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Case related Life Cycle Cost Analysis to support Façade Leasing

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List of abbreviations

BM Business Model

BSM Business Strategy Model

CBM Circular Business Model

CDS Circular Design Strategy

CE Circular Economy

EC European Commission

EMF Ellen MacArthur Foundation

FM Facility Management

HRV Heat Recovery Ventilation

IAQ Indoor air quality

LCCA Life Cycle Cost Analysis

NPV Net Present Value

OCC Opportunity Cost of Capital

PS Product System

PSS Product Service System

TCO Total Cost of Ownership

Introduction

The building industry is an economic key driver since its involvement in environmental impacts is strongly recognized: this sector is still one of the main responsible of GHG (Greenhouse gases as CO_2, CH_4, N_2O, etc.) emissions, in particular buildings generate approximately 40% of the CO_2 emissions, thus contributing in large measure to the global warming. At the same time, another relevant contribution is in waste generation: the building sector, indeed, is responsible for almost 35% of the total waste production.

The dissertation is intended to introduce the Circular Economy practices through which it will be possible to apply the principles of sustainability: the implementation of Circular Business Models in the building process may lead to opportunities in economic, environment, business and society terms. In particular, ones of the most significantly objectives of Circular Economy are the maintaining of material productivity over the entire lifecycle and the promoting of an efficient use of the raw materials. In this regard, it will be described how the Life Cycle Cost Analysis is one of the main decision-making support tool to include upstream of the design process, in order to evaluate not only the economic aspects but also the potential environmental impacts of a choice over the life cycle.

In the present case, the application of the Life Cycle Cost Analysis has been a support for analysing different alternatives of façade's refurbishment on a case study located in the Netherlands, in which it has been introduced the possibility to exploit the Circular Business Model called "Product as a service": through the leasing it sets a new form of relationship between the supplier and the customer, in which the optimisation of the useful lifetime of a component and the integration of its end-of-life phase in the design process become central. This new ownership model, whereby the manufacture remains the owner of his product that is temporarily stored in the building, requires a greater attention to the Total Cost of Ownership: it is possible to evaluate it thanks to the Life Cycle Cost Analysis by investigating which alternative could result the most cost-effective, and then that data could be a strong base for developing an ideal scenario in which the purchasing and the leasing system are compared.
This study has not the aim of providing the exact values of each cost item or the precise price at which a system could be immediately leased, since the macro-economic context is subject

to variables that could change in the long period, but rather it is intended to be a methodology developed for helping to calculate the performance contracts for leasable façades.

Furthermore, with regard to the thesis's structure, it has been developed following a gradual process of knowledge in which it starts from the theory of the Circular Economy and then to come to focus on one of its application in the built environment, the so-called "Performance Contract". The **Chapter 1** and **2**, indeed, contain a study based on the concept of the Circular Economy, barriers and opportunities, and its application and relevance in the building sector. In **Chapter 3** it has been analysed in more detail the practices related to the Circular Economy, in particular the models and the strategies adopted to achieve the aim, both in general and construction terms. In this chapter it has been also described the leasing system as the direct application of the Circular Business Model "Product as a service". As abovementioned, to support this form of collaboration between the stakeholders there is the need of tools focussed on the lifecycle approach: for this reason, in **Chapter 4** it has been introduced the Life Cycle Cost Analysis as the main method for assessing the Total Cost of Ownership and for integrating the end-of-life phase during the design process. Lastly, the **Chapter 5** contains the case study in which has been applied the steps described in the previous chapter in order to develop an analysis for supporting the façade leasing.

1. Towards circular economic model

1.1 The concept of Circular Economy

The concept of Circular Economy (CE) contains in itself a series of definition depending on the field which it is intended to be applied. For this reason, in this section the concept is based upon several studies and reports, trying to create an overview of them.
To deepen the concept, it is also necessary to make a comparison between the current Linear Economy model and the circular one, pointing out what are the obstacles and the opportunities.

1.1.1 Definition

In all probability, the Ellen MacArthur Foundation (EMF) was one of the first to mark and theorize the concept of the CE and its work is currently used as a core indication in Dutch academic and non-academic debates on CE.
Since from the first report of 2012, the CE is defined as "an industrial economy that is restorative by intention. It aims to enable effective flows of materials, energy, labour and information so that natural and social capital can be rebuilt".
This means that the concept of *end-of-life* is replaced by a new one which involve the shift towards the use of renewable energy, eliminating the use of toxic chemicals and seeking for the removal of waste through the superior design of materials, products, systems.

Another remarkable study about this theory is showed by Damen (*A resources passport for a Circular Economy*, 2012) who underlines how the conventional perception of the economic system as linear and open-ended loop is different from a closed system.
To clarify his thought, he uses the principles of thermodynamics as a terms for comparison: the *First Law of Thermodynamics* states that energy and matter can be converted and dissipated from one form to another, but cannot be created or destroyed, which means that waste should be integrated. This leads to the definition of Earth as a closed system where the economy and the environment are interconnected: as illustrate Kenneth Boulding in 1996 in his essay "*The economics of the coming spaceship Earth*", we have to think at the Earth as a spaceship that is facing a long journey and whose unique external source of energy is the sun. At some point the resources present at boarding could start to use up inevitably and the only chance of survival could be to recycle and re-grow the diminished stock.

This is the basic concept that everything creates input for anything else and help to understand the shift from what illustrate in Figure 1 to Figure 2.

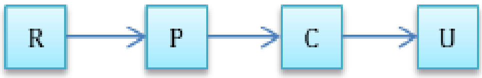

Figure 1 – The open ended economy (R:resources; P:production; C:consumption; U:utility)
(Source: Daman, *A resources passport for a Circular Economy*, 2012)

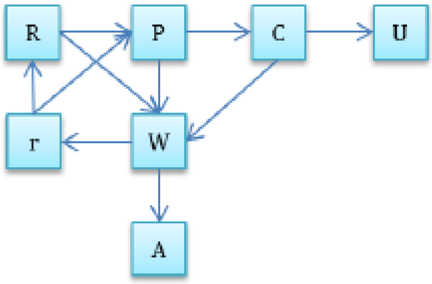

Figure 2 – The simplified Circular Economy (R:resources; P:production; C:consumption; U:utility; r:recycling; W:waste; A:assimilative capacity of the environment)
(Source: Daman, *A resources passport for a Circular Economy,* 2012)

Founded on the work of EMF and other contributions such as Damen 2012, Kot et al. 2013, Leising 2016, the following definition of CE is given:

"A Circular Economy is an economic system where products and services are traded in closed loops"

This implies an economy which is regenerative by design, with the aim to retain as much value as possible of products, parts and materials, preserving both economic and ecological importance. The goal should be to generate a system that allows for the long life, optimal reuse, refurbishment, remanufacturing and recycling of products and materials.
At the same time, materials can be reused by another manufacturer or in other products provided that they remain in their original material flow so down cycling is avoided; thus it is not necessary that the products must go back to their original manufacturer (open loop recycling).

1.1.2 Principles

According to EMF, the CE takes the cue from natural principles in order to be adaptable and resilient. A schematic overview of them is illustrate in Figure 3 through the "butterfly diagram". It is shown that there are two types of flows[1]: the biological one, designed to re-enter the biosphere safely, and the technical one, which are designed to circulate at high quality without entering the biosphere.

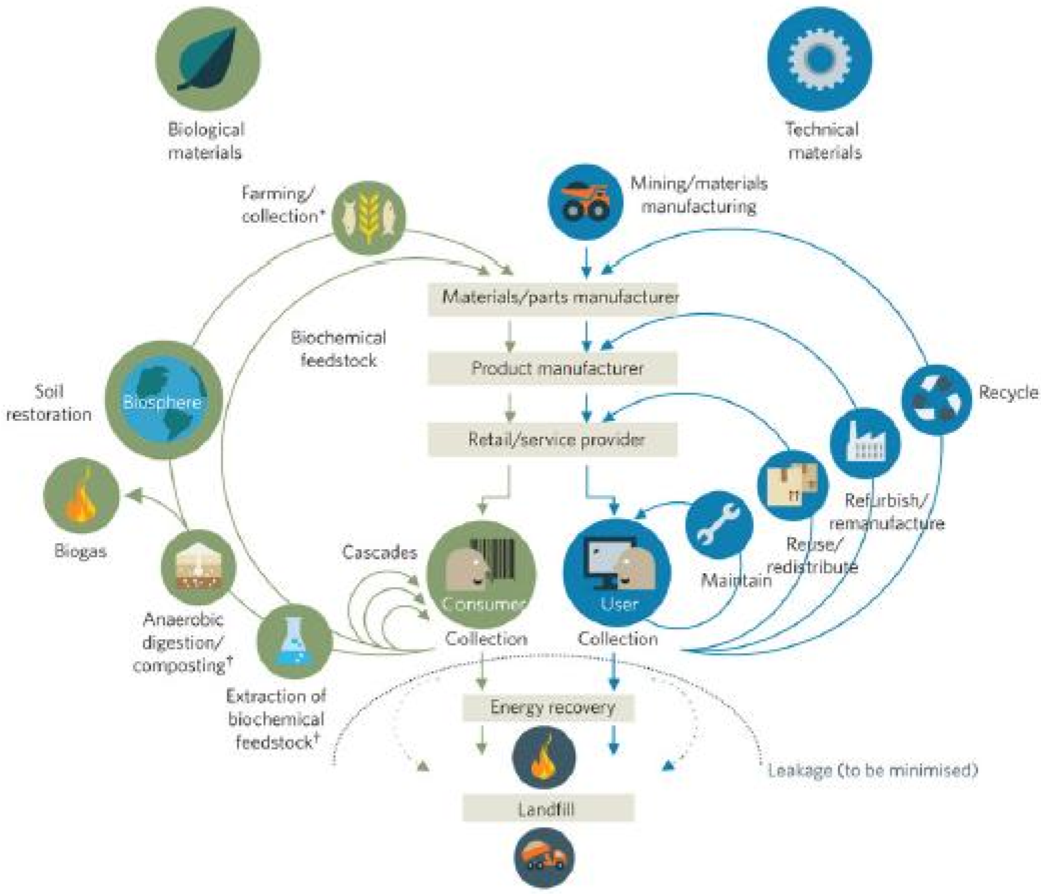

Figure 3 – The butterfly diagram shows bio-cycle and techno-cycle through economic system (Source: Ellen MacArthur Foundation, 2012)

In the techno-cycle it is important that the finite stock of materials is accurately managed: this means that *using* materials replaces the *consumption*. By fixing on value retention, materials are recovered from residual streams after use.

[1] McDonough W. and Braungart M., *Cradle to Cradle: remarking the way we make things*, 2002

On the other side, organic materials can be absorbed in the ecosystem by resources of biological processes. In the bio-cycle it is important to guarantee that the ecosystem and biological processes are allowed to function properly.
Only if the materials flows are not contaminated with toxic products and the ecosystems are not overloaded, the consumption can be integrated in this process. Thus, if the ecosystem is balanced, organic materials are renewable.

In accordance with these cycles, EMF illustrates three main principles[2]:

- Preserve and increase natural capital with the preservation of the finite stocks of non-renewable resources flows, and balance the renewable resource flows;

- Optimize resources based on the circulation of products, components and materials. Regarding the technical cycle, alternatives to achieve this principle are: recycle, remanufacturing, reuse and to implement Product-Service Systems (PSS). In relation to the biological cycle, one option is to adopt biogas to generate energy, for example;

- Foster the system effectiveness and reduce damage to human issues as related to food, health, education, mobility and shelter and externalities, such as land use, air, water and noise pollution, liberation of toxic substances and climate change.

Focussing on the technical side of the diagram (Figure 3), there is the idea that if the cycle remains as close to the top as possible (the smaller circles), the falling speed of value loss will cut down and the direct consequence is an increment of value. This could be chase following the strategy described below:

[2] Rodrigues Reigado C. et al., *A Circular Economy toolkit as an alternative to improve the application of PSS methodologies*, 2017

Maintenance

The performance of inspection or service tasks to maintain the functional capabilities of a product or material and thereby extend the lifetime. Maintenance occurs often as a scheduled activity.

↓

Repair

Restoring a product or component to its usable state after decay or damage.

↓

Recondition / Refurbishment

Repairing or rebuilding major components which are close to failure. This activity could be seen as a combination of maintenance and repair.

↓

Reuse / Redistribution

Reusing a product or component without treatment. Product value is captured by finding new users with different needs, wherefore the product is still suitable. This often involves a physical or digital trading place.

↓

Upgrade

Changing product parts or components, to improve the quality, value or performance of the product, so it can continue being useful.

↓

Remanufacture

Returning a used product to at least its original performance, with a warranty that it is equal or even better than the original or other comparable products.

Recycling

Through various separation processes, materials from products and parts can be reused to produce the same or new products.

Energy recovery

Winning back (part of) the embodied energy of a used product before disposal.

Disposal

The final resort of a material flow. In a CE it is preferred to search for ways to capture value in all other circles before disposal.

1.1.3 Schools of thought

To summarize these principles, turns out to be useful highlight other five assumptions presented by EMF:

- Design out waste;
- Build resilience through diversity;
- Shift to renewable energy sources;
- Think in systems;
- Think in cascades.

These are the summary of a several preceding schools of thought (listed below) by which EMF has set up the description of CE.

Table 1 – Key terms of schools of thought

School of thought	Key terms	CE principles
Regenerative design (John T. Lyle, 1970)	Processes regenerate the sources of energy and materials that they consume	Design out waste
Performance economy (Walter Stahel, 1976)	Product-life extension, Product –service systems, Performance-based	Think in systems
Cradle to cradle (M. Braungart, B. McDonough, 2005)	Waste equals food, Celebrate diversity, Use current solar income, Distinguish bio and techno cycle, Eco-effectiveness over eco-efficiency	All principles
Industrial Ecology (Frosch & Gallopoulos, 1989)	Minimize energy use, consumption of scarce materials and environmental impacts	All principles
Biomimicry (Janine Benyus, 1997)	Nature as model (imitation and learning), nature as measure (norms), nature as mentor (value)	All principles
Blue Economy (G. Pauli, 2010)	Cascading systems	Think in cascades
Permaculture (B. Mollison & D. Holmgren, 1978)	Diversity, stability, resilience	Build resilience

1.2 How much a Circular Economy differs from a Linear Economy

The main differences are observed in the s*tep plan* that is followed, the perception on what *sustainability* is and the value of *reuse practices*.

- A Linear Economy works following the “take-make-dispose” step plan, whereby resources are extracted and products are produced. Products are used until they are discarded and disposed as waste and the value is created by maximizing the amount of products manufactured and sold. A Circular Economy, as said before, works according to the 3R approach of “Reduce, Reuse & Recycle”, whereby the value is created by focussing on value retention.
- In a Linear Economy sustainability is developed by focussing on *eco-efficiency*. This entails maximizing the economic gain which can be realized with a minimized environmental impact. In a Circular Economy sustainability is improved by

improving the *eco-effectivity* of the system. This means that next to minimizing the negative impact of the system, the attention is put on maximizing the positive impact of the system by deep innovations and system change[3].

- In a Circular Economy reuse is intended to be as high grade as possible. A residual stream should be reused for a function that is equal (functional reuse), or of a higher value (upcycling), that the initial function of the material stream. For example: concrete can be grinded in to grains that are used to generate a similar wall as before. Within a Linear Economy, instead, reuse is principally seen in down cycling systems: a (part of a) product is used for a low quality purpose which reduces the rate of the material, and complicated the future reuse possibilities. For example: concrete is shredded and used as road filament[4].

The main obstacles of the current linear system are well illustrated by Azcárate-Aguerre J. in his report "*Integrated Façade System as a Product-Service System*", 2016:

- In a linear system there is not a continuous cycle but the supply chain is disconnected whenever a new Figure comes in the process: this leads to a lack of transparency in the initial production cost and the price of components increase inevitably;
- One of the main actor in the life-cycle process of a product, like the manufacturer, is dismissed from the supply chain after a one-time payment from the client: as a result, he loses the ownership of their products, even though he has the widest technical skills;
- As a consequence of this, the ownership moves on to the clients even if they have not the competences and for this reason they have to delegate to a third party their facilities.

Therefore, the CE highlights a strong distinction between the *consumption* and *use* of materials, focussing on a *functional service* model in which manufacturers or retailers increasingly retain the ownership of their products and, where possible, act as service providers. This shift has direct implications for the development of efficient and effective

[3] McDonough W., Braungart M., Bollinger A.,*Cradle to Cradle: creating healthy emissions: a strategy for eco-effective product and system design*, 2007
[4] Bocken et al., *Product design and Business Model strategies for a Circular Economy*, 2015

take-back systems and the proliferation of product -and business- model design attempts that generate more durable products, facilitate disassembly and refurbishment[5].

1.3 Which are the barriers?

There are distinct categories of barriers which are, at the same time, interrelated each other. Just thinking to a company with a culture diffident towards CE which it will not develop circular designs. Therefore, consumers will lack knowledge and curiosity towards circular designs since none of these are offered in the market. This means that cultural barriers can cause technological barriers which induce further cultural barriers.
They are mainly referable to these fields[6]: financial, legislative, cultural and technological.

- **Financial**

One of the main obstacles in this sphere are the *high upfront investment costs*: it is clear that Circular Business Models (CBMs) require upfront investments and the returns are uncertain or extended over a long term. And this latest could be a problem since many companies have a *short term perspective*.

Another remarkable barrier is the *low virgin material prices*: if the price of raw materials will continue to be low, there will not be a market suitable for the secondary resources. Especially since there are *higher costs for recycling and planning*: even now the costs linked to recovery are greater than those to start a new process, due to extra cost for managing, distribution, production and designing.

*Externalitie*s and *true pricing* are still uncertain due to not incorporating social and environmental costs in economic decisions: thus, there is a clear divergence between financial and material flows, which leads to incorrect market signals and absence of incentive for companies to take into account all the impacts in their products.

- **Legislative**

The first limitation is the *high taxation of labour* while materials are quite cheap: this means that financial governmental incentives still support the Linear Economy.

[5] Ellen McArthur Foundation, *Towards the Circular Economy*, 2013
[6] Kok L. et al., *Unleashing the Power of the Circular Economy*, Amsterdam, the Netherlands: IMSA for Circle Economy, 2013

Furthermore, circularity is not effectively incorporated in innovation policies and *competition legislation* reduces collaboration between companies.
A final barrier is *waste policies*: there is no many incentives to obtain high quality recycling.

- **Cultural**

The main difficulty is a *lack of awareness* and sense of urgency: a transition is necessary and understanding which is the added value of the concept represents the basis for a development.

Furthermore, one of the main macroeconomic indicators is the *Gross Domestic Product* (GDP) that does not indicate the real evolution or the regression of our society.

In conclusion, the resistance comes from *stakeholders* with huge interests in current state.

- **Technological**

It seems that the *development* goes at the same time *too slow* and *too fast*.
On one side, it is necessary that the innovations in materials science labs and product design studios are quickly incorporated into the mass market but this is slowed down by the information sharing and competitiveness. There will be needed new agreements between the partners to promote sharing but at the same time to protect intellectual property.
On the other side, the customers have a tendency to replace a product when a new one with improved technologies and designs is placed on the market: this happens before the older product reaches his end of life cycle. It is not possible to regulate the technological clock speed that renders a product less attractive, but it is feasible to replace a product by different solutions long before it is destined to be recycled.

There is also another aspect linked to the barriers in *design technology*.
First of all, the current products are not planned for future reusing or recycling, underlining an insufficient attention of end-of-life-phase.
Then, there is a lack of knowledge in Design Strategies since the current recycle conducts to down cycling because products are not designed to be a part of it.

In conclusion, all of these barriers are due to so called *path-dependence*[7]. Just thinking to energy policy in the Netherlands, based on fossil energy use: this brings more difficult to raise renewable energy systems. This means that the decisions taken in the past influence inevitably the actions and the decisions of today. Thus, the present-day thought is stopping the shift towards the Circular Economy, because it is led to follow always the same track.

1.4 Which are the opportunities?

According to EMF, SUN and McKinsey, adopting CE principles can bring advantages in *economic terms* above all.

As indicated by Ellen MacArthur Foundation (*Towards a Circular Economy: business rationale for an accelerated transition*, 2015) the economic opportunities can be summarised in four categories:

- Economic growth: calculations by McKinsey & Co. show how GDP could increase, implementing a CE. This could be achieved as a result of increased profits from circular activities and reduced cost of production by making more effective the use of inputs. The changing in input and output of economic production actions leads to a new and upper return for the work and thus it means and increase in income and expenses per household. The first effect is a higher GDP: European GDP could rise from 4% of the current scenario to 11% by 2030 and from 15% to 27% by 2050.
- Substantial net material cost savings: with the increase of world population it is inevitable that there will be still an increase in the demand for materials but with a CE this will be slower. In fact, as EMF states in the report of 2014 the CE gives the possibility to save over 70% of material than the business-as-usual models. Even just evaluating the direct eco-costs of the manufacturer or realizing the total cost of the impacts of raw materials, it is achievable the raw material savings.
- Job creation potential: this impact on employment would be extended from big companies to small and medium enterprise, across improvement and entrepreneurship. This is supported by an increase in expenses due to lower price and an increase in labour strength high quality recycling and repair practices.

[7] Kok L. et al., *Unleashing the Power of the Circular Economy*, Amsterdam, the Netherlands: IMSA for Circle Economy, 2013

- Incentives for innovation: trying to think about new systems to improve the CE, makes a breeding ground for spreading new ideas. The need is a new way of thinking not only about the materials and their design but also about the organization and the collaboration between the stakeholders.

