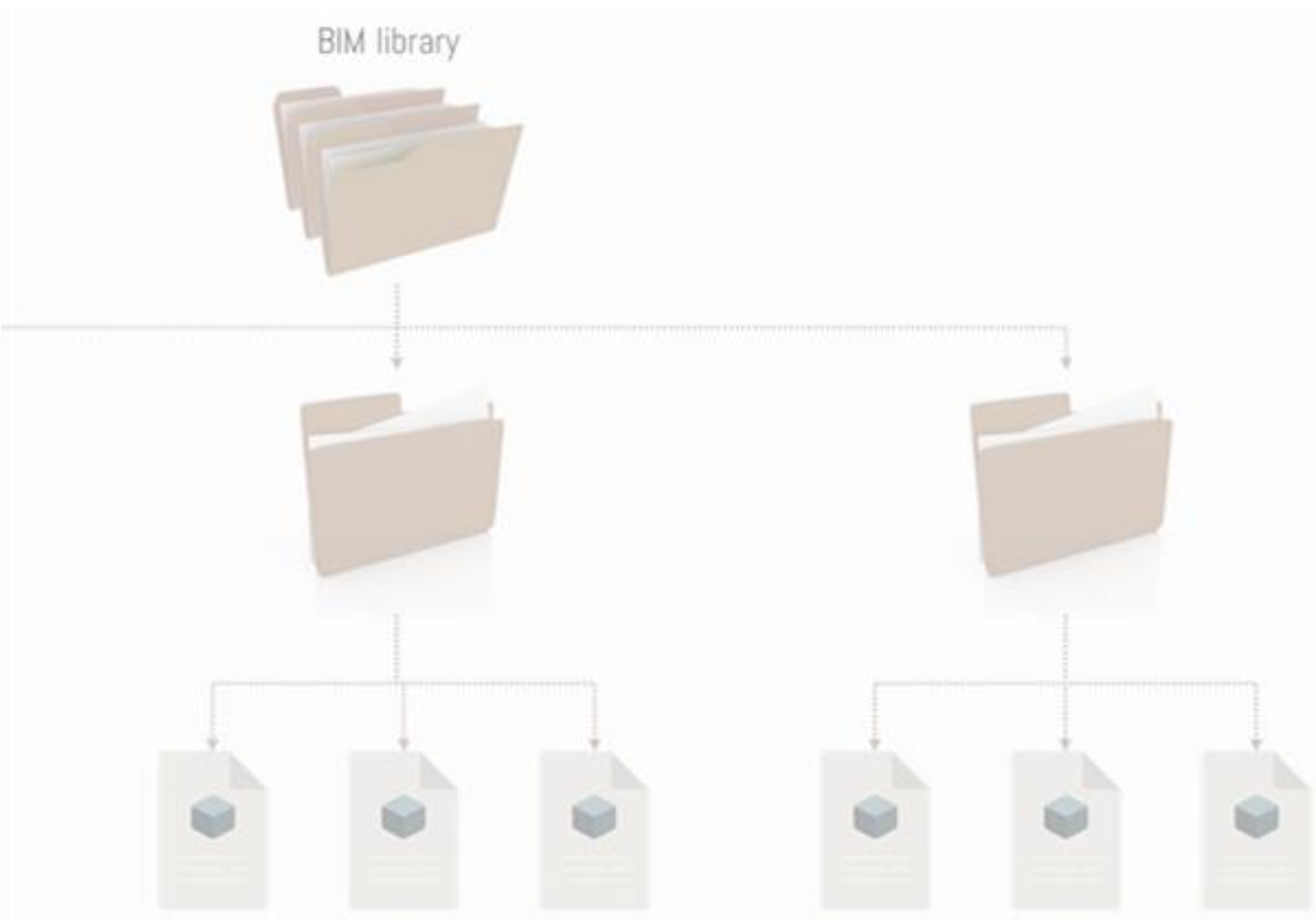
A BIM Components Library for Circular Energy Renovation Design



Title:

A BIM Components Library for Circular Energy Renovation Design

Report:

MSc Graduation Thesis | P4 LEVEL

Author:

Danai Moutou | Student number: 5354838

Institution:
Delft University of Technology
Faculty of Architecture
MSc Architecture, Urbanism and Building Sciences
Master track: Building Technology

Mentors:

1st Mentor: Thaleia Konstantinou | Façade and Product Design

2nd Mentor: Abdullah Alattas | GIS Technology

3rd Mentor: Michela Turrin | Design Informatics

TU Delft

Delft University of Technology
Faculty of Architecture and the Built Environment
01. West 110
Julianalaan 134
2628 BL Delft
The Netherlands

Acknowledgments

With this thesis, the master's period is completed, and I can confidently say that it gave me additional knowledge and tools for the future.

