Sustainability and Service Life of Curtain Walls

Stick and unitised system for short-term and long-term use in curtain walls

Thalia Anastasia Kakolyri
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MSc thesis - 2015
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Preface

This study was submitted as the final phase of the graduation thesis for the degree of Master of Science Building Technology within the Faculty of Architecture at Delft University of Technology. The main focus is the Facade Design and Sustainability and was supervised by dipl.ing. Tillmann Klein and dr.ir. Fred Veer from TU Delft. For the collection of the information from the facade industry, Alcoa Architectuursystemen in Harderwijk (NL), and Rollecate in Staphorst (NL), supported the research with specialised knowledge on curtain wall facade systems. Special appreciation is owed to Wijnand Manen (Alcoa), and Ad Versteegen, Pascal Schrijver and Mustafa Esen (Rollecate) for their technical input.

Thalia Anastasia Kakolyri
June 2015, Delft, the Netherlands
Acknowledgments

First and foremost I would like to thank my mentors for their support from the very beginning; Tillmann Klein who was always providing me with feedback from the perspective of the designer and helped me to understand better the world of ‘façades’, and Fred Veer who was always there as the voice of logic putting me back in track and sharing my thirst for mathematical problems and calculations.

I would like to express my gratitude to Wijnand Manen who gave me the insight from the facade industry and the area of aluminium profiles. Our conversations were very helpful in order to realise the real practice and the end-of-life of the façades with the recycling process. I am also grateful to Ad Versteegen and especially Pascal Schrijver and Mustafa Esen, who provided me with a lot of detailed information about curtain walls and the complete process of manufacture and assembly.

However, the whole trip of this thesis would not be the same without my family and close friends. So, I would like to thank all my friends who were with me from the very first day I came in the Netherlands and together we went through all difficulties. Thank you all for every funny moment and every wise advice. Special thanks to Antonio who was always patient in every moment of panic, trying to make every day special.

Most importantly, I would like to deeply thank my family for their support; my mum for always listening to me and finding solutions, my dad for reminding me that everything will be alright and my brother for sharing our thoughts.

Without the contribution of all these people this thesis would not be possible.
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Introduction
The past fifty years a lot of research is being carried out to investigate the causes of the environmental changes, their consequences and the ways we can improve, or at least keep stable, the current situation. Extreme weather conditions, increasing energy prices and the energy revolution have raised people’s awareness for nature and for the results of our actions. Even though we massively influence our ecosystem the last three hundred years, only recently we became conscious and realised the size of the problem. Regulations in the industrial and building sectors drive the production of environmentally friendly products and infrastructures of minimum impacts.

Today this rising awareness is evident in all aspects of our everyday life. The building industry has a special role, though, as it contributes to the half of the global resources’ extraction and waste. The total environmental impact arises from the combination of three parameters: the energy and emissions produced during the transportation, the operation as well as the energy comprised in the materials themselves (“Embodied Energy”). In the building industry, there are regulations defining the amount of energy that can be spent during the operation period. Especially the last years, buildings are designed with nearly zero energy demands, which results in a drastic change in the ration between the three parameters with embodied energy becoming now the main issue to be solved. Transportation is up to the project management and distance between the involved companies and the site and will not be analysed here.

LCA (Life Cycle Assessment) is a methodology used to identify the potentials of different design variables by comparing them (on the same basis) and defining which one is the best. The importance of having feedback during the decision-making phase has led to the creation of a variety of softwares integrating LCA analyses, like the GreenCalc+, the SimaPro, the GaBi together with the BIM softwares, even though they are not fully developed yet. This way of calculating, though, requires a lot of time and a sufficiently detailed design, which eliminates its use during the early design stage, when all decisions are made. Some basic guidelines, however, can help and improve the design proposals; for example, the sustainable optimisation can be qualitative as well as quantitative, which means that not only the quality of the materials is important, but also the amount.

Especially for a facade, which covers approximately the 30% of the building’s total embodied energy, the life span of the building must be acknowledged and reflected in the construction method. The shorter the life span of the facade, the less energy it should bind. Last but not least, the end of life scenario (even if it seems way too far in time) should be considered during the design, together with the potentials of reusing some elements. (Hildebrand 2012)
1.1 Research background

Some important points stated here from the background research on sustainable facade design and construction can be used as guidelines for my research.

The pace a building changes depends on its functionality and the demands of the markets and the users. According to (Crowther 2001), only few of the constructed buildings remain at their initial form for more than a few years or decades. Activities of repair, additions, maintenance and adaptations to new requirements continuously change the building. As long as the user’s demands change, the building has to follow up. Actually, there is not ‘a’ building, but a series of different buildings over time. The time period that a building will remain intact must determine the material selection and the energy that will embed in total.

(Hildebrand 2014) Closing the loops of the materials and components saves large amount of energy, because less new products will be needed and the embodied energy of the existing ones lives for longer. Information about every material is available and the designer must study the details thoroughly in order to choose the ones with the least environmental impact while matching with the design of each particular project. As it has already been mentioned, tools and softwares in relation with the expected life cycle of a building/construction can significantly eliminate the overall emissions produced and energy required by the building industry.

(Minjung 2013) It is proved that when most parts of a building, and most importantly of the curtain wall facade system, are disassembled and taken back at the end-of-life, they maximize the material and energy recovery. In this case, most of the materials are being recycled and the rest end up in landfill. With a design for disassembly, the cost through most phases of the processing is significantly reduced. However, there are two drawbacks that have to be considered and solved:

- The increased labour hours which cause increased expenses, and
- The lack of a trade system for second-hand curtain wall components to guarantee the profit from the recovery.

Therefore, the connections and the materials used should be designed to have the same life span with the building or examine the possibility of creating a market for second hand building elements, like the study made by Juan F. Azcarate Aquerre for his MSc thesis “Façades as a Product-Service system”.

(Heesbeen 2010) The contribution of an average building to the global emissions and extraction of resources is divided throughout its service life, which can mainly be divided to the operation and the materialisation. The operation includes all the actions needed to run a building (ventilation, heating, cooling, etc.), while materialisation is the actions which actually create the building and should be considered together with the actions throughout its life cycle (production, maintenance, demolition, renovation, raw material selection); thus from now on, the term will be used with this meaning. Until 2010 the operation was covering the 80% of the total amount of environmental impact, fact that gradually is changing due to the low energy building designs. This means that currently the emissions due to materialisation have a much more significant impact on climate change and, therefore, attention must be paid on this stage of the building’s life.

Even though sustainability in facade design has been intensively studied the last years, most research has been done for its performance and impact to the indoor climate. The efficiency of the building envelope directly influences the heating and cooling loads and thus the energy demands during the operation period. In order to maintain the balance between the operation and materialisation stages, there has been also a lot of research on materials used, their embodied energy and emissions for different facade categories (opaque, curtain walls, double façades, etc.). Some examples from TU Delft are the PhD research of Linda Hildebrand (2014), the MSc thesis of Charlotte Heesbeen (2010), as well as the Diploma thesis of Simone Hegner (2007) from ETH University in Zurich. However, all of these researches analyse and compare all different types of façades. What is missing is focusing on one kind and finding the most sustainable way of materialising and operating it.
This thesis is focusing on curtain walls and the way they must be designed to achieve lowest environmental impact during materialisation.

1.2 Problem statement

The proportion between the environmental impact of the materialisation and the operation phases has started to change with the operation becoming more efficient, due to the development of low energy buildings. Thus, the necessity of eliminating the emissions and energy spent during the materialisation has become more urgent. The wide use of curtain walls in office and commercial buildings – due to the extended glazed surfaces – signifies the starting point of a study for the way the façades can be materialised in the most sustainable way. The expected service life of a product – facade – is crucial for the decision making of the materials used, the construction techniques, the maintenance and the end-of-life; parameters that form its total environmental impact, and as such must be seriously taken into consideration during the design phase.

1.3 Research objectives

The goal of this thesis is to study the service life of a curtain wall and identify which is the best duration in terms of sustainability. Two scenarios, one short-term and one long-term, will be analysed and eventually compared in order to make the final decision and answer the research questions. For both scenarios the embodied energy and CO₂ emissions will be calculated. Time and expenses will be taken into consideration, but not thoroughly analysed though. The designs of the details and the material selection will be reconsidered and, if needed, changes will be implemented. The evaluation will be implemented for a stick curtain wall and a unitised as well. So, not only I will compare the different service lives of the same system but also the two systems themselves.

The area of Industrial design is used as a background in order to understand the role of service life in the design, as the industrial design includes a large variety of products with a different life span and design principles. However, in all cases assembly and disassembly are of great significance, in order to easily service and recycle the broken parts or the complete product at the end of its life. Product manufacture depends on the assembly of the parts while the sorting and recycling rate depends on the disassembly. Serviceability needs both. Through this way, circular economy can be enhanced and gradually become a basic principle in the industrial and construction industry.

There is a lot to be learnt from the product design. Therefore, I am going to study further this area and apply this knowledge to understand the facade industry and take decisions for my design proposal as far as it concerns the material selection, the maintenance during the service life and the end-of-life of a curtain wall.

To summarise, the objectives of the thesis are to:

1. Study the life cycle of the facade
2. Analyse the meanings of maintenance, renovation and refurbishment
3. Use the industrial design in order to learn and be inspired by the meanings of assembly/disassembly and serviceability
4. Create two facade scenarios of different life span and redesign the systems to eliminate the environmental impact throughout the materialisation and maintenance actions
5. Indicate which is the most sustainable expected service life of a curtain wall (short or long term)
6. Evaluate and compare a stick and a unitised facade system
1.4 Research question

The research questions that will be answered through this thesis are:
- How long should a curtain wall live to have minimum environmental impact?
- Does stick or unitised curtain wall provide the most sustainable materialisation and service life?

Design questions:
- What changes can be implemented on the current curtain wall systems to eliminate the environmental impact during their materialisation?

1.5 Methodology

The methodology that will answer the research and design questions comprises literature study, interviews and meetings with construction companies (Alcoa, Rollecate). Eventually, the design proposal includes the redesign of a stick curtain wall system in order to be suitable for a 15-year and 60-year service life. Its environmental impact is calculated in both cases and compared with the one of a unitised system.

The study focuses on the environmental impact of the construction and refurbishment of a curtain wall facade system. This means that the energy needed for the materialisation as well as for all activities required during the life cycle of the infrastructure has to be taken into account. Sufficient precision will guide us towards the final decision-making. Of course it is very important to highlight that the variable of people’s decisions (users, stakeholders, designers, etc.) cannot be taken into consideration for the calculations. Therefore, there is no need to get lost into the details and the endless calculations. The purpose of embodied energy and CO₂ calculations is to make informed decisions that lead to improvements in the way we spend energy. That is also the purpose of this paper.

All values are retrieved from the software CES Edupack 2014© where the total average environmental impact can be calculated with precision. The use of LCA tool is avoided in order to have simple and understandable from everybody calculations. What is more, the factors of time and cost are estimated based on the meetings with the facade companies. The final comparison of the systems and the service life scenarios indicate which facade system is more sustainable and for how long it should be designed to live.

1.6 Outline

The outline of this thesis is as follows:

Chapter 2 gives an introduction to the topic by defining meanings like circular economy, service life and their relation with the facade industry. Through this chapter it is highlighted the importance of closing the material cycles and evaluating all decisions during the design stage. The life expectancy of the whole system and the individual parts is crucial in order to provide accessibility to the ones with shorter life span in case of maintenance or refurbishment. At the end, the factors that will determine the final design outcome are thoroughly explained.

Chapter 3 is about the industrial design and its principles and techniques. The construction, and especially the facade, industry is not yet completely familiar with the concept of serviceability. Product design is a sector where the life span and the design for assembly and disassembly are highly integrated into the manufacture process. Therefore, the industrial design gives a lesson to façades aiming at eliminating the environmental impact and closing the material cycles.

Chapter 4 includes all the research on facade design and construction. The different construction systems are distinguished, the applicable materials are analysed and the complete life cycle of curtain walls is de-
scribed, where the importance of refurbishing is underlined. From the duration between the construction and the first refurbishment, three scenarios of 30 – 60 – 120 years service life arose.

Chapter 5 includes the redesign of the details and the evaluation of the embodied energy and CO₂ emissions of a stick and a unitised facade. In addition to this, the short-term and the long-term scenarios will be compared as well. The factors of cost and time are explained and finally, the two design possibilities are applied on the case study building of 3mE.

Chapter 6 presents the conclusions of the evaluations and comparisons.
2

Sustainability and Circular Economy in the facade life cycle
The construction and demolition sector is the largest contributor to waste all over the world and especially in UK it is generating 120m tones every year, according to the Green Building Council. Therefore, it is getting more and more essential to design and construct in a sustainable way so as to not eliminate the possibilities of our future generations. As it is identified at the picture 2.1, everything starts from the intention to be sustainable and as we go higher to the pyramid of materialization we go through all the life cycle and building process of a façade.

“When new stuff is being built like this, especially when it’s only for a 12-day event and it’s going to be deconstructed soon after, there really needs to be more thought about what will happen to those materials” said Strachan, who spoke at the Resource event.

“So much energy and effort goes into crushing up concrete and then cementing or gluing it back together,” said Graham Hilton, director of the Alliance for Sustainable Building. “It takes a huge amount of energy and uses more virgin materials. Things need to be made so that they are bolted together and then taken apart for reuse.”

Dan Epstein, senior director at sustainable design organization ‘Useful Simple Trust’, added: “There are so many products that we don’t know what to do with after a certain amount of time, we need to be thinking about these things from the beginning – assembly for disassembly”. (Cahalane 2014)

Thinking of the complete cycle of a product or infrastructure must become a part of the design. At this stage crucial problems can be solved spending much less energy and time. Although, nowadays, the increasing use of BIM softwares promotes the principle of working everything out during the design phase, there is still no concern about how a building will be maintained during its life cycle, how much energy it will need, what will happen to the materials at the end of their lives, etc. This fact must change in order to move towards a circular economy, closing the resource loops.

2.1 Circular economy in the construction industry

Nature is based on balanced closed cycles where the materials are used and then decomposed to be used as ‘food’ by the source they were drawn. In contrast, the material cycles in our industrialized society fail to close because either it is difficult to be distinguished after forming a complex component or the rate of the flows does not match. As a result, there is a major problem of waste accumulation and depletion of resources.

Currently, our economy is characterized as linear which means that we extract natural resources, with an increasing pace, turning them into products and disposing them at the end of their life, following the Linear Economic Model of “take - make - dispose”. This process is expected to bring, from 2020, 82 billion tons of raw materials worldwide in the economic system per year, from which the majority will be disposed through landfill or incineration. Therefore the meaning of circular economy is getting more and more important with a large number of experts supporting the swift from the linear to the circular economy. (Eykenaar 2012)
More specifically, circular economy aims at closing the resource loops, similarly to the natural ecosystems. According to Braungart and McDonough in their book ‘Cradle to Cradle’, all materials can be seen as nutrients within two main categories: the biological and the technical. The biological nutrients are organic and can re-enter the biosphere through decomposing, while the technical nutrients must circulate at high quality without entering the biosphere. At the same time, though, biological materials, like wood, can still be converted to technical depending on their usage phase. For example, wood chips can be combined with a synthetic resin, after their milled production waste, and become technical. Therefore, the distinguish of the materials to ‘biological’ and ‘technical’ is getting more challenging when considering such changes during their life cycle. In the meanwhile, technical materials can never behave biologically. Generally, what we need is “completely healthful products that either return to the soil or flow back to industry forever” say McDonough and Braungart. However, more than 95% of the building materials are hybrids, consisting of different layers and components; fact that excludes them from an infinite closed loop cycle. (McDonough and Braungart 2002)

In the building industry, the last decades, recycling is a preferable technique over incineration and landfill, especially for materials like aluminium, which has one of the highest rates in recycling recovery (90% – 95%). Thousands of tons are annually being collected for recycling and then exported for reuse (Tables 2.1.1, 2.1.2). Disassembly is the factor that defines the amount of materials that can be reused or recycled, closing their cycles. Up to date, the buildings are torn down and only afterwards the different elements are sorted out. In the majority of the projects the end-of-life was not considered during the design phase and there are no principles of disassembly applied, which leads to a certain amount of materials always being wasted.

Consequently, we can understand that the designers ought to consider the possibilities of reusing elements, easily repairing failures to extend their service life and, eventually, quickly sort out the materials for recycling, instead of ending up in landfill. In EU we still annually generate around five tonnes of waste per person and only little more than a third of that is effectively recycled. The conceptual diagram of the next page illustrates the main phases of a circular economy model. Every circle represents an opportunity to reduce the costs and the extraction of natural resources. The aim is to minimise the resources getting out from the circles so that the overall system functions in an optimal way. Despite all benefits of recycling, currently, recycling is mainly equal to downcycling (the quality is reduced after every recycling cycle) and the products always reach the landfill; fact that makes recycling yet not the best option to go for.

On the other hand, reusing has already started gaining ground in the building industry. Reusing doesn’t need any extra energy or materials, as it uses the existing elements extending their life cycle, even though most of the times they need to be refurbish before applied to new systems. One example of promoting the principles of reusing is the platform “turntoo” created by the architect Thomas Rau in 2011. This online platform promotes the performance-based consumption, according to which the manufacturers retain ownership of the products and the consumers pay only for the performance. In that way, innovation and
sustainability will be able to rise faster while the products will become more cost efficient as they will be returned directly to the respective companies at the end of their lives. (Eykenaar 2012)

Taking into consideration all the above, it is clear that the most efficient way to save resources and energy is to extend a product’s life through maintenance, or through the use of more durable materials. During the Façade Conference of 2014 in Lucerne, Ignacio Fernandez Solla (façade engineer in ARUP, Spain) analyzed the importance of considering the durability of adaptive façades when designing. This means that we have to predict the maintenance and the costs to have a reliable façade design and construction. But, first of all we have to answer the question: “How long do we want the construction (façade) to live?”. The answer, which equals to the total service life, will show us how many times we will need to refurbish or which materials are preferable to be used. Thus, defining the service life is decisive for the design and the choices made during the early stages. There is no point in designing long-lasting constructions, when they are supposed to live for a few years. (Solla 2014)

“...more than any other human artefact, buildings excel at improving with time, if they are given the chance.” “The longevity of buildings is often determined by how well they can absorb new services technology”. (Brand 1994)

2.2 Definition of ‘service life’

Service life is the time that a system (product, building, façade, etc) efficiently fulfils its performance requirements and it mainly starts after the construction and finishes with the demolition/disassembly; it is basically what we also call operation phase. The data for the service lives of the building components must be available to the designers so as to be considered for providing inner accessibility during the future maintenance actions. This is the basis to form the complete scenario of the façade life cycle and know exactly when a renovation must take place, which parts need to be replaced and how much time and money will it need. (Straub 2015)

The curve of the scheme represents the relationship between time and profit for a product. At the first stages, during manufacture, the curve rises slowly even though it happens that some products, like laptops and game consoles, are sold out even before they have been manufactured. The peak of popularity belongs to the stage of maturity, where the product is available on the market and proper advertising has promoted it to the public. After the peak period, sales start to gradually decrease, then faster, and at the end they slowly get eliminat-
ed. The overall life cycle of the product is more about its business vitality, thus every stage represented can be an area for the respective companies to compete and make profit. (Bakker, Hollander et al. 2014) It is obvious that most attention is paid at the middle (peak) period of the service life, even though the last stages are the most important in terms of sustainability. At the same time, the first stages (design, manufacture) are decisive for both the middle and last phases.