Other positive effects are reflected on the *environment*:

- Fewer carbon emissions: according to the data reported[8] from EMF, a CE may halve carbon dioxide emissions by 2030, compared to current levels (48% reduction of carbon dioxide emissions by 2030 across mobility, food systems, and the built environment, or 83% by 2050).
- Primary material consumption: taking into account the material consumption measured by car, construction materials, real estate land, synthetic fertiliser, pesticides, agricultural water use, fuels and non-renewable electricity, a CE could enable a reduction of 32% by 2030 and 53% by 2050[9].
- Land productivity and soil health: the CE promotes a wider land productivity and underlines the importance of the return of nutrients into the soil: that's because more biological materials pass through the anaerobic digestion or composting process. Thus, the worth of the land increases and the system results more balanced.

Furthermore, the EMF (*Towards a Circular Economy: business rationale for an accelerated transition*, 2015) has summed up four opportunities for the *entrepreneurs*:

- New profit opportunities: thanks to CE companies could reduce their material costs and create new markets to make profits. This is supported by the assurance of a constant supply, the optimization of energy consumption and waste reduction and the addition of value for consumers.
- Fewer volatility and extra security of supply: as said before, the CE lead to use more recycled materials with a higher labour costs and fewer material costs. The result is a lower company's exposure to volatile raw materials costs and thus a more stable Business Model and an increase of the resiliency of a company.

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[8] Ellen MacArthur Foundation, SUN, McKinsey & Co., *Growth Within: a Circular Economy vision for a competitive Europe*, 2015

[9] Ellen MacArthur Foundation, SUN, McKinsey & Co., *Growth Within: a Circular Economy vision for a competitive Europe*, 2015

- Demand for new service models: a CE could generate a request for new type of business services such as reversed logistics companies concerned with end of life cycles, marketers and sales platforms responsible for promoting longer lives and a correct use of products, and experts in the remanufacturing and product recovery. It is clear that for applying all the specific action just mentioned, it will be necessary to have more and more specialized entrepreneurs who are familiar with the process know how.
- Optimized customer relationships: new Business Models offer the possibility to involve the customers in different way such as rentals or leasing contracts. Thanks to these type of long-term relationship, the supplier retains the ownership of the products while the customer exploits the capability of them. The result is the satisfaction of the customer who does have not to think about maintaining or repairing the products.

At last, as described EMF (*Towards a Circular Economy: business rationale for an accelerated transition*, 2015) there are advantages also for the *citizens*:

- Increased disposable income: analysing three sectors (mobility, food systems and the built environment), if CE lead to lower products costs and services, the direct result is an increment of income for EU households.
- Greater benefit: every choice that the customers can do in a CE is highly customized according to their needs, because companies can provide more options and more quality.
- Reduced obsolescence: let the supplier maintains his ownership of the product means that the customer can avoid the premature obsolescence and can have the guarantee of using a high-quality product.

2. Circular Economy in building sector

The building industry is a sector full of complexity due to the large amount of actors involved and the conservative market deep-seated. For this reason, can be useful to give an overview concerning this sector, from the statistics to the construction discipline, the future aspects related to sustainability and innovations and the several included stakeholders.

2.1 The numbers linked to the building sector

First of all, it must be clear that this field acts in a completely different way than other industrial and non-industrial sectors: while the industrial sector aims to a higher standardization and its process is more focus on management principles, the building industry has different structures that relate to each other in order to create an interdisciplinarity and its approach is driven by the project. On the other hand, the non-industrial sector is easily adapted to changes, since it is focused on the customer demands (especially the consumer goods sector) and thus the culture is more dynamic.
Another relevant difference is that the building sector works with an extended timeframe, which is often over fifty years and therefore becomes difficult to manage the entire life cycle from the construction to the demolition; this is one of the reason related to the slow development of this industry.

A further remark concerns the building market which is still unstable after the period of stagnation due to the Global Financial Crisis of 2008. As the Figure 4 shows, between 2008 and 2013 had been a constant decrease of the level of total construction in Europe, except for the summer 2010. This drop is more relevant in the construction of buildings (which is the 77% of the total construction in the EU-28): for the civil engineering works, indeed, the effects of the crisis had been less remarkable, since it is around 23% of the total construction. Since 2013 the line diagram illustrates a steadily increase, until it reaches the 90% of the previous peak level.

Figure 4 – Construction production per type 2005-2017
(Source: database Eurostat)

This lability has an impact on the development of new approaches in building market, and furthermore the financing of building construction becomes even more difficult both for public institution and private builders. It leads to new forms of contract, such as "Public-Private Partnerships" (PPP) which implies a collaboration between the government and the private sector in order to have immediate funds to invest on a project of public interest. Contracts like PPP shall ensure the interest in a more sustainable programme, since they are based on long time partnership and include a detailed Life Cycle Cost Analysis (LCCA): the project and the relative phases are commissioned to one contractor who has to know which is the total project costs and how and when the government will repay him during the project's life time.

The need for a new challenge in the building industry is especially required due to its involvement in environmental impacts. Nowadays many buildings are designed in order to meet the requirements of the standard, but they are only a small percentage on the total: the building sector is still one of the main responsible of GHG (Greenhouse gases as CO_2, CH_4, N_2O, etc.) emissions, which have as consequence an increasingly higher level of global warming.

Focussing on the CO_2, the Figure 5 shows that buildings represents the 28% of global energy-related CO_2 emissions and the construction industry (including the manufacturing of materials for building such as steel and cement) represents another 11%.

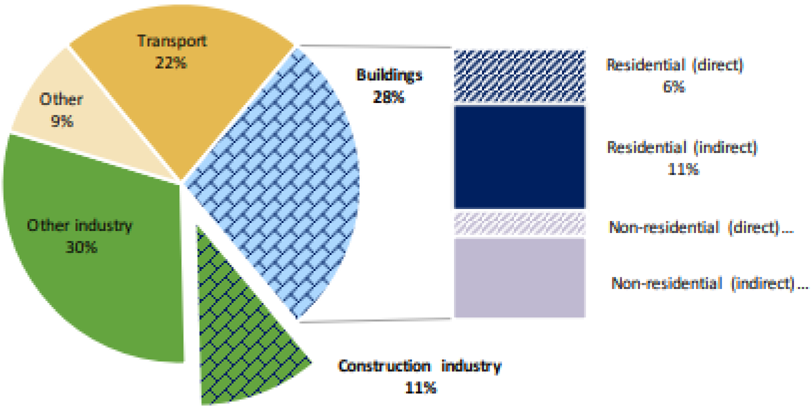

Figure 5 – Global energy-related CO_2 emissions by sector, 2015
(Source: Global Status Report, 2017)

This means that the building industry generates at least the 40% of the CO_2 emissions and thus is responsible for large part of environmental burden.

Another significant data is about the waste generation related to this sector. In the Figure 6 is illustrated how relevant is the contribution of the construction with a percentage of almost 35% as opposed to mining and quarrying (28.2%), manufacturing (10.2%) and other less considerable activity.

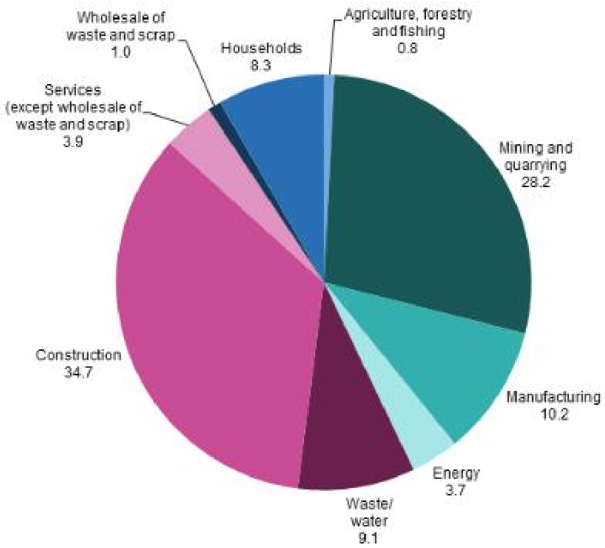

Figure 6 – Waste generation by economic activities and households, EU-28, 2014
(Source: Eurostat)

Thus, it is clear that the building industry could be an important economic key driver: the trends abovementioned allow for the emerging of CE practices, since this field is one of the biggest users of raw materials and energy. For this reason, applying the CE principles can be most significantly in order to maintain material productivity over the entire lifecycle (especially for reducing losses of non-renewable materials) and to promote an efficient use of the raw materials.

This implies a drastic change in the current way of thinking and acting, focused on short-term planning; through the implementing of practical tools, such as the LCCA, is possible to show to the industry how the CE could give a positive contribution and at the same time can help to achieve the objectives set by the Directives[10].

2.2 The Circular Economy Construction Discipline

The important role of the CE is gradually being recognised by the governance groups which have developed an action plan with the European Union (*EU Action Plan for the Circular Economy*, 2015) in order to take advantage from the CE practices for promoting a more sustainable economic growth and generate new opportunities.

As early as 2014 the European Commission (EC) decided to put in place a series of measures regarding the waste management; then that proposal has been updated and has been set several targets[11]:

- A common EU target for recycling 65% of municipal waste by 2030;
- A common EU target for recycling 75% of packaging waste by 2030;
- A binding landfill target to reduce landfill to maximum of 10% of municipal waste by 2030;
- A ban on landfilling of separately collected waste;
- Promotion of economic instruments to discourage landfilling;
- Simplified and improved definitions and harmonised calculation methods for recycling rates throughout the EU;
- Concrete measures to promote re-use and stimulate industrial symbiosis - turning one industry's by-product into another industry's raw material;

[10] ARUP, BAM, supported by Ellen McArthur Foundation, *Circular Business Model for the Build Environment*, 2017

[11] European Commission, *Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste*, Brussels, 2015

- Economic incentives for producers to put greener products on the market and support recovery and recycling schemes (e.g. for packaging, batteries, electric and electronic equipment, vehicles).

In 2015 the EC realized that would be more useful to present a new package covering the whole economic cycle: the *EU Action Plan for the Circular Economy*, indeed, includes several actions which contribute to closing the loop of product lifecycles. These actions concern:

- Production;
- Consumption;
- Waste management;
- Secondary raw materials and water reuse;
- Plastics;
- Food waste;
- Critical raw materials;
- Construction and demolition;
- Biomass and bio-based products;
- Innovation, investments and horizontal measures.

Talking in particular about the construction sector, its role in the environmental performance of buildings has been already established and for this reason the EC wanted to develop guidelines for use on demolition sites, including the treatment of hazardous waste, the separate collection of waste and an adequate recovery system.
Another aspect included in this action is to encourage design improvements which can reduce the environmental impacts and increase the durability and recyclability of the components. In this regard the EC has developed "indicators to assess environmental performance throughout the lifecycle of a building, and promote their use for building projects through large demonstration projects and guidance on Green Public Procurement"[12].

Government policy can ease or restrict the transition to the CE also through actions connected to taxation of consumption, legal structures and industrial strategy: for example, in the UK, new construction is exempt from VAT, while retrofit is not, adding a 20% cost

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[12] European Commission, *EU Action Plan for the Circular Economy*, Brussels, 2015

burden that could dissuade renovation projects. On the other hand, in Sweden the government proposed a lower rate of VAT for repairs on items.[13]

By reference to the Dutch government, which is the background of this dissertation, its policy is following the EU directive in the field of waste programme "From Waste to Raw Material" (Van Afval Naar Grondstof – VANG). The Netherland is being a leader in promoting partnerships with business to realise a Circular Economy and is encouraging several initiatives involving as many stakeholders possible.

Among those in the construction sector there are[14]:

- Circular city;
- Circular buildings;
- Bio-based building;
- Sustainable approach to ground work, road and hydraulic engineering;
- Sustainable concrete;
- The RACE coalition.

The last mentioned - *the Realisation of Acceleration of a Circular Economy* (RACE) – tries to encourage new BMs through a series of work packages[15] in order to:

- Define and stimulate circular design;
- Stimulate high-quality reuse of products;
- Analyse the barriers to the Circular Economy;
- Create a portfolio of circular projects that will serve as examples;
- Raise public awareness about the Circular Economy;
- Involve young people in the transition to a Circular Economy.

Furthermore, the Dutch regulation has several decrees about the performance of the buildings such as "The Buildings Decree" published in 2012, which contains the technical regulations representing the minimum requirements for all structures in the Netherlands (safety, health, usability, energy efficiency and the environment); the obligation shows the priority within the sustainability policy and the goals to achieve until 2020.

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[13] ARUP, BAM, supported by Ellen McArthur Foundation, *Circular Business Model for the Build Environment*, 2017

[14] Schut E, Crielaard M, Mesman M., *Circular Economy in the Dutch construction sector: A perspective for the market and government*, 2016

[15] Willmott T., *Netherlands aim for lead in the Circular Economy*, 2016

2.2.1 Sustainability and innovation

Next to the regulation regarding the Circular Economy, it is inevitably not mention the concept of sustainability and the related certifications, now established in all the environmental policy.
Focussing on the Netherlands, recent data on the sustainability of the Dutch building sector illustrate the same trend of the Europe: the large part of total waste produced comes from the build industry (37%) and 5% of the country's CO_2 emissions are caused by manufacturing of building materials (ABN Amro, 2014).
At the same time, as stated above, the building sector is favourable for sustainable solutions and for this reason several certification schemes and labels around environmental performance began to develop and to draw an increasing attention in Netherlands.
The *Energy Performance Coefficient* (EPC) was the first criteria to be introduced and was included in the Dutch Building Decree: through it, was possible to establish the energy efficiency of new buildings, in accordance with EU directive.
Around the same time was developed the *GPR Gebouw*, which was the first certification taking into account the whole lifecycle steps of a building, in order to determine the performance from an energetic, environment, health, user quality and future value point of view.
The *GreenCalc+* programme, was a method to evaluate all types of buildings from four sustainability point of view: material use, energy use, water usage and mobility.
A specific instrument for classifying and comparing building materials was introduced by the Dutch Institute for building biology and ecology (NIBE) and was called *DUBOkeur*.
In 2008 the Dutch government decided to develop the so called *Energy Label* as a tool for allowing home owners to become easily aware of the environmental performance of their potential new purchase. Since the 2015 this energy label has become obligatory to everyone selling or renting a house or building.
The most recent development in this field has been the *BREEAM-NL*. This certification was originally introduced in the United Kingdom and then was adopted by the Dutch Green Building Council (DGBC); actually the Energy Label and the EPC are incorporated within the *BREEAM* certification and it is the mostly used in the Netherlands. It differentiates five categories: Pass, Good, Very Good, Excellent and Outstanding.

On the other hand, the LEED certification is worldwide recognised. At first it took into account five aspects of the building industry: building design and construction, interior design, operations and maintenance, homes and neighbourhood development; actually it evaluates six categories (sustainable sites, energy and atmosphere, water, materials and resources, indoor environmental quality and innovation).
A timeline of the developments of these certifications is indicated below:

- 1995: EPC (Energy Performance requirement for new buildings);
- 1995: GPR-building (Measurement and certification scheme for overall environmental performance);
- 1997: GreenCalc+ (Instrument and index to measure sustainability of a building);
- 2004: NIBE (Classification and comparing of building materials);
- 2008: Energy label Public (label revealing the energy efficiency of a building);
- 2009: BREEAM NL (Sustainability certification for buildings);
- 2020: Energy neutral (All new buildings should be at least energy neutral from 2020 onwards).

This last point concerns the Dutch regulations and the implementation of future energy performance requirements.

A great support for promoting the transition should come from the research and the innovation; it is about rethinking a way to produce and consume, giving the waste a new and higher value, looking to the product as a whole. For this purpose, there needs to develop new technologies, processes, services and Business Model, able to respond to the new requirements of the economy and the society. The drive for innovation could also give a contribute to the competitiveness and modernisation of the EU industry[16] and for this reason the EC offers support to it by providing several financing programmes: the Horizon 2020, for example, is a programme that includes, among others, the initiative called “Industry 2020 in the Circular Economy” and funds innovative pilot projects supporting the objective of CE.

[16] European Commission, *EU Action Plan for the Circular Economy*, Brussels, 2015

2.3 The stakeholders involved

As stated above, the building industry has the characteristic to have a large number of actors involved and identifying them is important in order to understand which is their role and their influence in the supply chain. Each of the stakeholders has a personal interest and they could give a relevant direction to the development of the CE principles in the sector, both hindering and promoting them.

Talking about the façade construction, which is the subsector concerned by this dissertation, it could be useful to make an overview[17] both of all the stakeholders involved and their role, and then focussing attention on how they can take part to the shift from a Linear to Circular Economy.

Table 2 – Stakeholders group in the façade supply chain

Actors	Involvement
Investor	His aim is to obtain the higher value/investment ratio and the higher the profit potential is, the greater is his achievement and his satisfaction; obviously he tries to obtain it by combining quality, durability and low upfront investment. For this reason, the investor is often not directly concerned by the innovation, since it is an aspect less predictable and more affected by risks.
General building contractor	He represents a central resource since he takes responsibility during several steps of the building process; usually the general contractor – one or more than one in the case of a society – has specific abilities in different sectors and is able to identify the critical issues in order to overcome them in the short term and with the lower costs. His profit potential is the difference between the agreed price and the real costs and for him it is worth talking about innovation only if this last can bring a financial benefit.
Designer, architect, consultant	These actors should have the ability to accommodate the requests of the different stakeholders so that to integrate the needs and overcome the gap between design, functionality and technical requirement. They are one of the few that are interested to the innovation and can promote it starting with the project through technology and materials.
Façade builder	He turns what has been chosen during the design stage into a realisable construction in which the performance of the façade has to be ensured even

[17] Klein T., *Integral Façade Construction. Towards a new product architecture for curtain walls*, 2013

	though the integration of several subcomponents and the related amount of planning. He has to try engage in dialogue between the architect and the general contractor, since he has not only time and financial pressure but also the requests of a specific design to be followed, and for this reason he needs support from the supplier. For him the innovation can be translate in his way of working (design, production, assembly) and this can lead to financial benefit for all the company.
Supplier	On one side he is faced with the architect who chooses his products, on the other side with the façade builder who buys them; for this reason, the product should have a good flexibility in terms of architectural design but also a clear application for the façade builder. The work behind it is huge, starting with all the test at which the product has to undergo, until the delivery requiring a large and constant inventory in order to keep up the level of communication. For him adopting new systems and introducing innovation could require time and additional expenditure, but at the same time he could have the necessity to adapt his products to the needs of a specific project.
Facility Management	It is a field which is becoming increasingly relevant in the building process since its aim is to obtain the lowest maintenance effort and the clearest responsibilities in case of failure or damage: the facility management looks out for the constant monitoring and the energetic performance of the system, having a long term vision, including end of life scenarios.
User	From him perspective, the most important requirements related to the façade are high comfort, low energy consumption and little maintenance effort. It is also relevant to have flexibility so that adapting more easily the building to the necessities.

These actors can give a large support and find opportunities[18] towards a circular thinking as shown in the Table below:

[18] Azcárate-Aguerre J., *Integrated Façade System as a Product-Service System*, 2016

Table 3 – Opportunities and role of the building process's actors towards the Circular Economy

Actors	Opportunities and role towards the CE
Investor	Through the principles of CE is possible to obtain an increase flexibility which means more responsive constructions, following the user trends and reducing the vacancy risks.
General building contractor	Just for the role he plays in the building process, the contractor could provide guarantees about the circularity: he has the technical capabilities for setting up long-term contracts and for regulating the relationship with the subcontractor service delivery.
Consultant	Working with the facility management team, the consultant can develop strategies taking advantage of circular building's flexibility and can be the client's long-term advisory regarding the operational performance of the construction.
Supplier	Thanks to the CE his cash flow cannot be on the project acquisitions but on the performance of service contracts, thus eliminating the vulnerability of economic cycles. In this case the competition is based on the ratio between performance and costs, making room for innovation and resource effectiveness instead of a competition on the lower upfront price.
Facility Management	While with the Linear Economy the transfer of knowledge from the supplier to the manager is often complicated, the performance contract allows for having clearer information, so that to focus basically on strategic decisions about the future requirements of the building.
Building owner	Through the performance contracts, for example, the owner will have not to deal with a workload that does not fall within his field of interest; these contracts, indeed, describe how the supplier is responsible not only for the delivery but also for all the activities (such as the maintenance) during the useful life of its product.

This shift from a Linear to Circular Economy in the construction sector has to be supported by the lifecycle thinking, using tools that allowing the study of the environmental impact of a system during all the stages, such as the Life Cycle Analysis method (LCA).

