2019].

Use of materials with low-embodied carbon means designing the building with the aim of employing recycled materials in order to reduce the carbon footprint of the building [Castro & Pasanen, 2019].

<u>Design for recyclability</u>

In a product not all components can be reused or repaired, and buildings are no exception, so an important aspect is to design these components with a particular attention toward their recyclability, preferring materials that can be recycled over materials that can only be disposed in landfills. In buildings concrete and steel are among the most used materials and can be both recycled at the end of life of a building. Concrete can be separated from the structure and crushed to become a substitute of virgin raw materials, while steel can be melted and reshaped into new products [Minunno et al., 2018].

<u>Design for adaptability</u>

Adaptive reuse is *"a process to improve the financial, environmental, and social performance of buildings, it involves restoring and in some cases changing the use of existing buildings that are obsolete or are nearing their disuse stage"* [Sanchez, Esnaashary Esfahani, & Haas, 2019].

The aim of adaptive reuse is to reduce the amount of materials that go to landfills, reduce the amount of resources by maximizing the use and recycle of materials, reduce the demand of energy in the manufacturing of building materials stage, decrease the amount of greenhouse gas emissions and save embodied energy [Sanchez et al., 2019]. The way to achieve all these objectives is thanks to the life extension of components [Minunno et al., 2018].

According to Sanchez et al. the implementation of adaptive reuse on a building leads to around 35-38 percent in energy savings for what concern Primary Energy Demand, Global Warming and Water Consumption. Along with environmental benefits, there are also possible monetary savings, the study revealed that the construction cost could be reduced up to 70 percent [Sanchez et al., 2019].

The main barriers for the implementation of adaptive reuse are: high remediation cost and construction delays, technical difficulties for refurbishment works, and lack of skilled tradesmen [Sanchez et al., 2019].

Design for Deconstruction

Before the deconstruction takes place, the potential allocation and reusability of all components must be planned [Cai & Waldmann, 2019]. The selective deconstruction approach follows four steps [Gálvez-Martos, Styles, Schoenberger, & Zeschmar-Lahl, 2018]:

1. Dismissal of all hazardous substances such as asbestos.
2. Dismantling of re-usable parts such as glass, wood, sanitary ware, and radiators.
3. Removal of floor covering, ceiling, and combustible and non-combustible waste.
4. Recovery of wooden beams and steel frames to be re-used and smashing of concrete to produce aggregates.

If the deconstruction of the building is done correctly, according to Gàlvez-Maros et al., it is possible to save about 40 percent of embodied energy and more than 60 percent of concrete structure when using prefabricate slabs [Gálvez-Martos et al., 2018]. The main obstacle for the disassembly of a product is of economic nature, the disassembly of a product is done only if the cost of disassembled products is lower than the cost of manufacturing new ones. Also, the deconstruction process is time-consuming since all the components saved need to be tested, stored and certified before being put again the supply chain of materials [Minunno et al., 2018].

The right management of C&DW in order to recycle aggregates produces a net reduction of CO2 emission and primary energy savings, since there is no need to extract the same amount of virgin raw materials [Gálvez-Martos et al., 2018].

Both Design for Recyclability and Design for Deconstruction aim at reducing the environmental impact of construction by focusing on recyclability and reuse of components from a technical design point of view [Geldermans, 2016].

4.1.2.2 Building Information Modelling

Building Information Modelling (BIM) is *"a series of database files containing proprietary formats and data, which are digitally representation of physical and functional characteristics of a facility or component"* [Cai & Waldmann, 2019]. BIM is different from the classical 3D CAD drawing, because it uses data sets to create a virtual mock-up of an entire project, including elevation drawings and other complex tasks. BIM is a tool that supports to transform building designs, construction, and management [Rathnasiri, Jayasena, & Siriwardena, 2021]. A BIM is an useful tool that helps the evaluation of alternatives in a decision process [Rathnasiri et al., 2021], it can include supplemental information other than measures, such as energy efficiency rating, fire rating and more. Any change done in the BIM can be easily implanted in the 3D model and it is possible to see all the related impacts on a wider scale [Minunno et al., 2018].

The aim of BIM is to facilitate 3D modelling and information management [Rathnasiri et al., 2021], in the perspective of circular economy it will help recycling the materials and reusing the components, and at the same time minimizing the amount of wastes during deconstruction stage. It also plays a role in the design of disassembly of buildings, since it allows to keep track of the components of each building, their relationship with the overall structure [Minunno et al., 2018].

BIM can be also applied to retrieve data to evaluate the energy performance and sustainability assessment of a building, in this case it is named Green BIM [Rathnasiri et al., 2021]. Green BIM benefits include the possibility to conduct interventions and interpretation of data, such as solar shading analysis, day lighting analysis, resource management, and energy analysis, that otherwise with the only human intervention would be too costly and time consuming.

4.1.3 Construction

4.1.3.1 Material Bank and Material Passport/Database

A material and components bank can be defined as "*a manager who organizes the transfer of materials and components extracted from demolished or deconstructed structures to a new structure*" [Cai & Waldmann, 2019]. The aim of material bank is to include in the same place assessment, conditioning and storage, and certification of materials and components obtained from demounted structures [Cai & Waldmann, 2019]. The information stored within the bank are: global planning of demolition and deconstruction, reasonable extraction and collection of materials and components that can be recycled or reused, assessment and improvement of the quality of materials and components, storing and selling of materials and components in a factory or centre shop of the bank, and certification of materials and components [Cai & Waldmann, 2019].

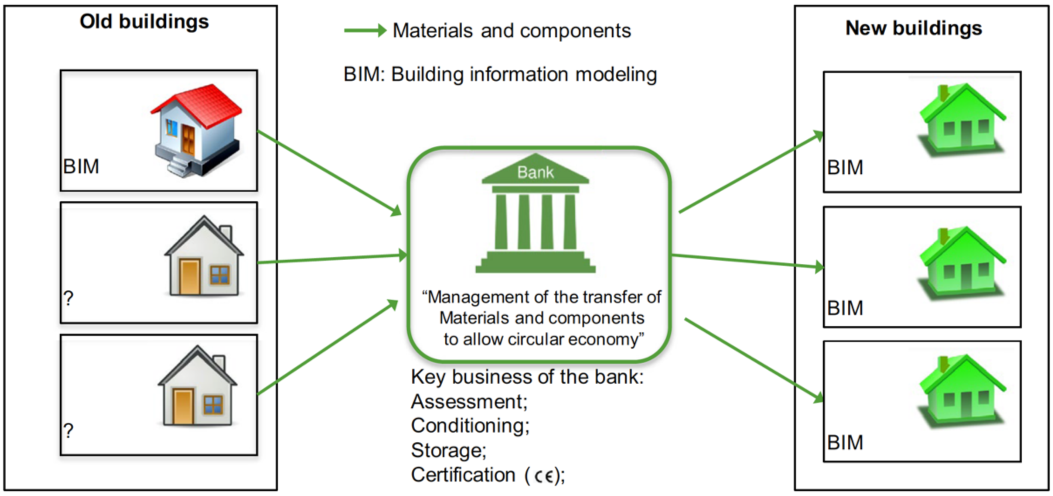

Figure 15: Concept of the material and component bank

Cai and Waldman have identified six objectives of a material bank:

1. Suggestion of a strategy for deconstruction.
2. Suggestion of a strategy for the collection of materials and components.
3. Assessment of the quality of materials and components based on the age of the building and environmental condition.
4. Treatment measures for materials and components for their conditioning, if needed.
5. Definition of transport plan and storage.
6. Assistance in deconstruction stage.

Along with the material bank a database containing all the materials and components used in the construction process and it is stored and updated during the life span of the building.

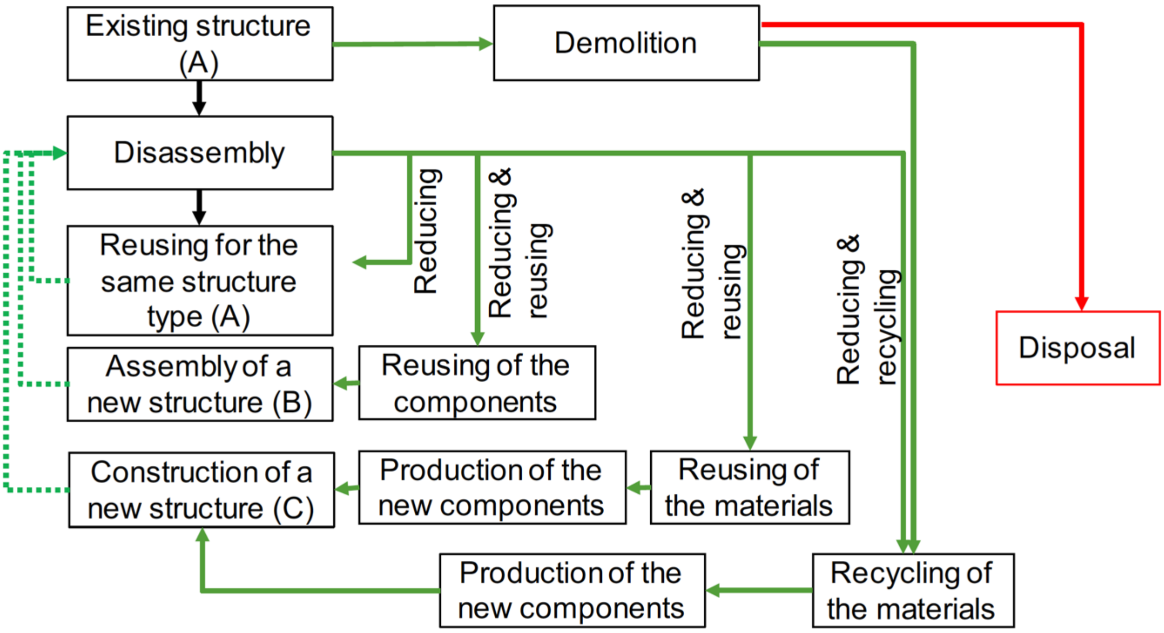

Figure 16: Management strategy of demounted structures

4.1.3.2 Use of prefabricate building

Prefabrication is defined as *"a manufacturing process that takes place in a specialized facility where various materials are joined together to form a component of the final installation procedure"* [Minunno et al., 2018].

Prefabrication can be classified into four levels: (i) the assembly carried out in the factory, (ii) volumetric pre-assembly, (iii) pre-assembly in factories of products that are not part of the building structure, (iv) pre-assembly of units that are part of the building structure [Minunno et al., 2018].

4.1.4 Operation and Use

4.1.4.1 HVAC System

The selection of a proper Heating, Ventilating, and Air Conditioning (HVAC) system is crucial, since it will reduce operational costs. Usually, the selection of HVAC system takes into account mainly the energy consumption. However, there also others factors to take in consideration, such as flexibility, reliability, and possibility to adapt to future change [Bac, Alaloosi, & Turhan, 2021].

HVAC systems in commercial buildings account for about 40 percent of total energy consumption [Chen, Zhang, Xia, Setunge, & Shi, 2020], but they are also responsible for water consumption. It has been estimated that the consumption of water related to HVAC system in an industrial building is up to 48 percent of total water consumption [Bac et al., 2021]. However, the impact of HVAC systems is usually evaluated together with services like plumbing and electrical equipment, and it has been estimated that the embodied carbon of building related services represents the 10-12 percent of total embodied carbon of a building [Kiamili, Hollberg, & Habert, 2020] Despite this value can seem very large, in the literature is considered small, when compared to the operational energy of a lifetime [Tan & Nutter, 2011]. According to Tan & Nutter, the emissions associated to the manufacturing and production of the ventilation system are the 8 percent of the overall operational emissions. However, the HVAC system has different environmental impacts, according to the region climate and energy source [Tan & Nutter, 2011].

However, the benefits related to the installation of a proper HVAC systems outclass the environmental impacts associated. It has been estimated that potential energy savings are in the range of 10-28 percent. Variable air volume supply and variable speed pumps are the most typical installation of HVAC systems, since they provide an amazing trade-off for what concern initial investment cost and energy performance improvement. Energy savings associated to variable air volume system are in the range of 30-50 percent, while the variable speed pumps can lead to a reduction of energy consumption of almost 50 percent [Chen et al., 2020]. The installation of close-loop ground-coupled heat pump can lead to higher reduction of energy consumption, 30-70 percent compared to other typologies of heat pumps, but the installation cost are 20-50 percent higher compared to variable air volume systems [Chen et al., 2020].