All decisions for a product’s properties and characteristics as well as its end-of-life possibilities must be considered during the design phase. The design is the beginning of anything else that eventually composes the rest of its lifespan, so it’s of initial importance. Product’s lifespan and service life can have different meanings; for example, from the perspective of the producer and designer, the end of the lifespan comes when the product is sold. However, this doesn’t mean that this is the end of its overall lifespan; actually it hasn’t even brewed one cup of coffee. New parties become involved then, like the users in the offices, workplaces or at home, as well as the producers of coffee beans, filters, etc. After a number of years the machine will start to wear out and it will be stored somewhere for indefinite time or thrown away. At this stage of the life cycle, some parts of the machine will start to wear out and it will be stored somewhere for indefinite time or thrown away. At this stage of the life cycle, some parts of the machine will end up in a repair shop in order to be reused while the rest will either be recycled or burned for energy recovery. (Bakker, Hollander et al. 2014)

Generally, the end of life comes by the time the user decides that the specific product does not serve his needs anymore. This doesn’t include only product’s functionality, as it may have be expected, but also a lot more parameters, such as: (Ashby 2009)

- The physical life: the time in which the product breaks down beyond economic repair
- The functional life: the time when the need for the product ceases to exist
- The technical life: the time at which advances in technology have made the product unacceptably obsolete
- The economical life: the time at which advances in design and technology offer the same functionality at significantly lower operating cost
- The legal life: the time at which new standards, directives, legislation or restrictions make the use of the product illegal
- The loss of desirability: the time at which changes in taste, fashion or aesthetic preference render the product unattractive

The most reasonable assumption for reducing the resource consumption is to extend the service life by ensuring the above parameters or by creating easily repairable products in case one of these aspects fails.

### 2.3 Definition of factors taken into consideration for this thesis

The service life of every product and construction is significant for the decision making and the sustainability of the system. The material selection and the detailing must be coherent with the expected life span in order to minimise the environmental impact of the materialisation. For the purposes of this thesis, I evaluate not only the impact of the materialisation but also of the possible activities (refurbishment, replacement) applied throughout the complete service life. Five parameters are used to calculate the environmental impact and evaluate the level of preference by the industry and users.

The factors chosen are:
- a. Embodied energy
- b. CO2 emissions
- c. Cost
- d. Time
- e. End-of-life

The first two indicate the environmental impact, while the rest show whether a system would be preferable in matters of cost and time for dis/assembly. The end-of-life scenario is always recycling and never
landfill, even though in some cases reuse is suggested, for at least one time, prior to recycling. For the design proposal, the embodied energy and CO2 emissions are accurately calculated while the data for the cost and time are estimated based on the interview with a facade company.

a. Embodied energy

The embodied energy is the energy that must be committed to create 1kg of usable material (e.g. 1 kg of steel stock, 1 kg of PET pellets, etc.) and is measured in MJ/kg. It includes the energy used to extract, process and manufacture as well as assemble, install, disassemble, deconstruct and/or decompose a product together with the human resources required. (Ashby 2009)

The primary embodied energy is an important indicator of the environmental impact, because it covers 20% of the building’s energy use. For most materials the largest impact occurs during the initial process, fact that makes its evaluation even more important. However, the total embodied energy presents a complete picture of the performance of a material, concentrating data both from the primary and the usage phase through the overall service life. In addition to this, the energy needed during the recycling (recycling embodied energy) to create a new product is also integrated into the total embodied energy of a material. For the material selection, both the embodied energy and the characteristics of the material must be taken into consideration. For example, a durable material with a long lifespan (e.g. aluminium) can have higher primary embodied energy but reduce the operating energy requirements of the building or have a 95% of material recovery through recycling, which justifies its selection. (Heesbeen 2010)

More specifically, the embodied energy is expressed as (MJ/kg) or (MJ/m²) and should be taken into consideration with the:

- Durability
- Ease of separation
- Use of locally sourced materials
- Use of recycled materials
- Size standardisation
- Elimination of waste
- Use of materials made of renewable energy sources

b. CO₂ emissions

Carbon dioxide emissions cover the 80% of the total greenhouse gasses emissions and they are the main emissions in the life cycle of the building materials. Therefore the study on the amount of carbon dioxide emissions provides a good indicator of the overall environmental impact. CO2 footprint is the associated release of CO2 in the atmosphere and is expressed in kg/functional unit (the functional unit varies between mass, area, piece, etc). Accordingly with the embodied energy, the data must be evaluated in relation with other properties or phases of the life cycle and not in an absolute sense. (Heesbeen 2010)

c. Cost

Cost addresses the economic impact of a material during its life cycle. The life cycle costs are the costs of a system or its parts throughout the life cycle, while fulfilling the performance requirements. This includes the cost for construction, operation, maintenance and end-of-life. More specifically, a universal equation according to (Minjung 2013), is:

\[ C_{net} = HL + E + W_1*S + T*Σ(W_n*Ki) + Σ(W_n*P/Dj) - Σ(W_n*Rk) \]

which is translated to:

(Cost in different phases = Labor + Machinery + Sorting + Transportation + Recycling/Disposal + Recovery)

where:

- H= execution hour (h)
L = labor cost (€/h)
E = equipment cost (€/kg)
S = cost of sorting process (€/kg)
T = cost of transportation (€/kgkm)
Kj = travel distances (km)
W = weight of materials (kg)
P/Dj = cost of recycling or disposal process (€/kg)
Rk = revenue from material or energy recovery

LCC (life cycle cost) assessments are increasingly used for the decision making and the evaluation of new designs and redesign alternatives. As a matter of fact, calculating the cost of the performance of a building or facade during its operational phase is crucial in order to minimise the cleaning, maintenance and energy requirements. (Straub 2015)

The total cost of the facade system will be formed by summing up the costs from all the materials used. In addition to this, the expenses for the maintenance or replacement activities are contributing to the total value. In case of refurbishment or replacement through disassembly (without tearing down the facade first), there are some difficulties that may increase the overall value of the system without providing the possibility of taking back an amount of it. These drawbacks are the:

• Increased labour hours which are translated to increased expenses, and the
• Lack of a trade system for second-hand curtain wall components to guarantee the profit from components’ recovery.

The investors and stakeholders, who give the final approval or rejection to a proposal, pay extra attention to the costs of each investment. Thus, it is very important not only to design an innovative architectural design but also to find ways to make it cost efficient.

d. Time

Time has a significance importance, especially in large projects where different companies combine large human resources and machineries needing a lot of energy and, of course, money. In such cases, not only the construction and assembly should be evaluated but also the future maintenance and refurbishment actions. Time needed for refurbishment or replacement of the outdated parts of a system depends mainly on the ease of assembly/disassembly. The level of connectivity between the different parts as well as their size and weight defines whether it is necessary to use large machineries and whether the workers are going to need one day, one week or one month to finish.

Usually mechanical connections need much less time than the adhesive ones, while welding is mostly irreversible. The complete process of disconnect – separate – and treat the waste needs a lot of labour from people of different specialisations so all the stages have to be simplified to be faster. Disassembly is the starting point of any future action and thus it is essential for even taking the decision to continue with the rest of the process. In the meanwhile, the assembly phase is very important for the manufacturers; every element has to be easily assembled to save time and extra costs.

The curtain wall facades, studied in this thesis, are one of the most suitable systems for fast dis-/assembly, refurbishment and replacement. Some systems are based on the removal of a lightweight cover cap (stick) and others need the remove and replacement of the complete panels (unitised). There are advantages and disadvantages for both cases which will be analysed later on.

e. End-of-life

End of life scenarios are the possible flows of the materials after they lose their initial functionality. More specifically for a building, at the end of its life, it goes through 4 phases which define the ‘future’ of its
elements, according to (Bloemen 2011):

• Phase 0: Decision for ending the life of the building based on technical, aesthetical, economical or legal reasons
• Phase 1: Decision to demolish or disassemble the building. Demolition considers all materials as waste, whereas in disassembly there is a high value of material reuse
• Phase 2: Transportation, sorting and cleaning of the different elements and materials
• Phase 3: Waste and material management. Decide to reuse, recycle, incinerate or landfill the materials

The scenarios that will be most likely applied are the landfill, incineration, recycling and reuse, which are further analysed below:

Landfill

Landfill is the worst case scenario, but is generally preferred as an easy way to get rid of our garbage. However, in many European countries there is a lack of available land and the pace of discarding materials is still too fast. This causes a serious problem because the waste cannot be absorbed and thus a lot of countries have introduced special regulations, like paying fines, to prevent this from continuing. (Ashby 2009)

Combustion for heat recovery

Incineration or combustion for heat recovery is highly developed in some countries as they even import waste from other countries in order to recover energy. For example Sweden annually imports 700,000 tons of waste to supply the waste-to-energy facilities. This technique is based on the fact that the materials contain energy which can be retrieved and reused by controlled combustion, capturing the heat. However, this is not as easy as it may sound. First of all the combustible and non-combustible materials must be separated. What is more, the whole process generates fumes that have to be filtered in order not to further pollute the atmosphere. Generally, the energy recovery is imperfect partly because it is incomplete and partly because the incoming waste carries a moisture content that has to be boiled off. As a result, the highest efficiency may reach 50%, and if recovered heat is used to generate electricity falls to 35%. (Ashby 2009)

Recycling

Recycling also needs sorting out of the different materials. It is strongly suggested for the individual households to use separate trash bins; fact that is reinforced in some countries by additional regulations. In the developed countries recycling reaches an extremely high rate. Through the recycling process waste can act as a resource for a new series of material cycles. Materials are recovered at the end of the product life returning into the use stream. It is the end-of-life scenario that is currently best adapted to extracting value from the waste stream. (Ashby 2009)

Reuse

From all the above techniques, reuse is the most sustainable because it doesn’t need any extra energy while it extends the service life of a material/product. The product may be then used for its original purpose (e.g. a second-hand car), or perhaps adapted for another purpose (e.g. converting a bus to a mobile home). Two big markets of reused products are the housing estate and the used cars and boats. Charity shops, also, acquire clothing, objects and junk and sell them to people who perceive them to have value. (Ashby 2009)

Reengineering or reconditioning

Reengineering is similar to reusing, but when it is about a more complicated or mechanical system it is
usually necessary to repair or replace some components. Reengineering is the refurbishment or upgrading of the product. This process is practical when the product design is standardised (e.g. aircrafts), or when its base technology is evolving so slowly that there is a market for the restored product. Some examples are housing, office space and road and rail infrastructures. Another kind of example is the office equipment, particularly the printing equipment and communication systems. These are services; the product providing them is unimportant to the users, as long as it works well. It makes more sense to lease a service (as we all do with telephone lines, mobile phones, internet connection providers, etc.) because it is in the leasers’ interests to maximise the life of the equipment.

To sum up, reusing and reengineering/refurbishing are the most sustainable scenarios for the extension of the product’s service life. However, reuse is still not widely practised, especially in the building industry. Mineral materials, like bricks, usually have permanent and irreversible bonding, which limits their flexibility and reusability/recyclability. In contrast, prefabricated concrete elements can be deconstructed and reused if the technical requirements are fulfilled. Material’s purity is essential for high quality of recycling and/or easy reusing. The most ideal scenario would be the use of only one material (homogeneity), so it would stay pure and 100% recyclable, but such a case is not feasible most of the times. (Hildebrand 2014).
Credits:
(Bakker, 2014)
3

Industrial Design
3.1 State-of-the-art

Industrial design in early 1900’s

The industrial design and market have gone through different phases over the time influencing the fashion and habits of the consumers. The principle before the 1900’s was to create the best product quality for the users, who would pay a large amount of money to get it. Expensive materials and handmade products were the first in preference for wealthy people. Later on, however, the companies realised that the high quality and the long life span of the products keep their profits lower than they could be. Therefore, gradually after the early 1900’s the quality of the products started being decreased, with the companies creating the so-called ‘planned obsolescence’. (iFixit 2014)

'Du Pont' company, which was selling nylon stockings, asked from the textile companies to weaken their resistance to tear even if they were previously advertised to be as strong as steel. In 1974 the revolution of disposable products started from ‘Bic’ company and the disposable shaving razors. The convenience of using a product once and then throwing it away to buy a new one spread fast and soon enough people started using disposable cameras from ‘Fujifilm’. On the same principle, ‘Apple’ manufactured the first iPod with only 300 charges. The examples of such production lines could go on and on, but the important is to realise that non awareness of the consequences of these actions led to people’s manipulation by the companies and to sacrificing the environment and the natural resources in the sake of profit. (iFixit 2014)

Figure 3.1.1 Strategies to reduce the life span of the products. (iFixit 2014)

‘Du Pont’ company, which was selling nylon stockings, asked from the textile companies to weaken their resistance to tear even if they were previously advertised to be as strong as steel. In 1974 the revolution of disposable products started from ‘Bic’ company and the disposable shaving razors. The convenience of using a product once and then throwing it away to buy a new one spread fast and soon enough people started using disposable cameras from ‘Fujifilm’. On the same principle, ‘Apple’ manufactured the first iPod with only 300 charges. The examples of such production lines could go on and on, but the important is to realise that non awareness of the consequences of these actions led to people’s manipulation by the companies and to sacrificing the environment and the natural resources in the sake of profit. (iFixit 2014)

Fig 1.2 shows the decrease of the products’ life span with only the lamps having a minor rise of 3%.

Figure 3.1.2 Life span of household products between 2000 and 2005, based on dutch data. (Bakker, 2014)
Industrial design in 2015

Nowadays, industrial design has changed the principles of the production line. It has already many years of experience within the sustainability sector, where the principles of both sides are integrated to one product. More and more the products are not only functional and attractive but also environmentally friendly. The materials used, the energy spent during their manufacture and their service life as well as the level of recyclability are only some of the factors that are taken into account. In addition to this, the customers have become more and more aware of ways to use more efficiently a device and dispose it in order to save resources. Information is always available within the product’s packaging making people aware of how to maintain and dispose it (Figure 3.1.3). At the same time, companies pay special attention that the new products coming out to the market fulfil all ecological regulations.

The production line is a complex process that needs specialised workers and machineries. Therefore, especially in smaller companies, the possibility of failure or the high extra costs for new machineries can lead to an innovative idea being rejected. The risk is always evaluated and thus a lot of times it is preferable to keep on working according to the already well-known way. In addition to this, experiments and tests are always expensive. So, we can even find the smaller companies within the English expression ‘you can’t teach an old dog new tricks’. However, bigger companies usually have a special research team experimenting and evaluating new techniques to improve the company’s products, but these are isolated cases. As a result, the designers must combine an ‘out of the box’ way of thinking with the compliance to the rules and guidelines from the companies.

The industry usually considers a hierarchy of three steps to choose which products are feasible and should be further developed by answering to the questions: (Tempelman, Shercliff et al. 2013)

- What is possible in principle?
- What is possible in practice? (as determined by the industrial state-of-art)
- What is possible with the equipment used for that method? (available suppliers)

After answering these questions, the ‘Manufacturing process triangle’ (function – quality – cost) states the extra principles of:

- Function = can it be done?
- Quality = can it be done well enough?
- Cost = can it be done cheaply enough?

Currently, it is clear that a product brings profit during its service life, and stops at the end of life. Making products last longer requires a change in the way of manufacture and promotion. As the profile of the industrial design changes, there will eventually be no deadline for a product and the producers will benefit from each product cycle. Every repair, update, division, sale, rent, etc. is an opportunity to close a cycle and create or maintain its value over time. Generally, companies usually follow a certain programme and business model, which is useful to understand in order to contribute in the change.

The kinds of business models currently applied are: (Bakker, Hollander et al. 2014)

1. **Classic long life model**: Production of high-quality products with long lifespan. The category includes mainly more expensive than the average products due to the quality warranty and the longer service life.
2. **Hybrid model**: Products of relatively short lifespan are manufactured which have to be combined with high-quality durable products, e.g. coffee pads. The profit comes from the need of regular replacement.
3. **Gap exploiter model**: This model bridges the gaps in the current system. It basically includes activities...
like repair, sell second-hand products, convert used products and promote them to a new market.

4. **Access model:** The provided service in this case is the ability to access and use a product, while the ownership remains to the provider. This model is useful when the user needs the product for just a limited time period, e.g. car, tools.

5. **Performance model:** The quality of the service is the most important parameter in this case. The provider chooses the means of providing a certain service/performance, while the user is only interested about the quality, e.g. printing, transportation, telecommunications.

In addition to the business models, there are certain strategies that designers have in mind when creating a new product. The strategy may address the user’s feelings and/or practical issues, like repair and an extended service life. The requirements, expectations and user’s behaviour differ in each case. A short explanation is given here for each of the six categories: (Bakker, Hollander et al. 2014)

1. **Design for attachment and trust:** Users develop special attachment bonds with the products they use, e.g. toys, puppets, etc.

2. **Design for durability:** Durability can be defined through the material selection. The optimum product’s durability matches with its economic and stylistic lifespan, achieving the highest levels of sustainability.

3. **Design for standardisation and compatibility:** Standards compete with the personal customisation in order to find a balance and manufacture a customised product which also has certain standardised parts for easy repair and upgrade. Digital technology, car manufacture are some examples of application.

4. **Design for easy maintenance and repair:** The original manufacturer, the gap exploiter as well as the user himself can apply maintenance and repair actions on a product; however in the case of the user, the warranty gets invalid afterwards. Standardisation of the parts and reversible connections are necessary for this strategy.

5. **Design for adaptability and upgradability:** Adaptation to different functions by part exchange is common, while upgrading is common mostly for the electronic equipment (computers, mobile phones, etc).

6. **Design for dis- and reassembly:** Disassembly is necessary in terms of sustainability when different materials are combined in one product. This is a relatively new design strategy, because only assembly was considered before. Additionally, reassembly allows not only easy adaptability and upgradability, but also a possible extension of service life by combining parts of different products.

All the above models and strategies help us understand the way industry works. Each case is applicable to certain companies. Although the main goal is always the profit, we can already see that sustainability has been integrated as a way of making money; which is the key for its further development. Standardisation, assembly and disassembly, long-lasting products, serviceability and adaptability are few of the meanings contributing to a sustainable design according to the product’s service life.