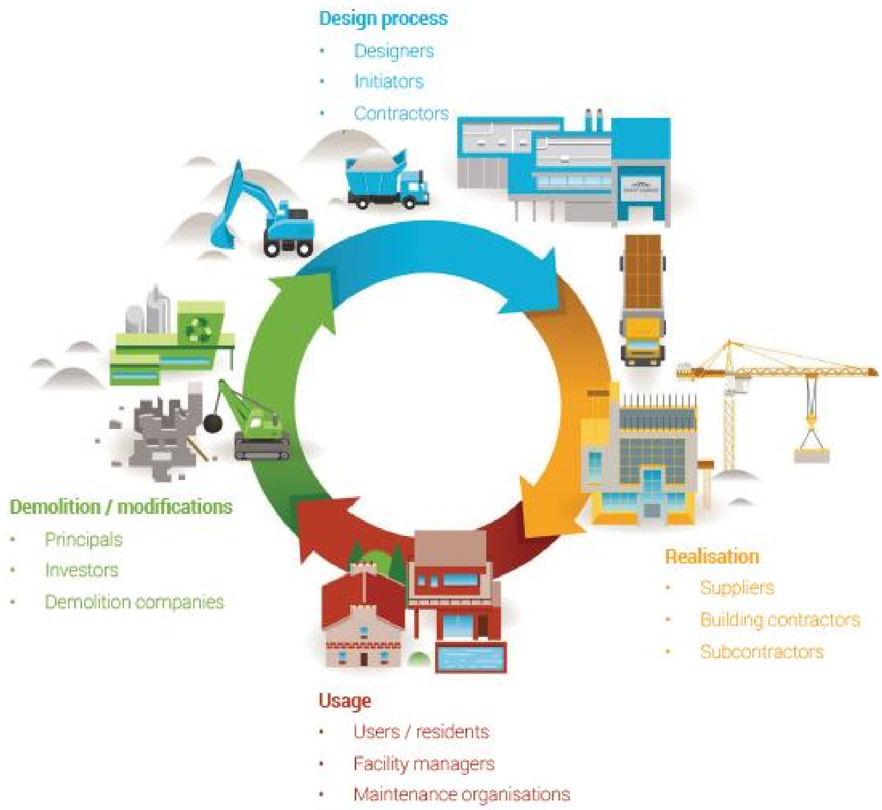


Figure 7 – Building process and related stakeholders during different stages
(Source: Leising, *Circular Supply Chain Collaboration in the Built Environment,* 2016)

As illustrated in the Figure 7, the building process is described by four lifecycle stage: the blue is the production and the design process, the yellow is the realisation, the red is the usage and the green is the end stage. Each of these phases is assigned an actor of the supply chain so that helping to make a distinction between:

- Property Management: it concerns the first part of the cycle in which there is the plan and the design of a building project;
- Facility Management: related to the red phase;
- Asset Management: it belongs to investors' analysis during the last stage of the process.

3. Circular Business Models

3.1 The meaning of *Business Model*

As a support for implementing the switch from a linear to Circular Economy, it is necessary to deploy a series of strategies to direct designers and business strategists.

In this case it is relevant to make a first distinction between what is a *Business Model* (BM) and a *Business Strategy Model* (BSM).

The BM is described by Osterwalden & Pigneur as “the rational of how an organization creates, delivers, and captures value”[19]: in other words it is the system that maps out how to create value through products and services. In this system there are all the key actions to ensure that the business can generate profits and this happens when the customer is willing to pay for those services.

On the other side, the BSM is the direction that the business will take to reach its goals. This means that it encompasses the steps, processes and possible changes that the business should follow as well as the strategies to overcome potential setbacks. For this reason, the Business Strategies should be up-to-date so they could comply the current demands.

The authors Osterwalder and Pigneur describe how a company expects to make profits following the structure of a Business Model called Business Model Canvas (Figure 8): it consists in nine building blocks that include the four main fields of doing business: customers, offer, infrastructure and financial viability.

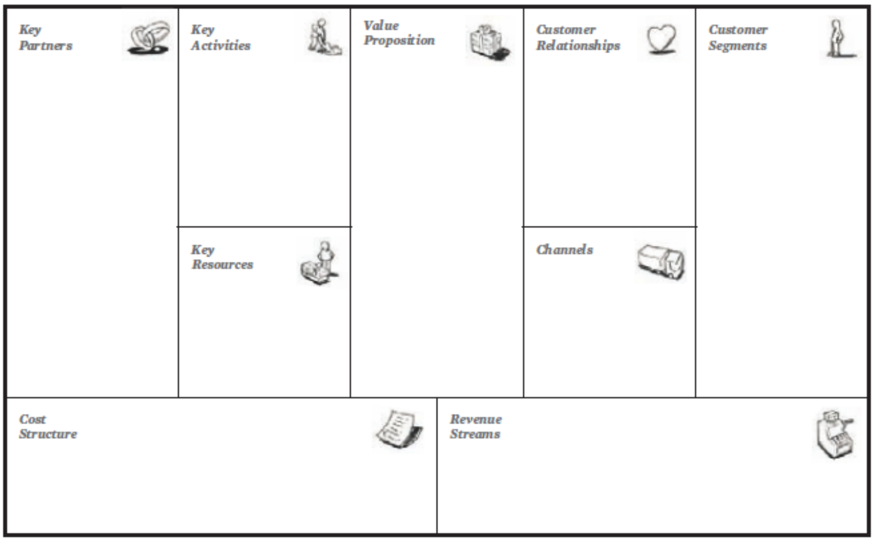


Figure 8 – Business Model Canvas
(Source: Osterwalden & Pigneur, *Business Model Generation*, 2010)

[19] Osterwalden & Pigneur, *Business Model Generation*, 2010

This canvas was developed to be a valid tool for understanding, discussing and analysing different suggestions into a work-group. Basically it can be traced back into three main categories:

- Value proposition: it is the core of the Business Model and embodies the reason why the customers are willing to pay for a service or a product and how they can be satisfied;
- Value creation and delivery: how the value proposition is generated and delivered to customers (key partners, key activities, key resources, customer relationship, customer segments, channels);
- Value capture: how the value is obtained and which are the costs related to it (revenue streams, cost structure).

3.1.1 Circular Business Models and Strategies

The model canvas above described seems to be focused on the “sell more sell faster strategy” and leaves little room for a new innovative and sustainable use.
Introducing the Circular Business Model (CBM) implies defining a model that makes profits over time: in this case there is not a deadline for a product, but there should be a specific design to make sure that the wheel keeps to turning so that the manufactures can take advantages from every turn taken.
According to EMF this Business Model Innovations (BMI) would permit an increased monitoring of resource stream through the value chain, new organism of control, closer relationship between the supply chain and the stakeholders and new services that take value from products and resources.

Nowadays there are many CBMs available and a brief review of them is described below.
Accenture LLP (a global professional services company) has categorised five CBMs which can be used singularly or in combination as a tool for companies to achieve at the same time the highest profits and the lowest costs and risks.

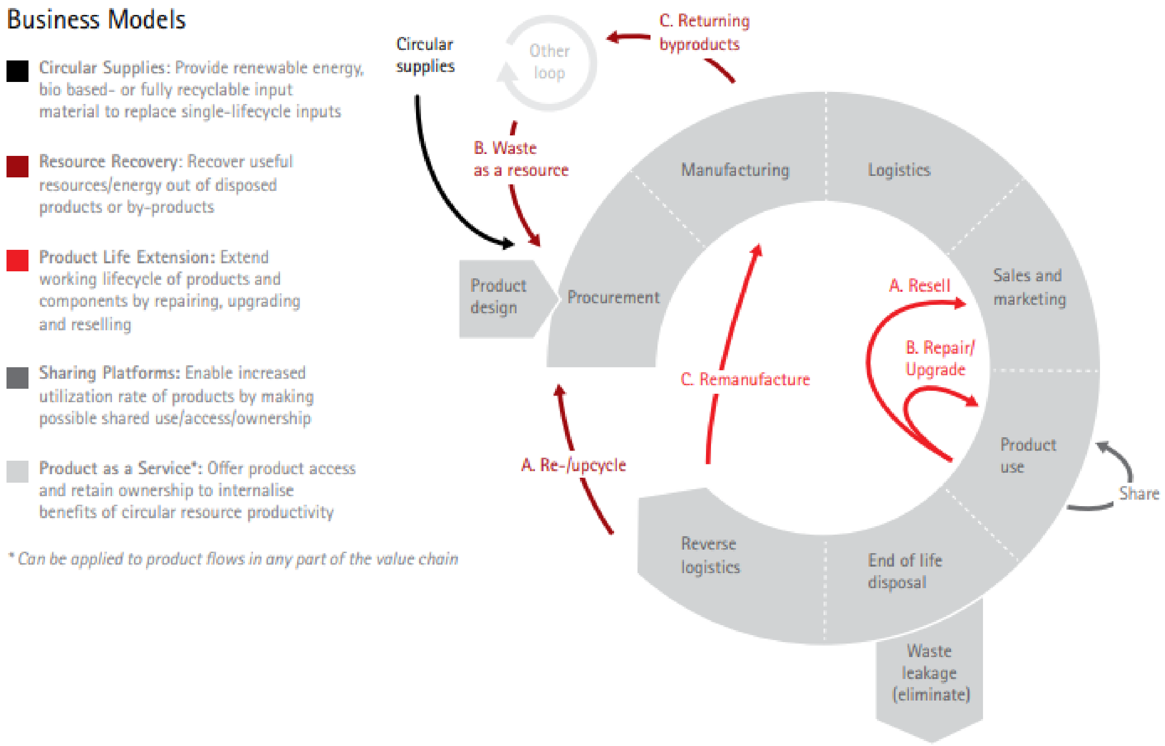


Figure 9 – Business Models in the value chain
(Source: Accenture strategy, *Circular advantage. Innovative Business Models and Technologies to Create Value in a World without Limits to Growth,* 2014)

- Circular supplies: is better suited for companies selling with scarce products, in which scarce resources are substituted with recyclable inputs;
- Resource recovery: this is based on closed loop recycled or cradle-to-cradle designs, whereby waste materials are turned into resources;
- Product life extension: allows to extend the lifecycle of products and components, preserving their value. Through repairing, upgrading or reselling, companies can obtain profits from products and materials that otherwise would go to landfill;
- Sharing platforms: is focused on those products that have a low ownership or use rate. Examples of this form of sharing can be find in the transport sector (BlaBlaCar) or in housing (Airbnb);
- Product as a service: is use mostly from those companies that have high operational costs and facility to grant a maintenance service. In this case there are new form of relationship between the supplier and the customer, through leasing or pay for use.

Moreover, it appears useful carrying on a literature overview of the different BSMs on the basis of two loops: the slowing resource loop and the closing one. This delineation is well described by Bocken et al. (*Product design and Business Model strategies for a Circular Economy*, 2015): the slowing resource loop consists in extending a product's life and thus its application so that slow down the flow of resources, while the second loop exploits the recycling, making a connection between post-use and production.

Table 4 – Overview of Business Model Innovations developed by Bocken et al. in the 2015

Business Model Strategies	Definition
Slowing resource loop	
Access and performance model	Providing the capability or services to satisfy user needs without needing to own physical products (Bocken et al., 2015).
Sharing economy	An economic system in which assets or services are shared between private individuals, either free or for a fee.
Leasing	A system whereby the consumer can benefit from using a product and the manufacturer can remain owner of its product.
Product-Service System (PSS)	Seeks to provide a new system in order to deliver the final capability of a product.
Extending product value	Exploiting residual value of products – from manufacture, to consumers, and then back to manufacturing – or collection of products between distinct business entities (Bocken et al.).
Reusing/reselling assets	Reusing products and components through resale or relocation.
Encourage sufficiency	Includes solutions that actively seek to reduce end-user consumption, in particular through a non-consumerist approach to promotion and sales (Bocken et al.).
Reflecting environmental costs	Bring to light the real costs of a product, included costs of emissions, resource extraction, land use and health impacts.
Closing resource loop	
Extending resource value	Exploiting the residual value of resources: collection and sourcing of otherwise "wasted" materials or resources to turn these into new forms of value (Bocken et al.).
Industrial symbiosis	Exploiting the geographical proximity between two or more companies, the wastes of one can be the raw materials for the other.

3.2 Circular Design Strategies

It is important to introduce specific Circular Design Strategies (CDSs) during the first steps of the design process: the longer this goes on, indeed, the more it will be difficult to make changes. Thus, in the Table below are described several CDSs applied for slowing and closing resource loops.

Table 5 – Overview of CDSs based on Bocken et al., McDonough & Braungart, Damen

Design Strategies	Definition
Slowing resource loops	
Designing long-life products	To ensure a long utilization period of products.
Attachment and trust	It is linked to an "emotional durability", by which is made an empathic connection between the users and the products.
Reliability	The ability to consistently perform its intended or required function, on demand and without degradation or failure.
Durability	It is related to a "physical durability", which means the ability to hold up against wear and tear without breaking down.
Design for product-life extension	To extend the use period of goods through the introduction of service loops listed below.
Maintenance	Actions necessary for retaining a piece of the goods to the specified operable condition to achieve its maximum useful life.
Repair	Restoration of a broken, damaged, or failed part to bring back into usable state.
Upgradability	The aptitude of a product to continue being use under changing conditions by improving the quality and value.
Adaptability	The ability of a product to response to the changed circumstances and that's why it is closely linked with upgradability.
Standardization and compatibility	The capacity to create a product in which its parts can match others.
Dis- and reassembly	To ensure that products and parts can be separated and reassembled easily.
Closing resource loops	
Design for a technological cycle	This strategy concerns the "products of service", namely those products that deliver a service and that can be continuously recycled.
Primary recycling	Is the reprocessing of materials into the same type of product, with the same properties.

Tertiary recycling	Is the reprocessing of a material into a product that cannot be recycled again, because of the structural breakdown of materials into their original raw core components.
Upcycling	Retaining or improving the properties of the material.
Cradle to cradle design	Is a biomimetic approach to the design of products and systems that takes inspiration from nature's process for the models human industry, considering materials as nutrients circulating in healthy.
Resource passport	An instrument created to facilitate the transfer of information and data between all the involved actor, in order to make reuse and recycling as easy as possible.
Design for a biological cycle	This strategy concerns the "products of consumption", namely those products that are consumed or wear during use.
Biodegradation and composting	Products of consumption are designed with safe and healthy materials (biological nutrients) that create food for natural systems across their life cycle.

3.2.1 Design Circular Buildings

According to previous explanations, the creation and the development of a new circular construction industry shall be supported by the use of several Design Strategies. For integrating the abovementioned strategies in the sector, it is crucial to look at the lifecycle of the building: the design should be optimised to guarantee a useful life of the construction and an integrated end of life phase.

The integration of the CDSs entails also a change in the ownership from the user to the supplier, so the final product, in this case the building or its components, is no longer sold but leased: it means that the customer pays for using a service instead of purchasing the product. Thus, the building is no longer considered as series of components forming one product but rather as a collection of materials that are temporarily stored within[20].

It will be explained in the following chapters how much is useful taking in account the Total Cost of Ownership (TCO) through a detailed Life Cycle Cost Analysis (LCCA) to have a complete overview of how this strategy can guide the decisions towards a net energy and financial savings.

[20] Leising, *Circular supply chain collaboration in the built environment*, 2016

To support these shifts, the sharing information plays an essential role and it can be achieved through the use of Building Information Modelling (BIM). This digital model enables the data collection during the several phases of a building lifecycle and it supports processes such as cost management, construction management, project management and facility management.

In reference to Table 5, in particular to the slowing resource loop, in the Table below is illustrated how those strategies are applied to the construction sector.

Table 6 – Overview of circular design principles based on Leising, 2016

Principle	Description
Modular building	Prefabricated components are used like walls or ceiling parts. The advantage of this principle is that material losses on site are minimal since parts have tailor-made dimensions and is permitted an easier assembly.
Extending life-time	Measures aimed at protecting a building against weather influences, for example using ventilation and drainage.
Anticipative building	Multifunctional usage of assets to enhance the adaptability, for example to integrate services, like solar panels, in facades or pavements.
Standardised dimensions	Structural components with standardised dimensions enhance reusability and will result in a higher residual value of the components and materials.
Separate construction and envelope	This leads to increase the adaptability of a buildings structure: it is important to make sure that the structure is able to allow new façade systems, so that architectonic appearances can change depending on the needs.
Integrate services	This could lead to higher flexibility around maintenance, renovation and replacement and the integration of new technologies.
Use dismountable components	Permanent joints (chemical or mechanical joints) increase the complexity of components, slow down the demolition process and thus decrease reusability. For this reason, components should be designed with loose connections so that facilitate an easy disassembly.
Use recycled resources	This is one of the main action to significantly reduce the environmental impact, because it means reduce the resource extraction and thus the impact related to energy and production. Moreover, local materials could be used to decrease negative impacts of transport.

Next to these actions, also the choice of materials plays an important role for reducing lifecycle impacts and increasing their useful life. The use of circular materials can allow on one side to save costs and on another side to maintain a positive residual value.
The Table below shows several options for circular materials usage.

Table 7 – Overview of circular materials options based on Leising, 2016

Principle	Description
Reduce material mass	For example, the preference in using lighter materials like steel framing instead concrete or wooden structures.
Eliminate toxic & non-degradable materials	The elimination of toxic substance like asbestos which are harmful to people and the environment.
Increase lifespan of materials	Even if materials like steel and concrete have long useful life in principle, the weather or other external factors could considerably prejudice their lifespan. So it is fundamental to take in account these factors and set up a design which is able to be protected and maintained regularly.
Improve a building's performance	Thermal performance for instance can be influenced by material usage. For example, green roofs can store water and cool buildings while facades with algae can generate energy and provide shade.

Recently the construction industry has been active to put into practice these principles, trying to involve all the stakeholders. Two relevant example are summarised below:

- **The Circular Building - Arup Studio, London 2016**

Thanks to Arup Studio in collaboration with Frener & Reifer, BAM and a large number of partners, during the London Design Festival was presented this prototype of circular building.
Through the gable ends it is possible to see the different layers of the building envelope and the cleverly crafted SIPS panels; this offers a visual story of the design process.
The structural frame is extendible, creating an additional area to allow the possibility for extension and future adaptation. With regard to the connections, they are left exposed as well as the steel frame: the traditional method of construction leaves room to new efficient way of assembling in a "flat-pack" style. For this reason, each panel consists of a series of pieces designed to fit in a specific part and has an individual QR code. In support of this, it was created a BIM model which contains all the material and components data.

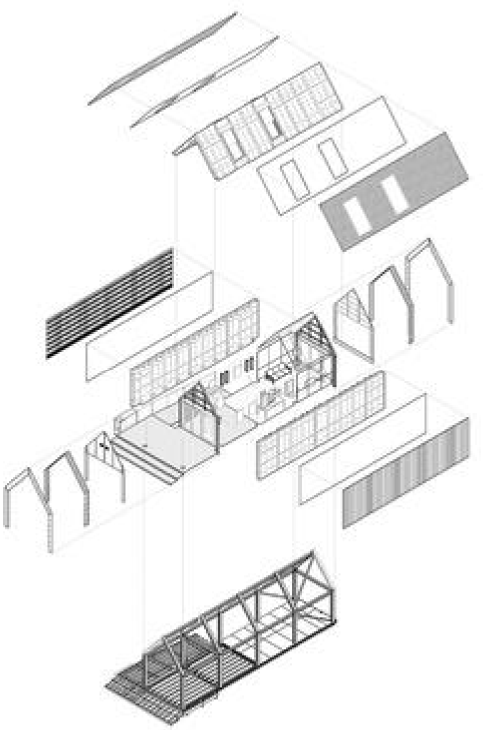


Figure 10 – Stewart Brand's Six S's diagram (Source: http://www.arupassociates.com)

Figure 11 – The Circular Building, London (Source: http://www.arupassociates.com)

According to the resource loop and the "re-use" actions, all the finishes of the interior were designated in order to respect the circular principles: for example, the carpet was supplied on a take-back scheme and the supplier agreed to replace it when used up, so that re-furbishing and reusing it and moreover the living zone is surrounded by an acoustic wall system made from recycled plastic bottles.

In order to create an optimised environment and an integrated management system, it was incorporated a work station that uses sensors to monitor the internal comfort, through a system which controlling the operable skylights, blinds and lighting.

In other words, it was possible to set up a design process that achieved circularity at every level, thanks to materials research and testing during each stage of the planning.

- **Product Development (PD) Test Lab - TU Delft**

This temporary eight-meter high building has been installed in the faculty courtyard in Delft and is composed by a series of elements that fit perfectly together like LEGO bricks.

In fact, all the components were produced by an automated milling machine (0.5 mm of accuracy) in order to set up an error-free building and to generate a minimum of waste.

Both the wall and the floor are prefabricated and composed by OSB boards (oriented strand board) with a layer of insulation between them, while the exterior envelope is in aluminium and the windows are fitted with double glazing.

Figure 12 – Product Development Test Lab, Faculty of Architecture and the Build Environment (TU Delft)

Thanks to the use of this OSB board, the Lab is a bio-based product and the floor elements can be reused; moreover, the entire façade is recyclable according to the principles analysed previously.

3.2.2 The performance contracts for a leasing system

Focussing on the CBM "Product as a service", it is useful to talk about a new type of contract based on the performance and which requires more resources and involves different types of actors.

The starting point is the research and the development, so that obtaining the technical knowledge related to all the aspects of this change: it is necessary, indeed, to educate the stakeholders towards a new way of thinking. In this regard it may be useful referring to the example (Figure 13) described by Azcárate-Aguerre J.in his report "*Integrated Facades as a Product-Service System*": through the following diagram he wanted to underline the difference between the Product System (PS) and the Product Service System (PSS), setting an excavator as the output to deliver to the client. On the left diagram the manufacturer is illustrated by a factory that delivers the product to the client (the briefcase) in return for money: the client becomes totally responsible for the entire service life of the excavator and has to invest an additional amount of money for maintaining the capabilities of what he purchased. The only responsibility of the manufacturer could be to provide spare parts and ensure a proper repair service, if it is part of a warranty agreement.