Part of the energy performance of HVAC systems is influenced by the thermal insulation of the building. The capacity of a building to remain cold during the hot season and warm in the cold season reduces drastically the need to rely on HVAC systems.

4.1.4.2 Use of renewable sources of energy

The construction industry is based, other than on the consumption of materials, on the consumption of energy: energy for the manufacturing of materials, energy for the transportation, energy for the appliances and energy for the end of life [Orsini & Marrone, 2019]. For this reason, the shift from fossil fuels toward sustainable renewable sources such as renewables is fundamental for this sector.

The production of renewable energy can be made on-site or off-site, in the first case the production of energy is made in the nearby of the building, while in the second case the energy is produced far from the building and it is brought to it thanks to the use of transportation tools, in the case of electric energy, the grid. The first solution, for the purpose of decarbonisation, is better since it will reduce the dependence from transportation systems, such as the grid for electric energy [Gil et al., 2021].

The use or renewable sources of energy is showing a global positive trend in the district heating system, in the European Union has seen an increase of 27 percent, in the US an increase of 13 percent [Zhang, Qi, Zhou, Zhang, & Wang, 2020]. A common assumption is that renewable sources of energy are meant only for producing electricity, but that is not the truth. There are also renewable sources that allow to produce other types of energy, such as thermal energy. An example is the installation of vertical-closed ground source heat pump system, that allows to extract geothermal energy from the ground, with very low carbon emission associated, a low investment and maintenance costs, and long life expectancy [Zhang et al., 2020]. Other common solutions for the decarbonisation of a building are passive solar home design, photovoltaic technologies, solar thermal systems , green roofs or rain gardens [Gil et al., 2021].

The use of solar radiation as renewable source of energy has seen an increase over the years, the main drawback of such technology is that solar radiation is not constant during the day (day/night cycle), but also during the year (in the summer the daytime is longer than night, while in the winter the situation is upside-down). Sometimes this fluctuation may lead to exceed the demand of energy. For this reason, the installation of photovoltaic panels goes along with the installation of storage systems, such as batteries [Gil et al., 2021]. However, it emerged from an interview with ARUP (that can be found in the appendix) that the installation of photovoltaic panels remains the most common solution for the production of electric energy due to their easy installation, same is true for heat pump and the production of thermal energy.

When the use of C&DW as source to manufacture building materials is not possible, they could be used for the production of energy. Also the implementation of electric vehicles for the transportation is a possible solution to reduce emissions related to the production and consumption of energy in the building sector [Orsini & Marrone, 2019].

4.1.4.3 Installation of batteries coming from EVs

As discussed above, the implementation of storage systems in building in order to match the production of energy and demand is essential. A possible solution, in full circular economy approach, is the reuse of batteries coming from the automotive industry. Automotive is facing a progressive electrification of the sector, meaning that vehicles are shifting from traditional internal combustion engine to electric engine. This means that batteries will become a more and more important component, and their correct disposal might become an issue [The European Commission, 2018].

Instead of recycling batteries that have been removed from vehicles, the battery can be remanufactured, and the cells can be provided with a second life in a storage application. Electric vehicles generally require high-performance batteries; hence, a battery is removed from a vehicle once the capacity declines past a certain point. It is estimated that this generally happens when batteries reach 70% to 80% of their original capacity. Batteries dismissed from this sector can still be implemented as support for building energy management system storing the energy generated by photovoltaic panels and not used during the daily activities [Wong, Al-Obaidi, & Mahyuddin, 2018].

4.1.4.4 Green Façades

Façades account for the majority of construction and demolition waste (around 70 percent), so the implementation on circular economy practices will achieve relevant results. Green façades can be installed in a building for the treatment of grey- and rainwater. In the outer layer of the façade contains plants that will treat the grey- and rainwaters, and at the same time provide micro-climatic benefits for the inhabitants. This solution consists in an indoor vertical wetland ecosystem that purify the liquid fraction of domestic wastewater. The vertical green wall has the ability to purify indoor air, offering a high quality air, and also the capability to produce food, since it can be installed with edible plants [Bertino, Menconi, Zraunig, Terzidis, & Kisser, 2019].

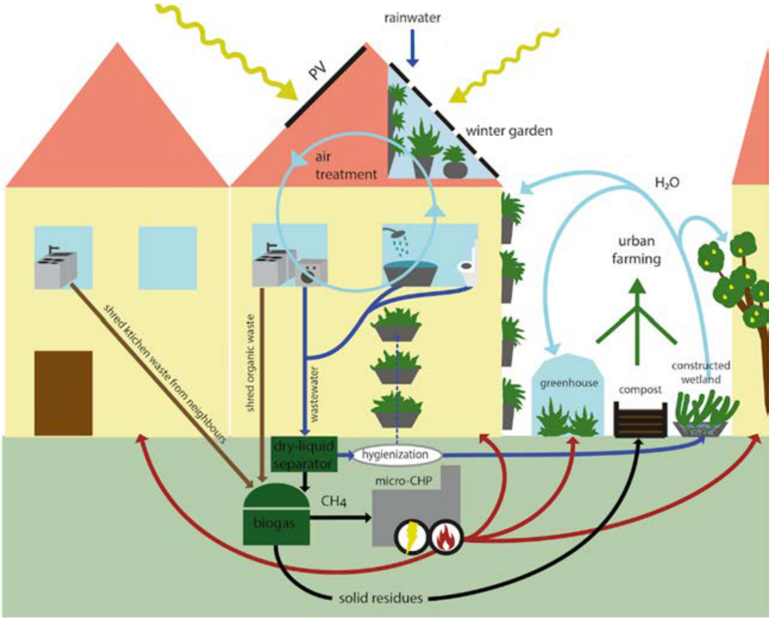

Figure 17: application of green façades into a building [Bertino et al., 2019]

4.1.5 Renovation and Demolition

In both renovation and demolition phases did not emerge new techniques of practices, but some of the ones previously analysed have repercussions in these stages as well.

Design for adaptability is a tool implemented in the design phase whose actual execution is accomplished in the renovation phase. Adaptive reuse of a building allows easy renovation processes of old buildings.

Design for deconstruction, similarly to design for adaptability, is a tool implemented in the design phase whose effect execution takes place in the demolition phase. An important step in the demolition phase is the correct collection of waste in order to put them back in the manufacturing flow. Also, thanks to a correct deconstruction of a building, saved components can be reused as they are in renovation projects.

4.1.6 Discussion

The results achieved by the solutions emerged from the literature review are summarized and discussed in this section.

Manufacturing of Building Materials

In the manufacturing of building materials stage two main solutions are find, the reuse of water and the use of substitute materials in the concrete mix. The purification of water via electrodialytic does not affect the release of carbon emissions associated to construction industry. However, it is a good application of circular economy concept. With this technology, water that has been used can find a second use and avoid further exploitation of drinkable water. What emerged from the analysis, is that the shorter process is enough to purify water. Since it is a process that uses only electricity, meaning that if coupled with renewable sources of energy it is possible to purify water in a sustainable way. The use of materials coming from construction industry or by-products from different sectors is a very valuable path to follow when looking at solutions to reduce carbon emissions in building materials. The best way is to reuse construction and demolition wastes, since they are made with similar materials as new building components, in this way physical characteristics are not compromised. However, it emerged that the use of by-products coming from different industries is a sustainable alternative way to produce building materials. Despite they will not have the same physical characteristics as concrete or aggregates, the cement mixes obtained meet the requirement to be authorized as substitute materials. This may be an important achievement for the decarbonization of other sectors other than construction. The possibility to reuse by-products for the manufacturing of building materials and their prevention from going to landfill will produce environmental benefits, but also economical, since it will reduce the cost of objects' disposal. However, the greatest savings are obtained with the substitution of concrete with wood. Its ability to subtract carbon dioxide from the atmosphere in its life before harvest, the possibility to recycle most of the wood used at the end of its life, and the possibility to burn it at the end of its useful life to recover energy make wood a sustainable choice for the substitution of concrete as main building material. The main concern about the use of wood is that an increase of the demand in the construction industry may lead to an unhealthy exploitation of forest that may jeopardize the ecosystems. It will be crucial prove the origin of wood that is use and be sure that it comes from sustainable and controlled sources.

Design

The design of a building is important in all of its life cycle stages. Design for deconstruction allows to produce less waste once the building has reached its end of life, and to recover the majority of components to reuse them in new projects. This is particularly useful in order to prevent further extraction of raw virgin materials. Design for adaptability is important because a building has to evolve as the needs of occupants evolve. It is important to reduce at the minimum the invasiveness of interventions in order to not cause harm to anyone. When possible, all the components should be designed with recyclability in mind, meaning that components should be made of materials that have a high level of recyclability. Once the design of the building is complete, everything successive intervention, keep under control its consumption, and any environmental analysis can be done by the use of a BIM system. All these aspects do not have a direct impact on the reduction of carbon emissions in the construction industry, however, they act as catalyst for the implementation of circular economy practices in other life cycle stages.

Construction

The construction of a building is one of the main sources of waste, in order to reduce waste in this stage the use of prefabricated building is suggested. In this way, building components are transported and assembled on-site minimizing the waste generated. This also reduce the amount of carbon emissions associated to the construction process since it requires less energy to assembly a prefabricated building rather than construct it in the traditional way. Further savings can be achieved if the assembly is conducted with machineries that use renewable source of energy. Buildings can act as a material bank, all the materials that have been used in the manufacturing of building components and it the construction phase are registered in a database that will help the deconstruction phase. This database allows the trackability of materials, that can be easily allocated to be reused, recycled, or remanufactured for the construction of new buildings or products. This solution, as in the design phase, does not have a direct impact of the reduction of carbon emissions, but it acts as a catalyst to make easier the implementation of solution that will have an actual impact on the decarbonisation.

Operation and Use

The operation and use stage is the one with most embodied emissions associates and the application of circular economy solutions in this phase should be prioritized. The first aspect to address is the installation of a proper insulating coat, that will help to reduce thermal losses in the building. This will also have an impact on the energy consumed, since that the building is more likely to have the right inner temperature, the need to turn on heating, ventilating, or air conditioning systems is lowered, leading to energy savings and lower carbon emissions released. However, the installation of a highly efficient HVAC system is still recommended, better if they exploit renewable sources to work. Thermal energy can be supplied by heat pumps that can extract geothermal energy from the ground. Electric energy can be supplied by photovoltaic panels, solar systems, or wind turbines. However, the systems installed highly depends on the type of the building and on the space available. In residential buildings with low space available, photovoltaic panels are the most suitable solutions since they can be easily installed on the roof. While, for industrial buildings, that have more space available, solar systems and wind turbines can be installed, along with photovoltaic panels. The main drawback of renewable energy is their inconsequence, the level of energy produced may change even on a daily basis according to the weather. For this reason, in some days the energy produced may exceed the demand of the building, while other days it may not meet the demand, forcing the building to supply energy from other sources. It is important to mitigate this effect thanks to the installation of storage systems. One of the most common solutions that also incorporates the principle of circular economy is the reuse of dismissed batteries from electric vehicles. In order to further reduce the carbon emissions, the excessive energy produced and that is not stored can also be delivered to the neighbourhood. The generation of energy from renewables, the installation of an insulating coat, and the installation of highly efficient HVAC systems do not represent the circular economy principles, however, they are an important step to achieve in order to address decarbonisation in the building industry.

As it was intuitable, the distribution among life cycle stages of CE practices is coherent with the need of intervention in that stage. The majority of practices wants to address the reduction of carbon emissions in the manufacturing of building materials stage, and they show that is possible to achieve important savings. Savings can be also achieved in all stages if the equipment and machineries are powered by renewable sources of energy.

4.2 How Circular Economy practices are applied in real cases?

The practices described in the section above are what is currently studied in the literature, but what is actually done in practices? In the next chapters different case studies will be described and analysed. As mentioned in the chapter 3 in the methodology section, these case studies were found in the literature research and were differentiated from the theoretical studies, in order to see if the solutions that are studied see applications in real cases. Each case study will be divided in two parts, one about the presentation of the work, and the other is a discussion of the benefits achieved and barriers that may occur.