Nevertheless, designers are the ones who create the new products (first in their mind and then on paper) and must continue thinking outside the restrictions that the companies try to impose. Innovation and sustainability progress at the same time and the one directly influences the other. The design for disassembly is based on the design for assembly and manufacture and its goal is to provide easy accessibility into a product for repair and recycle at the end of its life. Design for manufacture and assembly started having serious influence in the product design in the early 1980’s, when the simplicity brought the reduction of the amount of the separate parts. Easy assembly is decisive for the product’s manufacture, while easy disassembly is decisive for the product’s quality of life (repair, upgrade, maintenance) as well as its end-of-life. There is a whole list of guidelines and criteria that the designers should follow in order to develop the principles of disassembly – which are directly related with the applied assembly techniques – and thus the ability to repair, recycle and reuse products.
3.2 Design for assembly and disassembly

Designing for assembly and disassembly requires special attention for the connection techniques and the overall design. The designer should consider these design principles at the early stage and be in contact with the manufacturer, because over the 70% of the product costs are determined by this early stage of the life cycle. This kind of production encourages teamwork and cooperation creating simpler and more reliable products with lower costs. The designs are more efficient by using fewer parts and easy connections. The elimination of even just one screw can make a huge difference in the mass production, which is extremely profitable for the companies. For example, the redesign of Digital’s mouse by the engineer Bill Sprague saved $12,500 for the company. (Boothroyd, Dewhurst et al. 1994)

Generally, the amount of parts influences immediately the amount of work and time that is needed for the assembly and the disassembly. Therefore, before analysing the snap fit principles, some general guidelines that the designers ought to follow to achieve minimum number of parts, are: (Boothroyd, Dewhurst et al. 1994)

1. Avoid the connections that are not necessary. If the only purpose of a part is to connect two others, locate them at the same point and eliminate the part in-between
2. Always design for easy access for the assembly operations
3. Unify parts when possible even if this requires the use of more expensive materials. The savings will eventually be much more by avoiding complicated and costly operations
4. Use as many constraints as needed and not more

In spite of having minimum individual parts, applying the principles of assembly, and especially disassembly, needs some extra features to be considered during the design: (Tres 2006)

1. Space: enough space is necessary for the function and motions of the elements themselves, as well as for hands or tools to reach them during assembly and disassembly
2. Symbols: it is strongly advisable to use symbols on the elements in order to make easier the removal and servicing
3. Locators: integrated or extra parts will enhance positioning the parts at both manual and automatic assemblies
4. Workloads: the loads that the connection will need to serve during the materialisation and operation, e.g. mass loads, operational loads and impact loads
5. Extra functions: e.g. sealing against water, dust or even air is achieved by the use of additional parts, like O-rings
6. Motion for assembly: it is more convenient if the motion is linear, preferably push than pull, and for vertical assemblies, from top down
3.3 Assembly techniques - connections

There is a variety of assembly techniques for joining two parts together. The most suitable are chosen according to the materials, the design and the conditions under which the final product will be used. Two main categories are the welding and bonding. Welding requires the presence of heat, which can be generated through vibration of the two parts to be connected, that will melt their joint interface creating a strong and irreversible connection. Bonding is usually done by the use of adhesives. The adhesives generate mostly irreversible joints, whereas reversible connections are also possible if the adhesive can be removed (normally using heat). (Tres 2006)

It is clear that easy accessibility is not possible through the use of these kinds of connection methods. In contrast, snap fits and living hinges are two distinct methods that do not require any additional fasteners or integral mechanical system. These methods can produce irreversible joints, but also reversible ones are easy to be manufactured. Therefore they are widely used in many industries, including the construction as well. In order to acquire a better understanding these methods will be described more extensively. Due to the fact that they can be applied on plastics, steel and aluminium, the information will be valuable for the study of curtain walls in chapter 4.

a. Press fitting

Press fitting is a very simple assembly method that needs no additional components or fasteners. The one part, which is called male or “boss”, is force-fitted into its mate. Components of the same or different material can be joined through this method, but all properties must be considered during the design. Attention must be paid at the design of the male part which must be larger than the highest tolerance of its mating part for a successful joint. In a different case they create a “slide fit”, which will not be secure. The materials’ properties are normally checked at room temperature (23°C) as well as at the highest or lowest possible temperature that the parts may be exposed to. An example of press fit assembly is the cassette tape player. (Tres 2006)

b. Living hinges

Living hinge or molded-in hinge includes a very thin amount of polymeric material that bridges two heavy walls. It provides the ability to open and close or flex the connection for a large number of times without the use of any mechanical hinge. This method is very useful for thermoplastic parts and the most commonly used materials are the polypropylene (PP) and polyethylene (PE). Both materials can flex many times without breaking and they are easily processed and of low cost, facts that make them suitable for the living hinges. Although many other plastics have superior mechanical, thermal, chemical and electrical properties, they are seldom used due to their low flexibility. PP and PE can flex a million times before failing; all other plastics can only reach a few thousand times. Examples of living hinges are the world class connector, which connects the onboard computer to the engine controls, and the bracket, which organises the cables between the spark plugs and the distributor. (Tres 2006)

c. Snap fitting

Snap fit, just like press fit, is a simple assembly method of joining two parts without needing any additional components or fasteners. A snap fit, also known as lock arm, consists of a hook and a groove. For the assembly, the hook is completely or partially deflected by its mating part until it gets inside the groove. Then it returns to its original position. This interaction between the hook and the groove provides the connection with the gripping force. (Tres 2006)
For the snap fits dissimilar polymers or completely different materials can be used, such as metals and plastics. This method is used in a variety of industries and is extremely valuable as fastener integrated in the parts themselves, when manufacturing costs need to be reduced. There is no need for additional tooling and the assembly becomes much faster. It is widely used for the curtain wall construction and, therefore, it is analysed more thoroughly. As far as it concerns the aesthetics of the final products, the connection can be hidden from view depending on the design. In the meanwhile, the design must be done properly to avoid any breakage before or during the assembly. (Tres 2006)

The snap fits can be permanent or multiple (irreversible or reversible). The permanent connections, or one-time assembly, are used for disposable products that are assembled at the manufacturing stage and are supposed to never be removed. On the other hand, the multiple snap fits are not only applied in products, such as pen caps or bottle caps, that may be opened and closed many times, but also to products, like automotive parts, that need to be disassembled for servicing.

3.4 Serviceability

Assembly and disassembly provides an easy serviceability, which means that a connection can be taken apart to be fixed or upgraded and then reassembled back to the original design. The need of serviceability must be acknowledged by the designer beforehand, so that he can consider the viewpoint of the service person and determine whether special tools or fixtures will be needed, enhancing the ease of repair and maintenance of the final product. The guidelines mentioned before are also necessary for the service activities, e.g. the space for the easy access and tooling and the symbols to incorporate information on the elements about the materials and their properties. The symbols have to be common throughout the complete production line and ought to be explained in the service manual. (Tres 2006)

Serviceability equals to the extension of the product service life. The ability to repair, as it has been already mentioned, is possible the last years via the change of the production principles and the demands of the customers. Still, not all companies follow these guidelines. Therefore, there are online platforms which promote repair and encourage customers to not throw away their products without trying to fix them first. ‘iFixit’ is one of them using the logo: “Repair saves you money. It saves the environment. And it connects us to our things. Ditch the throwaway economy. Join the repair revolution.”

Especially in the industry of electronics landfill has serious consequences. It takes literally tons of raw materials, hundreds of labour hours, and enormous amounts of energy to manufacture the devices we use for less than two years. 70% of the energy that a laptop spends corresponds with just the manufacturing process, while for only a desktop the number is even higher, reaching 80%. The best shot we have to reduce the environmental impact of our electronics is to keep them around for as long as possible. All that energy, all that water, and all those emissions can’t be recovered during recycling. When recyclers shred phones and computers that could be repaired or reused, they are wasting both their embodied energy and materials. Repair is the first line of defence against waste. Users can extend the life of electronics and other products by replacing broken components, e.g. put in a better battery, and eliminate the stuff in landfills and recycler’s shredder. (iFixit 2014)
3.5 End of life

The end of life scenario of an industrial product usually is the landfill, because it is the easiest way to get rid of all our wastes. Recycling is the second option where the materials are melted and recovered for reuse in new products. However, recycling mainly equals to down-cycling, which means that the material value is gradually decreased until it eventually reaches the landfill as well. On the other hand, through recycling new products of similar or better value may be manufactured too; this process is known as up-cycling and it is extremely rare. So, recycling is mainly not closing the material cycles and thus it is not good enough for C2C purposes. (Eykenaar 2012)

Especially in electronics case, more than 20 million tons of waste is produced yearly. From this amount, only 25% is being recycled while 75% is in landfill. However, recycling is also considered a waste of energy and should not be practised. For example, when a mobile phone is melted down for recycling, 20% - 35% of the materials are lost as well as the energy that was used during its manufacture; energy enough to power 1,200 light bulbs of 60-watts. In addition to this, rare earth elements that are included in every electronic device (17 in one mobile phone) cannot be recovered through recycling. Even the metals, that cover a percentage of 40% in a cell phone, are alloyed together and thus roughly half are lost during recycling. Thus, repair is the only way out. Every phone that gets repaired or reused is one less to be manufactured. The best way to support both the economy and the environment is through the Circular Economy. First option should be repairing, if this is not possible then recycling and only when there is no other way, landfill. (iFixit 2014)

The total product lifespan, which equals also with the moment of end-of-life, influences directly the energy consumption it needs. The continuous technological development results in a gradual decrease in the energy consumption with a pace that depends on the respective product. However by studying the product’s characteristics and background rate of development, designers can estimate the expected service life and the approximate moment that a repair may be needed, achieving a balance between the environmental costs of production and usage. What should be highlighted here is also the importance of the product’s reputation by advertising and organising its overall image rather than its properties and functionality alone. (Bakker, Hollander et al. 2014)

3.6 Circular economy in Industrial design – references

From 1993 to 2009, we experienced a rise of 140% in the sales of electronics. People always want more and newer products. It is considered a sign of prestige to have the latest technological products, even though this is directly dependent on the age, the culture and the individual mentality of the person. However, recently, due to the economic and environmental crisis, consumers’ mentality has switched to repairing and reusing their products with some entrepreneur companies taking the initiatives and the larger ones following. The larger companies ruling the market still show some resistance to this philosophy, stating that the manufacture information is confidential and for any problem the devices ought to be returned exclusively to the respective company. Empowering their monopoly rises the prices and lowers the quality. In contrast, having a number of shops and companies responsible for repairs and end-of-life recycling decreases the costs for the users and ensures the quality enhancing circular economy (iFixit 2014)

Actions that can be done to extend the service life of the products are:

**Repair:** convert a broken product or component to functional

**Refurbish (recondition):** return a used product to a satisfactory condition by replacing or repairing the faulty components

**Remanufacture:** return a used product to its initial performance, providing a guarantee that its quality is
equal or even better than the one it had originally.

**Reuse:** use parts or elements in a different content, which means that more virgin materials need to be added to meet the original specifications.

On the other hand, new products bring together improvements especially in terms of energy efficiency; therefore extending the lifespan of an older product is not always the best case. At a certain point it needs to be replaced by a new more efficient. Thus, finding the right balance between service life and energy efficiency is the key for a sustainable design. There is no rule of thumb to determine the right moment to replace a product, as it depends on the product and its rate of development. According to these parameters, it is possible to approximately create the life cycle scenarios and calculate the effects on the overall energy consumption. The optimum ecological lifespan is when a further replacement won’t make a difference in the ecological performance of the product. However, current products last way less than they really could.

A breakthrough in the way of designing and manufacturing mobile phones is the ‘Phoneblocks’, based on the principles of easy assembly and disassembly. The idea of the ‘Phoneblocks’ was developed by Dave Hakkens during his graduation project at the Design Academy in Eindhoven, but this year it will be out on the market. ‘Phoneblocks’ is a mobile phone which consists of detachable components that fit together like a puzzle. Each component represents a different function; camera, screen, wireless internet, battery, antenna, etc. The components can be easily replaced in case of damage or upgrade without throwing away the phone. Currently, we use phones that are one unified block and if one component gets damaged, we throw away the whole device. With the new technology of phoneblocks, we can replace only the component that has to be fixed, keeping all the rest. The customers can choose components between famous brands or customize their own. All the parts are held together by two small screws. (Fairs 2013)

Even though the idea of phoneblocks started from an entrepreneur student, it got widely spread through internet. It immediately created over 900.000 followers and a lot of technicians and large companies appeared to be interested in developing and investing on it. Up-to-date, companies like Google, Blocks, CMNTY, etc. work as partners under the same cause; to start a new era in mobile phones.

Another example is the recyclable laptop developed from a team of students from Stanford and Aalto University in Finland. The laptop is designed to be disassembled in 10 steps without using any tools. All electronic components can be sorted out in two categories: the ones to be mailed to an e-cycling program and the others going to the recycling bin. The complete disassembly takes only 45 seconds because of the simplicity of the design. (Guevarra 2011)

Last but not least, the new low-cost market can create new job positions and enhance the economy especially in the developing countries. More specifically for the electronics industry, every 1000 tons of waste can create:

- 1 job position in case of landfill
- 15 jobs in case of recycling, or
- 200 jobs in case of repairing

![Figure 3.6.1 Easily disassembled laptop (Guevarra 2011)](image)

![Concept](image)

![Real product](image)
3.7 Conclusions of chapter 3

The philosophy of the industrial design and manufacture has been through different economic models and practices; the current principles are coherent with sustainability and saving of resources. Extending the service life and recycling are gaining more and more ground over the easy replacement of products. As a matter of fact 95% of the customers prefer companies that provide successful repair, like Patagonia, Dell and Lenovo.

These principles and guidelines currently applied for easy dis-/assembly as well as the importance of evaluating the expected service life for the decision making are two main factors considered through the next chapters.
Facade Design
4.1 Curtain wall facade

a. Definition of curtain wall facade

The development of curtain walls started in the early 19th century with the construction of Crystal Palace in London (1851) and the Menier Chocolate Factory in Paris (1871). As the name implies, curtain wall is a building skin/facade which carries no other loads than its own weight and the environmental forces which act upon it. It does not assist in the structural integrity of the building; on the contrast it delivers its loads to the main structure through the slabs and beams where it is connected. (Simpson 1999)

The use of a curtain wall provides: (Kazmierczak)

- Smaller wall footprint (larger floor area)
- Parallel scheduling (faster building construction)
- Lighter structure (less materials and transportation)
- Structural flexibility (better for seismic areas)
- Improved daylight access (flexible layout, indoor comfort)
- Structural independence (flexible layout, no extra loads to the main structure)

The overall success of a curtain wall façade system, for both aesthetics and technical performance, relies on the selection and detailing of its components. The first large-scale experiments took place in the 1950’s and since then there has been a continuous research and development which keeps on improving the technology and methodologies applied. As a result, currently there is a large variety of highly sophisticated curtain wall systems. Today, a successful design requires thorough knowledge about the materials and construction details, as well as great understanding of the required performance according to the environmental conditions (interior and exterior). (Murray 2009)

The facade design has significant importance for a project. Except from protecting the interior spaces from the outside weather conditions, it also constitutes the face of the building. According to the uniqueness of the design, the façade system can be characterized as standard or custom. There is a wide variety of standard systems in the market, which can be selected out of a catalogue with all their specifications. The standard components are generally less expensive and can offer a limited customization (different glass types, mullion profiles, etc). They are usually preferable for smaller-scale or smaller-budget projects or for curtain walls with no special requirements. On the contrary, custom systems are individually designed and used for a single building. They are more expensive and they can be designed to elaborate a higher technical and/or aesthetic performance. Last but not least, extensive testing and quality controls throughout the design and construction phases are essential, fact that rises the expenses and the time needed. In the standard systems such tests are not necessary because they are previously implemented and documented by the manufacturers. (Murray 2009)

The contemporary façade systems are highly complex, which makes the architects most of the times to collaborate with a team of experts, like façade specialists, building physics consultants, engineers, etc. Within such collaborations, the decisions can efficiently be taken for the best combination of materials, form and function. Although there is a great variety of options, most curtain walls are based on the same fundamental principles of design, following a hierarchy of frames and panels. The most commonly used systems are the stick and the unitized, which will be further analysed in paragraph 4.2. (Murray 2009)
b. Facade’s role

The use of disposable products or disposable constructions is a recent phenomenon. Demanding performance criteria, increasing needs and fashion trends want the rapid replacement of the products, even way before their expected end of service life. The industrial design has already developed a sophisticated production line for this special category in order to save energy, resources and of course money. On the other hand, the building industry has always to fulfill the standards for structural integrity, thermal performance, functionality and users’ safety and comfort. Therefore, lowering the quality is not an option.

The facade is a selective and permeable membrane that permits, rejects or filters any environmental parameter between the interior and exterior spaces. Air, light, heat, sound and water can be dissipated or allowed to come inside the building in order to provide to the user a comfortable environment. In case the facade fails in fulfilling all requirements, then additional active systems and components improve the overall performance. Simply stated, facade operates like clothing, with the difference that clothing protects one person while facade provides shelter to a smaller or larger group of people and processes. (Knaack, Auer et al. 2014) (Murray 2009)

Figure 4.1.1 Facade requirements (redesigned from Knaack, Auer et al. 2014)
The facade is one of the most important factors influencing the energy demands and comfort levels inside a building. It is directly related with the possible necessity of mechanical systems for cooling, heating, ventilation, etc. For example, the more efficient the shading system, the less cooling units are needed. Depending on the local climatic conditions and the internal gains, some active systems can be even avoided. The diagram demonstrates the impact of the quality of the facade to the energy demand of a typical air-conditioned office building in Central Europe. It is even obvious that the extended glass area contributes significantly to the reduction of the energy demands; fact that enhances the role of curtain walls in office buildings. Of course these parameters and their interrelation may change if additional passive or active systems are applied. (Knaack, Auer et al. 2014)

To be more precise with the role of the facade, it is ought to serve the thermal, hygienic, acoustic and visual comfort of the users. Although the comfort criteria differ for each user and between the different uses of a building (residential, office, commercial, etc.), there are some requirements that facilitate achieving the desirable comfort levels. (Knaack, Auer et al. 2014)

**Thermal requirements**

Room temperature is the mean value of the air temperature in the room together with the mean radiation temperature coming from the surrounding surfaces of the room. The human body absorbs and emits heat through convection (particles in the air) and radiation (through surrounding surfaces); therefore both are of equal importance for the total temperature level inside the room. Each person feels comfortable in slightly different temperature according to the clothes, activities or his habits. Despite this fact, the room temperature should be generally around 5-6°C different from outside, without exceeding the 26°C.

**Visual requirements**

Similarly to the thermal comfort, visual comfort significantly differs for every individual user. Sufficient lighting and minor differences in contrast usually facilitate easy navigation and comfort in a room. Enough daylight must be also available taking care, though, of possible overheating or glare problems.

**Hygienic requirements**

The interior air quality is very important especially for office buildings, as it influences the productivity level of the employees. Fatigue and lack of concentration consist the so-called ‘sick building syndrome’ (SBS). Dust, gases, CO₂, odours, viruses and bacteria decrease the air quality and the users’ comfort as well as their health safety. The answer to ensure high hygienic quality is natural ventilation.