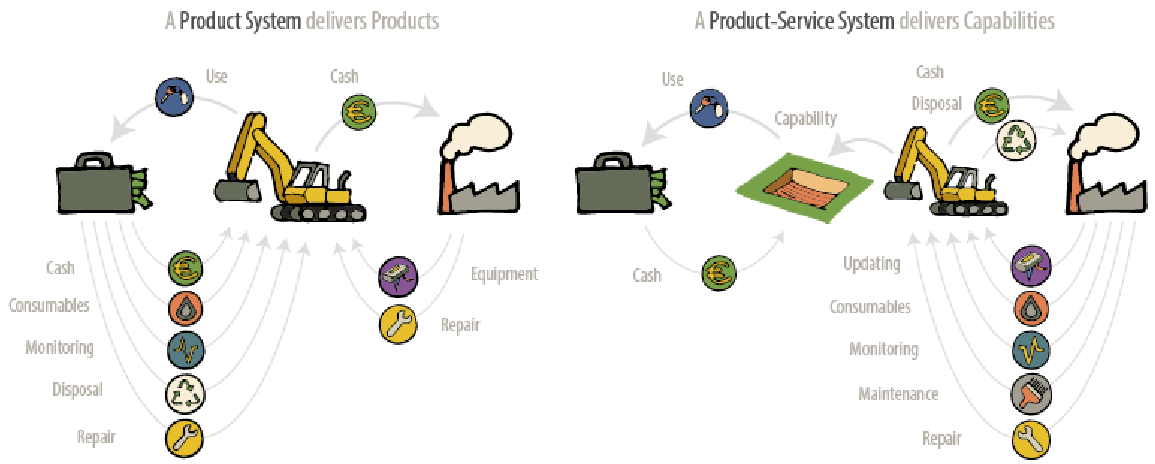


Figure 13 – The difference between PS and PSS illustrated by an excavator
(Source: Azcárate-Aguerre J., *Integrated Facades as a Product-Service System,* 2016)

On the right it is illustrated the model called Product Service System in which the manufacturer has the control over the product during its entire life, so that to retain ownership of the equipment guaranteeing the correct and continuous operation. In this case the client pays just for the use of the capabilities and has no responsibility for what does not fall in his field. On the other hand, the original manufacturer is the main actor of this system, since he has the adequate knowledge not only for ensuring a long-term servicing of the product but also for delivering performance with the lowest use of energetic and material resource.

To make this shift possible it is necessary to have solid foundation also from the financial point of view: a bank or a financial partner shall be included in the performance contract in order to raise capital and to overcome the problem between the products bought and services paid at different times. This could be a problem especially when related to a building: taking into account permanent component installed on a building, the Dutch law is used to refer to them as a property of the building's owner and thus it would therefore be necessary to review the current legal and financial conditions managing the strategy of regulators and investors.

In conclusion, the implementation of performance contracts should enhance a new collaboration between the stakeholders, from the supplier to the designer, the engineer, the manager and the client. Even if the manufactures have the technical capability for the creation of these contracts, the real estate developers and managers should promote this cooperation since they are less involved into the traditional Business Models and they have all the tools for evaluating the risks linked to a new way of action. It is important to set up an analysis that could better explain the conditions of this BM and how it could safely operate: a way to achieve this objective is to bring all the parties together around one table promoting an interdisciplinary collaboration.

4. Life Cycle Cost Analysis

4.1 Definition

The Life Cycle Cost Analysis (LCCA) is a useful method for evaluating the economic performance of a construction over its entire life.
Following the definition given by ISO 14040, the LCA is:

"*A technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a Product System; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases. LCA is often employed as an analytical decision support tool*"

The final outcome is the Total Cost of Ownership (TCO) which takes into account all the long-term expenses of acquiring, owning and disposing. The main assumption is that the building has several design options (related to all its components) which can differ depending on the initial investments, the operating costs, maintenance costs etc., even though they fulfil the performance required: the LCCA allows to make a comparison between these options, in order to select the best cost-effectiveness alternative. For this reason, this type of analysis should preferably be made upstream of the design process, while is still possible to review the design for ensuring a decrease in Life Cycle Costs.
In this case, indeed, the simulation compares different façade packages alternative, from the current situation to a higher performance system, obtaining the TCO of each model, as a purchase and through a leasing scheme.

This lifecycle approach has a central role in the shift towards the circular building sector: when it comes to introducing new model of ownership, optimizing the useful life of a building, integrating the end-of life phase, it cannot be excluded the Total Cost of Ownership and the related method to reduce it.
Therefore, the LCCA can be used as a robust tool measuring and evaluating products and Business Models deriving from Circular Economy.

4.2 The methodology

According to "*Guidelines for life cycle analysis*" published by the Stanford University Land and Building (2005), it could be useful to create a Decision Matrix (Figure 14) in which there are six categories ranked by their potential LCC benefit for the project.

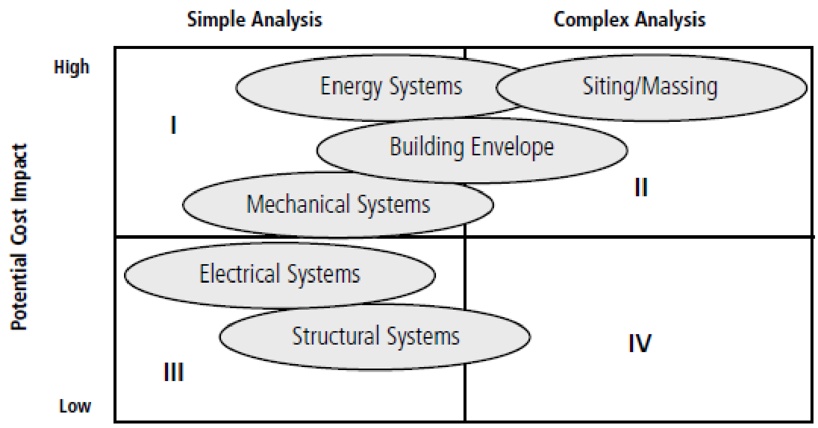


Figure 14 – Decision Matrix
(Source*:* Stanford University Land and Building, *Guidelines for life cycle analysis,* 2005)

This matrix can help during a decision-making, in order to determine which category has the priority. As the diagram shows, the vertical axis represents the potential cost impact, while the horizontal one stands for the complexity of the analysis related to the project.
Working on a façade, therefore, means focussing mainly on the range of low-effort and high-cost impact solutions, since the categories involved are building envelope, energy systems, mechanical systems and electrical systems (especially if the object is an integrated façade).

After choosing the categories of the study, the first step is to determine *clear objectives*: as has been mentioned before, in this dissertation the LCCA has the aim of capturing the cost-effectiveness of different alternatives over a long period, introducing then a comparison between the purchase and leasing scheme, in order to evaluate the relevance of this last.
Obviously, the following stage is *recognising the base case* and *developing other design options*: the number of alternatives taken into account could be endless for each project, but they have to be analysed in sufficient detail in order to capture all the differences. For this reason, the ideal would be considering roughly five alternatives for a building component; the choices related to the case study will be explain in the next chapter.

One of the essential step is the *collection of data*: depending on the type of information needed, it can consult the facility management team (whenever is possible) for obtaining material about the current scenario and the suppliers for production and servicing cost of their components. The guidelines developed by the Stanford University Land and Building shows which are the numerous costs related to the analysis, so that it can be breakdown as follows:

- **Component costs**

  These costs are the initial expenses incurred and can be include both construction costs as labour, material, equipment etc. and "soft" costs as design fees, permits etc.
- **Utility costs**

  These are related to the energy usage and non-energy one.

  Talking about the first one, through an energy simulation (by using profiles, occupancy rates, schedules etc.) is possible to obtain the energy consumptions: for each type of utility use there is a cost per unit of energy delivered (€/kWh) that will be charged to the alternative. Based on the choices made, another relevant data linked to the energy simulation is the environmental impact, e.g. the CO_2 produced during the generation of electricity or extraction of gas.

  The non-energy utility costs are the water, the sewer, the residual waste deposal etc., but in the present case it has been chosen to not take into account them.
- **Maintenance costs**

  They include all the costs with the purpose of keeping the system efficiency and they change depending on the type and the age of the building. For this reason, these kind of expenditures are difficult to estimate and it could be useful to make reference to the past actions and historical data. It can be helpful to separate the costs depending on the maintenance activities such as preventive, reactive, planned and deferred.

  It is important to underline that these costs could have a larger impact on the TCO but only recently the attention to them is increasing; at the same time, it appear to be the cost item to which has been paid less attention and less documentation.
- **Service costs**

  They include costs such as janitorial services, pest control, elevator maintenance etc. These expenses could belong to an installation labour needed during the initial phase of the construction or to a service labour concerning the action plans, such as the preventive or reactive maintenance.

- **End-of-life costs**

  These are not only referred to an expenditure, but they could be also related to an income, if the service provider manages with success the residual value from the components. Thus, the costs can be split into the residual value extraction and residual service life which represent an income, and the demolition and disassembly costs which represent an expense.

In the present dissertation it has been chosen to focus strictly on the component, utility, maintenance and service costs, in order to provide and draw up data related to more options; the last expense abovementioned is often hard to investigate, since require a specific planning background scheduled at an early stage in the design process, and in this case there was a lack of reliable data.

4.2.1 The macroeconomic context

Before it can move on to the calculation method, it is necessary to specify which are the assumptions made in the macroeconomic context, since the LCCA is projected over a long time period in which the parameters could be change.
Making a current-euro analysis, indeed, means to include the rate of general inflation, discount rates and price escalation rates.
First of all, the included values into the analysis are provided in terms on Net Present Value (NPV) which helps to make an easier comparison since the units are consistent. The NPV is used to develop a cash flows and then for making a comparison between investment proposals, where the flows of income could change over time. In order to obtain the NPV, the following equation is applied:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$

Where:
C_t = net cash inflow during the period t;
r = discount rate;
t = number of time periods;

One of the main factor that affects the changing of prices over the years is the inflation. It consists in a rise in price level of goods and services such as the energy, the products, the raw materials and labour; consequently, if the price increases, every currency acquires fewer goods and services and thus the inflation reflects a reduction in the purchasing power per unit of money. For this reason, it has been taken into account inflation rates for different types of resources through a market research referred to Netherlands.
It should be underline that most goods and services could have prices that not change at the same rate as inflation. But this value on average over time is close to the rate of inflation, so it is assumed that the escalation rate is zero for all the category.

It could be useful to establish a minimum and maximum deviation point, in order to give a limit below and above which it is recommended to do a recalculation, so that to guarantee a fruitful project for all the stakeholders involved. This is especially valid for the performance contract at which is necessary to preserve a right balance between the suppliers and the clients.

The data collected during the study for developing the LCCA can be divided into two categories: the energy data and the financial data.
The first ones represent the quotes of current energy prices based on average national ratio of the Netherlands and they can be obtained through a research on Eurostat database.
As the following Figures show, it has been taken into account both the electricity and gas prices during the first half of 2017.

Electricity prices for household consumers - bi-annual data (from 2007 onwards)
Last update: 17-05-2018
Table Customization show

TIME | GEO | Products: Electrical energy
Consumption: Band DE : Consumption > 15 000 kWh | Unit of measure: Kilowatt-hour | Taxes: All taxes and levies included
Currency: Euro

TIME / GEO	2013S1	2013S2	2014S1	2014S2	2015S1	2015S2	2016S1	2016S2	2017S1
Netherlands	0.2618	0.2121	0.2678	0.2056	0.2632	0.1977	0.2432	0.2011	0.2253

Figure 15 - Electricity prices for household consumers
(Source: Eurostat)

Gas prices for household consumers - bi-annual data (from 2007 onwards)
Last update: 17-05-2018
Table Customization show

TIME | GEO | Products: Natural gas
Consumption: Band D3 : Consumption > 200 GJ | Unit of measure: Kilowatt-hour | Taxes: All taxes and levies included
Currency: Euro

TIME / GEO	2013S1	2013S2	2014S1	2014S2	2015S1	2015S2	2016S1	2016S2	2017S1
Netherlands	0.0765	0.0774	0.0724	0.0733	0.0696	0.0694	0.0713	0.0713	0.0675

Figure 16 - Gas prices for household consumers
(Source: Eurostat)

Related to the energy consumption, there is another important indicator for calculating the CO_2 emissions: it can be calculated through the average national ratio of the Netherlands, distinguished on the basis of the type of fuel. These values are reported in "*Technical paper – Electricity specific emission factors for grid electricity*" published in 2011 by Ecometrica and are shown in the Table below.

Table 8 – Energy input data

Energy Values		
	Value	Units
Electricity cost	0,2253	€/kWh
Gas heating cost	0,0675	€/kWh
Electricity CO_2 ratio NL	0,4133	kgCO_2/kWh
Electricity and gas CO_2 ratio NL	0,3921	kgCO_2/kWh

With regards to the financial data, the values used for the calculations are listed in the Table 9.

Table 9 - Financial input data

Financial values		
	Value	Units
BTW Tax on Products	21	%
Rate of inflation (Products)	1,04	% per year
Rate of inflation (Energy)	3,6	% per year
Rate of inflation (Labour)	1,16	% per year
Energy safety margin	15	%
Supplier profit margin (Products)	4	%
Supplier profit margin (Services)	9	%
Residual Value insurance	1,0	% per year

In particular, it has been used the CBS Database (Centraal Bureau voor de Statistiek) for researching the most current inflation rate in Netherlands. With regard to the inflation on labour and products, it has been considered an average between the last seven years respectively for the category "engineering, building projects" and "engineering, manufacturing" (Figure 17); while for the energy inflation rate it has been considered the "Energy price index" as shown in Figure 18.

Topic | Periods

Yearly changes

CPA2008	2010 Year average	2011 Year average	2012 Year average	2013 Year average	2014 Year average	2015 Year average	2016 Year average	2017 Year average
	%							
711212 Engineering; building projects	0.8	0.3	1.7	1.2	1.6	3.3	0.8	-0.4
711217 Engineering; manufacturing	0.8	1.7	-0.3	1.5	1.2	-1.3	1.9	2.8

Source: CBS

Figure 17 - Services producer price index
(Source: CBS)

Consumer prices; price index 2015=100

Changed on: 7 June 2018

Expenditure categories: SA07 Energy, including other fuels

Topic

Periods	CPI	Derived CPI	Year-on-year change CPI	Year-on-year change Derived CPI
	2015 = 100		%	
2017	97.87	96.17	3.6	2.8

Source: CBS

Figure 18 - Energy price index
(Source: CBS)

4.2.2 The calculation method

Taking into account all the considerations done before, the costs and the parameters identified, the total life-cycle costs for each alternative is calculated as follows:

$$LCC = I + PV_{RECURRING} - PV_{RESIDUALVALUE}$$

Where:

LCC = Total Life Cycle Costs

I = Initial Investment costs in the year 0

$PV_{RECURRING}$ = present value of all the recurring costs (utility, maintenance, service etc.)

$PV_{RESIDUALVALUE}$ = present value of the residual value at the end of the study

In the specific case, the TCO includes the initial investment, the maintenance costs and the service costs (whenever available), combined with a tax rate of 21% (BTW) applied on products and services (excluding energy) purchased over the chosen period.

Once evaluated the traditional purchasing scheme, is introduced the leasing scheme which takes into account several financial expenses and many assumptions, since it is linked to the developing performance contract. The related method for calculating the leasing price will be illustrated in the following chapter, since it is strongly connected to the present study case.

5. The case study

5.1 The context: TU Delft Faculty of Civil Engineering and Geosciences

The building subject of study is the TU Delft Faculty of Civil Engineering and Geosciences (acronym CiTG in Dutch), located on Stevinweg 1, 2628 CN Delft.

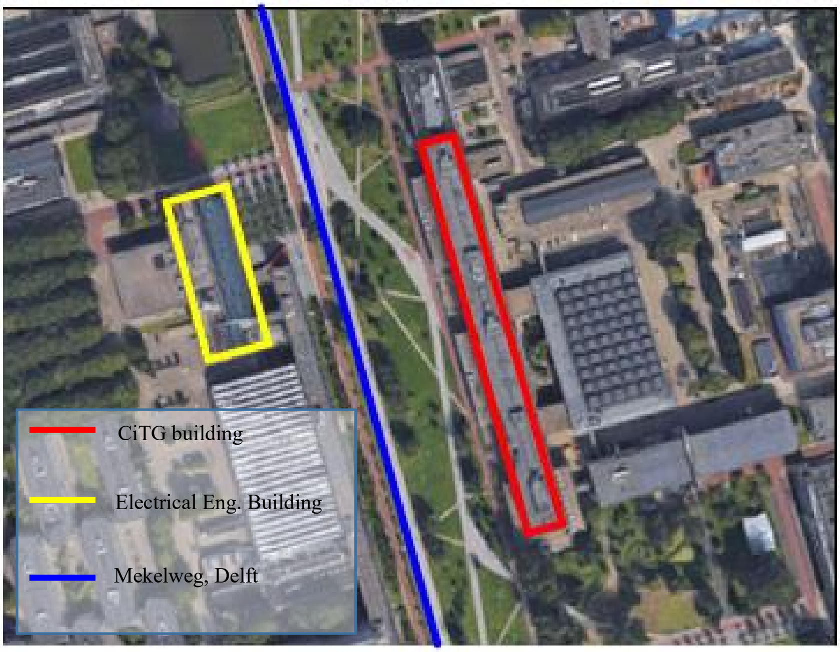


Figure 19 – The context around CiTG building

The entire faculty is composed of two different buildings: the small one is the new wing opened on 5 September 2005, while the other side is the oldest core, dating from the early 60's (Figure 20).

Figure 20 – The main façade of the CiTG building

As regards the calculations of the study, it has been taken into account the oldest, because it has never been renovated and it is more likely to be replaced in the next years.

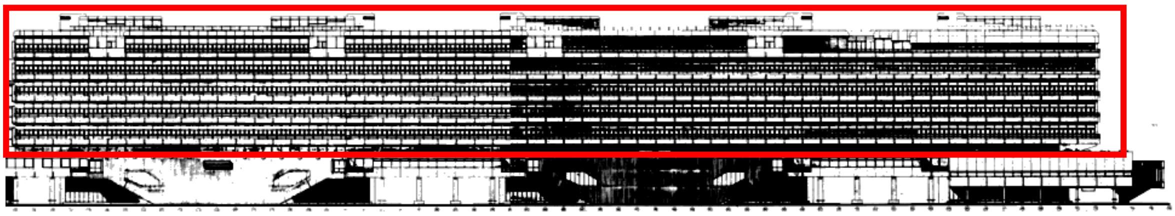


Figure 21 – West Façade of the CiTG building

The façade highlighted in the Figure 21 has five floors and it is composed by 59 floor windows, with a height of 3,11 m and a width of 3,6 m. The total window surface is almost 3300 m^2 and since it is a mostly regular building, which has an envelope with all the windows of the same size, it has been chosen to analyse just a module of façade. In particular, a module composed by four windows on the West side of the building (in which there are two offices) has been taken into account for doing the energy simulation, and then just one panel has been used for developing the LCCA charts.

All the details related to the building are summarized in the Table below:

Table 10 – Details about the CiTG building

Faculty of Civil Engineering and Geosciences (CiTG)	
Building Description	
Building owner	TU Delft
Location	Stevinweg 1, 2628CN
Year of construction	1960
Type	University
No. Of floors	5
Functional Characteristics	
Floor height [m]	4,2
Facade height [m]	21
Gross area by zone [m^2]	32,9
Heated area by zone [m^2]	32,9
Design no. of building occupants by zone	10
Technical information	
External envelope	Concrete & Glass
No. Windows	295
Window height [m]	3,11
Window width [m]	3,6
TOT Window surface [m^2]	3302,82
One panel surface [m^2]	5,60

5.2 Description of the envelope

Since one of the aim of the dissertation is to evaluate the best alternative of renovation through a LCC analysis, below are proposed five alternatives of façade's packages.
All these five solutions include necessarily this type of process:

- the removal of asbestos from joint and connections between window and concrete and from ceiling cladding;
- the removal of interior suspended ceiling;
- the replacement of window as a whole component;
- the placement of new window units;
- the renovation of new connections between the wall and the prefabricate elements;
- the reintegration of interior ceiling part.

5.2.1 The existing package – 0. Alternative

The so called "zero" alternative consists in renovating the façade as well as the West façade is currently. For reason of simplicity, it is assumed to have not neither shading system nor mechanical ventilation: the ones contributions are the infiltration and the natural ventilation. Indeed, each block of façade has two windows openable with a casement and an awning system.

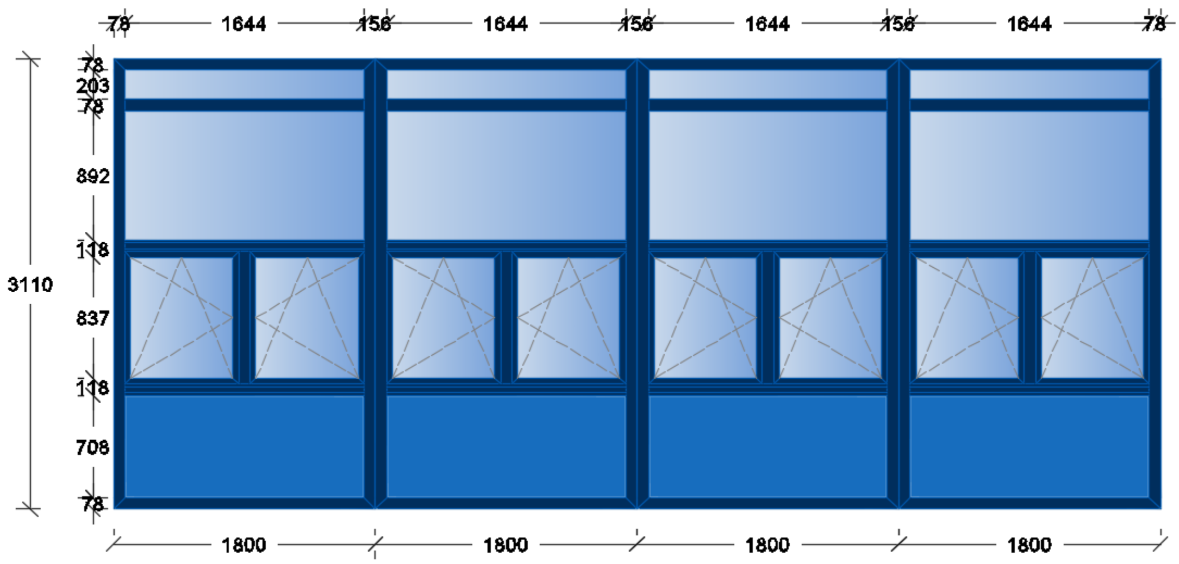


Figure 22 – The current façade

The transparent envelope is composed by a single glazing, an aluminium frame and an opaque panel, whose values of transmittance are shown in the Table 11.