4.2.1 Be Circular – Be Brussels

Be Circular – Be Brussels was an event held in 2016 in which fourteen circular construction projects have been awarded [Maerckx, D'Otreppe, & Scherrier, 2019].

The fourteen projects are listed in *table 7*.

Table 7: List of fourteen projects awarded at Be Circular - Be Brussels

Project Number	**Project Name**	**Type of Work**	**Building Type**	**Project Size (m^2)**
1	Petite Suisse	Extension	Housing	50
2	Clos Dupont	Extension	Housing	55
3	VLA	Renovation	Offices	120
4	CoPost	Renovation	Housing	135
5	Warland	Renovation	Housing	150
6	Dethy	Renovation	Housing & Offices	270
7	Dépôt Leemans	Extension	Housing & Offices	300
8	Moucherons	Renovation	Housing	325
9	Boondael	Renovation	Housing & Shops	1000
10	Deswaef	Renovation	Culture	1000
11	Tivoli	Renovation & Extension	Housing	1800
12	Tour à Plomb	Renovation	Culture	3000
13	Debatty	Renovation	Housing & Kindergarten	5000
14	Horta-ONSS	Renovation	Offices	43000

In the work presented by Maerckx et al., the fourteen projects have been analysed according to four dimensions: reuse of materials, design of the building, the training of the workers, and the partnerships made [Maerckx et al., 2019].

Reuse

All projects presented a reuse strategy in their proposal in different ways such as on-site, off-site, future reuse of materials at end-of-life, and incoming reclaimed materials. Among these projects, three of them applied the practice in a more creative way: Warland, Debatty, and Horta-ONSS.

The Warland project consisted in the renovation of a house. Reuse of materials played an important role in this case showing that reclaimed materials can be used not only in the construction phase, but also in the renovation one *figure 17*. At the end of project, nearly 6 tons of reclaimed materials were used [Maerckx et al., 2019].

Figure 18: renovation phase of the Warland project

Figure 19: before and after renovation of Debatty project

The Debatty was a renovation project for the floors of a municipality by including an insulating layer. Instead of evacuating the existing floors, they have been carefully deconstructed and eventually reinstalled after the renovation. In this way, there has been non need of further extraction and manufacturing of new materials [Maerckx et al., 2019].

Horta-ONSS was an interiors refurbishment project of offices. In this case, the renovation process had to use as much as possible reclaimed materials, this resulted in the reuse of interiors partition walls, reuse of techniques such as heating and cooling systems, and materials coming from another construction site owned by the company that was in charge of the work. At the end of the project, more than 610 m^3 of materials were recovered on site [Maerckx et al., 2019].

Design for change and deconstruction

For what concern the design phase only one project emerged for its execution, the Clos Dupont project. Initially the house had only the ground floor, and with an extension intervention a playground on the ground floor, an office space on the first floor, and bedroom on the second floor were added [Maerckx et al., 2019]. The extension project was intended with the adaptive design in mind, and the aim of each addition may change in the future as the needs of the family may change. This will be possible thanks to benefits thought in the design phase such as independent access, vertical circulation in the building, and connection to technical installation (supply and evacuation of water) [Maerckx et al., 2019].

All the extensions were designed to be connected to the existing structure to allow a fast and clean deconstruction in the future. The only elements that is attached permanently to the existing structure is a rail that permits the other components to the house [Maerckx et al., 2019].

Training of workers

This aspect for the purpose of the thesis is not relevant and for this reason it will not be thorough.

Partnership

In order to purse circular economy principles in the construction industry, partnerships, in the form of over-ordering and industrial symbiosis, have to be founded.

In over-ordering two possible scenarios can take places: in the best case, materials can be stored and reused in another project; in the worst case, the materials become part of the construction waste and hence a cost for the company that paid for them and now has to pay for their evacuation. Usually, in a medium/large company, the excess materials are not sufficient for another project, so there will be no use to store them, but on a smaller level they may be the exact quantity required by a contractor [Maerckx et al., 2019].

In an industrial symbiosis, partnerships among companies are made in order to substitute, partially or totally, the resources coming from the extraction of extraction of raw materials with the waste coming from a partner company. In the construction sector this can be also achieved among different projects within the same company [Maerckx et al., 2019].

In this field, three projects were of particular interest: Petite Suisse for what concern over-ordering, and Horta-ONSS and Tivoli for what concern industrial symbiosis.

Figure 20: Petite-Suisse renovation process made with over-ordered materials

Petite Suisse made a collaboration with the Debatty project that over-ordered insulation boards, these boards were recovered and reused for the insulation of the roof in the house [Maerckx et al., 2019].

The contractor of Horta-ONSS applied the industrial symbiosis principles on Logis Floréal building sites. On the first site there were wool insulating materials needed to be evacuated, while on the second site there was the need of insulating materials for 380 existing roofs. At the end, more than 486m^3 of insulating materials were saved from a site and, after being remanufactured, reused in a new building project [Maerckx et al., 2019].

Figure 21: Horta-ONSS materials ready to be reuse off-site

Figure 22: Tomato Chili's greenhouse made with reclaimed materials of Tivoli

Tivoli was a big renovation and extension project of a residential buildings, involving nearly 400 units. During the construction phase, several wastes were generated. In the neighbourhood, there was a company, Tomato Chili, that developed greenhouses using reclaimed materials, especially wood and glass that were highly present in the construction waste generate by Tivoli making it the perfect site to supply materials to Tomato Chili. In this way for the construction project the disposal of wastes was avoided [Maerckx et al., 2019].

4.2.2 Super Circular Estate

Super Circular Estate or Superlocal is a project in which a 10-floor high 100-apartment building block is deconstructed, and its components are reused in new building projects. This project is practical implementation of reuse of components saved at the demolition phase and a consideration of how an existing construction can be seen as a material bank.

In Superlocal project four reuse/recycling techniques were applied:

1. Reuse of concrete apartment blocks in one piece
2. Reuse of structural components such as slabs and walls
3. Recycling concrete waste into new blocks
4. Recycling grinded concrete into new concrete

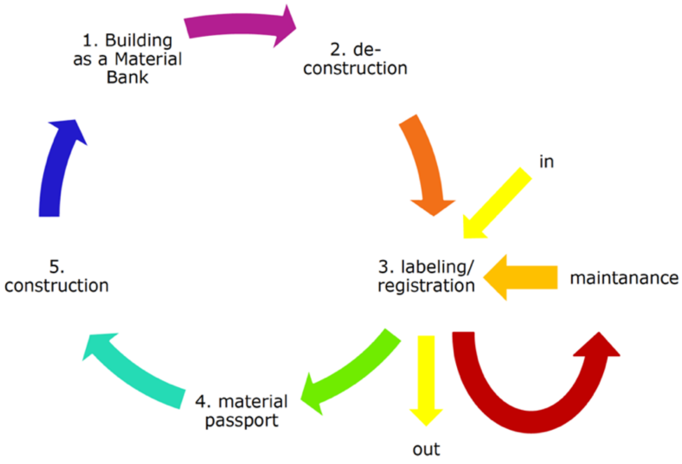

Figure 23: steps applied to the Superlocal project

It has been calculated that the environmental impact of the existing building, reported in *table 8*, are 2.3E04 GJ embodied energy, 2.9E03 tons of embodied CO_2, that with the pricing of carbons in 2019, 25€/tons of CO_2, resulted in 70k€ [Ritzen et al., 2019].

Table 8: environmental impacts of 12 main materials in the existing building

Material	Quantity (ton)	Embodied Energy (GJ)	Embodied CO_2 (ton)	Shadow costs (€)
Aluminium	1.03E+01	1.59E+03	8.45E+01	2.11E+03
Asbestos	1.81E+02	1.34E+03	2.82E+02	7.05E+03
Divers	1.79E+01	2.97E+02	6.23E+00	1.56E+02
Ceramic elements	4.40E+01	5.50E+02	4.41E+01	8.52E+02
Concrete	1.30E+04	1.33E+04	1.97E+03	4.93E+04
Copper	7.45E+00	1.52E+02	9.81E+00	2.45E+02
Glass	1.75E+01	4.26E+02	2.56E+01	6.40E+02
Masonry	6.38E+01	1.92E+02	1.47E+01	3.67E+02
Plastic	1.24E+01	1.00E+03	3.50E+01	8.74E+02
Steel	3.26E+02	3.79E+03	3.00E+02	7.50E+03
Natural stone	6.05E+01	5.12E+00	2.96E-01	7.40E+00
Timber	7.15E+01	6.64E+02	1.00E+02	2.50E+03
Total	**1.38E+04**	**2.33E+04**	**2.87E+03**	**7.16E+04**

The idea is to substitute the 10-flor high 100-apartment building block with four dwellings, and the largest of the four was selected as sample to conduct further analysis. The environmental impact associated to this dwelling are 3.35E02 GJ embodied energy, 4.62E01 tons of embodied CO_2, that considering the same price of carbon results in 1.15k€ of shadow cost [Ritzen et al., 2019].

Table 9: environmental impacts of four pilot dwelling

Material	Quantity (ton)	Embodied Energy (GJ)	Embodied CO_2 (ton)	Shadow cost (€)
Aluminium	2.60E-02	4.03E+00	2.14E-01	5.36E+00
Bricks	3.93E+00	1.18E+01	9.44E-01	2.36E+01
Ceramic	1.04E-01	1.97E+00	1.09E-01	2.74E+00
Concrete	1.96E+02	1.73E+02	2.59E+01	6.47E+02
Copper	3.25E-02	1.37E+00	8.46E-02	2.12E+00
Glass	3.38E-01	5.07E+00	2.91E-01	7.27E+00
Insulation	3.44E-01	1.36E+01	5.85E-01	1.46E+01
Paint	5.52E-02	3.25E+00	1.40E-01	3.50E+00
Plaster	6.24E-02	1.12E-01	8.11E-03	2.03E-01
Plastic	3.77E-01	3.10E+01	1.23E+00	3.09E+01
Rubber	9.84E-01	5.02E+01	3.74E-01	9.34E+00
Steel	1.24E+00	2.27E+01	1.78E+00	4.44E+01
Stone	5.00E-03	1.00E-02	5.80E-04	1.45E-02
Timber	1.23E+00	1.70E+01	1.45E+01	3.62E+02
Total	**2.05E+02**	**3.35E+02**	**4.62E+01**	**1.15E+03**

A key finding from this project is the energy savings related to the reuse of building components. The key building component is a tunnel shaped concrete element that is part of the load-bearing structure, since its removal is rather complex, and it requires about 1.5E02 MJ of energy. Also, it is important in the design phase how each component can be reused in multiple cycle instead of the linear approach. By looking at table it is possible to see that important savings can be achieved in terms of embodied energy, embodied carbon, and shadow cost, which are respectively 65 percent, 90 percent and 1000€ lower with respect the current building [Ritzen et al., 2019].

4.2.3 Emerging Concepts

In the work of Huovila et al. the merging concepts of different case studies coming from Europe, Asia, and Africa were investigated [Huovila, Iyer-Raniga, & Maity, 2019].

Europe

In Europe two emerging concepts were analysed: the Circle House in Denmark and the Alliander HQ in the Netherlands.Circle House in Denmark is a project that created 60 new housing estates with circular economy principles in mind and involved more than 30 Danish companies. These houses have been designed with the goal that at least the 90 percent of the whole building can be disassembled and reuse without compromising its value during the life cycle. The structure of the buildings consists in six concrete blocks that can be easily disassemble and reused, as can be seen in *figure 23*. The takeaway of this project is that by implementing circular economy principles both sustainable and economic advantages can be achieved, in terms of CO2 reduction and lower maintenance costs [Huovila et al., 2019].

Figure 24: concrete building blocks structure of the Circle House

The Alliander HQ is an extension process, that took place in 2015, that increased the number of occupants of the building from 600 to 900. About the 92 percent of materials was labelled as "circular". Circular economy took place in different ways: façades were made with waste wood, the extensions are made with steel and concrete recovered from the demolished parts, reuse of toilets and plates. Also, a material passport containing information about materials installed was made in order to allow their future reuse. Along the material sustainability, for what concern operation and use phase solar panels and underground water storage were installed, making the building CO_2 neutral [Huovila et al., 2019].