**Acoustic requirements**

The acoustic comfort is influenced by the sounds coming from outside as well as the sounds generated within the building. Examples of exterior sources of sound are the traffic, the construction sites, etc. Meanwhile, sounds generated from inside may be the conversations from nearby tables, music, walking people or noise produced by the mechanical installations.
Safety requirements

Safety is not involved in the comfort criteria, but is very important for the structural integrity of the system and the safety of the users themselves. Specifically for curtain walls, the load bearing function is eliminated to carrying exclusively the dead weight of the system and the wind loads. Thus the connections of the system to the main structure have to be carefully detailed and evaluated.

All parameters have to be taken into consideration at the same time. For example, if sound insulation is necessary for one building, operable windows are not suitable to provide natural ventilation because they will no longer ensure the noise protection. Therefore, another way for providing ventilation must be designed. Consultants have to compromise and find the combination that will best serve the building’s demands.

4.2 Applied materials

Currently the structural profile of a curtain wall is usually fabricated out of aluminium, due to its relatively high strength-to-weight ratio. Despite the fact that aluminium is now preferable, the first curtain wall facades were made out of steel. Steel is a heavier metal with high strength, able to cover larger spans. Nowadays, both aluminium and steel are widely used and the selection depends on the technical requirements and the aesthetic result to be achieved. The technological development of the façade systems together with the material properties resulted in introducing new materials to the façade industry, like glassfiber and u-PVC. Glassfiber has been recently added to the material palette, due to its advantage of creating lightweight and complex solutions, but of course more expensive, e.g. Municipality of Utrecht.

Within the façade unit, curtain walls incorporate the infill elements of glass, metal and stone, with glass being by far the most common. Metal and stone panels may require additional anchor clips to support their weight. The specifications and detailing of the glass unit in curtain walls have become quite complex in recent years in order to cover all technical and aesthetic demands. The architectural glass is mainly produced by the float process; a fully mechanised procedure in which the raw material is melted and eventually cooled and cut into large sheets of flat glass. The final product can be a regular clear glass or shaded in bronze, gray, blue, and green colour. (Murray 2009)

For the purposes of this thesis it is necessary to examine the different options of materials before taking the final decisions for the design. Each material has its individual properties, manufacture possibilities, connection techniques and overall restrictions which will be decisive during the detailing and evaluation of the environmental impact of the whole facade system. The sustainable criteria are the most important for this case, because eventually the environmental performance will be calculated. So, the detailing and material selection must serve this goal and enhance the sustainability of the design. The mechanical properties are, of course, taken into consideration too, in order to fulfil the structural requirements.

At the end of the paragraph all materials will be compared in one unified table to clearly present the differences and eliminate the ones that don’t meet the requirements. Through this process, I will eventually reach a conclusion and select the one which is more suitable for the design.

a. Aluminium

Figure 4.2.1 New city hall in Utrecht. (Brouns 2014)
The usual source of alumina is bauxite. Aluminium ore can mainly be found in Brazil, Surinam and Venezuela. This means that using it in Europe has fairly large transportation energy in the total energy consumption. However recycled aluminium is already being used for the production of new products decreasing significantly the energy demands. More specifically, more than 75% of the aluminium ever produced is still on the market because of the recycling process. (Heger and Sharff 2001)

**Production:** the aluminium profiles are manufactured by extruded sections. The extrusions are formed by prime or recycled aluminium and can be finished by anodising or painting. The extrusion is a process in which the aluminium is heated and forced through an extrusion die with the shape of the profile machined into it. Therefore they can have very complex shapes and be extremely detailed. They also include small recesses for the weather-strip rubber seals, the glazing and the thermal breaks. (Building 2015)

**Properties:** The aluminium profiles are lightweight, strong and stiff but, if necessary, their structural integrity can be further reinforced through the use of additional bars. They hardly need any maintenance, as they are very durable and non corrosive, fact that makes them widely used when the cost and the ease of assembly is of prime importance. (Ratcliffe 2008) (Fradelou 2013)

Although aluminium profiles are preferable in the facade design, they have high thermal conductivity which leads to a high U-value for the window unit. Aluminium is a poor insulating material, so the design of thermal breaks is extremely important in order to reduce the heat flow between inside and outside. The profiles consist of an inner and an outer shell connected through a heat-insulating material (usually plastic). This material works as a thermal break and contributes to the reduction of the U-value from 2.0 to about 1.0 or even 0.5 W/m²K improving the energy efficiency of the profile. However this technique increases the cost. (Fradelou 2013)

More specifically, the **advantages** of aluminium profiles are: (Fradelou 2013) (Manen 2015)

- Lightweight (20 g/cm³)
- High strength and stiffness
- Durability (>75 years)
- Low maintenance
- Water resistance
- Corrosion resistance (naturally generates a protective oxide coating)
- Ease in cleaning
- Low cost
- Most secure (compared with other kinds of frames)
- Recyclable and reusable (matter of design)

The **disadvantages** are: (Fradelou 2013)

- Good thermal conductivity (thermal breaks are necessary)
- Poor condensation resistance
- High primary embodied energy

**Recyclability:** Aluminium is renowned for its ‘cradle-to-cradle’ life cycle, as only 5% extra energy is needed during the recycling process and the greenhouse emissions have a reduction of 95%. (Heesbeen 2010)

More precisely, the recycling process includes melting the insulation and the plastic thermal break together with the profiles. All the extra materials are later removed and end up as waste. An additional percentage of 5% of car wheels is enough to provide...
the necessary magnesium levels and create the right type of alloy. The aluminium can be recycled endless times without losing its quality, in contrast with other materials like paper (6 recycling cycles) or plastic (8 recycling cycles). In fact, within the building sector aluminium achieves a great percentage of 95% recovery (table 4.2.1). Nevertheless, researches continue trying to get closer to the ideal 100% recycling rate in all sectors as well as use more recycled resources in the new products; the present recovery is up to 47% presenting a rapid increase of 12% within few years. (Manen 2015)

<table>
<thead>
<tr>
<th>Sector</th>
<th>EoL recycling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>95%</td>
</tr>
<tr>
<td>Transport</td>
<td>95%</td>
</tr>
<tr>
<td>Cans</td>
<td>60% (depending on the country)</td>
</tr>
<tr>
<td>Other packaging</td>
<td>40% (depending on the country)</td>
</tr>
</tbody>
</table>

Table 4.2.1 Aluminium recycling recovery (Manen 2015)

b. Steel

**Production:** Stainless steel is typically produced from a combination of recycled scrap and virgin charge materials melted in an electric arc furnace. (Heger and Sharff 2001) The steel profiles are manufactured by cold-rolled hollow sections produced by folding metal sheets. This production technique cannot provide highly detailed profiles, unlike aluminium profiles. The accuracy, however, remains high with close tolerances and recesses for weather-strip rubber seals, glazing and thermal breaks. (Fradelou 2013)

**Properties:** Steel sections present a lot of similarities in mechanical properties with the aluminium ones. Generally, they are extremely preferable when high strength and stiffness are required (without any additional element), mostly in order to cover large spans. They also provide high fire resistance, which makes their use common in some special kinds of buildings. Such combination of properties makes them widely used despite their relative high cost. (Fradelou 2013)

Similarly to aluminium, the main drawback of steel profiles is the thermal conductivity. Even though it is less in this case, thermal breaks are still necessary. Therefore the frame is divided in two parts (inner and outer) connected with the heat-insulating material (mainly plastic). Steel is the heaviest material among all materials used for openings on a facade and needs extra treatment against corrosion. However, when it is protected it almost does not require any maintenance. (Fradelou 2013)

More specifically the **advantages** of the steel profiles are: (Fradelou 2013) (Heger and Sharff 2001)
- High strength and stiffness
- Durability (>75 years)
- Low maintenance
- Water resistance
- Ease in cleaning
- Recyclable and reusable (matter of design)
- Fire resistance

The **disadvantages** are: (Fradelou 2013) (Heger and Sharff 2001)
- Good thermal conductivity (thermal breaks are necessary)
- Poor condensation resistance
- High embodied energy
- High production cost
- Heavy

**Recyclability:** Recycling in the metal industry is highly developed. Metals have great differences in density, electric and magnetic properties or even colour, fact that makes their separation comparatively easy. The value of metals makes their recycling economically profitable. (Heesbeen 2010)
c. Timber

The timber frames are the oldest to be used and have been greatly developed through all these years. The high availability and the aesthetic value are undeniable. Timber profiles are also used for curtain walls but it is mostly an architectural decision. The thermal properties of the material are much better than aluminium or steel, but a lot of attention needs to be paid in the detailing and the execution.

**Production:** The timber profiles can be made out of hardwood (oak, larch, sweet chestnut) or softwood which then is milled into the complex shapes required. (Fradelou 2013)

**Properties:** Except from the aesthetic value of wood and the ease in working with, it is a great thermal insulator which means that there is no need for a thermal break in the profile. More specifically the U-value of the timber frames is better than aluminium or steel, ranging from 0.3 to 0.5 W/m²K. Whereas the wood is not very weather resistant and can wear away, careful design, detailing and regular maintenance can make it last for a great period of time. (Fradelou 2013)

The weathering protection, if efficient, leads to a slow break down and wearing away of the fibres on the surface. Especially for the moisture protection, the designers must make sure that in case water gets inside the profile, it can easily drain away. In most applications, wood needs protection from water, cold, heat and ultraviolet light to serve a long life span. Coatings protect the wood from insects and pests preserving its high quality and efficiency with lower maintenance requirements. (Solutions 2013)

The advantages that characterise the wooden frames are: (Fradelou 2013)

- Durability (if well maintained)
- High thermal performance
- High availability (of material)
- Easy customisation
- Variety in finishes
- Recyclable and reusable (matter of design)
- Down-cycled to fuel
- Low embodied energy
- Renewable resource
- Easy to repair
- Low production cost

However, the disadvantages are: (Fradelou 2013) (Manen 2015)

- High maintenance
- Regular painting every 3-5 years and complete repaint every 10 years
- Lower life expectancy
- Lower weather resistance
- If not maintained properly, it can swell, rot, warp and stick
- Low fire resistance

Recyclability: Wood cannot be recycled, but only downcycled. For example, a piece of hardwood can be transformed into chipwood and later be down-cycled to fuel. The reuse of timber elements is only possible when they have been well maintained and carefully disassembled at the end of the product life.

d. u-PVC

There are many different plastics used for window profiles, but the most common is the PVC (polyvinyl chloride) with ultraviolet light (UV) stabilizers for sunlight protection. Processing oil to plastics requires a great amount of energy, almost equally intense to the metal industries. When plastic ends up in landfill, it decomposes very slowly and can eventually enter the food chain; thus it is strongly preferable to be
recycled. Although plastic is 100% recyclable, very often it is gradually degraded into uses of lower quality, remaining a material with open life cycle.

Currently, the PVC profiles are used only for windows and doors and not for curtain wall systems. The reasons are mainly the low stiffness of the material that makes it weak to span large facade openings as well as the absence of demand in the market, as the engineer of Rollecate, Pascal Schrijver, mentioned during our discussion about the manufacture of facade profiles. Additional steel elements are necessary inside the PVC profiles in order to be used in curtain walls. (Schrijver 2015)

**Production:** PVC frames are produced through the extrusion of the profile section, allowing the manufacture of very complex and detailed shapes. (Fradelou 2013)

**Properties:** The plastics used in the construction industry are easy to handle during the installation and assembly as they are scratch and impact resistant. They have low cost and do not need any special treatment against corrosion or moisture. Their thermal performance is excellent due to the low thermal conductivity and the low levels of heat transfer within the frame through the small chambers. The chambers can be also filled with insulating material which creates a thermal performance even better than timber frames. The colour and any texture are integrated to the material during the production process, so the final product doesn’t need any extra finish coating or extra maintenance. (Heger and Sharff 2001) (Fradelou 2013)

The most important drawback of plastics is the possible deformation due to high temperatures. The frame parts can slightly move because of these periodical deformations and create thermal gaps, while in case of fire it doesn’t provide any resistance. Generally, the plastic profiles are non-load-bearing as they are not rigid enough. A sufficient structural performance can be achieved through the use of larger sections (size close to the timber profile) or through additional metal reinforcements. Even though these techniques can make the profile stiffer, it is not enough for large scale constructions. Last but not least, PVC has a large environmental impact even though it is highly recyclable. (Fradelou 2013) (Heger and Sharff 2001)

The primary **advantages** of u-PVC profiles are: (Fradelou 2013) (Heger and Sharff 2001)
- Very high thermal insulation
- Lightweight
- Durability
- **Minimum maintenance** (never needs painting – integration of colour and texture within the material)
- Water resistance
- Corrosion resistance
- Ease in cleaning
- **Low cost** (compared to the other materials)
- Complex shapes available – high formability with less joints
- Recyclability

However, there are also some **disadvantages**: (Fradelou 2013) (Heger and Sharff 2001)
- High environmental impact
- Low stiffness
- Reinforcement required
- High thermal expansion
- Low fire resistance (combustible and smoke generating)
- Difficult to repair
- Loss of mechanical properties with high or low temperatures.

**Recyclability:** Plastics are typically organic polymers and polymers appear to have difficulties in sorting and recycling because they have nearly the same density, no significant magnetic or electric signature and can be almost of any colour. They can be identified by X-ray fluorescence or infrared spectroscopy, but these are expensive techniques. Furthermore, the whole recycling process consists of a large number of ener-
gy-consuming steps. Therefore, the value of the recycled polymers is typically 60% of the pure material, even though there have been some improvements. (Ashby 2013).

e. Glassfiber reinforced polyester (GRP)

Glassfiber reinforced frames have recently started to be used in the facade construction. Therefore the options on the section or the colour are still limited. The material has a lot of possibilities that still need to be explored and developed in order to reach its highest limits.

**Production:** Glassfiber frames are made by pultruded GRP sections and they can be highly complex and detailed.

**Properties:** GRP profiles are generally characterised as extremely strong, lightweight and highly energy efficient achieving U-values better that timber frames. They need minimum maintenance because they don’t rot or decay and their colour is integrated to the material. What is more they are extremely durable and corrosion resistant with low thermal expansion. (Fradelou 2013)

On the other hand, the use of GRP for the profiles increases rapidly the cost of the product. The expensive manufacture process and the time needed for the construction eliminate any possible customisation. Therefore, the final product doesn’t have large range of different designs and will eventually be fragile and difficult to be repaired, so the installation has to be done very carefully. (Fradelou 2013)

GRP profiles appear to have a lot of **advantages:** (Fradelou 2013)
- Superior thermal insulation
- Lightweight
- High stiffness
- Low maintenance (no need for painting)
- Water resistance
- Corrosion resistance
- Ease in cleaning
- Complex shapes available
- Low thermal expansion
- Smaller sections for the profiles (compared with the other materials)

However they also have some **disadvantages:** (Fradelou 2013)
- High production cost
- Low fire resistance
- Difficulty in repair
- Fragile – careful installation is necessary
- Non recyclable
- Limited availability in shapes and colours
- Limited producers

**Recyclability:** GRP is not recyclable and is not constructed by reusable resources, thus it has a high environmental impact. However, its durability and the fact that (almost) no maintenance is required during its life cycle balance out its high primary embodied energy. Currently, there are studies trying to find ways in making GRP more environmentally friendly and recyclable.
f. Combinations of materials

The materials previously described can also be combined to make more efficient solutions. Most widely used are the combinations of timber/aluminium and GRP/aluminium.

The timber/aluminium profiles have recently started replacing the timber frames due to the better combination of performance and aesthetics. The design consists of a wooden part at the interior side and an aluminium weather protective part at the exterior side. All kinds of wood can be used for the manufacture; even softwood can perform much more efficiently as it is well protected. This combination takes advantage of the beneficial properties from both materials and makes a new design with improved features. Thus, the aluminium layer decreases the maintenance demands while protecting the interior timber layer. In the meanwhile, the wood contributes to the high thermal performance of the overall facade system. Last but not least, the aesthetics of the wood at the interior is well combined with the modern attractive aluminium appearance from outside.

On the other hand, the two materials appear to have different thermal resistance and the periodical fluctuations in contraction and expansion increase the gaps between them and decrease the thermal performance. The overall cost of the frame is also more expensive than the simple timber or aluminium. (Fradelou 2013)

The GRP/aluminium combination has respectively to the timber/aluminium, the inner side made out of pultruded GRP section and the outer side made of aluminium extrusion. This new design is lightweight, stiff and strong due to the fibreglass, while the external aluminium cover creates an extra weather protecting layer that increases the life span of the overall product. What is more, because of the cover, less maintenance is required and in case of repair the aluminium layer can be replaced without influencing the rest of the frame. Despite these improved characteristics, the biggest advantage is the optimal thermal performance. The thermal properties of the fibreglass combined with the air cavities of the outer part and the insulation in-between increase the overall performance of the frame.

However, there is a differentiation at the thermal expansion of the materials which results in a decrease of the efficiency. In addition to this, the cost of the final product is relatively high and the part of the fibreglass is fragile and needs special care during the assembly/disassembly. (Fradelou 2013)

g. Collective table and results

The characteristics that are taken into consideration for the material selection are presented in the following table, but they are not equally considered. Therefore a weight value is used, which will be multiplied with the value of the material in each category in order to later on summarize them and realize which one has the best score. The higher is the score, the more suitable is the material. The values applied to the materials are comparative, and not absolute, in order to identify which material fulfils the parameter in highest or lowest level.

The most important factors (with a weight value of 5) are the: durability, life expectancy, recyclability/reusability and ease in repair, while next come (with a WV of 4) the: primary and recycling embodied energy and CO₂ emissions and low maintenance. We can see, thus, that the most important criteria are directly related with the sustainability and the principles of circular economy.

Some further explanation must be given here for the factors with the highest WV:

**Durability**

The durability indicates the resistance of a material in the weather condition and its ability to remain functional for a relatively long period of time. Durability is very important especially for the elements that are exposed to the weather conditions and protect the whole construction.
Service life

Service life numerically represents how long a product may live. This parameter should be considered during the design phase as the elements differ in life span. This means that the elements connected should have the same life expectancy or easy access must be provided to the inner layers, in case of replacement.

Recyclability/Reusability

Recyclability and reusability is the ability of a material to be separated from a waste stream for melting and remanufacturing or reuse, respectively. The two processes guarantee the extension of life of a material or element. Reusing is much more efficient than recycling, because no extra energy is needed. However, except from the material property of being recyclable/reusable, equally important are the design and the ability to sort the different products.

Ease of repair

The ease of repair closely depends on the material properties and the level of connectivity and, thus accessibility to the components. For example, aluminium is easily repairable due to its properties and the manufacture techniques that can be applied. In addition, the inner layers of a construction must be easily accessible for repairs, fact that is not always considered.

Primary & recycling embodied energy and CO₂ emissions

Primary embodied energy is the sum of all the energy required to produce any goods or services. The combination of embodied energy and CO₂ emissions represents the environmental impact of a material. The recycling embodied energy and emissions represent the environmental impact produces during the recycling process of a material. The accurate values are hard to be defined in absolute units. The production method and the transportation means have a large share in the value, however they change depending on the producer or location. Therefore, we mostly use the average of the different available values. In this case, CES Edupack 2014 software is used for the data collection.