Table 11 – The current façade package

0. Alternative				
	U	Unit	m^2 /panel	m^2 /4panels
Single Glazing 6 mm	4,23	W/m^2K	2,98	11,90
Aluminium Frame with thermal break	4,72	W/m^2K	1,43	5,70
Opaque panel	1,65	W/m^2K	1,16	4,66

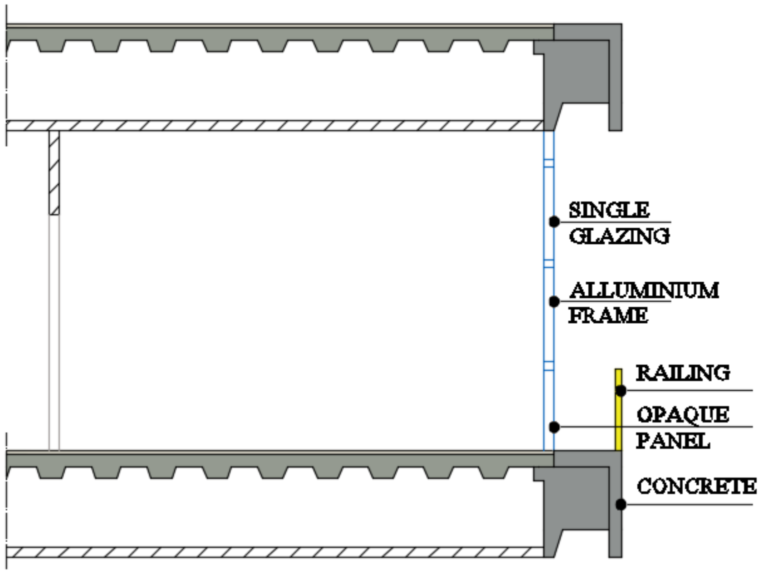


Figure 23 - Schematic section of the current façade

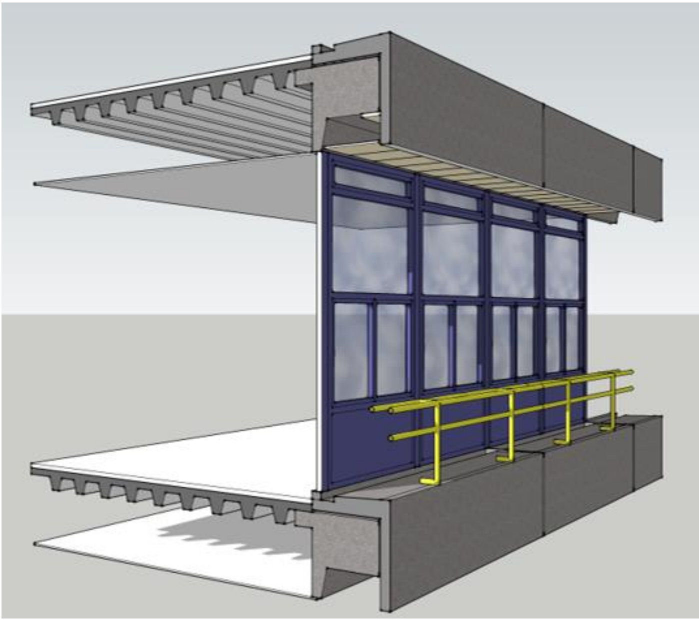


Figure 24 – The current façade 3D model

5.2.2 The replaced package – 1. Alternative

This package consists of replacing the current façade with a more efficient one: when referring to the efficiency, this is intended primarily in terms of energy savings. In this case, indeed, is installed an insulated façade with a double glazing, an aluminium frame with thermal break (whose value of transmittance is significantly lower than the current) and an aluminium sandwich panel with a non-combustible, structural mineral wool core.

Table 12 – The replaced façade package

1. Alternative				
	U	Unit	m^2 /panel	m^2 /4panels
Double Glass 4/16/4mm	1,15	W/m^2K	2,98	11,90
Aluminium extruded profile RT62	2,24	W/m^2K	1,43	5,70
Aluminium sandwich panel (2/146/2mm)	0,24	W/m^2K	1,16	4,66

With regard to the ventilation system, the night cooling ventilation is included in addition to the infiltration. This type of action, carried out during the night, is intended to expel excess heat and cool from the building: thanks to it, is possible to minimise or even avoid the use of mechanical cooling and improve the internal conditions. In order to make it possible, automated ventilation devices and control systems need to be installed on the top window.

Another important solution to avoid solar gain during the hot season and thus to reduce cooling loads is to install a shading system. In this case are considered the external shade roller blinds mounted on the frame.

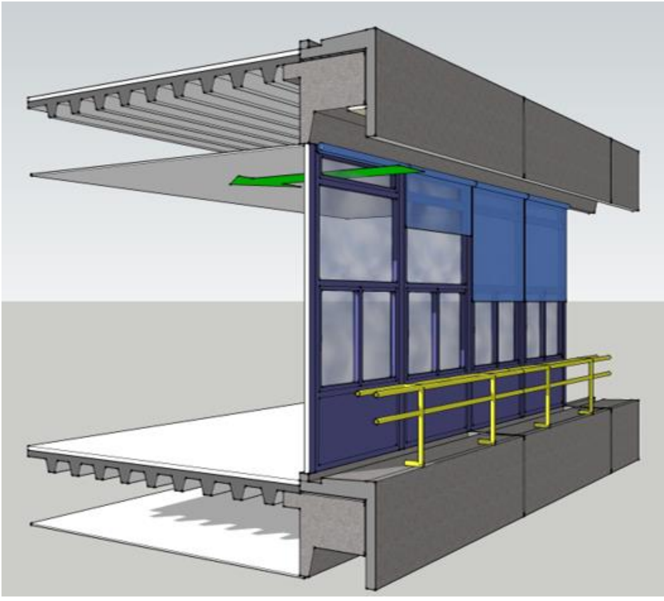


Figure 25 - The replaced façade 3D model

5.2.3 The double partial skin – 2. Alternative

This option does not show criticism related to a reduced floor area since the second skin is installed on the external side of the façade, where actually there is a railing.
By removing the yellow railing is possible to install an insulated glass between the concrete floor which acts like a second skin: this solution is called "partial" because the double skin is interrupted by the prefabricate element on the envelope, as it is shown in the Figure 26.
The air cavity of almost 60 cm between the two panels is totally natural since there are plans to set up electrically driven operable windows in glass skin instead the mechanical ventilation. Moreover, the interior window can be opened by the user for allowing an additional natural ventilation of the offices.
There are shade roller blinds in this case too, but they are fitted in the cavity.

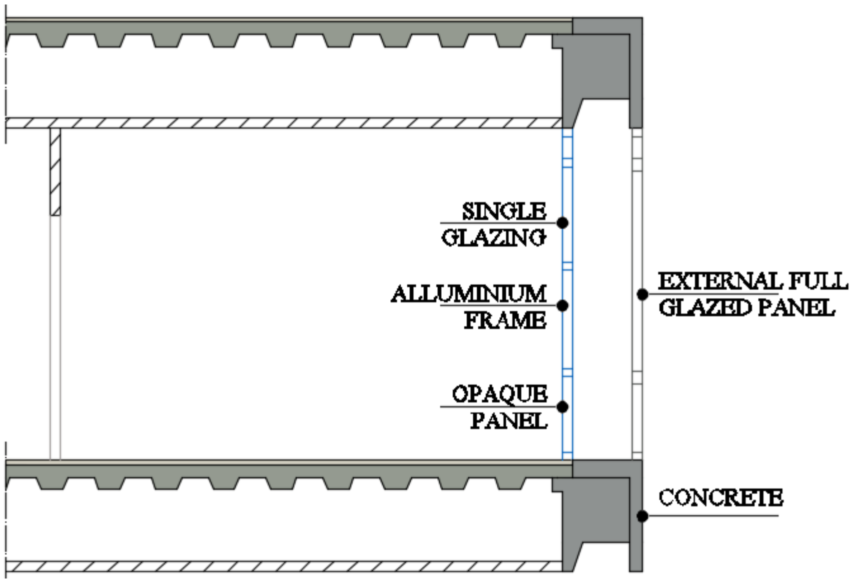


Figure 26 - Schematic section of the double partial skin

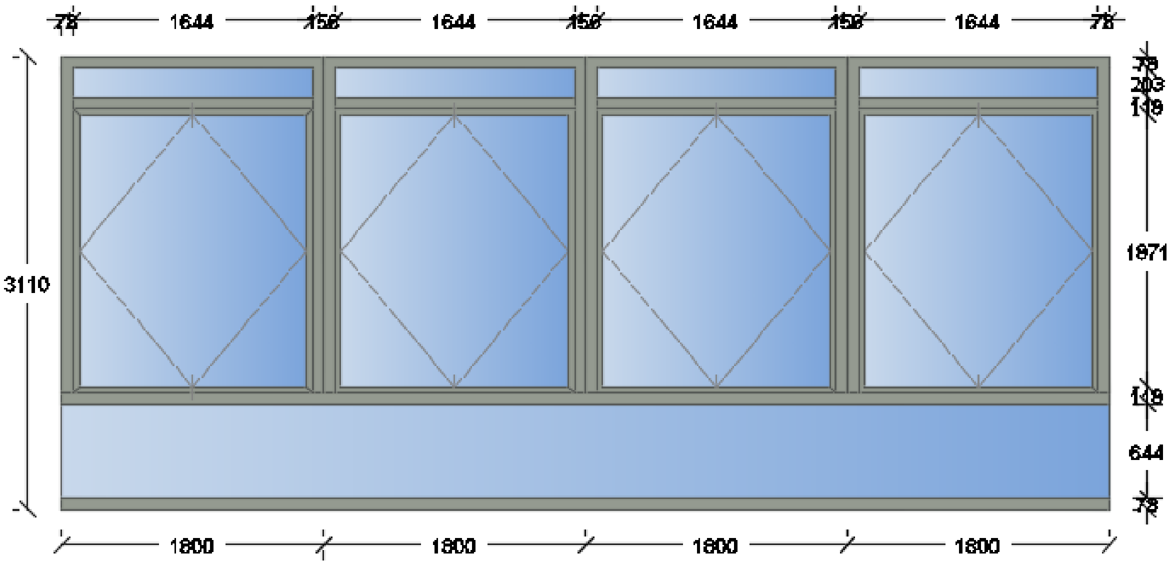


Figure 27 - The double skin installed

As illustrated in the Table 13, the external surface is fully insulated glazing instead of the internal one which has been decided to maintain unchanged and thus composed by a single glazing and an aluminium frame with a lower transmittance. The only element that it has been decided to replace on the internal surface is the opaque panel.

Table 13 – The double partial skin package

2. Alternative				
	U	Unit	m^2/panel	m^2/4panels
Internal single glass 6mm	4,85	W/m^2K	2,98	11,90
Aluminium Frame with thermal break	4,72	W/m^2K	1,43	5,70
Aluminium sandwich panel (2/146/2mm)	0,24	W/m^2K	1,16	4,66

External Double Glass 4/16/4mm	1,15	W/m²K	4,42	17,68
Aluminium extruded profile RT62	2,24	W/m²K	0,92	3,67

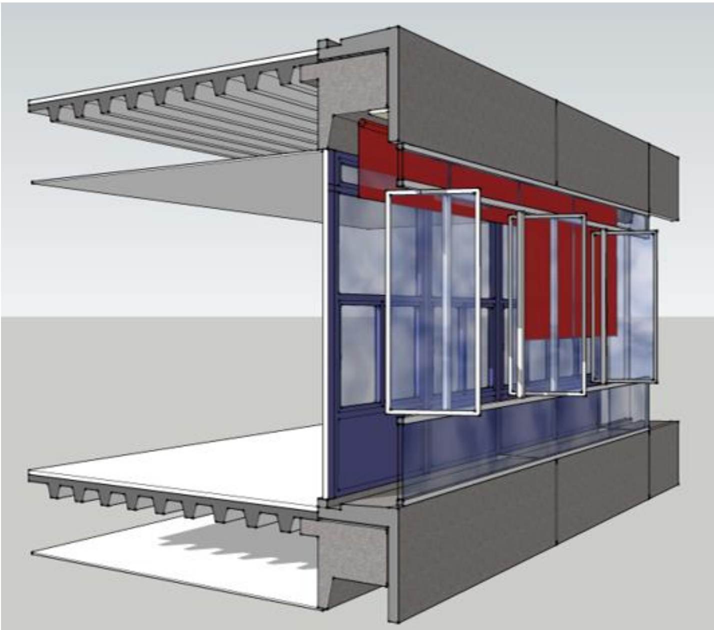


Figure 28 - The double partial skin 3D model

5.2.4 The double partial skin with HRV – 3. Alternative

This solution presents the same characteristics of the double partial skin abovementioned (as shown in Table 14) except for the introduction of the mechanical ventilation with a Heat Recovery Ventilation (HRV) in the cavity. This system during the heating season allows a preheating of the incoming outdoor with exhaust air by passing both of them through a heat exchanger, while during the summer season in which the outdoor temperature is higher than indoors, allows a pre-cooling.

Table 14 - The double partial skin with HRV package

3. Alternative				
	U	Unit	m²/panel	m²/4panels
Internal single glass 6mm	4,85	W/m²K	2,98	11,90
Aluminium Frame with thermal break	4,72	W/m²K	1,43	5,70
Aluminium sandwich panel (2/146/2mm)	0,24	W/m²K	1,16	4,66
External Double Glass 4/16/4mm	1,15	W/m²K	4,42	17,68
Aluminium extruded profile RT62	2,24	W/m²K	0,92	3,67

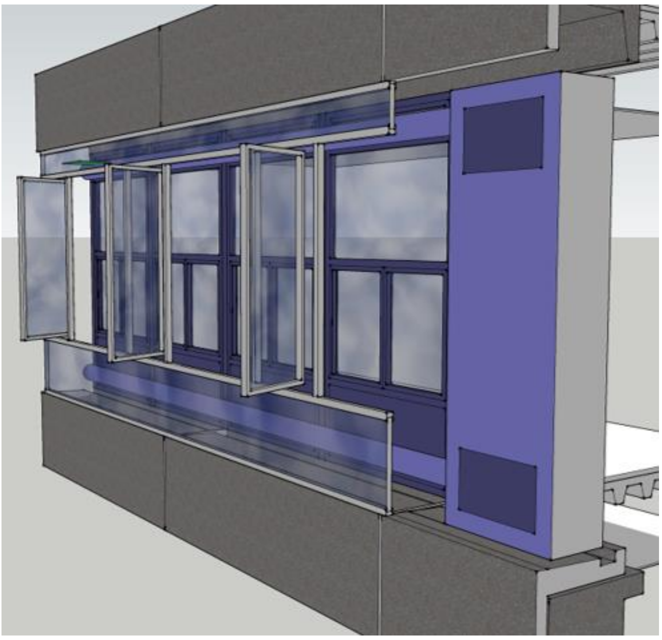


Figure 29 - The double partial skin with HRV 3D model

5.2.5 The double partial skin with HRV and the Electrochromic Glass – 4. Alternative

This solution presents the same characteristics of the double partial skin with HRV abovementioned (as shown in Table 15) except for the introduction of the Electrochromic Glass as an integrated shading system instead of the roller blinds. It has been supposed to use this type of shading system on the external surface, in particular on the openable windows as illustrated in the Figure 30.

The Electrochromic Glass (E.C. glass) can have several advantages including those of being controlled directly by building occupants, improving occupant comfort, maximizing access to daylight and outdoor views, reducing energy costs and guaranteeing to architects more design freedom.

The glass tints change on the basis of the amount of voltage applied to the glass: if is applied a low voltage of electricity, for example, this obscures the coating since the lithium ions and electrons transfer from one electrochromic layer to another. When the voltage is removed there is a reversal of polarity and consequently the ions and electrons return to their original layers, so that the glass returns to its clear state.

Table 15 – The double partial skin with HRV and the E.C. glass package

4. Alternative				
	U	Unit	m^2/panel	m^2/4panels
Internal single glass 6mm	4,85	W/m^2K	2,98	11,90
Aluminium Frame with thermal break	4,72	W/m^2K	1,43	5,70
Aluminium sandwich panel (2/146/2mm)	0,24	W/m^2K	1,16	4,66
External Double Glass 4/16/4mm	1,15	W/m^2K	1,49	5,97
External Double Glass 4/16/4mm with electrochromic system	1,15	W/m^2K	2,93	11,72
Aluminium extruded profile RT62	2,24	W/m^2K	0,92	3,67

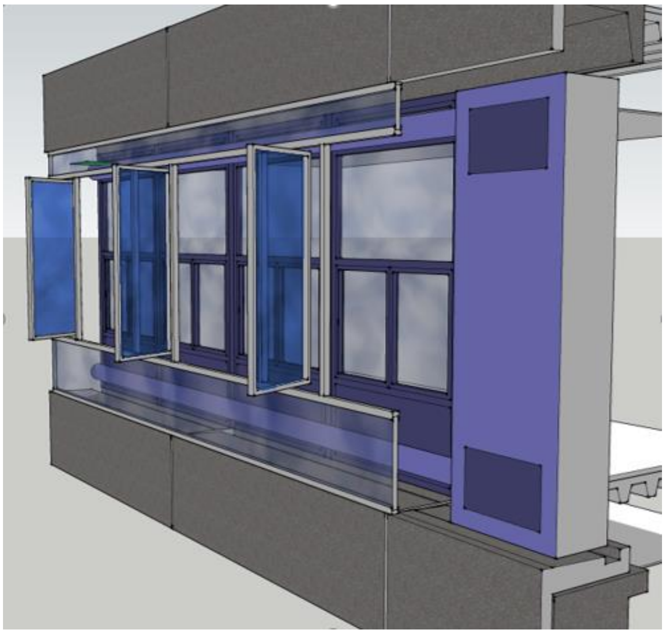


Figure 30 - The Double partial skin with HRV and E.C. glass 3D model

5.3 The Energy simulation

The first step of the study is the energy simulations on the five different options using the Design Builder software package. Through this process are obtained three type of information:

- the energy data to include into the life cycle analysis such as the energy consumption (kWh/year) and the CO_2 emissions ($kgCO_2$/year);
- the utility (energy) costs;
- the energy savings related to the different choices.

The calculations are made for two typical West-facing offices with a total of 30 m^2 floor area; the rooms on the North and South sides, and the hallway on the East side are set to adiabatic, as they will also be heated according to the same schedule as the simulated room. Below are illustrated the main assumptions and boundary conditions for the calculations:

- **Occupancy density**
  It is assumed an average occupation of 10 people during a typical work day, excluding public holidays. The value *density* is: 0,2830 (p/m^2).
- **Setpoint temperature**
  Defines the ideal temperature in the zone when heating or cooling is required.
  Heating: 20 °C
  Cooling: 24 °C
- **Ventilation**
  In the tab "Activity" is possible to fix the indoor temperature below which ventilation is shut off, through the option "min temperature definition". Indeed, if the indoor air temperature is greater than this setpoint temperature (and the schedule related to the natural ventilation is active) then natural ventilation can take place. In this case the *min temperature* is 20 °C.
  The next required data is the minimum fresh air per person: it is extrapolated from the UNI EN 15251 (Indoor environmental parameters for assessment of energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics). The standard specifies how design criteria can be established and used and how to define the main parameters to be used for building energy calculation. In this case the baseline categories (Figure 31) for identifying the parameters are two: the first one is referred to the renovated façade and the third one is referred to the existing model.

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Figure 31 –Different categories for evaluating buildings
(Source: UNI EN 15251, *Indoor environmental parameters for assessment of energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics*)

In the Appendix B of the standard (*Basis for the criteria for indoor air quality and ventilation rates*, UNI EN 15251) is described a method based on ventilation rate per person, which assumes that occupants are the only source of pollution.
Thus, with reference to the Figure 32, the *minimum air flow per person* is 4 l/s/pers with regard to the 0. Alternative, instead is 10 l/s/pers with regard to all the other alternatives.

		Airflow for building emissions pollutions (l/s/m²)		
Category	Airflow per person l/s/pers	Very low polluting building	Low polluting building	Non low polluting building
I	10	0,5	1	2
II	7	0,35	0,7	1,4
III	4	0,2	0,4	0,8

Figure 32 – Airflow per person and for building emissions pollutions
(Source: UNI EN 15251, *Indoor environmental parameters for assessment of energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics*)

The natural ventilation is composed not only by the fresh air for ensuring an appropriate IAQ (indoor air quality) but also by the *infiltration rate*: in the tab "Construction", indeed, it is taken into account the airtightness. The value is defined in air changes per hour (ac/h) and it is assumed to be constant throughout the simulation. Since there is no specific study on the envelope and its boundary conditions, it was considered appropriate to use an estimation according to the quality of the frames and the age of components. For this reason, it is assumed a rate of 0,7 vol/h related to the 0. Alternative, and a rate of 0,5 vol/h related to all the other alternatives.
Furthermore, as stated above, the first alternative allows the possibility to operate the night cooling ventilation. In this case has been necessary to change the schedule related to the natural ventilation in tab "HVAC", so as to set up a specific operating programme.
Lastly, the 3. and 4. Alternative dispose of *mechanical ventilation* through the HRV: in tab "HVAC" has been enable the function related to this type of ventilation, choosing a sensible heat recovery with an effectiveness equal to 0.70 and not

including an economiser. It has been also added a specific schedule regarding the operation of the HRV.