Asia

In Ahmedabad, India, was designed and realised a waste management system in order to handle the construction and demolition waste. The Ahmedabad Municipal Corporation implemented a mandatory system of permits for construction and demolition, this allowed to quantify the amount of waste generated. The management system was based on a partnership with Amdavad Envrio Projects Private Ltd. who was in charge of the management and process of waste. 16 dumping sites were designated for the collection of C&DW; the collected wastes were processed and into coarse and aggregates, and used to produce building materials, *figure 24*, while everything was centralized.

Figure 25: finished product made of processed wastes

Africa

This case study investigated the implementation of a an EcoKiln in Malawi, exposing the advantages of burnt clay bricks. Malawi is facing an increase of population of 2.8 percent per year, this is leading the country to a deforestation problem since fuelwood is the main source of energy [Huovila et al., 2019].

The advantages of using an EcoKiln are the use of coal as source of power, modularity, consistency and better quality, energy efficiency with low emissions associated. After two years of bricks production with EcoKiln the specific energy consumption dropped to around 0.6MJ/kg. Furthermore in Malawi, to reduce the consumption of coal, industrial wastes, such as tobacco dust, are used as alternative source of power, in this way, wastes that previously were destinated to landfill creating harm for health, have found a profitable use [Huovila et al., 2019].

With the use of EcoKiln raw materials are used more efficiently and the wastage of burnt clay bricks has been reduced from 40-50 percent to near 5 percent [Huovila et al., 2019].

Figure 26: EcoKiln bricks production

4.2.4 Design for Disassembly of a Danish Office

This study focuses on an office in Denmark and how to extend its service life and how reuse and recycle its elements through design for disassembly. The environmental impact of building aggregates can be significantly reduced if they are designed to be durable and reusable. In Denmark, but also all over the world, 30-40 year-old building are demolished, without fully exploiting the durability of cement [Eberhardt, Birgisdóttir, & Birkved, 2019].

The life cycle stage phases analysed in the case study are the manufacturing of building materials that includes extraction, transportation and production, renovation, and demolition. Since the focus of the materials, in the case study the consumption of energy for operation is not taken into account [Eberhardt et al., 2019].

The building has a total area of almost $40km^2$ with eight wings. Floor slabs, façades, core walls and columns are made mainly of prefabricated concrete. The assumptions made in this work about are the following:

- Assembly/disassembly are based on existing solution
- Utile life span of the building is in 50-80 years
- The materials are free of dangerous materials
- Concrete elements do not require any maintenance during their life cycle

For what concern the element of the building, the percentage of materials that can be reused at the end of life are:

- 90 percent of columns
- 90 percent of composite steel/concrete beams
- 80 percent of concrete beams
- 60 percent of concrete roof hollow slabs
- 90 percent of concrete floor hollow slabs
- 80 percent of concrete core walls

The life cycle assessment conducted highlighted that the highest environmental impacts are associated to the manufacturing of building materials and renovation stages, due to the high impacts for the production of the materials. Among the materials, the one that has the highest embodied environmental impacts is concrete, due to its structural importance and its largest share of the building's total mass. Elements such as windows, doors, and staircases, have lower embodied impacts since they account for a low share of the total building's mass [Eberhardt et al., 2019].

Two scenarios are modelled: one were the structural elements are disassembled at the building's end of life and reused in future projects, and one were the structural elements are substitute with different materials in order to reduce environmental impact of the building based on the ease in disassembling, reuse, and recycle potential [Eberhardt et al., 2019].

In the first scenario, the reuse of concrete results in 15 percent of potential CO_2 emission savings after one cycle of reuse, and 21 percent after two cycles. While the substitution of concrete with different materials, such as steel or wood, revealed higher potential emission savings [Eberhardt et al., 2019].

In the investigated scenarios it emerged that the material composition plays a significant role on the embodied environmental impacts of the building, as well as the number of cycles a component goes through.

4.2.5 Three European Case Studies

The three case studies investigated by Mangialardo and Micelli are typical office located in London, a town hall in Brummen, and an historical residential building in France.

The office in London is of considerable dimension and it was built after the Second World War. After it fall in disused it was planned its demolition in order to create a shopping centre. It was decided to keep the external structure and demolish only the internal parts. Instead of installing concrete columns, a steel structure has been preferred. All the obsolete parts of the building were demolished. At the end of the project, almost the 70 percent of the original building was reused, and the 50 percent of the original building was preserved [Mangialardo & Micelli, 2018].

The municipality in Brummen needed to increase its surface and instead of building a new building they decided to expand the existing one. The extension took place in form of modules, the 90 percent of them can be dismantled and adapted for other use. In this way the value of the structure can be maintained over different cycles. The modules are made of prefabricated wood components. All the information related to the interventions made are gathered in a material passport in order to be used when the building will be dismantled [Mangialardo & Micelli, 2018].

The residential building in France was listed by UNESCO and then transformed into offices. The transformation of this building was difficult due to its architecture and the fact that the exterior façades could not be addressed by the retrofitting operation. The thermal insulation, which was the most significant one, consisted of highly efficient insulating panels made of sustainable materials. At the end of the project, the annual heating of the building, whose surface is of 400m^2, was equal to the heating of a 100m^2 apartment [Mangialardo & Micelli, 2018].

4.2.6 Green roofs

Green roofs usually are covered with a thin layer of vegetation over a waterproof membrane. Green roofs are systems that protect the buildings but also the environment due to water mitigation, sound proofing, better water and air quality, thermal regulation of the building, and carbon storage [López-Uceda et al., 2018].

In the literature can be find several studies of recycle aggregates used in green roofs. Porcelain recovered from broken sinks, toilets, and tiles can be used in the construction of green roofs and reduce the embodied energy. By-products from metallic alloys used in the growth substrate have reported to have a positive effect on the growth of plants [López-Uceda et al., 2018].

López-Uceda et al. conducted tests on four types of growth substrate made with different percentage of fine mixed recycled aggregates with the goal to understand the leaching behaviour. They concluded that the presence of recycled aggregates does not make the sustrate hazardous, and that the leaching behaviour was similar to the refence scenario. Growth substrates with up 75 percent of recycled aggregates are feasible for construction [López-Uceda et al., 2018].

4.2.7 Insulation Materials

This case study is a comparison of the environmental impact and performance of two insulating products in the same market segment. The first product is made of recycled textile materials from a circular supply chain (*figure 26*); the second one is a common insulating material, made of stone wool (*figure 27*). The comparison is made according to a cradle-to-gate approach, since the service life for both products is long, around 50 years, and the end-of-life scenarios may be different. Emissions associated with the installation and disposal of the product are not included [Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017].

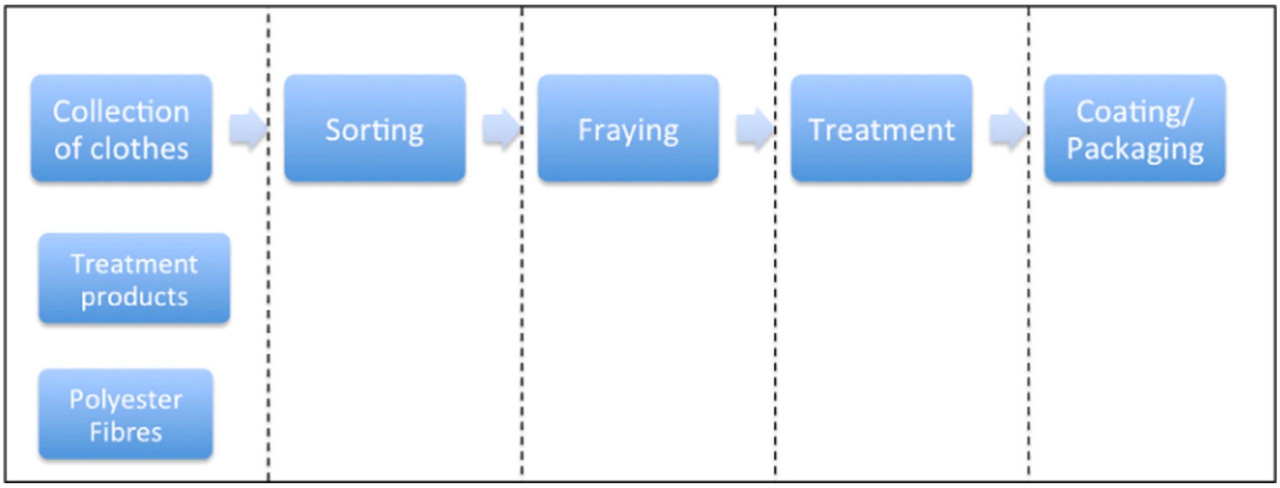

Figure 27: supply chain of product 1

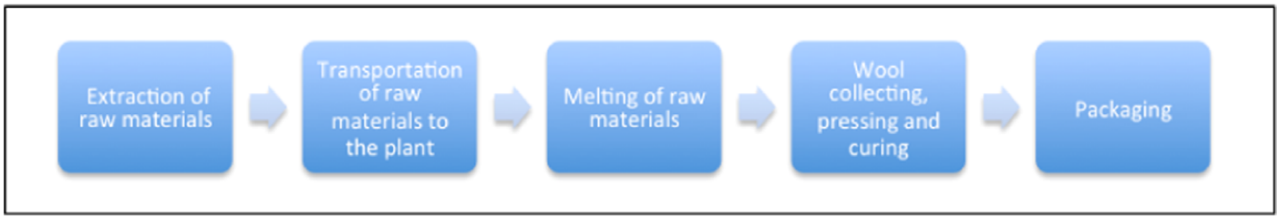

Figure 28: supply chain of product 2

The analysis, conducted using life cycle assessment, showed that the product 1 has lower carbon emissions generated during its production compared to product 2 that has a linear supply chain. For product 1, the highest impacts are associated to the transportation of the elements, since clothes need to be collected before transformed into insulating material [Nasir et al., 2017].

4.2.8 Woodscraper

The Woodscraper is a project in Wolfsburg, Germany, that aimed at showing the potentials of renewable raw materials. The skyscraper is designed for disassembly and reuse of building components and materials [Finkbeiner et al., 2019].

The main building material is wood, since it is a light weighted and renewable materials; at the end of life can be easily dismantled and recycled or returned into the biological cycle. The main concerns related to the use of wood are fire protection and sound insulation (due to the light weight) [Finkbeiner et al., 2019].

The project analysed in the work of Finkbeiner et al. is the construction of two building taking as example the Woodscraper building. The design of the buildings comprehended:

- Wooden façades column due to their advantageous cost, carrying capacity, and flexibility for what concern the positioning of windows.
- Load-bearing walls are made of wood and they are managed to be made narrow even though high fire requirements. They have been preferred over columns, that are thicker, and it will result in loss of living space.

- Non-load-bearing walls are made of metal stands and gypsum board, since they are cheaper than the wooden frames.

Figure 29: internal and external visualization of the building

4.2.9 Discussion

All the cases showed that the reuse of materials can be achieved in different forms, as reuse of materials salvaged in other projects, or as reuse of materials coming from the same project. In both the scenarios presented additional carbon savings were achieved thanks to the proximity of materials to be reuse to the intervention site (in the second scenarios since the reuse involved materials salvaged from the same building further savings were accomplished). The projects shown that the reuse of materials can be accomplished on different layers of the building, such as inner walls and floors, in the insulating structure, and furniture. A perfect example is shown in the Superlocal project. The Superlocal pilot project demonstrate how important savings can be achieved thanks to the implementation of circular economy practices. The reuse of materials and components from existing building lowers the environmental impact of new building and provide also economic benefits reducing shadow costs. The savings are achieved also thanks to the use of materials with a high level of recyclability such as aluminium, or with low embodied energy such as timber. To achieve further results it is important to ensure that these materials are recycled for more than one cycle. However, the achievement of these results is challenging. Technological efficiency and innovation is important to salvage building components that are in the most pristine condition as possible in order to avoid further manufacturing. An increase of level of technology and expertise of work force will lead to an increase of costs. On the other hand, a poor level of technological efficiency will lead to an increase of costs associated to energy consumption. The reuse of construction materials can find application also in less traditional use, as the Green Roofs case showed. Broken furniture that cannot be remanufactured or repaired can still find use in the construction of green roofs. Despite they are more an aesthetic component of the building, they still have a positive impact on the reduction of embodied carbon in the construction sector.