Low maintenance

Maintenance involves all actions to be implemented in order to retain or restore an item to its functional state. The fewer the actions required, the less the energy and the cost are.

The following table concentrates all the materials and characteristics that are important for this thesis and the further design proposal. Properties’ weight value (from 1 to 5) indicates the ones decisive for the material selection. Materials’ value (from 1 to 7, in order to have more accuracy) indicates the level of accomplishing the requirements. (Fradelou 2013) (Edupack 2014)

The weight values of the properties are subjective and depend on what is more important for the design proposal of this thesis. Even though the values are comparative, we can conclude that aluminium is the most suitable material to be used. On the other hand, steel and u-PVC are not far behind. Also GRP has a score of 221 which is high enough, but if we take into consideration that the sustainable criteria of recyclability/reusability and ease of repair have the lowest score, it is getting clear that GRP is not the best option in this case. Timber profiles have a score of only 157 which is far behind the rest.

Taking everything into consideration, all aluminium, steel and u-PVC seem to be a good choice. Looking closer at the table, though, the aluminium has higher values in the properties with weight values of 4 and 5, which are the most decisive. Therefore, the most suitable material is aluminium, even though steel wouldn’t be a wrong option as well.
<table>
<thead>
<tr>
<th>PROPERTIES / MATERIALS</th>
<th>Weight value</th>
<th>Aluminium</th>
<th>Steel</th>
<th>Timber</th>
<th>u-PVC</th>
<th>GRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightweight</td>
<td>3</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Durability</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>2</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>High strength</td>
<td>2</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Low maintenance</td>
<td>4</td>
<td>7</td>
<td>6</td>
<td>2</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Easily cleaned</td>
<td>2</td>
<td>7</td>
<td>6</td>
<td>3</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Low initial cost</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Low life cost</td>
<td>3</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Low thermal conductivity</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>5</td>
<td>7</td>
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<td>Complex shapes</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>7</td>
<td>5</td>
</tr>
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<td>High life expectancy</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Primary Emb.Energy &amp; CO₂ emissions</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>7</td>
<td>3</td>
<td>4</td>
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<td>Recycling Emb.Energy &amp; CO₂ emissions</td>
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<td>4</td>
<td>5</td>
<td>0</td>
<td>7</td>
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<tr>
<td>Recyclability / Reusability</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Easily repaired</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL VALUE OF MATERIAL</td>
<td><strong>276</strong></td>
<td><strong>265</strong></td>
<td><strong>157</strong></td>
<td><strong>256</strong></td>
<td><strong>221</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2.2 Comparison of all materials applied on curtain wall facades

Where:
- Weight value of properties’ importance:
  1 – 2 – 3 – 4 – 5: very insignificant – insignificant – neutral – significant – very significant
- Materials’ values:
4.3 Facade life cycle

The life cycle of a facade can be represented as a box having as inputs the resources, the raw materials and energy needed and as outputs the emissions to the environment. Throughout the different phases of the façade’s life, extra inputs are required and more outputs are, therefore, produced. It is, thus, important to identify the phases and their impact on the whole life cycle of the product in order to locate which must be the focus point. (Heesbeen 2010)

Basically, the façade’s life cycle can be divided into three phases: the materialisation (construction/storage/transport/assembly), the operation and the end-of-life. The operational phase can differ in duration from just two decades to one century, depending on the needs of the tenants and the overall condition of the construction. The three diagrams represent the duration and environmental impact of each phase for a life span of 30, 60 and 120 years. The materialisation phase produces the most emissions and requires the largest amount of energy even though it only lasts approximately 2 years. (For this thesis the storage and transportation will not be analysed because they are a matter of project management.) Thus, the longer the operational phase, the less often new buildings are constructed and less environmental impact is generated.

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![Diagram of product's/building's life cycle](image)

**Figure 4.3.1 Product's/building's life.** (Heesbeen 2010)

---

![Diagram of duration and environmental impact](image)

**Figure 4.3.2 Duration and environmental impact of materialisation/operation/end-of-life.** (Heesbeen 2010)

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a. Materialisation

i. Construction

The manufacture of a curtain wall starts by forming the structural profiles from steel, aluminium or wood. The production line is highly dependent on the chosen material. Steel façades have a made-to-order production, whereas aluminium elements have a serial production. More specifically, the aluminium profiles, which are the most widely used, are extruded into elements of 6m length and then adjusted according to the requirements of each project. For the steel façades, steel plates are formed and then bended and welded together to create the profiles. Wood is not a preferable material due to its weight, the necessity to have big-sized profiles and the high maintenance demands. Nevertheless, the fundamental requirements of a facade system are the same for any design; thus the facade industry is constantly working on creating...
low-cost systems with minimum amount of materials, while perfectly responding to the thermal and structural restrictions. (Schrijver 2015)

ii. Assembly

The assembly of a curtain wall facade depends on the system used. There is a variety of systems available in the market, but the most widely used are two: the stick (usually called ‘curtain wall’) and the unitised (also called ‘element façade’).

Stick system

In a stick curtain wall, the individual components are assembled piece by piece on the construction site. First, the primary structure of the mullions is anchored to the building structure and then the horizontal transoms are installed to span the distance between the mullions. Finally, the infill panels complete the facade, together with other secondary components, like shading systems or decorations.

Most stick systems are standardized and have relatively low cost. In addition to this, the transportation and handling are of low cost, due to the efficiency of the separate components. On the other hand, the assembly on site is highly dependent on the workers, and therefore it has a slower pace, higher labour costs and a higher chance for mistakes and failures concerning the quality and precision (compared with the factory fabrication). The stick system is usually used for low or mid-rise buildings. (Murray 2009)

Unitised system

A unitised facade is made out of prefabricated modules which have been assembled in the factory under controlled conditions and then shipped to the construction site and connected to the preinstalled anchors on the building structure. A typical unit spans one or two storeys in height and 1.2 or 3 meters in width, but these dimensions vary between different countries and even between different projects. Customised shapes and dimensions are very often as well. Each curtain wall unit is shipped on site fully glazed and ready to be installed, so the labour on site is minimized. The panel is manipulated by a crane from the top of the building or the above floor and is anchored at the floor slab or the beam.

The advantages of this system include the high quality control throughout the fabrication and the faster installation on site. What is more, the way the panels are connected with each other provides better handling of the building movements due to deflection or wind loads. However, the costs are much higher for low-rise buildings, because of the need to carefully transport big panels and the necessity for sequential installation. Sequential installation means that the one panel interlocks with the other, so they have to be installed in a particular sequence. The unitised systems are typically applied on high-rise and high-volume façades, because the expenses decrease significantly and actually the system gets much more cost efficient that the stick. (Murray 2009)
Both systems use the same principles as far as it concerns the accessibility and dis-/assembly in case of maintenance or at the end-of-life of the facade. In terms of detailing, their main differentiation is that stick system consists of smaller elements put together (profile, pressure plate, cover cap), while the element consists of just the profile and the thermal breaks (Figure 4.3.4). Then, two elements are connected by the insulting rubber, which also receives the possible movements from the panels. Generally the assembly process in this case is progressing horizontally (floor to floor), but for stick system it is vertical (zone to zone: one zone is the span between two mullions).

b. Operation

i. Quality of Performance

During the service life of the facade it is very important to maintain its performance quality. For example, the insulating gaskets can get brittle due to the temperature differences, creating thermal bridges and problems with the water tightness. This usually results in increased demands for heating/cooling mechanisms as well as damages on the facade profiles due to the presence of water. Thus, small changes may result in great differences in the terms of sustainability, energy consumption and user’s comfort. On the other hand, well-maintained systems can last much longer while having efficient performance.

ii. Renovation, Maintenance & Refurbishment

Renovation is the repair and, if necessary, the replacement of building elements and technical equipment, causing a minimum intervention. Maintenance is the repair of any failure or inefficiency due to the age of a system and, when needed, the replacement of building components and technical equipment. Depending on the condition of the elements, a refurbishment may be necessary, which means that the components are outdated and new features and technologies have to be added. The refurbishment usually takes place while the building is in use and thus it is very challenging to achieve good management and communication. The refurbishment has the greatest level of intervention out of the three mentioned and is the most important to be analysed. (Ebbert 2010)

Up to date, there are no actual practices of refurbishment in curtain walls. In most cases, either a building is demolished and a new one is erected or the owners try to extend its service life through small improvements. It is believed that it is much more expensive and less efficient to repair and upgrade an old facade, which might have problems also later on than build a new one which afterwards will bring a much higher income. However, the building shell represents the 20 – 25% of all the building’s value; thus demolition is not a wise move according to the financial criteria. Nowadays, most buildings in need of refurbishment are as old as 50 years and more, which means that they were constructed around 1950’s. At this period, the sustainable design for disassembly was not integrated to the constructions, and thus the facade systems are not easily accessible. However, very often a refurbishment takes place on buildings of historical importance, buildings within a tense urban environment or office buildings which need to keep the work flow running because of the limited alternatives. (Lutz and Einck 2013)

One example is the ten-storey office building of Social Security Administration’s Midwest Region in America, built in the early 1970’s. The curtain wall facade appeared to have insulating failures, water leakage and problems with the occupants’ comfort. At the same time, disruption at the operation of the services was not an option, so a pre-glazed unitised curtain wall system was hang to the original framing after the orig-
inal glass was removed. The operations were performed mainly from outside and lasted six months, providing a cost effective solution to the client. (Helfrich 2008)

The example of SSA building office is characterized as a renovation, when in fact was a complete replacement of the whole facade system. It is most likely that no maintenance took place throughout the service life of the facade; fact that contributed to the elements’ obsolescence and the need for a complete replacement.

In contrast, the façades currently designed and constructed are seriously taking into account the need of easy accessibility for all future actions. The curtain walls are assembled from outside the building using large machineries, like cranes and elevators. In principle, during the operation phase of the stick curtain wall facade, the cover cap can be temporarily removed in order to replace a broken glass or the obsolete gaskets. However, that is not possible in the case of a unitised system, where the whole panel must be taken down and be replaced by a new one or be repaired in the factory. In both cases the renovation is considered relatively easy, even though there are no recorded examples. (Manen 2015)

c. End-of-life

At the end-of-life of a curtain wall, the whole facade is demolished and then taken apart to be recycled. The different materials are sorted out and melted to create new profiles. In order to save time and costs, it is considered much easier to first demolish the construction and then, while on the ground, disassemble the different parts. (Manen 2015)

The whole process of recycling and extruding new aluminium profiles is fast, easy and relatively cheap. Every new mould for an aluminium extrusion costs approximately 1.500 €, while for a PVC the costs are extremely high; fact that justifies the large variety in aluminium extrusion profiles. Although the demolition can cause losses at the materials’ sorting process, it is preferable because it saves time and labour work which equals to money.

4.4 Refurbishment

a. The importance of refurbishing a facade

The refurbishment of buildings has social, ecological and economical importance. Every demolition is equal to wasted embodied energy, materials in landfills, emissions and the need to extract more resources for new constructions to replace the old ones. Therefore, it is very important to improve the existing buildings, instead of destroying them, towards the enhancement of sustainability within the society. Most crucial is the ecological burden of each construction and demolition as they contribute with a great percentage of the total energy and materials used as well as the emissions released.

In the same time, the economical impact has an important role too, especially for the stakeholders that are the ones taking all decisions. The buildings represent stored capital and thus the owners try to make the best out of them. The façades and technical installations, however, last around 30 years, while the load bearing structure can reach the end of its life after a century. Thus, a demolition after 30 - 40 years would be a waste of capital; but there is no refurbishment strategy to span this gap and extend the operational time. Most of the times the technical problems cause a gradual decrease in the overall performance of the
building, creating air leakage on the facade and increase in the operational costs.

Nowadays, the solution in such cases is usually the replacement of only the glazing, which may improve the thermal performance but not solve completely the problem (e.g. replacement of glazing in the glasshouses of the Architecture Faculty at TU Delft). In larger projects, the entire facade is normally replaced by a new one; fact that extends the operational life of the building. However, all resources and the energy embodied in the older facade are wasted. Last but not least, countries, like Netherlands or Germany, have regulations against the so-called ‘urban sprawl’, encouraging the investments within the cities while the ones in the countryside are becoming scarce. So the existing buildings have to be demolished or upgraded. (Ebbert 2010)

b. Why do we need to apply a refurbishment?

‘Refurbishment’ is the replacement of a component as it becomes outdated; it can be caused not only by technical reasons but also by the users’ needs or changes in the management of the building. Adaptability gives the freedom that a construction needs. It’s been already mentioned before that there is not ‘a’ building, but a series of different buildings over time. Especially for office buildings, it is also very often to apply changes on the facade of the building (and the interior spaces too) due to matters on the thermal performance, or the economical and technological developments. (Crowther 2001)

According to Klarqvist, there are two strategies for a building to be adaptable:
• Generality: the ability of a fixed situation to cater for various functions
• Flexibility and elasticity: the ability to adapt by modifying the size

Adaptability has more potential to be infinitely appreciated because a large degree of flexibility implies that the facade can be applicable in many contexts. The different rates of change between the elements used must be taken into consideration during the design phase. Some parts are more likely to tear and wear than others. For example, if a window breaks, the glazing must be interchangeable independently from the other elements. (Heesbeen 2010)

In order to make clear the reasons and frequency of the renovation actions applied on a facade, they can be divided into three categories: the technical, the functional and the aesthetic ones. More specifically:

i. Technical reasons

1) The system consists of different materials with different life spans. In detail, the insulating gaskets and the thermal break of PE live for approximately 30 years, while the aluminium elements can last for more than 70 years. The silicone, in-between the facade and the wall, needs to be replaced every 10 years in order to maintain the high efficiency of water tightness and thermal insulation of the construction. Therefore, actions are necessary every a decade for the silicone and every 30 years for the gaskets and thermal breaks. (Manen 2015)

Figure 4.4.1 Connection of a curtain wall with the wall / Elements’ lifespan (Alcoa 2015)

* 30 years is the mainly the service life of most elements
2) Technological developments have rapidly decreased the U-value of the facade systems and thus all older systems need to be replaced by new ones. For example, the double glazing openings have already started being replaced by triple in the residential buildings in the Netherlands. Other example may be the improvement of the infill or the weight of the glazing. On the other hand it needs, here, to be highlighted that although the U-value had a great decrease since the 1950’s, the last decade it appears to have a much slower pace and thus we can predict that in the future the U-value will be only slightly improved, so no decisive development is expected within this factor. (Ebbert 2010)

3) Within the improvement of the performance and the function of the interior spaces, the users sometimes decide to integrate ventilation or shading system. It is much likely that users experience the space differently than what the designer had in mind and in such cases, the complete unit needs to be replaced. (Ebbert 2010)

ii. Functional reasons

In case the use of a building is changed, the facade must be adjusted in order to cover the new requirements. Especially for office or educational buildings, it is not uncommon to apply changes in demand of more working places, bigger offices, etc. or of a complete change in the use of the building. Thus, adaptability in this category of buildings is of great importance.

iii. Aesthetic reasons

Applying renovation actions for aesthetic purposes is not common. It can only be justified if it is combined with a technical upgrade, a functional change or for marketing reasons (a new building face can be a good advertisement for a company). For stick curtain walls it is mainly achieved by applying different shapes or colours of cover caps.
c. When do we need to apply a refurbishment?

Taking into consideration the life span of the different elements of the facade, we can realise three main points, after 10 years, 30 years and more than 70 years. More specifically, the connection of the facade with the wall requires most regularly actions of maintenance which mainly include the replacement of the silicone strip. This operation is relatively easy and not expensive, although it is important to apply it on time in order to maintain the performance of the facade in high levels. More important is the replacement of the Insulating gaskets and thermal breaks of the curtain every 30 years, approximately. These soft plastics gradually turn brittle creating air and water leakage, which results in discomfort and problems to the facade (degradation of materials, rust, etc.).

In conclusion, refurbishment actions are required to the facade every around 25 - 30 years. A building can last for 70 or 100 years, but for office/commercial/educational buildings probably after around 60 years there might be a transition in the use or the owners which influences the facade design and construction.

4.5 How long can our facades live? – 3 life-cycle scenarios

Having an overview of the life cycle of the facade and taking into account the frequency of possible refurbishment activities, the main reference points are after 25-30 years and after around 60 years, especially for an office building. It is useful at this point to further analyse the characteristics of a facade that would last 30 or 60 years, in order to specify the advantages and disadvantages. In addition to these scenarios, it is interesting to examine a, rather extreme, scenario of a facade for 120 years too, as aluminium can last for a century.

a. 30 years service life

![Figure 4.5.1 Performance Vs Service life](image)

**Figure 4.5.1 Performance Vs Service life**

**Characteristics**
- Designing for the near present
- No refurbishment
- Complete replacement after 30 years
- The whole number of elements/panels must be recycled and remanufactured

**Advantages**
- Use of the latest technological developments

**Disadvantages**
- Expenses for complete replacement (construction of a new facade, transport and assembly)
- Ecological impact due to the need of new materials every 30 years
- Ecological impact due to the recycling of aluminium at only \( \frac{1}{4} \) of its life span
• No possibility of reuse (extending the life cycle)
• A percentage of materials is wasted through recycling

Designing for a facade with 30 years life span is comparable to the products of short-term use; used for a short period and then thrown away. This kind of products usually has relatively simple design and cheap materials in order to save costs for the manufacturing company. Generally they also have some replaceable parts in order to extend the life span of the product while keeping the high quality services.

For example the kind of shaving razors that is widely used consists of two parts: the handle and the head with the blades. The handle is usually plastic and lasts for many months, while the head has to be replaced every few days or weeks. This serves hygienic reasons as well as functional, because the blades gradually lose their sharpness and can even become dangerous. For more comfortable use the connection part of the handle and the head provides flexible movement. Except from the fact that by “refurbishing” the razors, they can last for much longer than the disposable (single-use) products, it is interesting to look at the connection of the parts and the easy disassembly and assembly it provides. It is a snap-fit connection where the parts are designed to be smooth and without sharp edges which would make the disassembly difficult.

Translating these principles into the facade design, the curtain wall of 30 years must have easy connections between the structure (which lasts much longer and shall be maintained) and the outer parts of the facade, which will be regularly replaced. This has to come in agreement with the facade requirements of structural integrity, thermal performance and aesthetics.

As a result, it is very much likely that the facade won’t be so different from the ones currently constructed, but the design can be simpler and the materials should belong to the same category as far as it concerns their durability. A conceptual idea is the use of biodegradable materials or materials that are extremely easy to be recycled, like paper or plastic. However, great significance has the environmental impact of this concept which has to be evaluated. The biodegradable materials create a very sustainable concept, but in case of mass production, large areas of land have to be used for their production; and this will probably cause problems to the food production.