- **Shading**
  With regard to the zero alternative, no shading systems have been taken into account, instead of the 1. 2. and 3. Alternative which are provided of external roller blinds. A proper operational schedule has been created, taking into account a greatest need of them during the summer period and the week days. The same applies for the last alternative, even if is not provided of roller blinds but has the E.C. glass.
- **Lighting**
  In this case has been used rough data for lack of more accurate estimate. The simulation is done on the basis of an occupancy programme, considering the working hours.

5.3.1 The results

Based on the main assumptions abovementioned and the different characteristics of each package, Energy Builder provides heating and cooling design calculations for determining the size of heating and cooling equipment.
The simulation of design values takes into account several specifications listed below.

Heating design simulations:

- Constant external temperature set to the winter design external temperature;
- Wind speed and direction set to design values;
- No solar gain;
- No internal gains (lighting, equipment, occupancy etc.);
- Heated zones are heated constantly to achieve the heating temperature set point using a simple convective heating system;
- Schedules are not used for heating design calculations which are based on a steady state analysis which does not account for timing.

Cooling design simulations:

- Periodic steady-state external temperatures calculated using maximum and minimum design summer weather conditions;
- No wind;

- Includes solar gains through windows and scheduled natural ventilation;
- Includes internal gains from occupants, lighting and other equipment.

The following Figures show the results related to the five alternatives.

Zona	Temperatura Comfort (°C)	Perdita di Calore in Regime Staz...	Potenza di Progetto (kW)	Potenza di Progetto (W/m2)
− Edificio 1 Capacità Totale di Riscaldamento di Progetto = 2,700 (kW)				
− Blocco 1 Capacità Totale di Riscaldamento di Progetto = 2,700 (kW)				
West Facade - Office	19,82	2,16	**2,70**	82,0795

Zona	Potenza di Progetto (kW)	Portata di Progetto (mc/s)	Carico di Raffrescamento...	Sensibile (kW)	Latente (kW)	Temperatura aria (°C)
− Edificio 1						
Blocco1:WestFacadeX0...	6,08	0,3977	5,29	4,67	0,62	23,1
Totali	**6,08**	**0,3977**	**5,29**	**4,67**	**0,62**	**23,1**

Figure 33 - Heating and cooling design calculations 0. ALTERNATIVE

Zona	Temperatura Comfort (°C)	Perdita di Calore in Regime Staz...	Potenza di Progetto (kW)	Potenza di Progetto (W/m2)
− Edificio 1 Capacità Totale di Riscaldamento di Progetto = 1,280 (kW)				
− Blocco 1 Capacità Totale di Riscaldamento di Progetto = 1,280 (kW)				
West Facade - Office	20,21	1,03	**1,28**	39,3765

Zona	Potenza di Progetto (kW)	Portata di Progetto (mc/s)	Carico di Raffrescamento...	Sensibile (kW)	Latente (kW)	Temperatura aria (°C)
− Edificio 1						
Blocco1:WestFacadeX0...	4,47	0,2627	3,89	3,60	0,29	25,0
Totali	**4,47**	**0,2627**	**3,89**	**3,60**	**0,29**	**25,0**

Figure 34 – Heating and cooling design calculations 1. ALTERNATIVE

Zona	Temperatura Comfort (°C)	Perdita di Calore in Regime Staz...	Potenza di Progetto (kW)	Potenza di Progetto (W/m2)
− Edificio 1 Capacità Totale di Riscaldamento di Progetto = 1,200 (kW)				
− Blocco 1 Capacità Totale di Riscaldamento di Progetto = 1,200 (kW)				
Occupied zone	19,38	0,96	**1,20**	36,2064
Cavity zone	0,85	0,00	**0,00**	0,0000

Zona	Potenza di Progetto (kW)	Portata di Progetto (mc/s)	Carico di Raffrescamento...	Sensibile (kW)	Latente (kW)	Temperatura aria (°C)
− Edificio 1						
Blocco1:CavityZone	0,00	0	0,00	0,00	0,00	-
Blocco1:OccupiedZone	4,09	0,2373	3,55	3,00	0,55	24,0
Totali	**4,09**	**0,2373**	**3,55**	**3,00**	**0,55**	**21,8**

Figure 35 - Heating and cooling design calculations 2. ALTERNATIVE

Zona	Temperatura Comfort (°C)	Perdita di Calore in Regime Stazi...	Potenza di Progetto (kW)	Potenza di Progetto (W/m2)
− Edificio 1 Capacità Totale di Riscaldamento di Progetto = 1,220 (kW)				
− Blocco 1 Capacità Totale di Riscaldamento di Progetto = 1,220 (kW)				
Occupied zone	19,16	0,98	**1,22**	36,9112
Cavity zone	1,92	0,00	**0,00**	0,0000

Zona	Potenza di Progetto (kW)	Portata di Progetto (mc/s)	Carico di Raffrescamento...	Sensibile (kW)	Latente (kW)	Temperatura aria (°C)
− Edificio 1						
Blocco1:CavityZone	0,00	0	0,00	0,00	0,00	-
Blocco1:OccupiedZone	3,89	0,2247	3,38	2,84	0,54	24,0
Totali	**3,89**	**0,2247**	**3,38**	**2,84**	**0,54**	**21,8**

Figure 36 – Heating and cooling design calculations 3. ALTERNATIVE

Zona	Temperatura Comfort (°C)	Perdita di Calore in Regime Stazi...	Potenza di Progetto (kW)	Potenza di Progetto (W/m2)
Edificio 1 Capacità Totale di Riscaldamento di Progetto = 1,220 (kW)				
Blocco 1 Capacità Totale di Riscaldamento di Progetto = 1,220 (kW)				
Occupied zone	19,16	0,98	**1,22**	36,9112
Cavity zone	1,92	0,00	**0,00**	0,0000

Zona	Potenza di Progetto (kW)	Portata di Progetto (mc/s)	Carico di Raffrescamento...	Sensibile (kW)	Latente (kW)	Temperatura aria (°C)
Edificio 1						
Blocco1:CavityZone	0,00	0	0,00	0,00	0,00	-
Blocco1:OccupiedZone	2,46	0,1348	2,14	1,71	0,44	24,0
Totali	**2,46**	**0,1348**	**2,14**	**1,71**	**0,44**	**21,8**

Figure 37 - Heating and cooling design calculations 4. ALTERNATIVE

Although, is useful to make a simulation about the energy performance based on real weather data and on HVAC system. Through the tab "Simulation" it is possible to generate the needed energy data, by selecting a time interval; in this case the interval is annual as regards to the energy consumption and is monthly as regards to the internal and solar gains.

Below are shown the data related to the energy consumption of two offices (4 panels); the other outputs are listed in the Appendix A.

- **0. Alternative**

Table 16 - Energy consumption 0. Alternative

Energy consumption	Electricity [kWh]	District Cooling [kWh]	District Heating [kWh]
Heating	0.00	0.00	2227,06
Cooling	0.00	1680,87	0.00
Interior Lighting	1219,34	0.00	0.00

Table 17 - Energy consumption normalised by floor area 0. Alternative

Energy consumption normalised by floor area	Electricity Intensity [kWh/m2]	District Cooling Intensity [kWh/m2]	District Heating Intensity [kWh/m2]
Lighting	37,06	0.00	0.00
HVAC	0.00	51,09	67,69

- **1. Alternative**

Table 18 - Energy consumption 1. Alternative

Energy consumption	Electricity [kWh]	District Cooling [kWh]	District Heating [kWh]
Heating	0.00	0.00	667,63
Cooling	0.00	1084,26	0.00
Interior Lighting	1206,37	0.00	0.00

Table 19 - Energy consumption normalised by floor area 1. Alternative

Energy consumption normalised by floor area	Electricity Intensity [kWh/m2]	District Cooling Intensity [kWh/m2]	District Heating Intensity [kWh/m2]
Lighting	37,06	0.00	0.00
HVAC	0.00	33,31	20,51

- **2. Alternative**

Table 20 - Energy consumption 2. Alternative

Energy consumption	Electricity [kWh]	District Cooling [kWh]	District Heating [kWh]
Heating	0.00	0.00	433,12
Cooling	0.00	1346,98	0.00
Interior Lighting	1225,19	0.00	0.00

Table 21 - Energy consumption normalised by floor area 2. Alternative

Energy consumption by normalised floor area	Electricity Intensity [kWh/m2]	District Cooling Intensity [kWh/m2]	District Heating Intensity [kWh/m2]
Lighting	37,06	0.00	0.00
HVAC	0.00	40,74	13,10

- **3. Alternative**

Table 22 - Energy consumption 3. Alternative

Energy consumption	Electricity [kWh]	District Cooling [kWh]	District Heating [kWh]
Heating	0.00	0.00	264,72
Cooling	0.00	980,95	0.00
Interior Lighting	1225,19	0.00	0.00

Table 23 - Energy consumption normalised by floor area 3. Alternative

Energy consumption normalised by floor area	Electricity Intensity [kWh/m2]	District Cooling Intensity [kWh/m2]	District Heating Intensity [kWh/m2]
Lighting	37,06	0.00	0.00
HVAC	0.00	29,67	8,01

- **4. Alternative**

Table 24 - Energy consumption 4. Alternative

Energy consumption	Electricity [kWh]	District Cooling [kWh]	District Heating [kWh]
Heating	0.00	0.00	270,25
Cooling	0.00	435,43	0.00
Interior Lighting	1225,19	0.00	0.00

Table 25 - Energy consumption normalised by floor area 4. Alternative

Energy consumption normalised by floor area	Electricity Intensity [kWh/m2]	District Cooling Intensity [kWh/m2]	District Heating Intensity [kWh/m2]
Lighting	37,06	0.00	0.00
HVAC	0.00	13,17	8,17

5.3.2 The energy comparison

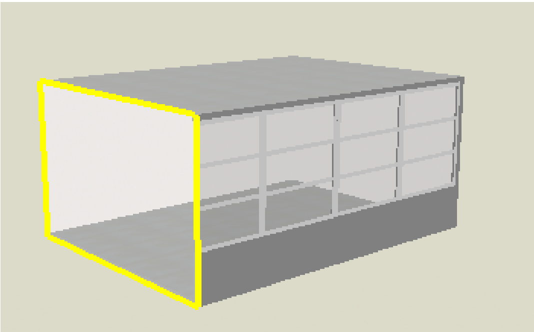


Figure 38 - The Energy Builder Model (0. and 1. Alternative)

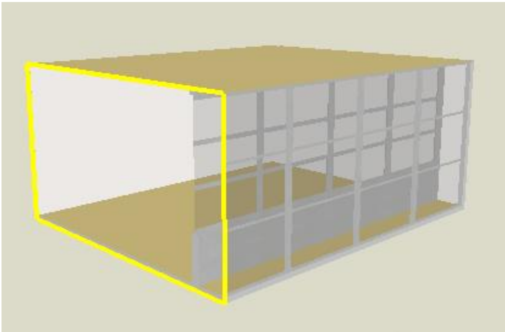
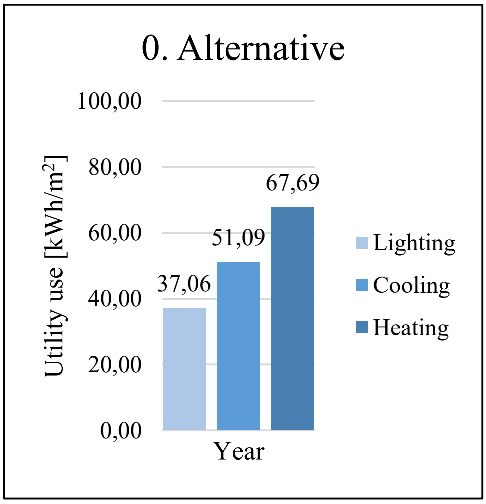
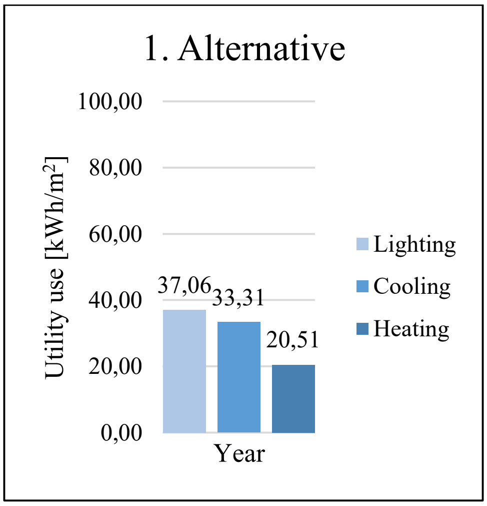
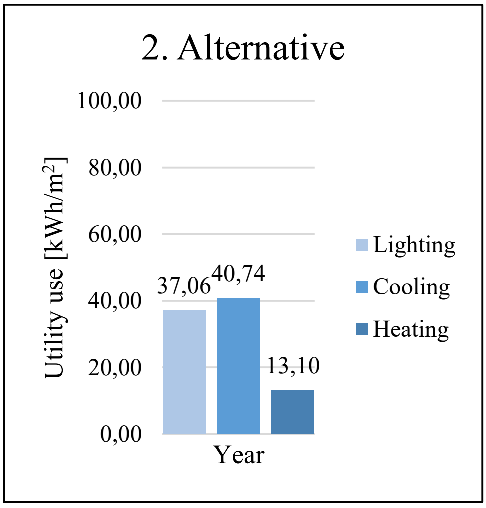
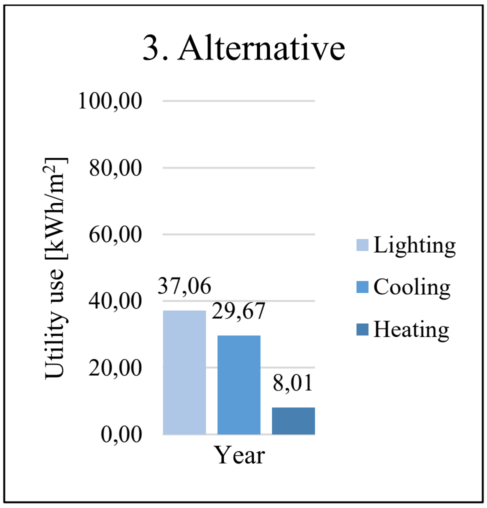


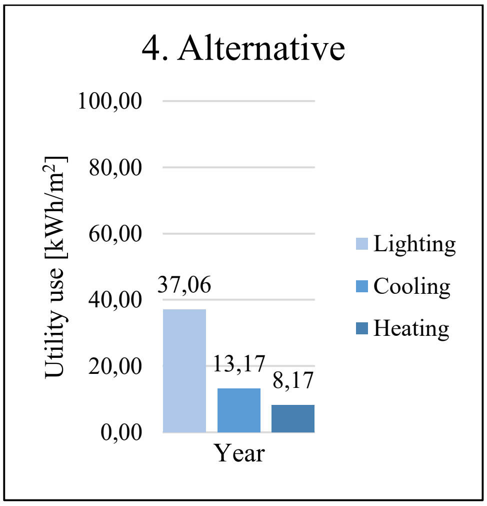
Figure 39 - The Energy Builder Model (2., 3., 4. Alternative)











These five bar charts are related to the energy consumption of the five alternative proposed. By comparing the annual energy consumption for heating, the diagrams show a drastic drop of almost 70% after installing a replaced façade, from 67,69 kWh/m^2 to 20,51 kWh/m^2 and the result increases through the installation of the double partial skin with an energy savings of almost 80%. The most relevant improvement is between the current façade and the double partial skin with the Heat Recovery Ventilation: this ventilation system allows to reach almost the 88% of energy savings, by lowering the heating consumption from 67,69 kWh/m^2 to 8 kWh/m^2. The result does not change significantly if the comparison is made between the double partial skin with and without the Electrochromic Glass: the value of heating consumption, indeed, is quite similar in both cases.

In contrast, with regard to the cooling energy demand the most relevant improvement is between the current façade and the double partial skin with the HRV and the Electrochromic

Glass. Thanks to this integrated shading system described in the previous paragraph, the bar chart shows a decrease to almost 75%, from 51 kWh/m^2 to 13 kWh/m^2.
As regards to the other alternatives, the diagrams illustrate how the replacing of the façade can allow a greater energy savings in cooling consumption compared to the double partial skin without HRV: in fact, while the cooling demand in the 1. Alternative is 33 kWh/m^2, in the 2. Alternative is 40 kWh/m^2 and that is due to the cavity that during the hot season acts like a buffer zone accumulating solar gains.
The diagrams show in every alternative a performance improvement in cooling demand but at the same time it is not so much remarkable because the reduction in infiltration rate shall ensure the cooling and ventilation demand.

Furthermore, by making a comparison on the electricity demand, the diagram illustrates no changing between all the alternatives.

Through these outputs is possible to obtain the utility costs for each option, taking into account every consumption and multiplying it by the corresponding €/kWh mentioned in the previous chapter. The following values are referred to a module composed by 4 panels; subsequently, in the LCCA chart the utility costs have been reported to one panel, so as to enable an easier comparison between all the costs item.

Table 26 - Utility costs of the different alternatives

	€/module
Utility costs 0. Alternative	803,74

	€/module
Utility costs 1. Alternative	561,14

	€/module
Utility costs 2. Alternative	608,75

	€/module
Utility costs 3. Alternative	514,91

	€/module
Utility costs 4. Alternative	392,38

5.4 Component Costs

The following step for obtaining the TCO of each alternative is to collect the cost of all the components chosen. In this case the involved suppliers have been contacted after a detailed description of the project and on the basis of the characteristics of their products it has been possible to receive their offers. The related information documents of the chosen products are listed in the Appendix B.

All the prices indicated in the Tables below are based on one panel, considering three types of cost: the product price, the market price (adding a rough supplier profit margin of 5% to the product price) and the installation cost (if it has not already included in the product price). In this last cost item is also included the service cost for the installation, since it has not been possible to spin off it from the total cost provided by the supplier.
Then by adding up the product and the installation cost it is obtained the initial construction investment.

Table 27 - Component costs 1. Alternative

1. Alternative			
	Prod. Price	Market Price	Installation
Double Glazing	84,82	89,28	-
Kawneer RT62 frames	1.117,43	1.176,24	592,10
Paroc Aluminium sandwich panel	52,38	55,00	-
Roller blinds	802,75	845,00	-
Ventilation grill	240,00	250,00	-

Table 28 - Component costs 2. Alternative

<table>
<tr><th colspan="4">2. Alternative</th></tr>
<tr><th></th><th>Prod. Price</th><th>Market Price</th><th>Installation</th></tr>
<tr><td>Internal single glass 6mm</td><td rowspan="2">-</td><td rowspan="2" colspan="2">-</td></tr>
<tr><td>Aluminium Frame with thermal break</td></tr>
<tr><td>Paroc Aluminium sandwich panel</td><td>52,38</td><td>55,00</td><td>-</td></tr>
<tr><td>Roller blinds</td><td>802,75</td><td>845,00</td><td>-</td></tr>
<tr><td>External Double Glass 4/16/4mm</td><td>125,87</td><td>132,50</td><td>-</td></tr>
</table>

Kawneer RT62 frames	1.025,24	1.079,20	592,10

Table 29 - Component costs 3. Alternative

3. Alternative			
	Prod. Price	Market Price	Installation
Internal single glass 6mm	-	-	
Aluminium Frame with thermal break			
Paroc Aluminium sandwich panel	52,38	55,00	-
Roller blinds	802,75	845,00	-
External Double Glass 4/16/4mm	125,87	132,50	-
Kawneer RT62 frames	1.025,24	1.079,20	592,10
ComfoAir 200 HRV	2.010,00	2.110,50	-

Table 30 - Component costs 4. Alternative

4. Alternative			
	Prod. Price	Market Price	Installation
Internal single glass 6mm	-	-	
Aluminium Frame with thermal break			
Paroc Aluminium sandwich panel	52,38	55,00	-
Electrochromic Glass	1.464,60	1.537,83	219,69
External Double Glass 4/16/4mm	42,48	44,71	-
Kawneer RT62 frames	1.025,24	1.079,20	592,10
ComfoAir 200 HRV	2.010,00	2.110,50	-

5.5 Maintenance and Service Costs

The maintenance and the service are two costs item difficult to estimate, since every project has a specific and different management and so the only way for an accurate calculation is obtaining information from the Facility Management (FM).

In the Table 31 are listed the main data related to the different alternatives, divided on the basis of the type of maintenance:

- The preventive maintenance such as the paintings, cleanings and every systematic inspection for preserving the operating condition;
- The reactive maintenance as an estimate of the % of failure rate during the service life;
- The planned maintenance such as the replacement of a component when it reaches its end of life.

Table 31 - Maintenance data of the different alternatives

	Maintenance (Preventive)	Maintenance (Reactive)	Maintenance (Planned/Repl.)
0. Alternative	€/panel	%	Service life
Paintings @ 6years	80,00		
1. Alternative	€/panel	%	Service life
Double glazing			
breakage 2%		0,02	25,00
Kawneer R62 Frames			
Inspection and Maintenance @1year	13,00		75,00
Roller blinds			
Failure rate 2% @25years		0,02	25,00
Ventilation grill			
Failure rate 2% @25years		0,02	25,00
2. and 3. Alternative	€/panel	%	Service life
Double glazing			
breakage 2%		0,02	25,00
Kawneer R62 Frames			
Inspection and Maintenance @1year	13,00		75,00
Roller blinds			
Failure rate 2% @25years		0,02	25,00
Heat recovery ventilation			
Inspection and maintenance @2years	30,15		35,00
Filters replace @ 1/2 year			37,80
4. Alternative	€/panel	%	Service life
Double glazing			
breakage 2%		0,02	25,00
Electrochromic Glass			
breakage 2%		0,02	25,00

As regards to the service costs, it has been possible to give a rough estimation of the €/m^2 of the several services starting from the total cost supplied by the FM of CiTG referred to a surface of 3500 m^2.