The adaptive design of the building permitted an easy intervention of extension. The intervention was conducted without doing any invasive and time-consuming work. The adaptability can also be seen in the demolition phase, since it allows to easily disassemble the building. However, the joints that connect each module, may represent a barrier for further recycle purpose. One of the main barriers to the manufacturing of a product with recycled materials is the level of purity of such materials. The presence of different types of material may make the process of recycle longer and more expensive, since resources have to be deployed to separate those materials. The same can happen with modular buildings, once the module has reached its useful life, after being reused over and over, it can be recycled to produce new modules or other building components. However, the presence of joints and rail, usually made of metal, can make the recycle of more difficult if they cannot be easily removed.

Table 10: comparison of solutions between theoretical and case studies

Solution	Theoretical Study	Case Study
Reuse of Water	x	x
Use of different materials	x	x
Recycle and Reuse of materials	x	x
Recovery of materials from waste	x	x
Design for X	x	x
Virtualization	x	
Modular Buildings	x	x
BIM (building Information Model)	x	
Material Passport	x	
Prefabricated elements	x	x
Demountable Walls	x	x
HVAC (Heating, Ventilation and Air Conditioning)	x	
Renewable sources of energy	x	x
Green Façades	x	
Green roofs		x
Adaptive reuse	x	x
Substitution of old elements with newer ones	x	x
Reuse of existing buildings	x	x
Collection of reusable building components	x	x
Management of waste at local level	x	x

Another aspect that is crucial to the implementation of circular economy practices is collaboration among companies, since they proved that what is a waste for a company can be a precious resource for another. Both the case of over-ordering and the case of industrial symbiosis have an impact on the reduction of carbon emissions. The first case the savings are achieved thanks to the reuse of materials that otherwise would be stored in a warehouse for long time, since the quantity usually is not high enough to fully accomplish another big project. However, small renovation projects can benefit of such materials. This solution, other than environmental benefits, can bring also economic benefits for both parties. The company that over-ordered the materials can sell them and avoid storage cost, while the company in charge of the renovation project can buy them at a lower cost than market price. The same consideration done for the case of reuse materials regarding transportation are also true in this case. In industrial symbiosis the same environmental and economic benefits can be achieved even at higher level. The final goal is to have companies that can collaborate in order to produce less or no waste at all, while reducing the materials, water, and energy used. The main difficulties faced by the implementation of industrial symbiosis are the finding of companies that can benefits of each other by-products or waste, and the finding of a location big enough to host all the companies in order to reduce to the minimum the transportation of materials.

The distribution of techniques of case studies is not completely similar to the distribution of techniques of theoretical studies. As can be seen in *table 10,* in case studies the solutions found in the theoretical section are not applied completely. The implemented solutions aim to minimize the carbon emissions associated to the manufacturing of materials, however in the case studies more attention is paid to the demolition stage rather than the operation and use.

5 L'Innesto case study

L'Innesto is a project developed by ARUP, which is a consulting engineering company born in 1946 in London. Now ARUP is a global company present in 35 countries with 85 offices and more than 12 000 employees. Among their big projects there are the Sydney Opera House in Sydney in 1973, the Centre Pompidou in Paris in 1977, the Lloyd's Building in London in 1986, it is currently working on the towers of Sagrada Familia in Barcelona [Arup, 2021].

5.1 Methodology

The data collection about this project consisted in two phases: the first one was an interview with some members of ARUP sustained in August 2020, and the second one, conducted on the same period, was a research on websites and reports. At the interview participated an ESG consultant and an architect, both members of the ARUP team. During the interview, that lasted around 1 hour due to business appointments of ARUP employees, different topics were discussed, and they can be divided in three categories. The first is about the definitions used, L'Innesto is defined a carbon neutral building, what does that mean, and how is similar and/or different to ZCBs and ZEBs definitions. In the second category were discussed which life cycle stages they focused on and which technologies will be installed. In the last topic the employees of ARUP highlighted which are the main barriers they face while designing the project, and how the usually overcome these barriers. The full interview can be found in the Appendix at the end of the thesis.

The other sources used are the official website of ARUP and the official website of L'Innesto project.

5.2 Project Description

L'Innesto is the winning project of C40 Reinventing Cities, an international contest held in 2019 and promoted by the city of Milan, FS Sistemi Urbani, and EIT Climate Kic. It is a partnership among Fondo Immobiliare di Lombardia, Barreca & La Varra, Arup, A2A, Stantec, Mobility in Chain, Ariatta, Starching, Borlini & Zanini. L'Innesto is a renovation project that aims to create a fourth-generation district heating system, powered by renewables, pre-assembled and near zero energy building, that will be easy to disassemble and reuse. It is the first zero carbon social housing in Italy, and it will have 72 percent of green areas. L'Innesto will connect the historical neighbourhood of Precotto, whose area, around 70 percent, will be redesigned as public park and pedestrian core, and the former industrial area of Bicocca, that currently provides housing and services to the nearby university campus [España, 2019]. It will provide 400 new apartments and 300 places for student to where to stay [InnestoMilano, 2020].

L'Innesto is defined as carbon neutral building, which means that the energy consumption and the carbon emissions are minimized. The goal is to achieve zero carbon balance within 30 years. ARUP, even though acknowledged that some life cycle phases have larger environmental impact than others, wants to address neutrality at building level. Actually, with this project a further step is done, in fact in the assessment of the impact services in the neighbourhood, such as mobility, are considered.

Table 11: CE practices and strategies adopted in L'Innesto project

Manufacturing of Building Materials	Design	Construction	Operation and Use	Demolition
Use of Wood	Design for deconstruction	Material Passport	Renewable sources of energy	Design for deconstruction
Use of recycled materials	Design for adaptability		Heat pumps	
Use of materials with a certified path				

For what concern the manufacturing of building materials, the use of sustainable materials is favourited; with the term sustainable are intended materials that have a low embodied energy, renewable materials, used materials or that have some recycle content, and materials coming from local players. Another important aspect in the selection of materials used is that they must come from a green supply chain, so the use of material passport, or materials that have a certified path. The main material will be wood, because it checks all the requirements sought by ARUP. Wood is a carbon storage material, it is renewable and has a certified path, such as FSC forests.

In the design phase, L'Innesto has been designed for deconstruction, in order to simplify the dismantling and the recycle and recovery of materials, and for adaptability, technologies installed can be modified and adapted to fulfil the future needs of occupants.

For what concern the operation and use stage, the selection of technologies follows the carbon waste hierarchy based on reduction of consumption, thanks to the implementation of energy efficient solution; use of renewable solutions in order to reduce the amount of CO_2 generated; and development of offset solutions. Only the first two steps are followed, while the last one is done on the overall project. The approach that ARUP followed was to evaluate the resources available on the territory, and eventually develop their own solution. In the L'Innesto project was the electrification of thermal energy production thanks to the installation of pumps that allows the recovery of energy from sewage. Also, energy will come from renewable sources, such as solar thermal plants and an energy recovery plant managed by A2A. Generally, the technologies installed strongly depends on the availability of space, in the L'Innesto project the available area will allow to install a solar thermal plant.

For the demolition phase the district has been designed for deconstruction so there is a team of people that will take care of the dismantling and waste management.

5.3 Discussion

This project is the apotheosis of what can be achieved when circular economy practices are combined together, and on this aspect in particular that L'Innesto differs from the projects discussed above. Whereas the previous projects focused on a couple of solutions, L'Innesto tries to implement as much solution as possible, with the aim to achieve the most carbon savings along the whole lifespan of the building. The building aims to achieve carbon neutrality within 30 years, showing that even with very efficient and sustainable technologies it is difficult to achieve neutrality in a short range.

During the interview potential barriers were discussed; while deciding whether to apply a solution or another an aspect to consider is the regulation at national level that may prevent its installation. Unfortunately, this barrier cannot be overcome. During the design phase the proposal of a sustainable solution may be turned down by stakeholders, if they are reluctant or sceptical toward it. This problem may be surpassed with additional effort in showing that similar or better results can be still achieved when installing a green technology, and this is one of the causes that prevents the shift in favour of newer solution. Technologies themselves can act as a barrier, the problem with international companies is that they manufacture products according to their standards, that may vary from country to country. When a technology needs to be installed in a country different from the one it was originally thought for, additional calculation and tests have to be conducted. However, the main barrier is cost, and it is also the common thread among the already discussed ones.

6 Barriers and Lever to Circular Economy practices

6.1 Barriers

The adoption of a technology or practice is influenced by several factors. In this section, the analysis of barriers can be divided in three groups: the barriers described in the literature, barriers that emerged from the analysis of practices and technologies for the application of circular economy practices, and the barriers arisen during the interview with ARUP.

In their work Mahpour analysed the main barriers affecting construction and demolition waste management and prevent the adoption of circular economy practices, and are listed in *table 10* [Mahpour, 2018].

Table 12: potential barriers that may affect the C&DW management

	Potential Barrier	**Description of Barrier**
1	Ineffective C&DW dismantling, sorting, transporting, and recovering processes	Efficient C&DW recirculating is essential for moving toward circular economy
2	Not green designing of construction projects	Green construction projects designing is beneficial for moving toward circular economy
3	Using finitely recyclable construction materials	Most of the times recycling C&DW is an important part of circular economy. So, it is recommended to use recyclable materials

4	Overemphasizing recycle and non-environment-friendly methods during C&D phase of construction projects	Although exploiting recyclable materials are recommended, non-environment-friendly methods and frequent recycling some C&DW (e.g., plastic and paper increase unwanted recycling of micropollutants). Reusing and upcycling are two healthier alternatives
5	Preferring off-site C&D wastes sorting/C&DW landfilling over on-site sorting due to lack of incentives	Lack of incentives to recirculate construction materials motivates stakeholders to get rid of the C&DW as soon as possible by off-site sorting and direct landfilling instead of on-site sorting
6	Inadequate policies and legal framework to manage C&DW as well as lack of supervision on C&DW management	Transition to circular economy in C&DW management requires policies, legal frameworks, and supervision
7	Lack of producer-based responsibility system in production of construction materials	The producer should be responsible not only for construction materials production but also for C&DW recovery
8	Lack of clearly defined national goals, targets, and visions to move toward circular economy in C&DW management	This lack increases the uncertainty and demotivates the stakeholders to act purposefully and leads to low public pressure to promote circular economy in C&DW management
9	Inadequate awareness, understanding, and insight into circular economy in C&DW management	Low knowledge level inhibits a substantial intent or change toward circular economy in C&DW management
10	Inherent complexity of transforming to circular economy in C&DW management	It is difficult to consider various issues i.e., manufacturing, energy and material, business models, product design, service and distribution process, data management etc. simultaneously while transforming to circular economy in C&DW management
11	Lack of integration of suitable C&DW management	There is a lack sustainability integration between C&DW management hierarchical levels
12	Lack of empirically based literature on the barriers	The existing literature on barriers to circular economy in C&DW management is fragmented and mostly conceptual
13	Risk aversion	C&DW management stakeholders prefer taking smaller and safer steps rather being involved in disruptive changes of moving toward circular economy in C&DW management
14	Undeveloped individuals’ engagement	Undeveloped individuals’ engagement is necessary for transitioning to circular economy
15	User preference for new construction materials over reused/recycled ones	Building users prefer buildings built with new materials over those with recovered materials
16	Uncertain aftermaths of moving toward circular economy in C&DW management	It is not clear whether transitioning to a circular economy is beneficial to all or not. Many people e.g., scavengers may lose their livelihood because of this transformation

17	Non-standardized C&DW reduction reporting as well as lack of accessible data	Data unavailability and non-standardized C&DW reporting that lacks appropriate indicators to measure C&DW reduction and reuse hinder appropriate C&DW management
18	Lack of funding to implement circular economy in C&DW management	Lack of funding hinders planning to promote circular economy in C&DW management
19	Tendency to manage cost and time rather than C&DW	Proper C&DW management is often not a serious concern for the stakeholders
20	Agency and ownership issues in C&DW management	C&DW collectors usually get C&DW and dispose them of, not thinking about improving wastes quality
21	Lack of commitment by top urban manager to move toward circular economy in C&DW management	If top urban managers are not committed to transition to a circular economy in C&DW management, either no significant progress will be achieved or other staff will not have enough motivation to work efficiently, although definite goals have been defined
22	Ineffective C&DW management	If the entire C&DW management is ineffective or unwilling to transform linear economy to a circular one, it is deemed ineffective provoking a variety of problems i.e., corruption, outsourcing, environmental problems, using obsolete technologies, lack of international cooperation, etc.