Therefore, it seems reasonable to propose the use of highly recyclable materials with minimum emissions. The high percentage of material recovery will help reduce the rate of extracting new resources. This problem is even more intense in developed countries (Diagram 4.5.2); thus there is an urgent need to change the way of building. (Heesbeen 2010)
b. 60 years service life

Characteristics
• Designing for the near future
• Refurbishment is required once, halfway of the total life span of the elements
• Recycling of the elements at the end-of-life of the facade
• Operations of refurbishment: the cover cap is temporarily removed and the gaskets and thermal breaks are replaced (stick) or the panels are taken back to the factory for refurbishment and then reinstalled (unitised)

Advantages
• Refurbishment is less expensive and environmental burden than a complete replacement
• Refurbishment saves more time than the replacement of the facade system
• Possibility of reuse, in case the building is demolished prior the end-of-life of the elements
• Less resources required

Disadvantages
• The current designs are not made for reuse
• Demolition is preferable prior the sorting of the materials to save time and money
• Refurbishment is currently not applied

This scenario is in agreement with the present design guidelines in the facade and construction industry. The requirements include high quality and easy accessibility from outside which also serves the demands for a fast assembly on site. The elements used differ as far as it concerns the life span, which makes the maintenance and refurbishment necessary.

In principles, the design supports this kind of activities, but in practice they are not really applied. In fact, there has never been reported such an example. Due to the fact that the buildings are still not that old, we cannot have any certain conclusions whether they will be refurbished in the near future or not. For older buildings, built in 1950’s, a complete replacement of the facade is preferable, as already presented above with the example of SSA in America. Assuming that there will be cases of refurbishment, this scenario seems more sustainable because fewer materials and investments are required during the life cycle of the building. Last but not least, the time required, and thus the disturbance, is much more during a complete replacement.
Characteristics

- Designing for the future
- Refurbishment is required every approximately 30 years (3-4 times depending on the weather and maintenance condition)
- Recycling of the elements at the end-of-life of the facade
- Operations of refurbishment (3-4 times): the cover cap is temporarily removed and the gaskets and thermal breaks are replaced (stick) or the panels are taken back to the factory for refurbishment and then reinstalled (unitised)

Advantages

- Refurbishment is less expensive and environmental burden than a complete replacement
- Refurbishment saves more time than the replacement of the facade system
- Reuse at the end-of-life of the building, as the life span of the facade may be longer than a building
- The least new resources required (compared to the other two scenarios)

Disadvantages

- Need to predict the possible future developments; the facade systems must be flexible
- There is no guarantee that the predictions will be accurate and really be realised
- After 120 years there might be a great difference in the way of constructing, which means that the facades must be torn down and replaced (even before the end of their life) or that some buildings will remain with an outdated facade

According to (Heesbeen 2010), the longer a building lives, the smaller is the environmental impact through its materialization. The whole process of manufacture and construction needs a lot of energy and produces a large amount of emissions; thus the extension of life of a building equals to less energy and emissions being wasted. In addition to this, maintenance activities guarantee high-quality performance of the system in order to avoid extra thermal losses and energy demands.

On the other hand, designing a facade for such a wide time frame requires considering the future developments and the way they can be integrated later on to the existing system. Replacing the double glazing with triple and the insulating break with a new kind of material/technique are only some examples. Therefore, the new facades should be ready to integrate the upcoming developments, which of course are not yet known. Although these predictions might be calculated, things can turn out differently with diverse outcomes or no developments at all. In such a case, we would probably have created a facade, e.g. oversized, spending much more resources than actually needed, which has a great environmental impact, if calculated for a large amount of constructions. In contrast, in 120 years probably the technological developments will be radical and convert the facades to outdated faster than their initial end of life. Through
these simple examples it is getting clear that 120 years are a lot to predict what will happen. Despite the fact that in principles it is more sustainable to extend the service life of our products, a balance should be found, because otherwise this might eventually result in more wasted energy.

4.6 Conclusions of chapter 4

Considering all scenarios and trying to answer the question “how long can our facades live”, we can conclude that the facade has to fulfil all requirements and expectations at any time during its service life. The energy demands of the building as well as the comfort levels of the occupants depend on the quality of the facade performance. Therefore, maintenance activities are necessary in a regular basis. In addition to this, refurbishing the outdated elements extend the service life of the overall facade saving material resources and energy. Thus, it is essential at the design phase to consider the overall life span of the facade and the building and the possibility of refurbishment so as to integrate the respective principles.

Considering the scenarios for a sustainable service life and trying to answer the question “how long can our facades live?”, we can conclude that there is not one perfect answer. The choice to design a facade for 30, 60 or 120 years depends on the needs of the investors and the criteria that are set. In the first case, flexibility and adaptability to technological developments are the most important criteria. However, the second scenario can be the answer to a long-term investment for a company or office building. The scenario of 120 years is considered rather extreme in terms of the amount of information that the designer needs to have for the future, but of course is not impossible.

For the design proposal and evaluation, the two scenarios of 30 and 60 years will be further analysed to find out which is the most sustainable way of designing the curtain walls.
Sustainability and Service Life of Curtain Walls

Thalia Anastasia Kakolyri

Credits:
(Skyline Architecture Blog, 2013)
5

Design Proposal
5.1 Design and evaluation goals

Keeping the two scenarios of 30 and 60 years, I will evaluate the amount of embodied energy required and CO₂ emissions produced in each case and compare the results to find out which is the most sustainable. In addition, time and cost must be considered because they both have a decisive role for the investors and the final decision making.

It is, though, more interesting to create a wider difference between the two time points and reduce the first one to 15 years, which will span a range from 10 to 20 years service life. In this way, I can evaluate two service lives that fulfil different criteria and market demands. More specifically, the short-term case is suitable for start-up and smaller companies with an economic program of 5 to 10 years or institutes with rapid changes in their human resources. Flexibility is of great importance in such cases. On the other hand, the long-term scenario is suitable for companies and institutes with a stable and organised economic program, where the configuration of the building won’t have great differences.

For the purposes of the research, a case study building is used to apply both scenarios. The design proposal involves the detailing of the facade systems, while the evaluation addresses the embodied energy and CO₂ emissions for an area of 4m high and 2.8m wide, according to the facade grid of the case study. In both cases, a stick curtain wall and a unitised system will be examined so as to see whether the unitised facade has less environmental impact. Lately, it is getting more and more preferable over stick because of its high quality, the ease of construction inside the factory (under controlled conditions) and the fast assembly on site, but the environmental factor should not be neglected.

5.2 Case study – Building of 3mE at TU Delft

The building of ‘Mechanical, Maritime and Materials Engineering’ faculty (3mE) is chosen as case study, located at the campus of TU Delft. The building of 3mE was built in 1953 and was recently renovated in 2003. The total floor area is 46.120 m² and the total facade area is 17.400m².

The selection of an educational building is preferable due to the great possibility of having regular changes in need of extra spaces for studios, library, studying areas etc. TU Delft is annually increasing the rate of admitted students, having a rise of around 400 students from 2014 to 2015 alone. We have also seen examples that certain uses are moving within the campus of TU Delft, such as the Architecture Faculty or the library, and thus the buildings have to quickly adapt. It is comparable with the requirements of an office or commercial building.

Architecturally, 3mE faculty consists of four wings connected with a long corridor. The design is modular and the façade systems alternate between curtain walls, at the corridor and the ground level, and big windows at the upper floors. The wall construction is based on the typical Dutch system having the brick facade, insulation and concrete inside. This system assists in having the exterior face of brick while taking advantage of the concrete for the interior spaces.

Figure 5.2.1 Case study of 3mE faculty & outside view
Legend
1. Interior concrete wall 240mm
2. Mineral wool insulation 80mm
3. Exterior brick wall 70mm
4. Window profile (aluminium)
5. Double glazed unit
6. Sound insulation and aluminium frame

Figure 5.2.2 Drawings of 3mE and details of the window connection
5.3 How long should curtain walls live to have minimum environmental impact? (Refurbishment Vs Replacement)

a. Short-term curtain wall (15 years)

The main characteristic of this scenario is the flexibility to all functional changes of a building while using the latest technological developments. In addition to this, the owners invest gradually during the complete life cycle of the building and not just at the beginning. This is very convenient when there is no big capital and the owners want to make smaller investments.

Thus, the curtain wall has to be replaced thrice or twice, at a building with life span of around 60 years. The structure can remain until the end, as aluminium has a very long life span, while the rest of the facade system (exterior part) must be replaced with new elements. The number of replacements depends on whether 15 or 20 years are considered (due to the possibility to stretch the service life 5 extra years). All materials should be categorised in terms of durability so as to be replaced at the same time. All in all, for the purposes of the thesis, the lowest amount of materials and money resources ought to be used.

On the other hand, if we consider a building designed and constructed for app. 20 years, the whole facade will eventually be disassembled together with the building. So, in this case the structure has to be taken into consideration for the calculation of the environmental impact. This scenario will be considered as a separate case, but yet again a time range of 60 years is going to be used, in order to have a common background for the evaluations (more details can be found in paragraph 5.4).

The option of applying not only stick, but also unitised system must be calculated. The case study has a large facade area due to its configuration; fact that enhances a comparison between the two systems. Both options of refurbishing and reusing the unit or recycling all parts are going to be tested, respectively to the stick curtain wall.

b. Long-term curtain wall (60 years)

The life span of a building is usually around 60-70 years. Having a facade with 60-years service life means that it will be disassembled at the same time with the building. This can be financially convenient for companies with long-term programs and more stable economy. In such cases, there is only the need to refurbish the facade after around 30 years from the construction, in order to replace the outdated elements and improve the overall performance. The investment is mainly at the construction phase while the refurbishment is faster and much more economical than a complete replacement (short-term scenario).

The materials composing the curtain wall must be durable and of high quality. In order to find a more suitable option than PE foam for the thermal break, graphs were made in CES Edupack for the different thermoplastics. The embodied energy and CO₂ emissions were taken into consideration as well as the durability and recyclability of the materials. Eventually, the thermal break is being replaced by Nylon (polyamide).
Although its primary demands for energy are more than PE, the recycling ones are less. Most importantly, nylon is a very durable thermoplastic, since it is normally used in construction machineries, exposed to the weather conditions and the harsh industrial atmosphere where it can last for at least 10 years. The other materials used at the comparison graphs were eliminated from the selection due to reasons like high cost, reduced durability, low recyclability, etc.

The unitised curtain wall will be used in this case as well, even though reuse is rather unlikely. So, only the evaluation of recycling will be implemented.

In all cases, the final stage (after 60 years) is always recycling the materials. For the calculations, this will be measured as if a new system was to be constructed.

5.4 Assumptions and Constraints

At this point of the research, it is necessary to identify the assumptions made and the constraints considered for the design and the evaluation stage.

Having a common background is essential for making a reasonable comparison with valid results; therefore a span of 60 years in total is considered for all cases (the facade has to be recycled after 60 years), to present the environmental impact of both short-term and long-term scenarios. In addition, the parameters of time and cost (including transportation and labour on site) are approximately evaluated in order to present a complete overview, even though they are very much dependent on the management of the project. One facade construction company is used to acquire comparative information. Any unexpected damage during transportation or facade’s life cycle, e.g. broken glass, is not added to the total values.

The values applied are the average available data from the software CES Edupack 2014, while the percentage of material recovery through recycling is the highest possible. What is more, the materials are assumed to reach the recycling shredder without any losses during the disassembly or transportation. Last but not least, the thermal and overall performance of the facade is considered as efficient and not directly related with the detailing of the systems and thus a possible analysis is not included within the scope of the thesis.

At the same time, in terms of performance the Dutch regulations require the use of triple glazing to all new façades to achieve the lowest possible U-value; older facade systems have also to be replaced with triple glazing. Therefore, it is expected within 50 years to have only triple glazed façades, and thus, double glazing is not evaluated for the long-term scenario.

In spite of the assumptions made, there is also the constraint of creating a feasible product close to the existing manufacture line and construction techniques. The production line consists of a series of machineries working with high accuracy; any possible replacement due to a new design might cost a tremendous amount of money which will probably cause the product’s rejection. As far as it concerns the human resources, the parameter of experience cannot be neglected because it is essential for fast and flawless construction operations.

To sum up, the parameters consisting the assumptions and constraints are:
• Span of 60 years in total
• Time and cost for manufacture, assembly, transportation, labour comparatively estimated
• No unexpected damage occurred
• No material losses during disassembly and transportation to recycling shredder
• Highest percentages of material recovery through recycling
• Values acquired: average data (CES Edupack 2014)
• Façade’s performance: efficient
• Only triple glazing is evaluated for the long-term scenario
• Feasibility, experience, current equipment considered for the redesign
5.5 Redesign of the details

The curtain walls incorporate a well developed, technologically informed and complex design. In addition to this, the production line of the mass production is directly dependent on the series of machineries operating, as it is already stated in the constraints. The improvements that can be suggested, thus, are limited and mainly refer to the replacement of certain materials or to small interventions.

More specifically, for both short-term and long-term use, the stick curtain wall was adjusted in terms of durability and principles of design for disassembly. Thus, first of all, the thermal break of PE foam is replaced with Nylon (PA) in the 60-years case due to durability reasons, and, secondly, the silicone is replaced by adhesive flexible tape with aluminium cover at the interior connection of the facade with the wall for both scenarios*. The flexible tape provides the necessary tolerance in case of possible movements and the aluminium works as a protection layer giving a better appearance in the same time. The details of the next page show the connection of the stick system with the wall of 3mE building for both options of service life. The redesigns are based on the architectural systems of Alcoa©.

More into the details of the stick curtain wall,

• The 15-years design has been simplified as follows:
  a. the interior gaskets are thinner, because there is no need to incorporate tolerance for different width of gaskets; and thus different width of glazing
  b. the complex insulating part, at the connection with the wall, is replaced by a simple aluminium tube

• The 60-years design remains much closer to the current systems. Some small interventions include:
  a. the snap-fit connection of the cover cap is redesigned for easier disassembly (DfD) (Figure 5.5.1)
  b. the PE foam thermal break is replaced by nylon (extra durability)

In addition to the study and evaluation of the stick curtain wall in the different scenarios of service life, the system is also compared to the unitised facade, as has already been mentioned. The unitised (also known as “element facade”) has not changed from the currently used, because minimum number of materials are used in a compact and simplified design which provides highest quality and performance. The detail (Figure 5.5.2c) is applied for both 15 and 60-year cases.

*For the scenario of complete disassembly of the facade (including the structure), silicone may be used to save time and materials.

Figure 5.5.2 Proposed details for the stick and unitised systems.

Figure 5.5.1 Reversible snap-fit
Stick curtain wall for 15 years service life [plan view / section]

 Stick curtain wall for 60 years service life [plan view / section]

**Legend**
1. Aluminium profile
2. EPDM gasket
3. Triple glazing
4. PE foam thermal break
5. Aluminium pressure plate
6. Aluminium cover cap
7. Aluminium corner connection with silicone
8. Flexible tape and aluminium cover
9. Nylon, PA thermal break

Figure 5.5.3 Details of the design proposal of the stick curtain wall for the window connection
5.6 Calculating the Embodied Energy and CO$_2$ emissions

The area that will be evaluated for all systems is one vertical element of 4m height with the horizontal of 2.8m long and the infill glass area with dimensions 4*2.8m. This part is selected because, if multiplied, it can form the complete facade. The size of the elements is based on the grid applied in the case study. The connection with the wall is not calculated because the results would be relative to the ones calculated for the simple elements.

The evaluation of the different cases is done through hand calculations using the average values acquired through the database CES Edupack 2014©. Generally, there are many methods and softwares to calculate the environmental impact of a material or even of a whole construction. The most commonly used is the method of LCA (Life Cycle Assessment), which is very detailed but time consuming and needs information from all stages of the life cycle of the element evaluated (manufacture, transportation, storage, maintenance, etc). Softwares are available too, like GreenCalc+ or SimaPro, but they wouldn’t add to the research of this thesis any more information than the hand calculations. Through the database and the formulas used the accuracy is high enough. Anyhow, we should not forget that the purpose is to compare the results and not use them as absolute numbers.

a. Evaluations implemented

The evaluations implemented can be divided into three categories according to their goal to:
1. Discover which facade system is more sustainable (stick/unitised)
2. Discover which service life is more sustainable (short-term/long-term)
3. Discover the progress of the recycling process within the next years (% of material recovery)

In addition to this, both double and triple glazing is tested at the profiles to realise the difference and, thus, the impact of the glazing. However, as it was mentioned at the assumptions in paragraph 5.4, only triple glazing is tested for the long-term scenario because of the high demands in the thermal performance of façades by the Dutch regulations. Currently the triple glazing provides a U-value of 0.7, while the double only a value of 1.1 or 1.0. However, a new type of double glazing achieves having 0.8 U-value, but it is too expensive. Thus, what the future will bring depends on the price of this double glass unit or the development of new types of insulating glazing; but until then, triple glazing is preferable. (Schrijver 2015)

What is more, for the short-term scenarios the possibility of extending the service life from 15 to 20 years is examined by refurbishing twice instead of thrice. Of course, the more refurbishments applied, the larger the environmental impact; but it is still interesting to see the difference that one refurbishment brings.

More specifically, the embodied energy and CO$_2$ emissions are calculated for the following scenarios:
a. Stick curtain wall for 15 years. All system will be torn down and recycled*
b. Stick curtain wall for 15 years. The outer part will be replaced while the structure will remain*
c. Stick curtain wall for 60 years. Refurbishment will be implemented once after 30 years of operation
d. Unitised curtain wall for 15 years. All system will be recycled at the end of its life*
e. Unitised curtain wall for 15 years. The system will be refurbished while keeping the aluminium frame*
f. Unitised curtain wall for 60 years. Refurbishment will be implemented once after 30 years of operation

The above evaluations are implemented based on the percentage (%) of the current material recovery through recycling as well as the predicted future one, in order to obtain an overview of the rate of development.

* The extra scenarios of double/triple glazing and twice/thrice refurbished are added.
b. Comparisons to be implemented

1. Comparison between the two SHORT-TERM scenarios of STICK systems (a and b)
2. Comparison between the short-term and long-term scenarios of the STICK system (c and a) (c and b)
3. Comparison between the two SHORT-TERM scenarios of UNITISED systems (d and e)
4. Comparison between the short-term and long-term scenarios of the UNITISED system (f and d) (f and e)
5. Comparison between STICK and UNITISED systems (a and d) (b and e) (c and f)
6. Comparison between DOUBLE and TRIPLE glazing for the short-term systems (both stick and unitised)*

Note: - The above comparisons will be implemented according to the present as well as the future recycling values.
- For the short-term facades, the number of refurbishments will be examined first, and then the most sustainable solution will be used for the rest of the comparisons.