- Cleanings @year = 2.100,00 €
- Paintings @6years = 350.000,00 €
- Demolition Costs = 340.000,00 €
- Removal asbestos = 180.000,00 €
- General Costs current façade @10years = 100.000,00 €
- Expected General Costs replaced façade @10years= 150.000,00 €

Table 32 - Service data of the different alternatives

	Service (Maintenance)	Service (Disassembly)
Current façade	€/m^2	€/m^2
Cleanings @ year	0,60	
Paintings @ 6years	100,00	
General Costs @ 10years	28,57	
Replaced façade	€/m^2	€/m^2
Demolition Costs + Asbestos removal		148,57
Cleanings @ year	0,60	
Inspection and Maintenance @1year	40 €/unit	
Expected General Costs @ 10years	42,86	

5.6 Preliminary financial case

After the collection of all the necessary data, it has been developed the LCCA in which the relation between purchased and leased scheme has been analysed for both the single case and all the packages.

In particular, in the Component LCCA chart (Appendix C) is illustrated the cost relation between all packages on Year 1 and on the LCCA's period in NPV, in which there is the breakdown of all the expenses related to each component: when the study is separated on the basis of the single components, on the one hand it is easier to evaluate the potential and behaviour in terms of each package's TCO but on the other hand the output is a rough cost-to-benefit relation, since the results are not the precise amount of money spent during the chosen period or the precise price at which the package could be leased. Thus, in this LCCA

chart it has been obtained the Total Cost of Ownership, the Total Lease Price (provided with a fixed rate) and the Total Cost Year 1 of every system.
As mentioned in the previous chapter, the TCO takes into account the initial investment, the ownership costs and the taxes (BTW); on the other side, the rough estimation of the Lease Price includes the initial investment, the ownership costs and the residual value insurance by applying a 1% per year on the product price of each component. Then it has been possible to calculate the Total Cost Year 1 taking into account the Lease Price adjusted according to the rate of inflation on products during the LCCA period.

Through the Components LCCA chart is possible to give a first observation about the difference between the several choices:

Table 33 - Main outputs from the Component LCCA chart

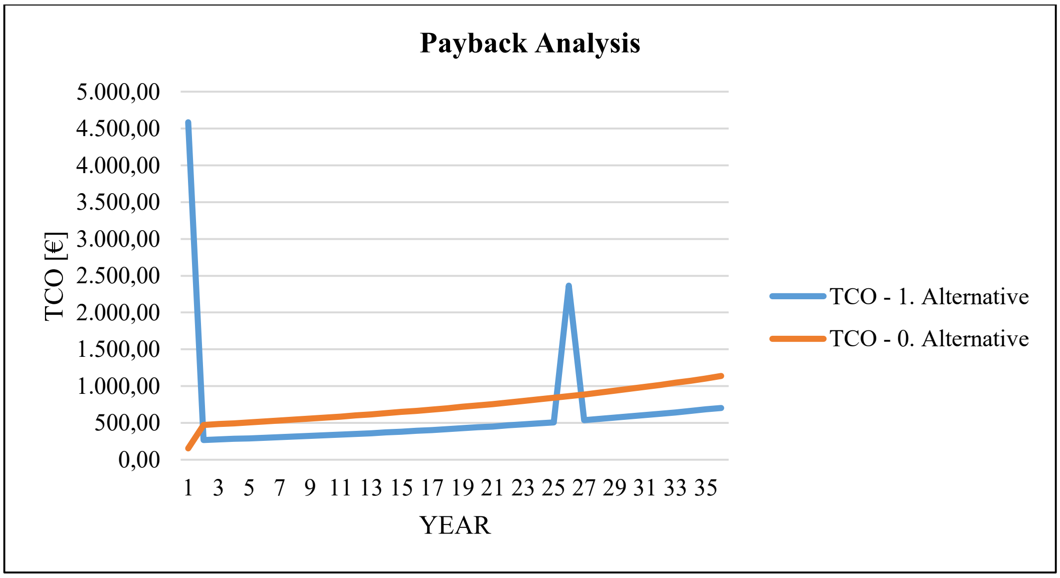
0. Alternative	
In. Investment	0,00
Energy	14.156,65
TCO	24.041,88
Cost Year 1	562,00
1. Alternative	
In. Investment	2.889,47
Energy	9.883,64
TCO	20.488,90
Lease Price	18.494,86
Cost Year 1	432,34
2. Alternative	
In. Investment	2.598,34
Energy	10.722,07
TCO	25.492,48
Lease Price	17.077,33
Cost Year 1	399,20
3. Alternative	
In. Investment	4.608,34
Energy	9.069,34
TCO	25.174,71
Lease Price	18.229,23
Cost Year 1	426,13

4. Alternative	
In. Investment	5.406,48
Energy	6.911,13
TCO	24.122,67
Lease Price	14.851,78
Cost Year 1	347,18

Even though in the current system the initial investment is zero since it is supposed to not add new components, the TCO is quite high because of the great energy expenses. The latter added to the maintenance and service costs makes this alternative unprofitable, since the rapid obsolescence of the system will require an increasing labour and thus an increasing expense due to the ascending labour costs in the future.
From the TCO point of view, the Table 33 shows that the 1. Alternative is the most cost-effective; this option, indeed, includes the removal of the current façade for installing a more efficient package in which the utility costs are compensated by the lowest maintenance costs. At the same time the 1. Alternative has also one of the lowest up-front price and so appears as the most attractive from the common decision-making strategy.
On the contrary, when the Lease Price is introduced, the energy consumption becomes more influent on the total calculation and the taxes on products are not taken into account; for this reason, alternatives with a higher energy savings result more convenient. In particular, in terms of Cost Year 1, the 4. Alternative allows a saving of almost 40% compared to the current situation: even if the last alternative could not attract under the “lower initial cost” point of view, it should be considered the general framework in which during the 35 years of the study the prices could increase and in particular it is expecting a faster rise in the price of energy against products and services and consequently a faster rise in current façade costs than in the last alternative.

Subsequently, the 0. and 1. Alternative have been chosen for analysing and comparing more accurately the TCO within the related 35-year breakdown analysis shown in the Appendix D. In this case one time and recurring costs are compensated on the basis of the respective inflation rate at the time when they take place; obviously there is a slight different between the Component LCCA chart and the single Alternative LCCA charts since in the first chart the failure rates are calculated statistically (2% of components are expected to fail over a service-life) while in a 35-year study these expenses could happen at any time. For these reason, it has been supposed to take into account the worst-case in which the reactive maintenance occurs at the end of the service-life, and so when the expenses are the highest. Another difference is due to add an energy safety margin to the utility costs for taking into account a possible negative user behaviour and so for compensating the gap between an ideal and real model.

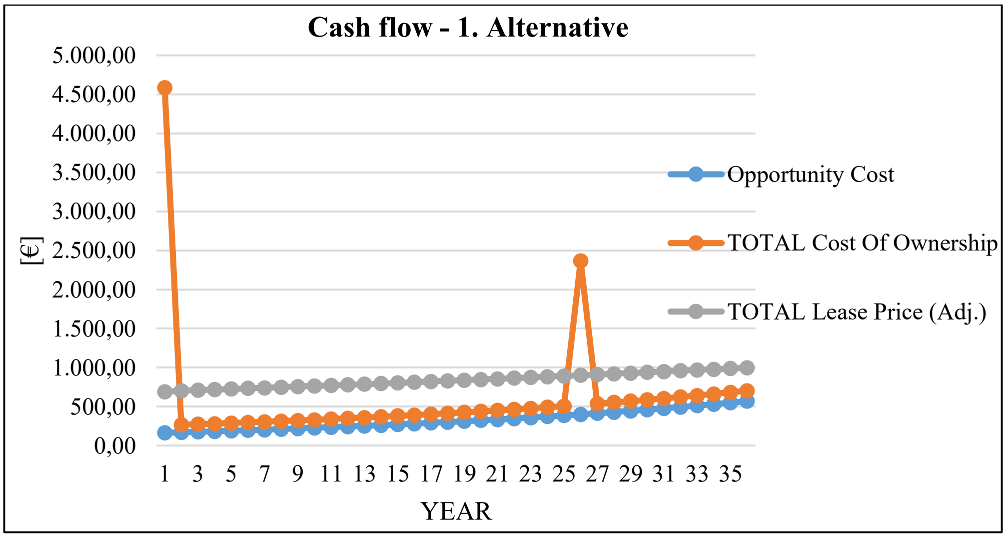
Through the comparison between the 0. Alternative LCCA chart and the 1. Alternative LCCA chart it has been possible to establish the payback period: Payback Analysis allows to evaluate the time when an option has the same life cycle cost as the base case, and it occurs at the point of intersection between the lines. As shown by the line chart below, the orange line illustrates the cumulative cost of doing nothing in a retrofit project scenario and it requires zero initial cost, while the blue line illustrates the cumulative cost of the 1. Alternative; the point at which the two options have the same cumulative cost is roughly at the second year, and it means that the 1. Alternative results in a two-year payback.



The 1. Alternative LCCA chart allows also to evaluate in more detail the Lease Price and the Opportunity Cost of Capital (OCC): this last is calculated as a 5% on the TCO and represents the amount of money "sacrificed" or "gained" by investing the initial capital (which may be in cash or credit) into an alternative investment. This means that the OCC evaluates how the resources are managed by an organization in activities not directly related to its core business. Using a leasing model could mean exploiting those resources in other investments that could result more attractive: through the leasing, indeed, the resources of

an organization are only minimally used into the renovation (the small fee needed to pay, for example) and are unlocked for being spent in other way.
Other financial values have been taken into account in order to calculate the Total Lease Price: it has been obtained, indeed, as the sum of the TCO fixed rate, the supplier profit margin of 9% (by considering the assumption that they are provided by the same supplier during the LCCA period) and the taxes (applied on the TCO fixed rate).

Starting from this data, it has been developed a cash flow analysis (Appendix E) that makes a direct comparison between the purchasing and the leasing scheme related to the 1. Alternative.
The Total Cost of Ownership of the renovated package is estimated to be just above € 22.000 over a 35 year study. It can be seen that the 20% of the total cost is spent during the first year, mainly for the demolition of the previous package and the construction of the new one. At the same time, taking into account the abovementioned opportunity costs of capital amounting to almost € 12.000, it can be estimated a potential overall cost of the panel equal to almost € 34.000 (TCO+OCC): by considering now the Total Lease Price around € 30.000 and by mentioning what it has been said about the leasing and the "no opportunity sacrifice", it is possible to account the total cost per panel of the 1. Alternative (Total Lease Price – OCC) as just above € 18.000.
The graph below shows the cash flow described above over the 35 year LCCA, in which there is a comparison between the purchase and lease scheme.



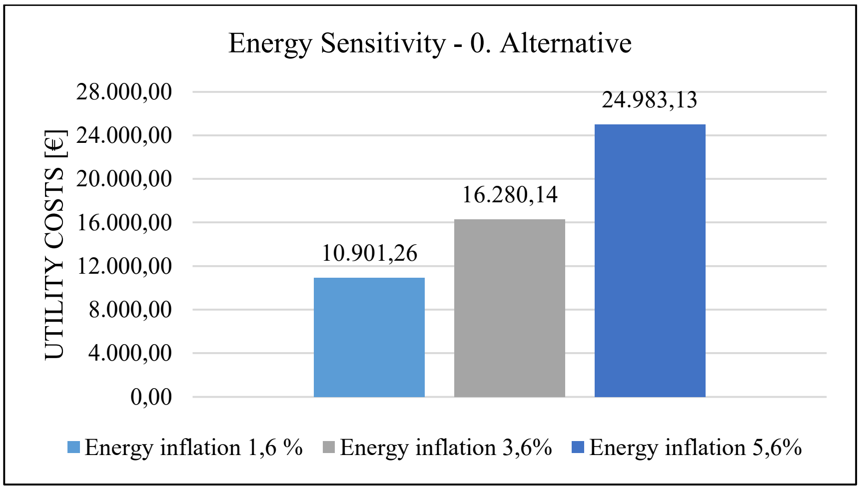
Furthermore, in the cash flow analysis it can observe what could be the profit of the suppliers after the selling of the façade panel amounting to almost € 600 during the LCCA period, in which almost the 40% is allocated in the first year. The profit obtained after the first year, indeed, are not so significant since it could be allocated to different suppliers than the original one. At the same time, the profit for the performance contractor related to the leasing system in Year 1 is just under € 50, but when looking to the total amount over the entire LCCA period the profit becomes almost € 2.000 per panel.

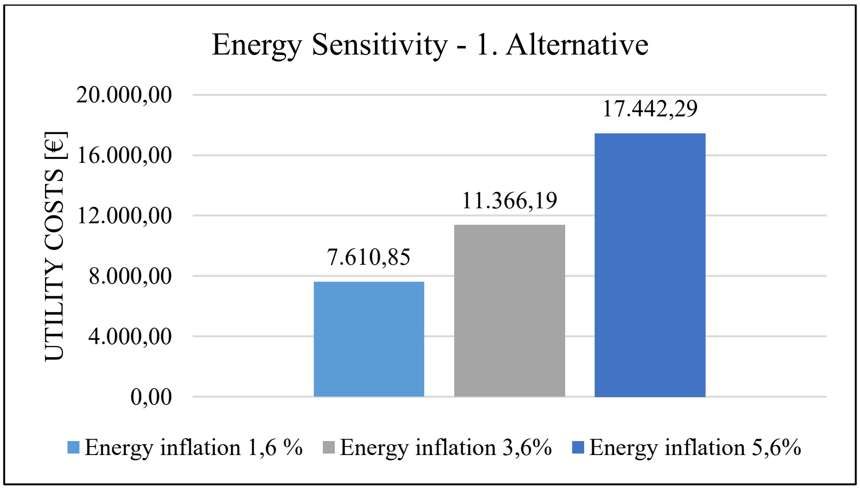
5.6.1 Sensitivity Analysis

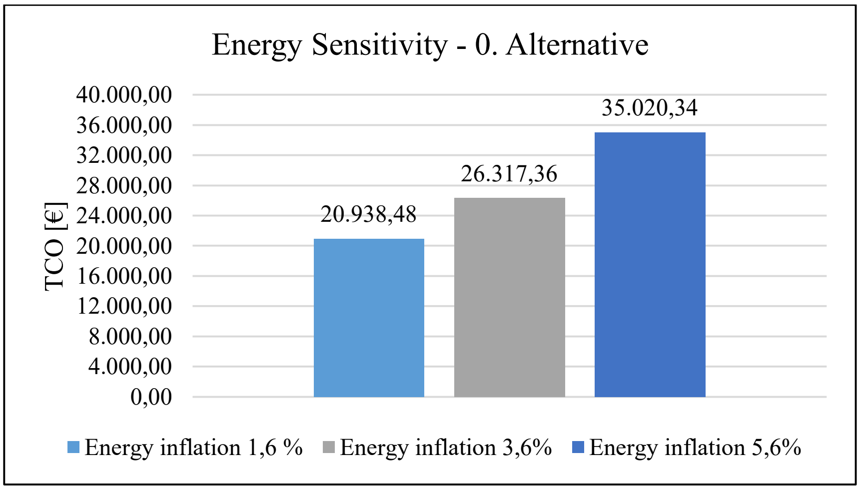
The conducted analysis has been developed under a series of assumptions and variables that could change over time, since they are strictly connected to the socioeconomic and geopolitical situation. For this reason, it could appear useful to make a sensitivity analysis in which is studied the impact of different values on a particular dependent variable.
In particular, the categories that have been analyses are the energy price, the failure rate related to the reactive maintenance and a different contract period.

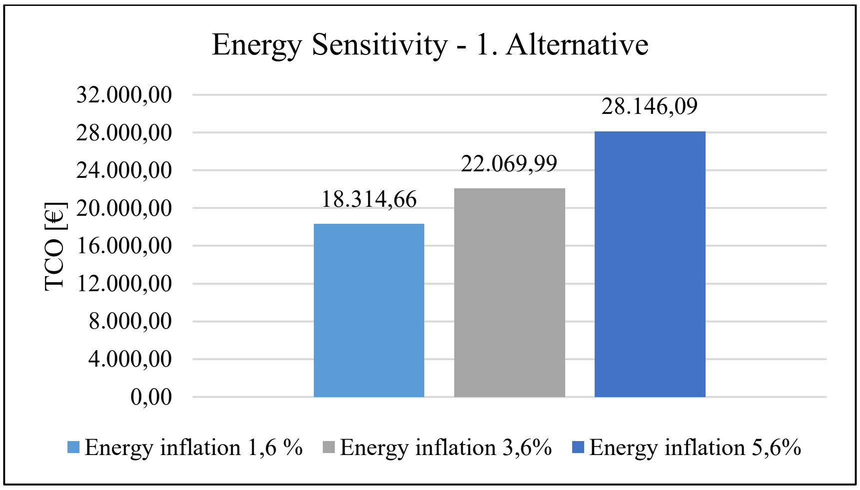
- Energy price

The utility costs are calculated according to the rate of inflation and taking into account an energy safety margin; since the inflation on energy price is a variable highly dependent on the energetic strategy of a country, it has been decided to build up two hypothetical scenarios with a lower and a higher rate that could reflect an optimistic and pessimistic case. As shown in the bar charts below, the variation has been applied on the base case and on the 1. Alternative in order to figure out the influence of the energy price on the TCO of the two options.


Energy Sensitivity - 0. Alternative
UTILITY COSTS [€]
28.000,00
24.000,00
20.000,00
16.000,00
12.000,00
8.000,00
4.000,00
0,00
10.901,26
16.280,14
24.983,13
Energy inflation 1,6 %
Energy inflation 3,6%
Energy inflation 5,6%


Energy Sensitivity - 1. Alternative
UTILITY COSTS [€]
20.000,00
16.000,00
12.000,00
8.000,00
4.000,00
0,00
7.610,85
11.366,19
17.442,29
Energy inflation 1,6 %
Energy inflation 3,6%
Energy inflation 5,6%


Energy Sensitivity - 0. Alternative
TCO [€]
40.000,00
36.000,00
32.000,00
28.000,00
24.000,00
20.000,00
16.000,00
12.000,00
8.000,00
4.000,00
0,00
20.938,48
26.317,36
35.020,34
Energy inflation 1,6 %
Energy inflation 3,6%
Energy inflation 5,6%

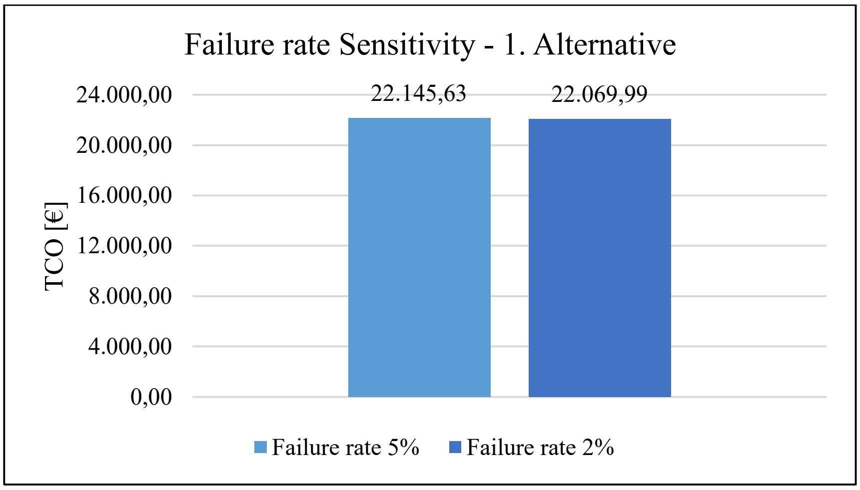


According to the recent trends in Netherlands, the estimated value of inflation in energy price is around 3,6%; under the base conditions the utility costs of one panel over 35 year LCCA are around € 16.300 in the 0. Alternative and around € 11.400 in the 1. Alternative. The respective Total Costs are around € 26.300 and € 22.000: this means that in the base case the influence of the energy price on the total is just above 60% and in the 1. Alternative is just above 50%.

A decrease of 2% on the inflation rate (1,6%) would result in a reduction on the TCO of 20% in the 0. Alternative and of 17% in the 1. Alternative; on the contrary an increase of 2% on this rate (5,6%) would result in a rising cost, switching to a TCO of € 35.000 (rise of 25%) in the 0. Alternative and a TCO of around € 28.000 (rise of 22%) in the 1. Alternative.

- Failure rate

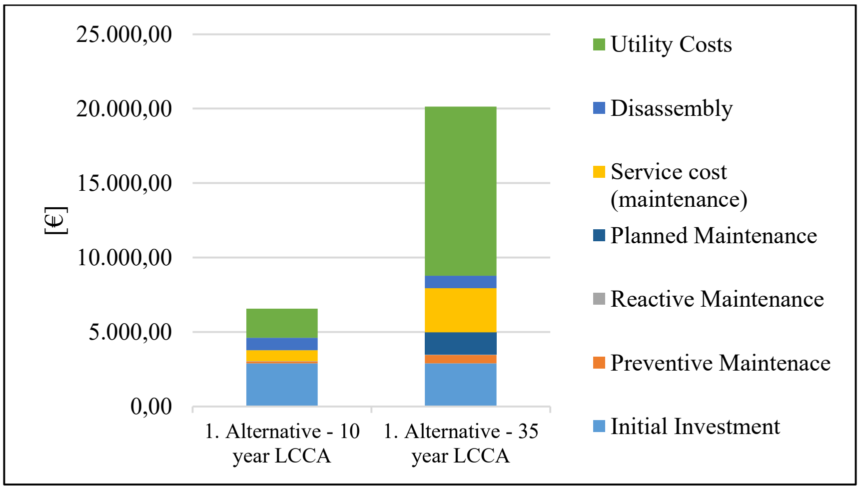
As mentioned in the previous paragraphs, the failure rate of a component is a value strictly approximated, since it is not possible to give an accurate estimation of how much and when it could occur. In the 1. Alternative LCCA chart it has been considered the pessimistic case in which the component could fail at the end of its service-life, when the expenses related to the maintenance are the highest. Through the sensitivity analysis it has been possible to understand the influence of this value on the total costs, when it increases from 2% to 5%.