Potential barriers to reuse are analysed in the work presented by Densley Tingley et al. [Densley Tingley, Cooper, & Cullen, 2017].

- Perceived risk in specifying reused materials.
- cost: reuse could be more expensive.
- composite construction (for structural steel: concrete and metal deck flooring with shear studs connected to steel floor beams).
- lack of reuse markets and supply chains.
- time constraints which favour demolition over construction; and
- inaccessible/irreversible joints.

In the article the barriers to the introduction of reverse logistic in the construction industry may be categorized into two main categories: industry specific barriers (e.g., the building is not designed for dismantling), and organizational barriers (e.g., time constraints) [Densley Tingley et al., 2017].

Cost is the biggest challenge that circular economy has to face, since all the other barriers can be reconducted to cost. If a technology is not available in a country or it is not tested, it will require money to be tested again or to make additional evaluation in order to make such technology in compliance with the regulation of the country. Even the inertia that prevents shifting toward more sustainable practices is driven by cost, "*changing from known business could result in more costs a company sustains*". The last section of the work of Densley Tingley et al. consisted in understanding which barriers, according to the interviewees, should be prioritized. The three main answers were cost, availability and storage, and no client demand/ client perceptions. As can be seen, these barriers are not strictly linked to the engineering part of construction industry, but they are systemic barriers [Densley Tingley et al., 2017].

The implementation of construction and demolition wastes can be hindered by several factors. Ghisellini et al. identified those barriers and grouped them in four main categories: Political and Market, Financial and Economic, Technical and Information, and Managerial and Organizational barriers [Ghisellini et al., 2018].

In the Political and Market category, the identified barriers are: lack of guideline at municipal level for the management of construction and demolition waste, lack of coordination activities by the municipal departments, focus only on the short lifespan of the building, lack of guidelines for reuse of waste, lack of quality standards for the reuse of waste, lack of a compulsory environmental impact assessment for the companies, lack of a mature market that allows the buying and selling of construction and demolition waste, and a consistent supply of construction and demolition waste [Ghisellini et al., 2018].

The financial and economic barriers are related to the high investment costs for the waste technologies, and high cost for the separation, treatment, and recycle of construction and demolition waste [Ghisellini et al., 2018].

From a technical point of view the main barriers are governments' lack of expertise in sustainability, and lack of knowledge about the performance of building components made with recycled aggregates [Ghisellini et al., 2018].

The managerial and organizational barriers are the lack of awareness of environmental protection thanks to the correct management of construction and demolition waste, lack of social responsibility by construction companies, and lack of awareness about the possible uses of construction and demolition waste [Ghisellini et al., 2018].

For what concern the barriers that emerged form theoretical and case studies, not all the above-mentioned barriers were found.

The reuse of materials can be difficult to achieve for different reasons, in the work presented by Maerckx et al. regarding the winning projects of the contest Be Circular – Be Brussels, some barriers were presented. For reuse, a key factor is the sensitivity of stakeholders, if the demand for reused materials and components comes from the client, their implementation is simplified, since there will not be the need to convince the client about the benefits of such materials. Another obstacle in this field is the regulatory requirements, such as energy and safety requirement, a building has to obtain. Also, taxes on recovered materials can play a significant role and they can act as both obstacle and lever, too high and the reused of reclaimed materials will not be exploited enough; low taxes can incentivize the reused of these materials [Maerckx et al., 2019].

Another barrier that affects the reuse of materials is the quantity and quality of secondary materials. If the reuse of materials will become more and more popular, the quantity of secondary materials available will be lower, making it more difficult their retrieval. Also, the quality of secondary materials is relevant, the better the quality, the better will be the quality of manufactured materials. The collection of secondary materials might be hindered by the absence of effective recovery infrastructure and by the difficulties of successfully separate materials. All these aspects lower the level of trust that contractors have regard to secondary materials [Nußholz et al., 2019].

In the design for change and disassembly stage, the main barrier is the correct understanding of the requirements desired by the client, that sometimes may not be easily expressed. Also, the construction of a correct deconstruction plan of the building and its correct transmission to those who will handle the end-of-life phase, may be considered as a barrier. The last dimension analysed in the work of Maerckx et al. was the partnership between different companies in the form of over-ordering and industrial symbiosis. The barriers in this section are the correct matching of demand and offer among different companies, about the materials need and the right quantity and availability; the incorrect sharing of information of the projects among the players involved in the partnerships, creating a B2B network [Maerckx et al., 2019]. Despite modular and prefabricated buildings are a useful tool for the reduction of embodied carbon, they may cause some obstacles to reuse of materials. Once a module has reached its end of life and cannot be reused, it can still be recycled. However, the presence of bolt and nut joints might make the harvest of materials more difficult, since before the recycle there must be a separation process that divides the different materials [Akanbi et al., 2018].

During the interview with ARUP several challenges have to be faced while making choices about which solutions to install. The first barrier is regulation at national level. Sometimes regulations do not allow the installation of a particular solution or the use of a particular material and unfortunately there is not possibility to overcome this barrier. The next barrier that has to be faced is cognitive inertia towards sustainable solutions. Sometimes, stakeholders are reluctant to accept the possibility to install a sustainable solution. This process makes difficult the shift from the current practices in favour of more innovative ones. An example provide directly from the experience of ARUP is that in Italy the majority of building is constructed using reinforced concrete, and it is very difficult to make stakeholders accept the idea of using different materials (i.e., wood), even if the performance is the same or even better. Also, the technology itself sometime can act as a barrier, especially if a solution is developed in a country different from the one it has to be installed. This is due to the fact that standards may change from country to country, so additional calculations and tests have to be conducted, in order to make it compliant to the national standards and regulation, leading to an increase of costs. Last, the most important barrier is cost, all the previous-mentioned barriers have an impact on cost: the need to show the performance of a sustainable materials to a stakeholder, and the need to run additional calculations and tests to adapt a solution to national requirement are expensive processes that have an impact on the overall investment.

6.2 Levers

To overcome these barriers, it is possible to leverage on some factors. Material passport, containing all the information related to the materials used in the building, can be a lever. If paired with a plan for reuse, it can help avoiding many obstacles such as uncertainty of schedule for the deconstruction and implementation of materials, organization of construction site and storage, and related costs. Also, being part of a network around reclaimed materials that allows to work in a just-in-time manners is an important lever [Maerckx et al., 2019]. The use of BIM models will play a significant role in the correct transmission of information about the procedure for the right dismantling of a building, but also about possible modification and adapt its use to the needs of clients. The effectiveness of BIM is greater when the information about the building are gathered during the whole lifecycle [Akanbi et al., 2018]. The design of a building can foster the implementation of circular economy practices for what concern the salvaging of materials in the demolition phase and their eventual use as new source in the manufacturing stage. A building that has been designed as a reversible system and whose information, in which are highlighted the steps to follow for the deconstruction, were sent to a database, can have a positive impact on the accomplishment of circular economy solution [Maerckx et al., 2019].

According to Nußholz et al., a compulsory sorting done on-site, the increase of recovery companies will have a positive impact of the implementation of circular economy solutions in the construction sector. Also, the presence of certifications for recovered materials will increase the level of trust [Nußholz et al., 2019].

A solution that will push the implementation of circular economy practices is partnership among companies. This partnership can take the form of industrial symbiosis or temporary collaboration between companies. The key factor, within a company, that allows to build partnership between building site is the transversal knowledge that a person has [Maerckx et al., 2019].

However, the most positive impact of the installation of sustainable solutions is given by the willingness of stakeholders. If clients have a positive attitude toward sustainability, they will be more inclined to the installation of green solutions, even if they may have a higher cost. A way to overcome cognitive inertia is to provide some examples of other successful projects in which the solution has been installed and the benefits derived. The installation of sustainable solutions is expensive, however in the last years the effort to make them more affordable has increased. A huge impact has to be accounted to governments which have given incentives to all the clients that chose to install solutions that help in the decarbonisation process in the construction industry. Also, the effort along the whole supply chain will have a positive impact on the overall acceptance of all the described solutions.

6 Conclusions

Construction industry is of the sectors that contributes to a large part of carbon emissions released in the atmosphere. The trend of the increasing number of people living on Earth, combined with the high level of carbon emissions associate to the buildings, has moved the attention to this problem. First steps in this direction are already be taken by governments and organisations which have released policies to make buildings more sustainable, mainly in terms of energy efficiency. This results in the development of buildings with low carbon emissions associated, Zero Carbon Buildings, and buildings that are almost independent from an energetic point of view, Zero Energy Buildings. However, these buildings are difficult to achieve, especially for what concern the carbon neutrality. These concepts have not been associated to the implementation of circular economy practice, so the main question that this thesis aims to answer is "How circular economy can foster carbon neutrality in the construction industry?" In order to do so the literature present on *Scopus* has been examined. This research highlighted 65 relevant articles in which were described different solutions that were in line with circular economy principles that can help to reduce the embodied carbon of a building. The implementation of circular economy practices is in line with Sustainable Development. Sustainable Development is defined as: *"the development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* [Mason, 2020]. Sustainability and Sustainable Development do not regard only the environment, but also the health of the society preventing the suffering of people or areas from the actions taken by the humanity.

From the analysis of literature review emerged that two life cycle stages are more responsible for the emissions of carbon dioxide than others: the manufacturing of building materials and the operation and use. The distribution of the articles showed that the attention is pointed toward these stages, in fact the majority of papers is concentrated toward finding a more sustainable way to produce the building materials. The solutions investigated revealed that is possible to reduce the embodied carbon of building materials by recycling construction and demolition waste, reusing by-products of other industries, or by substituting such materials with materials that have low embodied carbon. From the solutions investigated emerged that the use wood is the best solution to adopt and, according to Robati et al., it can reduce the embodied carbon of 13 percent, while also providing economical savings. Important savings can be achieved by also installing an efficient HVAC system powered by renewable sources of energy.

The analysis of the case studies found in the literature revealed that not all the solutions studied are actually implemented in real cases. The main solution applicated are the use materials made with sustainable materials, the use of prefabricated and modular buildings, and the correct management of waste. The interview with ARUP showed that carbon neutrality can be achieved thanks to the implementation of circular economy practices, even though the results are not immediate. L'Innesto project is the practical example of that, the use of wood along with the use of renewable source of energy played a significant role.

From the review of literature and the interview with ARUP, several barriers that may hinder the implementation of circular economy practices emerged, but also some levers that may drive their implementation. Among the barriers that obstacle the implementation of circular economy solution the most relevant one is cost. Additional costs are required in order to run simulation to prove that a new material can be suitable for substitution in the manufacturing of building materials, or to see if it is compliant to the regulation of the country where it has to be installed. While for the drivers that may foster the implementation of sustainable solutions, the willingness of stakeholder the most important. The more a client cares about the environment and sustainability, the more they will be inclined to install sustainable solutions.

The main limitation faced during the work is that this topic is wide, and the analysis of the literature was difficult to conduct alone, so some data may have gone missing.

The next step for this research could be a further exploration of barriers and lever related to the implementation of circular economy solutions.

7 Bibliography

Abergel, T., Dulac, J., Hamilton, I., Jordan, M., & Pradeep, A. (2019). *2019 Global Status Report for Buildings and Construction. UN Enviroment programme* (Vol. 224).

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Davila Delgado, M., Bilal, M., & Bello, S. A. (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling*, *129*(October 2017), 175–186. https://doi.org/10.1016/j.resconrec.2017.10.026

Andrade, J., Araújo, C., Castro, M. F., & Bragana, L. (2019). New Methods for Sustainable Circular Buildings. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012037

Andresen, I., Wiik, M. K., Fufa, S. M., & Gustavsen, A. (2019). The Norwegian ZEB definition and lessons learnt from nine pilot zero emission building projects. *IOP Conference Series: Earth and Environmental Science*, *352*(1). https://doi.org/10.1088/1755-1315/352/1/012026

Arup. (2021). ARUP.