* One case is selected as all the rest would be formed proportionally. For the complete tables and graphs see Appendix.

c. Formulas used

For the calculation the area of 4m high and 2.8m wide is considered from the case study building of 3mE, so for the embodied energy:

\[ Em.\ En = V \times \rho \times Em.\ En.\ prim \] (for each material)  \hspace{1cm} (1)

Where,
\( Em.\ En \) = Embodied energy of the evaluated area (MJ)
\( V \) = Volume (m\(^3\))
\( \rho \) = Density (kg/m\(^3\))
\( Em.\ En.\ prim \) = Primary embodied energy (MJ/kg)

More specifically, for the primary embodied energy

15-years curtain wall

- Stick curtain wall (a & b)

\[ Em.\ En.\ total = \sum Em.\ En \ (Al + PE + EPDM + Glazing) \]  \hspace{1cm} (2)

Where,
\( Em.\ En.\ total \) = Total embodied energy of the evaluated area (MJ)
\( Al \) = Aluminium of profile, pressure plate and cover cap
\( PE \) = PE foam thermal break
\( EPDM \) = gaskets
Glazing = 2 * Low-e glazing (for double glazing) and 3 * Low-e glazing (for triple glazing)

- Unitised curtain wall (d & e)

\[ Em.\ En.\ total = \sum Em.\ En \ (Al + EPDM + Glazing) \]  \hspace{1cm} (3)

Where,
\( Em.\ En.\ total \) = Total embodied energy of the evaluated area (MJ)
\( Al \) = Aluminium of profile, pressure plate and cover cap
\( EPDM \) = gaskets and thermal breaks
Glazing = 2 * Low-e glazing (double glazing) and 3 * Low-e glazing (for triple glazing)
60-years curtain wall

- Stick curtain wall (c)

\[
Em.\,En.\,total = \sum Em.\,En \, (Al + Nylon + EPDM + Glazing)
\]  

(4)

Where,
Em.En.total = Total embodied energy of the evaluated area (MJ)
Al = Aluminium of profile, pressure plate and cover cap
Nylon = Nylon (PA) thermal break
EPDM = gaskets
Glazing = 3 * Low-e glazing (triple glazing)

- Unitised curtain wall (f)
Same as (3)

**For the recycling embodied energy**

For the recycling process, the highest percentage of material recovery is considered in each case, while the losses are covered with primary resources. More specifically the percentage of recovery is:
- Aluminium: 47% (Manen 2015)
- PE foam: not recovered (0%)
- EPDM: not recovered (0%)
- Low-e glazing: 90% (depends on the coating: the simpler the coating, the higher the recycling rate)

For the future it is predicted to have recycling material recovery that reaches:
- Aluminium: 90%
- PE foam: 40%
- EPDM: not recovered (0%) - recycling of EPDM is still quite challenging
- Low-e glazing: 90% (no further development is expected, as the percentage is already high)

The following formulas are only about the current values, because the future ones function accordingly.

The recycling embodied energy of each material is calculated from the formula:

\[
Em.\,En.\,(r) = V \times \rho \times Em.\,En.\,recycle, \, for \, each \, material \, respectively
\]

(5)

Where,
Em.En.(r) = Recycling embodied energy of the evaluated area (MJ)
V = Volume (m³)
ρ = Density (kg/m³)
Em.En. recycle = Recycling embodied energy (MJ/kg)

15-years curtain wall

- Stick curtain wall (b)

From (1) and (5) of each material, the total embodied energy of recycling is:

\[
Em.\,En.(r)total = 47\% \times Em.\,En.(rec)al + 53\% \times Em.\,En.al + Em.\,En.epdm + 90\% \times Em.\,En.(rec)glazing + 10\% \times Em.\,En.glazing + Em.\,En.pe
\]

(6)

*al = aluminium of cover cap only
• Stick curtain wall (a)
  
  Same as (6), but al = aluminium from the complete system

• Unitised curtain wall (e)

  \[ Em.\, En.\, (r) = Em.\, En.\, epdm + 90\% \times Em.\, En.\, (rec)\, glazing + 10\% \times Em.\, En.\, glazing \]  

  \[ (7) \]

• Unitised curtain wall (d)

  \[ Em.\, En.\, (r) = 47\% \times Em.\, En.\, (rec)\, al + 53\% \times Em.\, En.\, al + Em.\, En.\, epdm + 90\% \times Em.\, En.\, (rec)\, glazing + 10\% \times Em.\, En.\, glazing \]  

  \[ (8) \]

60-years curtain wall

• Stick curtain wall (c)
  
  Same as (6).

• Unitised curtain wall (f)
  
  Same as (7).

For the end-of-life energy

The end-of-life is when the whole facade will be recycled. Hypothetically, a new system will be manufactured and thus, it is going to be the same with the recycling one.

  \[ Emb.\, En.\, (EoL) = Emb.\, En.\, (r) \]  

  \[ (9) \]

As a result, the total embodied energy required is:

  \[ Em.\, En.\, total = Em.\, En.\, prim + Em.\, En.\, (r) + Emb.\, En.\, (EoL) \]  

  \[ (10) \]

The Em.En.(r) is adjusted for each case depending on the parameter of having 2 or 3 replacements or 1 refurbishment, for the scenario of 60 years.

* The calculations for the CO₂ emissions are done accordingly.
5.7 Comparison of the results

Starting with the current condition of the double glazed systems, which will have lower environmental impact than the triple; the different comparisons introduced in paragraph 5.6 are presented. The case of extending the service life to 20 years for less refurbishment activities, and thus less energy spent, is applied; and later it will be compared with the 15 years service life to indicate the difference.

For all graphs below, the indications (a, b, c, d, e, f) from § 5.6(a) are used as well as the following icons for an easier understanding:

<table>
<thead>
<tr>
<th>Stick</th>
<th>Unitised</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>d.</td>
</tr>
<tr>
<td>b.</td>
<td>e.</td>
</tr>
<tr>
<td>c.</td>
<td>f.</td>
</tr>
</tbody>
</table>

More specifically the analysis highlights the following:

• SHORT-TERM scenarios of STICK system (a / b)
From the tables below we can see that for the stick curtain wall, recycling the complete system every 20 years requires around 27,000 MJ of embodied energy and 1,550 kg of CO₂ emissions. However, by keeping the aluminium structure we can achieve a reduction of approximately 5000 MJ. It was expected that there would be a reduction, but identifying the amount of savings to the 1/6 of the total spent is an important factor in order to awake the common consciousness.

• SHORT-TERM scenarios of UNITISED system (d / e)
The same relation is presented for the unitised system as well.

• SHORT-TERM STICK and UNITISED systems (a / d) (b / e)
Comparing tables 5.7.2 and 5.7.3, the total embodied energy and emissions required for the unitised are more than the stick either when keeping the structure or not. However the difference is small (2,000MJ). That is mainly because unitised facade uses slightly more aluminium.
Moving to the **triple glazed** systems, within this category we can analyse and compare the long-term scenarios as well as understand the difference that one layer of glass causes to the overall environmental impact.

- **SHORT-TERM scenarios of STICK system (a / b)**
  The values of the triple glazing are proportional to the double for the scenarios a and b, presenting an overall increase of approximately 7,000 MJ. For these results, it is getting clear the contribution of the glass unit for the total impact of the system. Even just one layer of glass adds 7,000 MJ to the embodied energy of the facade.

- **SHORT-TERM scenarios of UNITISED system (d / e)**
  The same difference appears also at the unitised system, because it is a matter of glazing and not of the system itself.

- **UNITISED and STICK system (a, b, c / d, e, f)**
  Table 5.7.6 presents all different scenarios for both systems giving the chance to compare not only the impact of the systems but also the scenarios within each facade system.

First of all, it is obvious that the long-term use of the facade is preferable for any system, as it has the least environmental impact out of the three cases. As it has been mentioned before, keeping the aluminium structure of the curtain wall/elements saves a respectful amount of energy and emissions. However, even the most sustainable option of the short-term service life has 5,000 MJ more energy demands than the long-term (11,000MJ when the structure is not reused).
Generally, the stick curtain wall appears to be more sustainable in all cases of service life. The difference, though, remains extremely small. Around 1.000MJ of energy and 100kg of emissions are the extra demands from the unitised facade. Because of this limited differentiation in the environmental impact, the final decision would be more dependent on the designer’s preference, the price and ease of handle and labour on site.

Constructing a new facade now means that it will need to be refurbished or replaced after at least 15/20 years. The efficiency of recycling has presented a great development the last decades and is expected to keep on progressing with a fast pace. Therefore, even though until now the values calculated contain the current percentage of material recovery, it is interesting to see the values using the expected material recovery within the next years. The results will be also compared with the present condition in order to visualise the pace of improvement in the area of recycling.

• PRESENT and FUTURE (in relation with the % of material recovery)

As the percentage of material recovery and usage in the new systems is increasing, it is predicted a great decrease in the environmental impact in the future. The materials with a great difference are the aluminium, with a rise of 43%, and the insulating plastics of PE and Nylon, which currently are downcycled and cannot be reused to such demanding applications of the construction industry. However, the intense research and technological development predict a material recovery of 40% for these plastics for the years to come. The new values are rather optimistic, but it is not unlikely to happen, especially for aluminium which has one of the highest recycling rate anyway. On the contrary, EPDM is even harder to be recycled and reused; thus the recycling rate remains to 0% for the calculations.

As a result, fortunately the future shows a decrease in the environmental impact of the curtain wall construction that ranges from ~6.000MJ (scenarios a, d) to a worst case of ~2.000MJ (scenarios b, e), depending on the system and service life applied. Generally, the long-term use presents the least improvement due to the limited materials used and wasted during the 60 years of façade’s life span. On the other hand, the short-term façades need material supplies much more often and thus appear a larger difference.

Figure 5.7.7 Present & Future - triple glazed (all scenarios)
Last but not least, the number of refurbishments influences the environmental impact of the facade. The more activities applied on the building, the more materials, energy, emissions and labour needed. Therefore, it is interesting to identify the difference appeared by extending the service life from 15 to 20 years for the short-term facade.

**NUMBER of REFURBISHMENTS**
As it was expected, refurbishing thrice the facade has larger environmental impact than refurbishing twice. The amount of materials replaced and their recyclability contribute significantly at the total values. More specifically, when keeping the structure, there is a rise of ~5,000MJ, while at the opposite scenario the rise reaches ~9,000MJ of embodied energy. The table presents the values for the stick and the unitised systems; so we can see that the rise is proportional as well as the total impact on each case.

---

**Figure 5.7.8 Number of refurbishments - triple glazed (all scenarios)**
5.8 Cost and Time analysis

The cost and time estimations are two variables that depend on the company/-ies working on a project as well as the location of the site in relation with the company. Therefore, an accurate calculation is feasible when it is addressed to a specific project, or if it includes a collection of information from many different companies across the country. For the purposes of this thesis the collection of data from the Dutch companies would be extremely time-consuming and therefore it is avoided.

On the other hand, 3mE building is used as case study throughout the research and is useful to be used for the cost and time estimation too. The building, as already presented, consists of four similar wings. The complete facade area of the one side of a wing is approximately 100m² and will be used as a reference for the estimations. What is more, the facade company Rollecate© agreed on providing information about the construction and assembly time of each system for the purposes of the research. More specifically, according to the given information, the stick curtain wall would need around 60 working hours in the factory for manufacture and assembly of the mullions and transoms, as well as 150 hours for the assembly on site of the complete area of 100m². On the other hand, for the unitised facade 100 hours are required for the manufacture and complete assembly of the elements in the factory, while only 20 hours are enough for positioning the elements on the facade on site.

Although the estimation of time might be easier, the cost evaluation is very much dependent on the current prices of the company and the agreement between the stakeholders; thus it might be not valuable to calculate the accurate values. However, at the table 5.8.1 the initial cost per referenced unit is presented for all cases, by considering only the materials. The values were retrieved from CES Edupack 2014©, which collects data from companies around Netherlands and calculates the average values. As a result, the difference between the two facade systems is extremely small with the element facade being slightly more expensive. However, the total price of the facade is relevant to the area that needs to be covered. Especially for the unitised system, the larger the area the lower the price compared to the stick. So, we can assume that the price difference will get wider for an area of 100 m², or 800 m² - if all wings of the case study are included - with the unitised system being much cheaper.

<table>
<thead>
<tr>
<th>Facade system / Primary cost (Euros)</th>
<th>double glazing</th>
<th>triple glazing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stick 15 years Service Life</td>
<td>279.30</td>
<td>392.46</td>
</tr>
<tr>
<td>Stick 60 years Service Life</td>
<td>-</td>
<td>404.59</td>
</tr>
<tr>
<td>Unitised</td>
<td>288.25</td>
<td>401.41</td>
</tr>
</tbody>
</table>

Table 5.8.1 Primary cost based on the applied materials (Edupack 2014)

In addition to this, the labour is always decisive for the expenses of a construction project. Thus, considering the working hours and the conditions in each case, the unitised facade is more cost efficient than the curtain wall. The overall working hours for the 100m² are about 120, from which approximately 100 are inside the factory; fact that ensures good conditions for the workers and no extra transportation. In this case their wages are lower than when working on site. In contrast, for the construction of the stick curtain wall, more than double time is required (210 hours) and for 2/3 of that the workers need to be on site, exposed to the environmental conditions. Thus, the labour is also getting more expensive.

All in all, the element facade is more cost and time efficient for medium and large facade areas due to the mass production of the panels and the fast assembly on site. On site, more than 50 elements can be put in place in one day. On the contrary, the same area would take weeks to be finished when using curtain wall. Considering the factor of transportation, both systems have similar demands, but the elements are quite easier to be transported on site, because it is more convenient to handle the completed panels than all smaller parts and screws. As a result, there are a lot of parameters contributing at the final choice and, of course, all of them are dependent on the project, the budget, the companies involved and, last but not least, the designer’s demands.
5.9 Applying the proposals on 3mE

The facade represents the overall impression of the building and as such the designers pay a lot of attention on the final result. The case study of 3mE stands for 60 years combing the traditional Dutch with the modern style. The brick facade has white colour and all ground floor is covered by curtain wall systems. The figure 5.9.1 represents the current facade of the building.

![Figure 5.9.1 Visualisation of current facade of 3mE](image)

The decision of applying curtain wall or element facade on the wings of the building would also influence its appearance. The two systems have different possibilities and restrictions. First of all, the curtain wall has mainly simpler design with vertical and horizontal elements which create a regular or a rather random pattern. In this case there is the possibility to span the complete height of the building or the height of just one floor by preserving the parts in-between of the white brick wall. This design solution maintains the look of the initial facade while applying a new efficient glass system.

![Figure 5.9.2 Visualisation of stick curtain wall applied on facade of 3mE](image)
On the other hand, the unitised system gives a lot more design options as it can keep the regular grid of the vertical and horizontal elements or have a completely different distribution of shapes. Triangles, rhombus, hexagons or completely customised forms are very common in this kind of facade. However, in this case the complete height of the building has to be covered removing the parts of the brick wall. A completely new appearance is given to the building. The disadvantage here is the slightly wider profile which is visible on the facade, in comparison with the stick curtain wall.

Figure 5.9.3 Visualisation of unitised facade applied on facade of 3mE

The figure 5.9.3 represents the fully glazed application on 3mE. However, playing between with opaque and transparent parts would also create interesting patterns.

As a result, both design scenarios provide highly sophisticated and efficient systems able to be refurbished so as to live longer. According to the economic program of the university and the wishes of the designer, the final decision will be made between the two analysed systems as well as a service life of 15 or 60 years.
5.10 Conclusions of chapter 5

The analysis of both stick and unitised facade systems highlighted that there is no great differentiation between their environmental impact. The stick requires slightly less embodied energy and produces less CO$_2$ emissions, but the difference can be even neglected in some cases. Therefore, the factors of cost, time and design come to the forefront for the decision making. Considering the cost and time, the unitised provides a faster manufacture and assembly process under controlled conditions and thus it is preferable.

What is more, the long-term service life is much more expensive as it requires less natural resources and energy during the complete life span of the building. Refurbishing the system once is enough to maintain the facade efficient for 60 years or even more.
Conclusions
The aim of the research was to find the most sustainable service life and construction system of curtain walls. The systems described and compared are the stick and the unitised. The description of the complete facade life cycle indicated the importance of refurbishment and whether replacing all the system or only the outdated parts (keeping the aluminium structure) is a better option. In order to investigate more on the current production techniques and systems, the industrial design was used as a reference.

The parameters defining which facade system is preferable for a project are plenty. The environmental impact, the cost, the time, the overall appearance and impression of the building are the ones studied in this thesis. The level of importance of each one depends on the designer and the individual stakeholders who set the goals and performance criteria. For the purposes of the research, the environmental impact has the most significant role, and more specifically, embodied energy and CO₂ emissions are set as indicators for the further evaluation and comparison. The rest of the factors are used in order to achieve having a more complete overview of the characteristics of each system and the preferences of the stakeholders.

Through the analysis of a short-term and a long-term scenario of service life, the outcome shows that both facade systems have similar environmental impact with the stick acquiring the first place of sustainability, even though the difference from the unitised is very small. As far as it concerns their service life, the long-term use is much more sustainable in both cases, as it requires approximately 5,000 MJ less energy than the short-term scenario where the aluminium structure is reused. For the case where the structure is recycled in every replacement the difference is even wider, reaching the 11,000MJ. Thus, the result of the evaluations is in agreement with the literature background, which supports the principle of ‘the longer a product lives, the more sustainable it is’.

Looking more into the details of the different evaluations, the type of glazing (double/triple) is of great significance because even one extra layer of glass adds 7,000 MJ of embodied energy to the facade unit. What is more, the range of replacements between two and three contributes with an amount of 5,000MJ extra energy, if the structure is reused, and 9,000MJ, when the structure is recycled; thus, if having a short-term service life, it is preferable to apply the 20-years service life and replace twice until the end-of-life of the building after around 60 years. Last but not least, the technological development of the recycling process is going to bring an increase in the percentage of material recovery and a decrease in the required embodied energy and emissions for the facade construction in the near future. Especially recycling of aluminium is improving in a very fast pace and hopefully 90% of recycled aluminium will be used in the new constructions.

Taking everything into consideration, currently there is no program considered during the design phase. The facade is designed and constructed with the goal of achieving highest thermal performance without involving characteristics, such as the durability of the elements. The curtain walls have been designed with ease of accessible and dis-/assembly, although no refurbishment has been done by now. Replacing the old system with a new one is mainly the case. From the research of this thesis, it is getting clear the importance of changing our way of thinking and constructing for a specific life span, including the principles of refurbishment and circularity.

In conclusion, despite the fact that the final decision depends on the requirements of the design and the demands of the stakeholders, the unitised system (element facade) appears to be the most preferable solution from the two compared for large facade areas (≥100m²). Even if initially we saw that it has slightly more energy demands, it needs way less time, and thus costs, to be manufactured and assembled. The workers spend most of the time inside the factory and just few hours on site, while the whole process is controlled ensuring the quality and efficiency of its performance, which should not be neglected during the overall evaluations. The savings from transportation save also a respectful amount of CO₂ emissions, fact that contributes positively towards the preference for the unitised system. So, should we continue using both curtain wall systems? Although it seems likely that unitised system is going to overwhelm the
market in the next years due to its design, manufacture and assembly advantages, the stick system will still be more preferable for smaller facade areas.