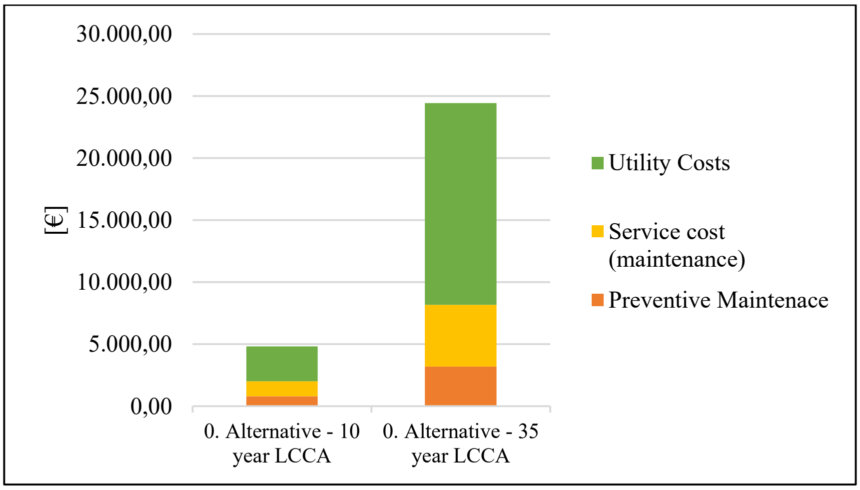


As illustrated in the chart above, the difference in terms of TCO is not relevant: this is because the only change after the switch to a greater failure rate is allocated to the 25th year under the reactive maintenance, and this values is not big enough to significantly modify the total costs over 35 years.

- Different contract period

It is clear that on the basis of the contract period there will be a series of financial values calculated for being fit to that precise aim. Generally, it happens when it is considered a longer period than the one in the present case; on the contrary, taking into account a shorter leasing period, for example 10 years, it does not require any other adjustment. For this reason, it has been decided to make a sensitivity analysis on the 0. Alternative and 1. Alternative over a period of 10 years, in which the results show how the installation and the disassembly become much more influent on the total costs of the 1. Alternative, while the utility costs still remain the most important cost item in the 0. Alternative.





Looking at the leasing, it appears reasonable focussing more on the residual value extraction, since at the end of a shorter contract period the components could have reached just a little percentage of their service life; thus not fully exploiting the capability of a product could result financially unhealthy and ecologically irresponsible.

Conclusions

Taking into account the abovementioned observations about the sustainability of the buildings, it can be said that the façade represents a relevant component, since it has different tasks including the protection of the inner space from the external environment, the architecture aesthetics and the energy performance of a building. It is precisely because the façade has a great influence on the interior climate that it plays an important role in sustainable development and thus in circular building. On the basis of the Circular Economy principles, a circular façade allows to integrate the end-of-life phase, gives preference to the use of dismountable components which increase reusability and recyclability, reduces the request of raw materials since it aims to extend the useful life and it can be separated from the main structure in order to increase the capacity to transform and to adapt to new requirements.

In the present thesis it has been shown that the LCCA is a valid approach for evaluating these strategies of the CE: the role of the analysis can be broken down in three steps, starting from the check of assumptions at product or service level, examining then the alternatives and the related limitations or possibilities, to end up with the set of the objectives, in order to provide elements for helping the business processes and their progress.
In this case, the LCCA has been applied for assessing the relevant of the leasing system in the refurbishment of a façade. It is clear that for providing the accurate value of the leasing during the LCCA period it would be necessary the involvement not only of different stakeholders but also of legal and financial specialists in order to provide clear conditions for the performance contracts; for this reason, it has been decided to develop a general methodology that could be useful not only for the present case but also for future research with regard to circularity of a façade. By building up this type of analysis it has been obtained an initial idea of which renovated option could be the most cost-effective and could be leasable.

It can be concluded that the application of Circular Economic Business Models in the building field, such as products-as-a-service, is still in an experimental phase since are still many the barriers to deal with. Taking into account all the considerations made before, it can be said that on one side the change should be start from the institutions through clear regulations and specific objectives, and on the other side there is a need to create a new supply chain, in which it is promote the collaboration between all the stakeholders. It is necessary to work and think in a different way, encouraging the use of tools able to provide reliable data that can be a basis for developing new form of contracts and financing models: the Life Cycle Cost Analysis can be the tool for obtaining relevant information, providing robust measurements during the decision process at an early stage.

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Appendix A

- **Internal and solar gains**

Table 34 - Internal and solar gains 0. Alternative

Internal & solar gains [Wh/m^2]	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
General Lighting	3266,0	2840,1	2982,1	3124,0	3266,0	2840,1	3266,0	3124,0	2982,1	3266,0	2982,1	3124,0
Occupancy	3711,9	3214,6	3262,0	3337,1	3396,4	2949,2	3369,0	3228,9	3128,3	3516,7	3326,4	3557,1
Solar gains windows	2676,9	5129,5	10505,8	13073,3	17573,9	17573,9	18716,1	15575,7	10149,2	6215,5	3294,2	1949,8
Zone sensible heating	15181,2	11856,8	6923,7	3036,2	748,9	250,5	52,0	55,3	403,0	4236,8	9869,3	14955,3
Zone sensible cooling	-10,3	-87,5	-1087,8	-2138,3	-6880,2	-8898,8	-10663,8	-9071,1	-3218,5	-977,5	-102,4	-11,6

Table 35 - Internal and solar gains 1. Alternative

Internal & solar gains [Wh/m^2]	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
General Lighting	3266,1	2839,9	2981,9	3124,1	3266,1	2839,9	3266,1	3124,1	2981,9	3266,1	2981,9	3124,1
Occupancy	3497,1	2995,4	2944,4	2907,2	3024,0	2705,7	3005,2	2940,1	2958,2	3115,2	3082,6	3384,9
Solar gains windows	634,7	1794,8	3450,7	4812,0	6819,0	7167,7	8013,2	5674,0	3211,4	1855,0	1041,8	524,7
Zone sensible heating	4637,5	3362,2	1237,2	57,8	419,0	847,3	138,6	354,5	1161,0	503,8	2692,2	5049,2
Zone sensible cooling	-16,0	-92,8	-1068,2	-3193,9	-5525,0	-4503,2	-5517,4	-4505,1	-1229,5	-1435,0	-64,8	-9,8

Table 36 - Internal and solar gains 2. Alternative

Internal & solar gains [Wh/m^2]	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
General Lighting	3265,9	2839,7	2981,9	3123,7	3265,9	2839,7	3265,9	3093,5	2981,9	3265,9	2981,9	3123,7
Occupancy	4030,2	3441,9	3321,2	3306,4	3308,5	2895,6	3274,3	3156,1	3171,2	3592,0	3553,5	3914,7
Solar gains internal windows	114,9	504,8	1002,1	1495,2	2010,9	1988,2	2760,1	1592,9	779,2	441,3	206,9	91,0
Solar gains external windows	1010,3	2862,4	5507,0	7675,4	10877,2	11429,5	12799,8	9053,8	5117,1	2957,0	1659,4	835,1

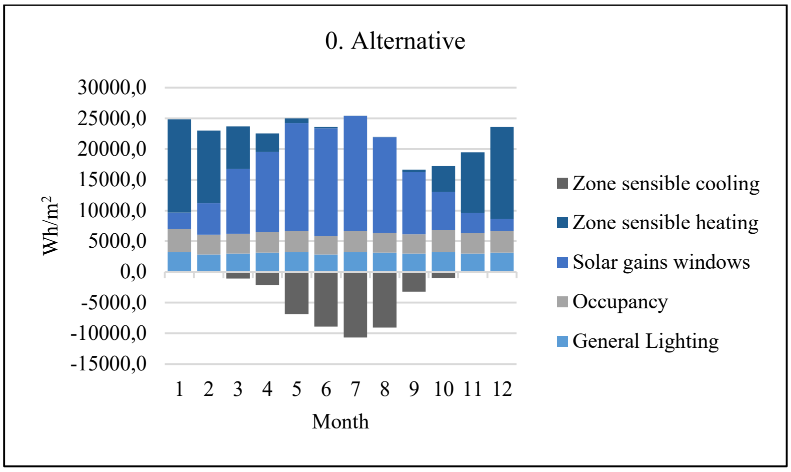
Total Solar gains windows	1125,2	3367,2	6509,1	9170,6	12888,1	13417,7	15559,9	10646,7	5896,2	3398,4	1866,3	926,2
Zone sensible heating	3614,6	2496,4	671,8	10,3	0,0	0,0	0,0	0,0	0,0	228,7	2023,6	4019,7
Zone sensible cooling	-34,5	64,4	-934,1	-3241,4	-5922,3	-6104,1	-7715,1	-5872,1	-1589,5	-1919,5	-212,3	-26,9

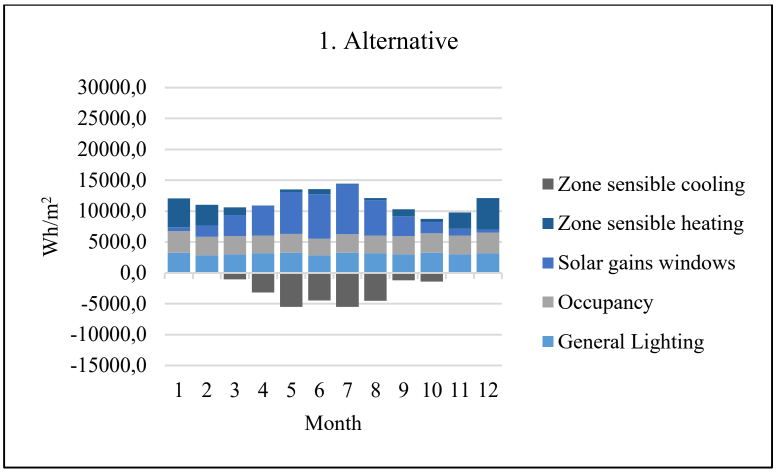
Table 37 - Internal and solar gains 3. Alternative

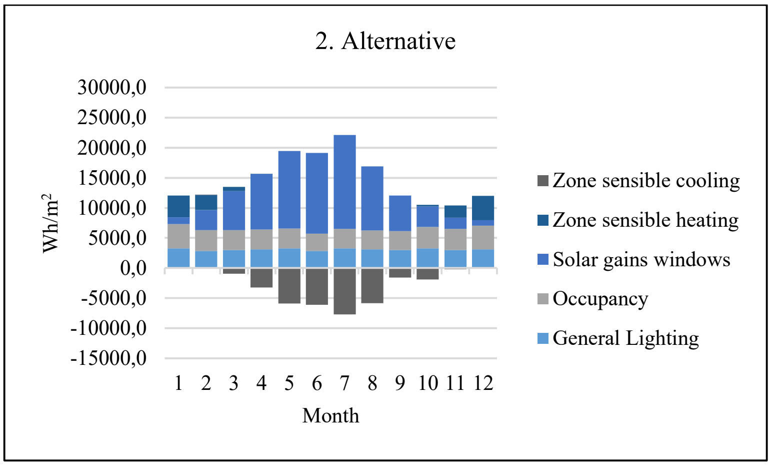
Internal & solar gains [Wh/m^2]	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
General Lighting	3265,9	2839,7	2981,9	3123,7	3265,9	2839,7	3265,9	3093,5	2981,9	3265,9	2981,9	3123,7
Occupancy	4272,2	3678,5	3479,7	3386,9	3389,3	2963,4	3326,1	3213,9	3252,6	3660,9	3730,2	4127,9
Solar gains external windows	9,4	42,0	84,4	126,7	170,3	168,2	233,8	134,6	65,6	36,9	17,2	7,6
Solar gains internal windows	1010,3	2862,4	5507,0	7675,4	10877,2	11429,5	12799,8	9053,8	5117,1	2957,0	1659,4	835,1
Total Solar gains windows	1019,7	2904,4	5591,3	7802,2	11047,5	11597,7	13033,6	9188,4	5182,7	2994,0	1676,6	842,7
Zone sensible heating	2206,6	1555,4	423,2	23,9	0,0	0,0	0,0	0,0	0,0	152,1	1097,4	2395,9
Zone sensible cooling	-653,1	-738,7	-1543,0	-3282,5	-5591,0	-5637,3	-6816,1	-5563,8	-1879,3	-2239,3	-670,3	-577,1

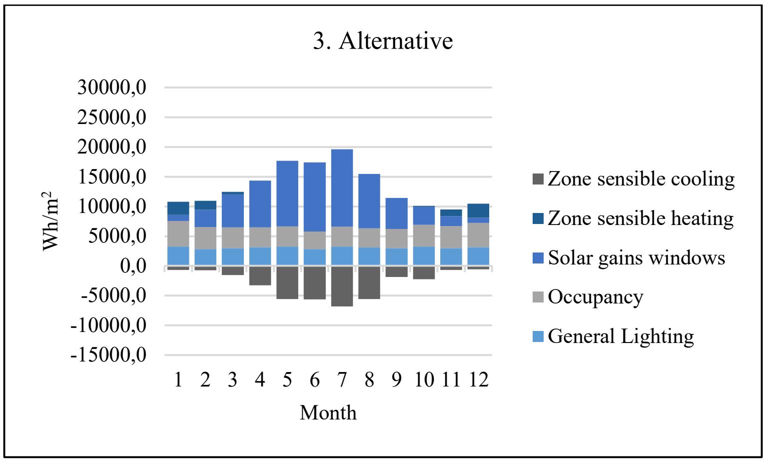
Table 38 - Internal and solar gains 4. Alternative

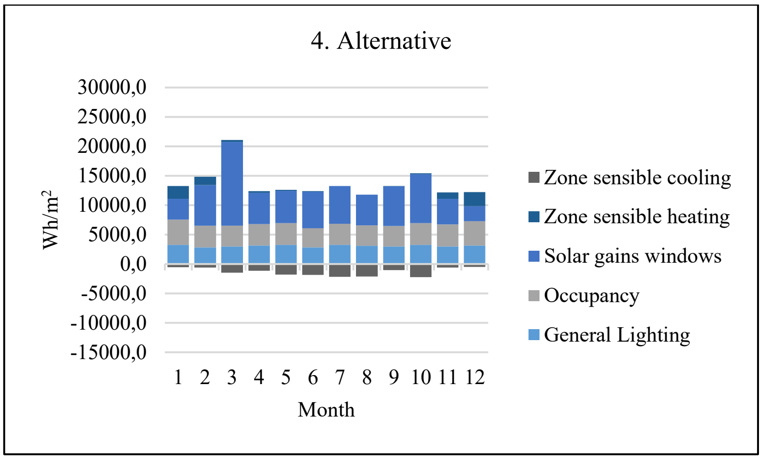
Internal & solar gains [Wh/m^2]	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
General Lighting	3265,9	2839,7	2981,9	3123,7	3265,9	2839,7	3265,9	3093,5	2981,9	3265,9	2981,9	3123,7
Occupancy	4277,4	3685,4	3507,9	3665,5	3706,0	3230,8	3555,1	3467,3	3495,8	3691,8	3737,7	4135,2
Solar gains external windows	40,8	97,1	235,0	50,8	55,7	61,1	70,2	52,0	75,6	97,4	49,6	26,9
Solar gains internal windows	3513,3	6780,4	14023,3	5268,0	5434,1	6157,9	6381,4	5148,2	6660,3	8232,6	4329,4	2549,9
Total Solar gains windows	3554,1	6877,5	14258,3	5318,8	5489,7	6219,0	6451,6	5200,2	6735,9	8330,0	4379,0	2576,8
Zone sensible heating	2158,8	1444,3	351,5	253,8	141,3	71,7	0,0	0,0	43,9	126,4	1049,9	2377,2
Zone sensible cooling	-564,4	-617,4	-1458,6	-1153,1	-1772,5	-1877,8	-2199,3	-2120,4	-1024,2	-2257,1	-605,3	-509,4


0. Alternative
30000,0
25000,0
20000,0
15000,0
10000,0
5000,0
0,0
-5000,0
-10000,0
-15000,0
Wh/m²
1 2 3 4 5 6 7 8 9 10 11 12
Month
Zone sensible cooling
Zone sensible heating
Solar gains windows
Occupancy
General Lighting


1. Alternative
30000,0
25000,0
20000,0
15000,0
10000,0
5000,0
0,0
-5000,0
-10000,0
-15000,0
Wh/m²
1 2 3 4 5 6 7 8 9 10 11 12
Month
Zone sensible cooling
Zone sensible heating
Solar gains windows
Occupancy
General Lighting


2. Alternative
30000,0
25000,0
20000,0
15000,0
10000,0
5000,0
0,0
-5000,0
-10000,0
-15000,0
Wh/m²
1 2 3 4 5 6 7 8 9 10 11 12
Month
Zone sensible cooling
Zone sensible heating
Solar gains windows
Occupancy
General Lighting





- **Envelope and ventilation**

Table 39 - Ventilation 0. Alternative

Envelope and ventilation	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Infiltration [kWh]	-157,3	-148,2	-151,8	-129,1	-109,1	-93,0	-84,7	-75,2	-78,2	-106,0	-133,1	-152,7
Nat.Vent. [kWh]	0,0	0,0	0,0	0,0	-18,0	-31,7	-32,0	-32,0	-37,8	0,0	0,0	0,0
mech+nat+inf [vol/h]	0,4	0,4	0,4	0,4	0,5	0,7	0,7	0,7	0,7	0,4	0,4	0,4

Table 40 - Ventilation 1. Alternative

Envelope and ventilation	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Infiltration [kWh]	-209,4	-200,6	-213,1	-190,5	-155,6	-120,7	-113,4	-100,5	-107,9	-156,8	-182,6	-204,5
Nat.Vent. [kWh]	0,0	0,0	0,0	0,0	-112,8	-227,9	-230,5	-205,7	-191,2	0,0	0,0	0,0
mech+nat+inf [vol/h]	0,5	0,5	0,5	0,5	1,0	1,6	1,8	1,7	1,6	0,5	0,5	0,5

Table 41 - Ventilation 2. Alternative

Envelope and ventilation	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Infiltration [kWh]	-213,2	-206,0	-226,6	-207,1	-180,7	-154,9	-145,6	-131,2	-132,4	-162,6	-185,7	-207,0
Nat.Vent. [kWh]	0,0	0,0	0,0	0,0	-65,4	-132,4	-132,0	-129,6	-125,6	0,0	0,0	0,0
mech+nat+inf [vol/h]	0,5	0,5	0,5	0,5	0,8	1,1	1,2	1,2	1,1	0,5	0,5	0,5

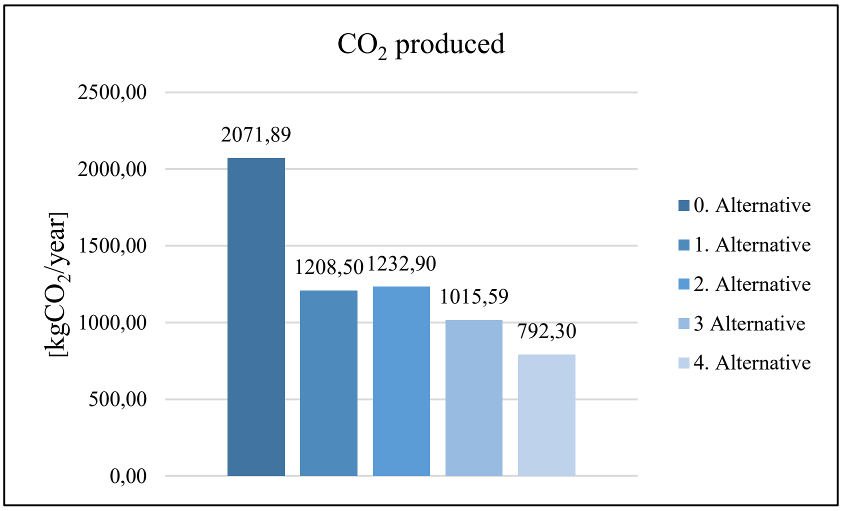
Table 42 - Ventilation 3. Alternative

Envelope and ventilation	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Infiltration [kWh]	-185,9	-180,3	-211,1	-195,0	-168,3	-142,7	-134,3	-122,2	-123,7	-155,3	-167,0	-179,2
Nat.Vent. [kWh]	0,0	0,0	0,0	0,0	-61,5	-124,9	-126,4	-123,6	-118,4	0,0	0,0	0,0
mech+nat+inf [vol/h]	0,6	0,6	0,6	0,6	0,9	1,2	1,3	1,3	1,2	0,6	0,6	0,6

Table 43 - Ventilation 4. Alternative

Envelope and ventilation	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Infiltration [kWh]	-186,5	-181,8	-214,3	-164,7	-131,4	-104,1	-99,0	-90,3	-102,6	-157,0	-168,1	-179,4
Nat.Vent. [kWh]	0,0	0,0	0,0	0,0	-46,7	-96,5	-105,3	-99,4	-94,0	0,0	0,0	0,0
mech+nat+inf [vol/h]	0,6	0,6	0,6	0,6	0,9	1,2	1,3	1,3	1,2	0,6	0,6	0,6

- **CO_2 produced**



Appendix B

Appendix C

Appendix D

Appendix E

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