Ascione, F., Bianco, N., De Masi, R. F., Dousi, M., Hionidis, S., Kaliakos, S., … Vassilakopoulou, K. (2017). Design and performance analysis of a zero-energy settlement in Greece. *International Journal of Low-Carbon Technologies*, *12*(2), 141–161. https://doi.org/10.1093/ijlct/ctw003

Aversa, P., Daniotti, B., Dotelli, G., Marzo, A., Tripepi, C., Sabbadini, S., … Luprano, V. A. M. (2019). Thermo-hygrometric behavior of hempcrete walls for sustainable building construction in the Mediterranean area. *IOP Conference Series: Earth and Environmental Science*, *296*(1). https://doi.org/10.1088/1755-1315/296/1/012020

Awad, N. (2018). Zero Energy Buildings.

Bac, U., Alaloosi, K. A. M. S., & Turhan, C. (2021). A comprehensive evaluation of the most suitable HVAC system for an industrial building by using a hybrid building energy simulation and multi criteria decision making framework. *Journal of Building Engineering*, *37*(September 2020), 102153. https://doi.org/10.1016/j.jobe.2021.102153

Bertino, G., Menconi, F., Zraunig, A., Terzidis, E., & Kisser, J. (2019). Innovative circular solutions and services for new buildings and refurbishments. *WIT Transactions on the Built Environment*, *183*, 83–91. https://doi.org/10.2495/ARC180081

Bortoluzzi, C. R., Pereira de Sousa Lima, M., Marchant, A. K. S., & Vàzquez Padilla, V. M. A. (2019). *nZEB: Best available technologies and practices*.

Budds, D. (2019). How buildings contribute to climate change? Retrieved from https://archive.curbed.com/2019/9/19/20874234/buildings-carbon-emissions-climate-change

Cai, G., & Waldmann, D. (2019). A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study. *Clean Technologies and Environmental Policy*, *21*(10), 2015–2032. https://doi.org/10.1007/s10098-019-01758-1

Castro, R., & Pasanen, P. (2019). How to design buildings with Life Cycle Assessment by accounting for the material flows in refurbishment. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012019

Chamie, J. (2020). World Population: 2020 Overview. Retrieved from https://yaleglobal.yale.edu/content/world-population-2020-overview

Chen, S., Zhang, G., Xia, X., Setunge, S., & Shi, L. (2020). A review of internal and external influencing factors on energy efficiency design of buildings. *Energy and Buildings*, *216*. https://doi.org/10.1016/j.enbuild.2020.109944

D'Agostino, D., & Mazzarella, L. (2019). What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *Journal of Building Engineering*, *21*(October 2018), 200–212. https://doi.org/10.1016/j.jobe.2018.10.019

D'Amico, B., Pomponi, F., & Hart, J. (2021). Global potential for material substitution in building construction: The case of cross laminated timber. *Journal of Cleaner Production*, *279*, 123487. https://doi.org/10.1016/j.jclepro.2020.123487

Densley Tingley, D., Cooper, S., & Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production*, *148*(2017), 642–652. https://doi.org/10.1016/j.jclepro.2017.02.006

Eberhardt, L. C. M., Birgisdóttir, H., & Birkved, M. (2019). Life cycle assessment of a Danish office building designed for disassembly. *Building Research and Information*, *47*(6), 666–680. https://doi.org/10.1080/09613218.2018.1517458

Efrat, Z. (2014). World ' s Top Global Mega Trends To 2020 and Implications to Business , Society and Cultures Executive Summary Definition of a Mega Trend, 14.

Ellen MacArthur Foundation. (2017). The Circular Economy in detail.

España, Z. (2019). Arup's Milan site regeneration proposal wins C40's global Reinventing Cities Competition. Retrieved from https://www.arup.com/news-and-events/arups-milan-site-regeneration-proposal-wins-c40s-global-reinventing-cities-competition

European Parliament. (2010). DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings.

European Parliament. (2018). DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018. https://doi.org/10.1007/3-540-47891-4_10

Fenner, A. E., Kibert, C. J., Woo, J., Morque, S., Razkenari, M., Hakim, H., & Lu, X. (2018). The carbon footprint of buildings: A review of methodologies and applications. *Renewable and Sustainable*

Energy Reviews, *94*(December 2017), 1142–1152. https://doi.org/10.1016/j.rser.2018.07.012

Finkbeiner, J., Günter, K., Meissner, J., Merz, C., Stahl, F., Kruse, D., & Ernst, M. (2019). Woodscraper - Highrise according to the circular economy. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012021

Foster, G. (2020). Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resources, Conservation and Recycling*, *152*(October 2019), 104507. https://doi.org/10.1016/j.resconrec.2019.104507

Gálvez-Martos, J. L., Styles, D., Schoenberger, H., & Zeschmar-Lahl, B. (2018). Construction and demolition waste best management practice in Europe. *Resources, Conservation and Recycling*, *136*(May), 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016

Geldermans, R. J. (2016). Design for Change and Circularity - Accommodating Circular Material & Product Flows in Construction. *Energy Procedia*, *96*(October), 301–311. https://doi.org/10.1016/j.egypro.2016.09.153

Ghisellini, P., Ji, X., Liu, G., & Ulgiati, S. (2018). Evaluating the transition towards cleaner production in the construction and demolition sector of China: A review. *Journal of Cleaner Production*, *195*, 418–434. https://doi.org/10.1016/j.jclepro.2018.05.084

Ghosh, I. (2019). 70 years of urban growth in 1 infographic. Retrieved from https://www.weforum.org/agenda/2019/09/mapped-the-dramatic-global-rise-of-urbanization-1950-2020

Gil, G. O., Chowdhury, J. I., Balta-Ozkan, N., Hu, Y., Varga, L., & Hart, P. (2021). Optimising renewable energy integration in new housing developments with low carbon technologies. *Renewable Energy*, *169*, 527–540. https://doi.org/10.1016/j.renene.2021.01.059

Gopinath, A., Bahurudeen, A., Appari, S., & Nanthagopalan, P. (2018). A circular framework for the valorisation of sugar industry wastes: Review on the industrial symbiosis between sugar, construction and energy industries. *Journal of Cleaner Production*, *203*, 89–108. https://doi.org/10.1016/j.jclepro.2018.08.252

Huovila, P., Iyer-Raniga, U., & Maity, S. (2019). Circular Economy in the Built Environment: Supporting Emerging Concepts. *IOP Conference Series: Earth and Environmental Science*, *297*(1). https://doi.org/10.1088/1755-1315/297/1/012003

IEA. (2020). *Tracking Building 2020*.

InnestoMilano. (2020). L'Innesto.

IPEEC Building Energy Efficiency Taskgroup. (2018). Zero Energy Building Definitions and Policy Activity, 40.

Italian Government. (2013). National plan for increasing the number of " nearly-zero energy buildings " Guidelines and development framework, (October).

Iyer-Raniga, U. (2019). Zero energy in the built environment: A holistic understanding. *Applied Sciences (Switzerland)*, *9*(16). https://doi.org/10.3390/app9163375

Kiamili, C., Hollberg, A., & Habert, G. (2020). Detailed assessment of embodied carbon of HVAC systems for a new office building based on BIM. *Sustainability (Switzerland)*, *12*(8). https://doi.org/10.3390/SU12083372

López-Uceda, A., Galvín, A. P., Ayuso, J., Jiménez, J. R., Vanwalleghem, T., & Peña, A. (2018). Risk assessment by percolation leaching tests of extensive green roofs with fine fraction of mixed recycled aggregates from construction and demolition waste. *Environmental Science and Pollution Research*, *25*(36), 36024–36034. https://doi.org/10.1007/s11356-018-1703-1

Lozano-Lunar, A., Barbudo, A., Fernández, J. M., & Jiménez, J. R. (2020). Promotion of circular economy: steelwork dusts as secondary raw material in conventional mortars. *Environmental Science and Pollution Research*, *27*(1), 89–100. https://doi.org/10.1007/s11356-019-04948-y

Maerckx, A. L., D’Otreppe, Y., & Scherrier, N. (2019). Building circular in Brussels: An overview through 14 inspiring projects. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012059

Magro, C., Paz-Garcia, J. M., Ottosen, L. M., Mateus, E. P., & Ribeiro, A. B. (2019). Sustainability of construction materials: Electrodialytic technology as a tool for mortars production. *Journal of Hazardous Materials*, *363*(October 2017), 421–427. https://doi.org/10.1016/j.jhazmat.2018.10.010

Mahpour, A. (2018). Prioritizing barriers to adopt circular economy in construction and demolition waste management. *Resources, Conservation and Recycling*, *134*(December 2017), 216–227. https://doi.org/10.1016/j.resconrec.2018.01.026

Mangialardo, A., & Micelli, E. (2018). *Rethinking the construction industry under the circular economy: Principles and case studies*. *Green Energy and Technology*. Springer International Publishing. https://doi.org/10.1007/978-3-319-75774-2_23

Mason, M. (2020). What is sustainabilty and whay it is important? Retrieved from https://www.environmentalscience.org/sustainability

Minunno, R., O’Grady, T., Morrison, G. M., Gruner, R. L., & Colling, M. (2018). Strategies for applying the circular economy to prefabricated buildings. *Buildings*, *8*(9). https://doi.org/10.3390/buildings8090125

Napier, T. (2016). Construction Waste Management.

Nasa. (2020a). Cilmate Change: How do we know? Retrieved from https://climate.nasa.gov/evidence/].

Nasa. (2020b). The Causes of Climate Change. Retrieved from https://climate.nasa.gov/causes/

Nasir, M. H. A., Genovese, A., Acquaye, A. A., Koh, S. C. L., & Yamoah, F. (2017). Comparing linear and circular supply chains: A case study from the construction industry. *International Journal of Production Economics*, *183*, 443–457. https://doi.org/10.1016/j.ijpe.2016.06.008

National Geography Society. (2019). Urbanization. Retrieved from https://www.nationalgeographic.org/encyclopedia/urbanization

Nußholz, J. L. K., Nygaard Rasmussen, F., & Milios, L. (2019). Circular building materials: Carbon saving potential and the role of business model innovation and public policy. *Resources, Conservation and Recycling*, *141*(August 2018), 308–316. https://doi.org/10.1016/j.resconrec.2018.10.036

Orsini, F., & Marrone, P. (2019). Approaches for a low-carbon production of building materials: A review. *Journal of Cleaner Production*, *241*, 118380. https://doi.org/10.1016/j.jclepro.2019.118380

Palmieri, S., Cipolletta, G., Pastore, C., Giosuè, C., Akyol, Ç., Eusebi, A. L., … Fatone, F. (2019). Pilot scale cellulose recovery from sewage sludge and reuse in building and construction material. *Waste Management*, *100*, 208–218. https://doi.org/10.1016/j.wasman.2019.09.015

Pan, W. (2014). System boundaries of zero carbon buildings. *Renewable and Sustainable Energy Reviews*, *37*, 424–434. https://doi.org/10.1016/j.rser.2014.05.015

Pan, W., & Pan, M. (2019). Opportunities and risks of implementing zero-carbon building policy for cities: Hong Kong case. *Applied Energy*, *256*(September), 113835. https://doi.org/10.1016/j.apenergy.2019.113835

Rathnasiri, P., Jayasena, S., & Siriwardena, M. (2021). Assessing the applicability of green building information modelling for existing green buildings. *International Journal of Design and Nature and Ecodynamics*, *15*(6), 763–776. https://doi.org/10.18280/ijdne.150601

Ritzen, M., Oorschot, J. Van, Cammans, M., Segers, M., Wieland, T., Scheer, P., … Abujidi, N. (2019). Circular (de)construction in the Superlocal project. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012048

Robati, M., Oldfield, P., Nezhad, A. A., Carmichael, D. G., & Kuru, A. (2021). Carbon value engineering: A framework for integrating embodied carbon and cost reduction strategies in building design. *Building and Environment*, *192*(October 2020), 107620. https://doi.org/10.1016/j.buildenv.2021.107620

Rose, C. M., Bergsagel, D., Dufresne, T., Unubreme, E., Lyu, T., Duffour, P., & Stegemann, J. A. (2018). Cross-laminated secondary timber: Experimental testing and modelling the effect of defects and reduced feedstock properties. *Sustainability (Switzerland)*, *10*(11). https://doi.org/10.3390/su10114118

Saeli, M., Senff, L., Tobaldi, D. M., La Scalia, G., Seabra, M. P., & Labrincha, J. A. (2019). Innovative recycling of lime slaker grits from paper-pulp industry reused as aggregate in ambient cured biomass fly ash-based geopolymers for sustainable construction material. *Sustainability (Switzerland)*, *11*(12), 1–15. https://doi.org/10.3390/su11123481

Sanchez, B., Esnaashary Esfahani, M., & Haas, C. (2019). A methodology to analyze the net environmental impacts and building's cost performance of an adaptive reuse project: a case study of the Waterloo County Courthouse renovations. *Environment Systems and Decisions*, *39*(4), 419–438. https://doi.org/10.1007/s10669-019-09734-2

Santamouris, M. (2016). Innovating to zero the building sector in Europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change. *Solar Energy*, *128*, 61–94. https://doi.org/10.1016/j.solener.2016.01.021

Sierra-Pérez, J., García-Pérez, S., Blanc, S., Boschmonart-Rives, J., & Gabarrell, X. (2018). The use of forest-based materials for the efficient energy of cities: Environmental and economic implications of cork as insulation material. *Sustainable Cities and Society*, *37*(September 2017), 628–636. https://doi.org/10.1016/j.scs.2017.12.008

Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., & Wzorek, Z. (2015). The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. *Journal of Cleaner Production*, *95*, 45–54. https://doi.org/10.1016/j.jclepro.2015.02.051

Tan, A. J., & Nutter, D. W. (2011). CO2e emissions from HVAC equipment and lifetime operation for common U.S. building types. *International Journal of Energy and Environment*, *2*(3), 415–426.