To sum up,

- Both stick and unitised facade have approximately the same environmental impact
- Unitised system provides better working conditions and saves a lot of time and expenses
- Stick system requires more time and costs and daily transportation, as most of the work is done on site
- As the environmental impact is similar for both cases, the ease of manufacture and assembly highlights the advantage of element facade
- Long-term service life should be applied on façades, always considering the possibility of refurbishing when needed
7

Recommendations/Future Research
This research should work as a step towards materialising sustainable curtain walls, and façades generally. There are many ways of continuing the research. First of all, an idea might be reconsidering the assumptions made for this thesis. For example, the façade’s performance can be taken into consideration so the materialisation will be approached in relation with the building physics and the overall behaviour of the façade. Different materials should be tested as far as it concerns their thermal properties, their environmental impact and their durability and cost. Through this method, new materials may replace the existing ones by providing a better balance between their impact and performance. Facade construction companies, like Alcoa, can significantly contribute by having experiments and evaluation tests implemented within their facilities. The combination of research and practical experience would bring the best results.

What is more, more parameters evaluated throughout the system’s service life would provide information about the weak points of the overall process. Within this concept, the material losses during disassembly, transportation or recycling would be acknowledged too. In addition to this, the comparison shouldn’t be eliminated only to curtain walls. In contrast, the different glass façades can be evaluated and compared according to the same parameters. The results will be valuable to identify the worst cases in order to improve them.

Last but not least, it would be interesting to optimise the most widely used facade systems. Their performance, cost or aesthetics make them obtain highest positions of preference, but what about their environmental impact? The optimisation can be implemented parametrically, by setting the various parameters and trying to find the best balance between the materialisation and operation stages. Some of these parameters might be the embodied energy, the durability, thermal performance, etc.
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Literature
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Conferences


Software used

Appendix
## I. Materials’ properties

### I.I General properties

<table>
<thead>
<tr>
<th>Materials/Properties</th>
<th>Density (kg/m³)</th>
<th>Emb.Energy primary (MJ/kg)</th>
<th>Emb.Energy recycling (MJ/kg)</th>
<th>CO₂ emissions primary (kg/kg)</th>
<th>CO₂ emissions recycling (kg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>2690</td>
<td>201</td>
<td>25.1</td>
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<td>1.98</td>
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<tr>
<td>PE foam</td>
<td>949</td>
<td>80.9</td>
<td>49.5</td>
<td>2.78</td>
<td>3.89</td>
</tr>
<tr>
<td>Nylon, PA</td>
<td>1130</td>
<td>121</td>
<td>42</td>
<td>7.97</td>
<td>3.33</td>
</tr>
<tr>
<td>EPDM gaskets</td>
<td>1050</td>
<td>112</td>
<td>/</td>
<td>3.97</td>
<td>/</td>
</tr>
<tr>
<td>Low-E glazing</td>
<td>2460</td>
<td>18</td>
<td>14.7</td>
<td>1.15</td>
<td>0.806</td>
</tr>
</tbody>
</table>

### I.II Thermal properties

<table>
<thead>
<tr>
<th>Materials/Properties</th>
<th>Melting point (°C)</th>
<th>Glass temp. (°C)</th>
<th>Thermal conductivity (W/m°C)</th>
<th>Max service temp (°C)</th>
<th>Min service temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>567</td>
<td>/</td>
<td>113</td>
<td>169</td>
<td>-273</td>
</tr>
<tr>
<td>PE foam</td>
<td>128</td>
<td>-19.5</td>
<td>0.419</td>
<td>99.5</td>
<td>-94.9</td>
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<tr>
<td>Nylon, PA</td>
<td>215</td>
<td>49.5</td>
<td>0.243</td>
<td>124</td>
<td>-94.5</td>
</tr>
<tr>
<td>EPDM</td>
<td>-52</td>
<td>0.336</td>
<td>163</td>
<td>-47.9</td>
<td></td>
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<tr>
<td>Low-e glazing</td>
<td>/</td>
<td>510</td>
<td>0.963</td>
<td>197</td>
<td>-273</td>
</tr>
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</table>
## II. Material recovery through recycling, currently and in the future

<table>
<thead>
<tr>
<th>Materials/Recycling recovery</th>
<th>Present (%)</th>
<th>Future (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>47</td>
<td>90</td>
</tr>
<tr>
<td>PE foam</td>
<td>/</td>
<td>40</td>
</tr>
<tr>
<td>Nylon, PA</td>
<td>/</td>
<td>40</td>
</tr>
<tr>
<td>EPDM</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Low-e glazing</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>
III. Evaluation of stick curtain wall for 15 years

III.1 Tear down and replace the complete system (a)

<table>
<thead>
<tr>
<th>Complete length (m)</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>6.8</td>
<td>0.001243</td>
</tr>
<tr>
<td>PE foam</td>
<td>6.8</td>
<td>0.000822</td>
</tr>
<tr>
<td>EPDM gaskets</td>
<td>6.8</td>
<td>0.000335</td>
</tr>
<tr>
<td>Low-E glazing *2</td>
<td>4</td>
<td>0.01</td>
</tr>
<tr>
<td>Low-E glazing *3</td>
<td>4</td>
<td>0.01</td>
</tr>
</tbody>
</table>

From Appendix I and from the table above:

Primary Embodied Energy for the considered elements:

\[
\begin{align*}
\text{Em.En.al} & = V \times \rho \times \text{Em.En.prim.al} = 4570.128 \text{ MJ} \\
\text{Em.En.pe} & = V \times \rho \times \text{Em.En.prim.pe} = 429.136 \text{ MJ} \\
\text{Em.En.epdm} & = V \times \rho \times \text{Em.En.prim.epdm} = 267.892 \text{ MJ} \\
\text{Em.En. doublegl} & = V \times \rho \times \text{Em.En.prim.doublegl} = 3542.4 \text{ MJ} \\
\text{Em.En. triplegl} & = V \times \rho \times \text{Em.En.prim.triplegl} = 5313.6 \text{ MJ} \\
\end{align*}
\]

So, \textbf{Em.En.prim.total = 8809.557 MJ}, for double glazing, and \textbf{10580.757 MJ}, for triple glazing

Recycling Embodied Energy (current data):

\[
\begin{align*}
\text{Em.En.(r)al} & = 47\% \times \text{Em.En.recycling.al} + 53\% \times \text{Em.En.prim.al} \\
\text{Em.En.(r)pe} & = \text{Em.En.prim.pe} \text{ (non-recyclable material)} \\
\text{Em.En.(r)glass} & = 90\% \times \text{Em.En.recycling.glass} + 10\% \times \text{Em.En.prim.glass} \\
\text{Em.En.recycle epdm} & = \text{Em.En.prim epdm} \text{ (non-recyclable material)}
\end{align*}
\]

Recycling Embodied Energy of the considered elements:

\[
\begin{align*}
\text{Em.En. recycle al} & = V \times \rho \times \text{Em.En.(r)al} = 2690.395 \text{ MJ} \\
\text{Em.En. recycle pe} & = 429.136 \text{ MJ} \\
\text{Em.En.recycle glass} & = 2 \times V \times \rho \times \text{Em.En.(r)glass} = 2957.904 \text{ MJ} \\
& = 3 \times V \times \rho \times \text{Em.En.(r)glass} = 4436.856 \text{ MJ} \\
\text{Em.En.recycle epdm} & = 267.892 \text{ MJ}
\end{align*}
\]

So, \textbf{Em.En.recycle total = 6345.329 MJ}, for double glazing, and \textbf{7824.281 MJ}, for triple glazing

Lastly for the end-of-life, \textbf{Em.En.(EoL) = Em.En.recycle total}

So the Total Embodied Energy, together with the CO₂ emissions which are calculated with the same way, is:

<table>
<thead>
<tr>
<th>Glazing / Replacements</th>
<th>Replace twice</th>
<th>Replace thrice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazing</td>
<td>27845.54 MJ / 1595.49 kg</td>
<td>34190.87 MJ / 1952.10 kg</td>
</tr>
<tr>
<td>Triple glazing</td>
<td>34053.60 MJ / 1956.74 kg</td>
<td>41877.88 MJ / 2396.04 kg</td>
</tr>
</tbody>
</table>

* the calculations are the same also when using the future material recovery (applying the respective %)
### III.II Reuse aluminium structure (b)

<table>
<thead>
<tr>
<th>Material</th>
<th>Complete length (m)</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>6.8</td>
<td>0.001243</td>
<td>0.00845</td>
</tr>
<tr>
<td>PE foam</td>
<td>6.8</td>
<td>0.000822</td>
<td>0.00559</td>
</tr>
<tr>
<td>EPDM gaskets</td>
<td>6.8</td>
<td>0.000335</td>
<td>0.0023</td>
</tr>
<tr>
<td>Low-E glazing *2</td>
<td>4</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Low-E glazing *3</td>
<td>4</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*Red: calculated elements

The calculation method is the same with the previous case III.I, but for recycling the aluminium structure and pressure plate are not considered; only the cover cap.

So the Total Embodied Energy and CO₂ emissions are:

<table>
<thead>
<tr>
<th>Glazing / Replacements</th>
<th>Replace twice</th>
<th>Replace thrice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazing</td>
<td>23004.26 MJ /1295.03 kg</td>
<td>26928.95 MJ /1501.41 kg</td>
</tr>
<tr>
<td>Triple glazing</td>
<td>29212.32 MJ /1656.28 kg</td>
<td>34615.96 MJ /1945.35 kg</td>
</tr>
</tbody>
</table>

* the calculations are the same also when using the future material recovery (applying the respective %)
IV. Evaluation of stick curtain wall for 60 years (c)

<table>
<thead>
<tr>
<th></th>
<th>Complete length (m)</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>6.8</td>
<td>0.001243</td>
<td>0.00845</td>
</tr>
<tr>
<td>Nylon, PA</td>
<td>6.8</td>
<td>0.000822</td>
<td>0.00559</td>
</tr>
<tr>
<td>EPDM gaskets</td>
<td>6.8</td>
<td>0.000335</td>
<td>0.0023</td>
</tr>
<tr>
<td>Low-E glazing *3</td>
<td>4</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>

From Appendix I and from the table above:

The Primary Embodied Energy is the same with the case III.I and III.II for triple glass, but PE foam is replaced with Nylon, PA which has \( \text{Em.En.nylon} = V \times \rho \times \text{Em.En.prim.nylon} = 764.266 \text{ MJ} \)

So, \( \text{Em.En.prim.total} = 10915.89 \text{ MJ} \)

Recycling Embodied Energy: only the gaskets and the glazing will be replaced, but for the end-of-life all materials are included.

So, \( \text{Em.En.recycle total} = 4704.75 \text{ MJ} \) and \( \text{Em.En.(EoL)} = 8159.41 \text{ MJ} \)

The Total Embodied Energy is:

\( \text{Em.En.total} = 23780.05 \text{ MJ} \)

and respectively for the CO2 emissions:

\( \text{CO}_2 \text{ total} = 1406.91 \text{ kg} \)
V. Evaluation of unitised curtain wall for 15 years

V.I Recycle and replace the complete panels (d)

<table>
<thead>
<tr>
<th></th>
<th>Complete length (m)</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>6.8</td>
<td>0.0014438</td>
<td>0.00982</td>
</tr>
<tr>
<td>EPDM gaskets</td>
<td>6.8</td>
<td>0.0008</td>
<td>0.00544</td>
</tr>
<tr>
<td>Low-e glazing *2</td>
<td>4</td>
<td>0.022</td>
<td>0.088</td>
</tr>
<tr>
<td>Low-e glazing *3</td>
<td>4</td>
<td>0.022</td>
<td>0.088</td>
</tr>
</tbody>
</table>

From Appendix I and from the table above:

**Primary Embodied Energy** for the considered elements:

- Em.En.al = V * ρ * Em.En.prim.al = 5308.41 MJ
- Em.En.epdm = V * ρ * Em.En.prim.epdm = 639.744 MJ
- Em.En. doublegl = 2 * V * ρ * Em.En.prim.low-e = 3542.4 MJ
- Em.En. triplegl = 3 * V * ρ * Em.En.prim.low-e = 5313.6 MJ

**So, Em.En.prim.total = 9490.55 MJ**, for double glazing, and **11261.75 MJ**, for triple glazing

**Recycling Embodied Energy:**

- Em.En.(r)al = (V * ρ) * (47% * Em.En.recycling.al + 53% * Em.En.prim.al) = 3125.01 MJ
- Em.En.recycle glass = 2 * (V * ρ) * (90% * Em.En.recycling.glass + 10% * Em.En.prim.glass) = 2957.90 MJ, or
  = 3 * (V * ρ) * (90% * Em.En.recycling.glass + 10% * Em.En.prim.glass) = 4436.86 MJ
- Em.En.recycle epdm = Em.En.epdm = 639.744 MJ

**So, Em.En.recycle total = 6722.66 MJ**, for double glazing, and **8201.61 MJ**, for triple glazing

Lastly for the end-of-life, **Em.En.(EoL) = Em.En.recycle total**

So the Total Embodied Energy, together with the CO₂ emissions are:

<table>
<thead>
<tr>
<th>Glazing / Replacements</th>
<th>Replace twice</th>
<th>Replace thrice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazing</td>
<td>29658.54 MJ /1714.59 kg</td>
<td>36381.20 MJ /2096.60 kg</td>
</tr>
<tr>
<td>Triple glazing</td>
<td>35866.60 MJ /2075.84 kg</td>
<td>44068.21 MJ /2540.55 kg</td>
</tr>
</tbody>
</table>

* the calculations are the same also when using the future material recovery (applying the respective %)
V.II Refurbish and reuse the panels (e)

<table>
<thead>
<tr>
<th>Material</th>
<th>Complete length (m)</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>6.8</td>
<td>0.0014438</td>
<td>0.00982</td>
</tr>
<tr>
<td>EPDM gaskets</td>
<td>6.8</td>
<td>0.0008</td>
<td>0.00544</td>
</tr>
<tr>
<td>Low-e glazing *2</td>
<td>4</td>
<td>0.022</td>
<td>0.088</td>
</tr>
<tr>
<td>Low-e glazing *3</td>
<td>4</td>
<td>0.022</td>
<td>0.088</td>
</tr>
</tbody>
</table>

Primary Embodied Energy is the same with case V.I, so:
So, Em.En.prim.total = 9490.55 MJ, for double glazing, and 11261.75 MJ, for triple glazing

For the Recycling Embodied Energy the EPDM and the glazing is taken into account:
So, Em.En.recycle total = 3597.65 MJ, for double glazing, and 5076.60 MJ, for triple glazing

Last, the end-of-life is the same with the case V.I, so Em.En.(EoL) = 6722.66 MJ (double glass) or = 8201.61 MJ (triple glass)

So the Total Embodied Energy and CO₂ emissions are:

<table>
<thead>
<tr>
<th>Glazing / Replacements</th>
<th>Replace twice</th>
<th>Replace thrice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazing</td>
<td>23408.51 MJ /1326.70 kg</td>
<td>27006.16 MJ /1514.77 kg</td>
</tr>
<tr>
<td>Triple glazing</td>
<td>29616.57 MJ /1687.95 kg</td>
<td>34693.17 MJ /1958.71 kg</td>
</tr>
</tbody>
</table>

* the calculations are the same also when using the future material recovery (applying the respective %)
VI. Evaluation of unitised curtain wall for 60 years (f)

<table>
<thead>
<tr>
<th></th>
<th>Complete length (m)</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>6.8</td>
<td>0.0014438</td>
<td>0.00982</td>
</tr>
<tr>
<td>EPDM gaskets</td>
<td>6.8</td>
<td>0.0008</td>
<td>0.00544</td>
</tr>
<tr>
<td>Low-e glazing *3</td>
<td>4</td>
<td>0.022</td>
<td>0.088</td>
</tr>
</tbody>
</table>

Primary Embodied Energy is the same with case V for triple glazing, so:

So, $\text{Em.En.prim.total} = 11261.75 \text{ MJ}$

The Recycling Embodied Energy is the same with case V.I, except that this time the system is refurbished only once (after 30 years of service life).

So, $\text{Em.En.recycle total} = 5076.60 \text{ MJ}$

The end-of-life is again $\text{Em.En.(EoL)} = 8201.61 \text{ MJ}$

So the values are:

$\text{Em.En.total} = 24539.97 \text{ MJ}$

and $\text{CO}_2 \text{ total} = 1417.19 \text{ kg}$
VII. Collective table (Embodied energy & CO₂ emissions for all cases)

### Embodied Energy (MJ)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Recycling cycles</th>
<th>UNITISED double glazing</th>
<th>UNITISED triple glazing</th>
<th>STICK double glazing</th>
<th>STICK triple glazing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycling complete system</td>
<td>2 times</td>
<td>29658.54</td>
<td>35866.60</td>
<td>27845.54</td>
<td>34053.60</td>
</tr>
<tr>
<td></td>
<td>3 times</td>
<td>36381.20</td>
<td>44068.21</td>
<td>34190.87</td>
<td>41877.88</td>
</tr>
<tr>
<td>Reuse aluminium</td>
<td>2 times</td>
<td>23408.51</td>
<td>27006.16</td>
<td>23004.26</td>
<td>29212.32</td>
</tr>
<tr>
<td></td>
<td>3 times</td>
<td>29616.57</td>
<td>34693.17</td>
<td>26928.95</td>
<td>34615.96</td>
</tr>
<tr>
<td>60 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refurbish once (30 years)</td>
<td></td>
<td>24539.97</td>
<td></td>
<td>23780.05</td>
<td></td>
</tr>
</tbody>
</table>

### CO₂ emissions (kg)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Recycling cycles</th>
<th>UNITISED double glazing</th>
<th>UNITISED triple glazing</th>
<th>STICK double glazing</th>
<th>STICK triple glazing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycling complete system</td>
<td>2 times</td>
<td>1714.59</td>
<td>2096.60</td>
<td>1595.49</td>
<td>1956.74</td>
</tr>
<tr>
<td></td>
<td>3 times</td>
<td>2075.84</td>
<td>2540.55</td>
<td>1952.10</td>
<td>2396.04</td>
</tr>
<tr>
<td>Reuse aluminium</td>
<td>2 times</td>
<td>1326.70</td>
<td>1687.95</td>
<td>1295.03</td>
<td>1656.28</td>
</tr>
<tr>
<td></td>
<td>3 times</td>
<td>1514.77</td>
<td>1958.71</td>
<td>1501.41</td>
<td>1945.35</td>
</tr>
<tr>
<td>60 years</td>
<td></td>
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<td>Refurbish once (30 years)</td>
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## VIII. Primary cost analysis (based on materials only)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Price (euros/kg)</th>
<th>Total length (m)</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
<th>Density (kg/m³)</th>
<th>Primary Cost (€)</th>
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<td><strong>STICK 15 YEARS</strong></td>
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<tr>
<td>Aluminium</td>
<td>1.69</td>
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<td>0.001243</td>
<td>0.0084524</td>
<td>2690</td>
<td>38.42</td>
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<td>PE foam</td>
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<td>6.8</td>
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<td>7.32</td>
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<td>6.8</td>
<td>0.000335</td>
<td>0.002278</td>
<td>1050</td>
<td>7.24</td>
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<tr>
<td>Low-E glazing</td>
<td>1.15</td>
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<td>0.01</td>
<td>0.04</td>
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<td>113.16 per glazing</td>
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*Note: The primary cost analysis is based on materials only.*