The European Commission. (2018). Horizon Europe Cluster 5 - Climate, Energy and Mobility, 1–26. Retrieved from https://ec.europa.eu/research/pdf/horizon-europe/annex-5.pdf

TMD STUDIO LTD. (2020). Net Zero Carbon Buildings Concepts and Assumptions. Retrieved from https://www.tmd.studio/blog/2020/01/19/zcb

United Nation. (2018). 68% of the world population projected to live in urban areas by 2050.

Wong, Y. C., Al-Obaidi, K. M., & Mahyuddin, N. (2018). Recycling of end-of-life vehicles (ELVs) for building products: Concept of processing framework from automotive to construction industries in Malaysia. *Journal of Cleaner Production*, *190*, 285–302. https://doi.org/10.1016/j.jclepro.2018.04.145

World Building Green Council. (2021). Embodied carbon call to action report. Retrieved from https://www.worldgbc.org/embodied-carbon

Zhang, Y., Qi, H., Zhou, Y., Zhang, Z., & Wang, X. (2020). Exploring the impact of a district sharing strategy on application capacity and carbon emissions for heating and cooling with GSHP systems. *Applied Sciences (Switzerland)*, *10*(16). https://doi.org/10.3390/app10165543

Appendix

What we report to you today is our approach to ZCB, our main developments. We will also speak about the Innesto project, but the focus will be mainly on our approach.

Talking about the Innesto: in the page of your website, it was defined as "carbon neutral" project. What does "carbon neutral" project mean?

With respect to a ZEB or ZCB, we tried to achieve carbon neutrality, which means that not only we take into consideration the use of the b and we try to minimize the E consumption and C emission, but we focus on the initial phases of the building, also on the embodied energy, we used some tech approaches that also helped to minimize the energy and carbon emissions. Sometimes some technologies can have such a beneficial impact that we can achieve carbon neutrality, on all life cycle stages. For example, if I use wood, I can assume that wood can work as a carbon storage and stock carbon emissions. As much as I use wood, I can say that, for example, this solution has beneficial effects on the overall building strategy and the total balance is neutral.

Usually when you speak about net zero in Europe, it is considered only from energy perspective and so in this project we are going forward and consider all the main components, not only the ones related to energy. We considered the impact of the mobility on the CO2 emissions. We did an overall assessment that considered the main strategies such as the use of green solutions and also the possibility to offset the main remaining the main part of CO2 with other solutions like the possibility to extend the district heating to other users and also by developing an offset found the allows to offset the remaining part the CO2 emissions.

We can say that you tried to put together the definition of both ZEB and ZCB, with "carbon neutrality"

We do not speak only about the use of the building, but about the all life cycle stages, we do not only take into consideration carbon emissions and energy consumption during the use of the building, so, not only the operational phase, but also in the initial and end of life phases.

We considered also components, like mobility, that usually are not considered; while materials are almost at life cycle approach in the best practices, not in the usual practices.

This leads to the second question that is: what supply chain/ life cycle stages of the building have been considered in ensuring "carbon neutrality"? The life cycle stages considered in the thesis are: manufacturing of the materials, design of the building, construction, operation and use, renovation and demolition/end of life. Did you consider all of theme, or maybe did you consider different stages?

When we design something using this approach, we try to address all life cycle stages, which means we do not focus on one small piece. It is known that some life cycle stages do have larger impact with respect to others, so if you want to achieve a significant effect of course you will have to prioritize something. Speaking of materials, the most relevant phase is the production; the embodied energy phases (extraction, production, installation). Also, there is a large impact due to end of life materials, because also materials recycle and reuse have an impact on the environment. We focused more on what is more relevant to the topic we are addressing. If we talk about technology and material we focus more on initial and end of life phase; while if we speak about energy and all things related to the operation of the building, we focus more on the operation and use stage. My answer will be different from the one Andrea will give you, because I focus more on the embodied energy, initial and end of life phases, while he focuses more on the operational phases.

I agree with Margherita; if you consider a typical life cycle, usually we have almost of 30/40% of CO2 emissions during the construction, 50% during operation and the remaining 10% at the end of life. What we do, is that we try to minimize where possible, we do not have a prioritization of a certain components, but we try to achieve the best on all the phases.

Another question was: if you prioritize certain phases for the CO2 reduction, but from your previous answer we can say that you address first the phases have more impact, and then you also act equally on all the life cycle.

So, what technologies or practices/approaches where selected for ensuring “carbon neutrality”? If it possible try to divide them for each life cycle stage.

Concerning the initial phase, of course we are focusing a lot on materials, trying to increase the use of sustainable materials; sustainable for us means a low embodied energy, possibly renewable and maybe with some recycle content or used materials, and local materials. We also want to make sure that our materials are from a sustainable supply chain, so we prefer materials that can prove their path, materials that have the EPDS or the material passport, something that is not yet commonly used. Considering technologies, at the end we are trying to focus on technologies that can be, at some point, modified and adapted. Flexibility in order to extend the use of building or structure. Also, technologies that help end of life of the building, for example, de-constructable structure or building, so when you do not need them anymore, you can recover most of them without throwing them away. I’ll mention again the use of wood, because assuming that you can consider it as a carbon storage material, it is really helpful, not only because it is a renewable material, but also because if you provide that it comes from certified forests (FCI certification) it means it really helps sustainable procedure, due to carbon subtraction.

From the operational point of view, what we did is to adopt the carbon hierarchy where you follow a path based on reduction of consumption, so by implementing energy efficient solution, use of renewable solution to reduce the amount the CO2, and the last step is to develop some offset solution to achieve carbon neutrality. Usually this is the approach, in the Innesto project we followed the first two steps and the last step, regarding the offset, was done on an overall approach. In general, the main technologies that we are considering from an operational point of view are renewable solutions and, in the nearby environment, the most important solution you can use is the electrification of thermal energy production, so the use of pumps and the installation of PBC systems. In the Innesto project was really interesting the development of a fourth generation district heating where we used heat pumps that recover energy from sewage, solar thermal plants and also we purchase energy from an energy recovery plant managed by A2A, so this is our approach that consider the main resources that are available on the territory and then develop our innovative solutions. Usually it is not so easy to install for example a solar thermal plant, but in this case was considered because we had an area where it could be installed. So, the main steps are first energy efficiency and the second one is to use renewable energy solutions.

Do you have for example priorities between technologies? For example, PV have priority over the wind turbine

In the urban environment it is not useful and sometime possible to install for example wind turbine, so what we can install it is linked to the availability of the space and also the general conditions. PV is the best system to produce electric energy in a renewable way and heat pumps are the best solution to produce thermal energy in a renewable way. Of course, you can try to use CHP powered by by-fuels but in this moment is not so easy to find by-fuels and also you have some problems related to combustion so in the end PV system is the best solution to be used in the urban environment.

I think the context is what makes you prioritize thing. For example, some clients may be more interested in something than others and consider sustainability as something that goes together with internal comfort and wellbeing; so, maybe they want to make the best of most of them. Also, there are public institutions that give guidelines and you have to stick to them, for example, something that is usually is not considered because nobody cares that much, and a guidelines says that it is important then you have to make it a priority, so it is really depends on the context.

Once you installed everything on the building and the building has come to its end of life, how do you manage the remaining CO2 that is embedded in the building?

So, you mean what happen when the building comes to its end of life?

Yeah

Usually, as designer we work at the design phase, it is not that common that people asks to handle with the end of life. It happens, but it is unusual. When we design, we do have in the team people who take care of the decommissioning and the waste program management. So, sometimes there are some waste management's plans aware that some system do want you to specify the deconstruction and demolition waste management ahead before the construction because they know at some point someone will have to take care of it, so if there is already a plan it is easier. Speaking as a designer I think this phase is something we do take into consideration before; it happens less that we have to say something when the building is already built. Usually happens the other ways, somebody has to deal with an existing building, and we try to find solutions on how to reuse it, make it retrofit, or repurpose the building. It is something that comes from the new user rather than the previous one.

We can say that when you can and it is possible you try to refurbish the building in order to make it more sustainable, otherwise in the demolition phase you try to reuse all the components that can be reused.

Yeah, we try to stick the waste hierarchy. When possible, you don't think at building as something like a waste, but something you just need to fix. But then if that is not possible you will have to retrofit it, the next step is to reuse some components, and the last stage is to recycle. There are other two phases that are: use of energy from waste combustion and landfill, but both are not sustainable, that's why you try to stop at recycling. This is the waste hierarchy, of course if a client wants to tear build down and build a new one, economy drives thing, you cannot say much more, but you can try to make it cleaner and advise to the best. Sometime is not possible just to save all the buildings, with respect to economic feasibility and sustainability.

Do you consider also the requirement of the client or you propose your solutions? During the selection of the technologies installed in a building, other than the priority between technology, you consider also the requirement from the client or other stakeholder?

We worked together with A2A and together with a client we decided which were the best solution to be adopted. The Innesto case was a participative process where the district heat provider and also water supplier decided to work together to develop an innovative solution like the heat pumps that recover energy from the sewage. In the end the first point was the client to achieve relevant objective in terms of CO2 emission reduction and innovative energy solutions.

Always related to technology and stakeholder, what are the main challenges that you face while developing these kinds of buildings? For example, some technologies are too expensive, some stakeholders are not well informed, and they are reluctant to install these kinds of investments, or regulations cannot allow you to install the best technology, so you have to downgrade them and accept some trade-off

I think you mentioned all of them. Cost is the biggest challenge, because also the other factors you mentioned are related to cost. If a technology is not common and it is not available in the territory or not well tested you need money to test it again, or maybe some of technical standards do not take into consideration a specific technology or solution you have to make extra calculation to make it work and that is expensive. I think cost is one of the biggest challenges, the biggest effort is to try to show at our clients that is worth and that at the end of the day they will be happy to have some technology, but this is not so easy, because you cannot really demonstrate it, it is something new what you are trying. Some green technologies are really common, like photovoltaics, but some others are not that used, talking about materials it is really hard to go away from the current practices, here in Italy we build everything with reinforced concrete, it is very hard to try to change thing, even if materials do work in different way and can make the same performance, at the end is very hard to use something different from what the business is used to.

How do you manage to address these challenges? Do you act in some way to make thing work?

I will try to collect the best practices around all our offices when there is something we don't know here in Italy, but maybe some colleagues already did, so we can say to our clients that we did it in other countries, and maybe we also have worked on it, because we work on projects with other offices, so you can somehow demonstrate that something is feasible, maybe not usual, but feasible and with benefits. The key is to show that something has been done and try to do something bigger when you can. We try to collect best practices.

What can change from energy perspective, cost is for sure an important element. In the Innesto developing a participative process where also the district heating provider participated was easier, when a third party invests on innovation you can try to maximize the use of innovative solutions and it differs from project where the clients is the only investor, so we have to optimize the environmental impact but also economic stability of the intervention.