My interest in this subject started when I learned the concept of Circular Economy. Its great potential in bringing benefits to mitigate the negative impact of the construction industry on the environment triggered me. Combining this with my curiosity about learning about Building Information Modelling (BIM), I decided that this graduation topic was the optimum.

I would like to thank my mentors for their guidance and support. Dr. Ing. Thaleia Konstantinou and Dr. Abdullah Alattas helped me to overcome to the difficulties that arose during the research and design process. I would also like to thank Dr. Michela Turrin for her helpful comments and remarks.

Contents

Research definition

1. Introduction

1.1. Background

This study will intend to combine façade energy renovation strategies with circular design to improve energy performance and overall sustainability and circularity of the existing building stock. Circularity can help overcome the current design problems of façade energy renovation projects. Circular façade components can create high-performance results while minimizing on-site construction time. Large-scale sustainable renovation solutions should reduce CO_2 emissions by reducing operational energy and foresee savings in the material used through circular approaches to reuse components.

BIM technology can facilitate energy renovation projects by following circular design principles. More specifically, a BIM components library that will be developed is the ideal tool to promote circularity. A BIM components library can offer most of the benefits of standardization, which is the key aspect of a successful circular design and the link between CE and BIM. Also, the library can have a level of flexibility to provide solutions to renovation projects with different characteristics.

Over the last years, the concentration of CO_2 has increased due to the burning of fossil fuels, like coal and oil. The CO_2 gas creates the greenhouse effect, which results in a higher global temperature. The existing buildings stock produces the most energy-related CO_2. There is a need to rapidly improve the energy efficiency in existing buildings to reduce global energy use and promote environmental sustainability (Annex50, 2012). The goal of the European Union is to become climate-neutral by 2050 and create an economy with net-zero greenhouse gas (GHG) emissions. This is the primary target of the European Green Deal and the Paris Agreement in 2016, where the transformation of the European countries into a modern, recourse-efficient, and competitive economy with net-zero greenhouse emissions was decided.

By 2050 the goal is to reduce the emissions in the building sector by 88-91%, which is the largest of all industries, with nearly 40% of the energy-related CO_2 emissions. This can only be reached when all existing buildings become energy neutral with the deep renovation (Konstantinou, 2014).

By renovating the older building stock to nearly zero-energy buildings (nZEB) and the legislation for the new buildings, the CO_2 2050 reduction goal can be reached. However, because of the large number of facilities that must be renovated in Europe (around 170 million), the traditional renovation methods may not be ideal to ensure this transition to nZEB. Traditional renovation techniques require extensive on-site labor. There is a higher risk for errors and damages due to the difficulty of monitoring the construction process in a controlled environment (D'Oca 2018).

The minimum disturbance of the occupants during the renovation without needing them to be relocated and the minimum time and cost of the refurbishment process are essential for an efficient renovation. Prefabrication of the retrofitting components can achieve high-performance results while minimizing on-site construction time. Large-scale renovation solutions should save CO_2 emissions by reducing operational energy and foresee savings in material use through circular approaches to components' reuse. (Konstantinou, 2015).

The circular economy (CE) is a regenerative approach in which resource inputs and waste generation, emissions, and energy leakages are minimized by narrowing (through efficient resource use), slowing (by temporally extended use), and closing (i.e., cycling) material and energy loops (Ellen MacArthur Foundation, 2013; Mendoza et al., 2017). Thus, the transition to a circular built environment is critical to achieving a resource-effective and sustainable society and achieving the EU sustainable goals.

The focus is currently on waste management and recycling within the building sector. However, a central principle of the CE is first to optimize the "technological cycle" with solutions like maintain, reuse and remanufacture to prevent waste (Ellen MacArthur Foundation, 2013). Buildings' existing facade components could be replaced by "circular building components" during the renovation process. Therefore, we can gradually make the building stock more circular and sustainable. Moreover, if the refurbishments to the existing buildings only target the nZEB and not the circularity, they will help reduce the built environment's operational impact but can significantly add to the embodied impact (Ibn-Mohammed et al., 2013; Pomponi, 2017). Developing circular building components for facade retrofits can reduce operational energy resource-effective.

The design phase plays a crucial role in ensuring resource efficiency (Malmqvist, 2018). Waste prevention in the design phase is being considered more, with many studies focused on waste management, resulting in well-established high recycling rates of construction and demolition waste within the industry; however, with low value due to down-cycling (Adams, 2017). More economically and environmentally beneficial use of recovered building materials is the direct reuse of materials and components, which requires minimal energy consumption than the energy and material resources needed for material recycling (Akanbi et al., 2017). The most economically and environmentally impactful CE within the built environment can be achieved by a high degree of reuse material recoverability. CE requires a design in which buildings are considered a composite of components, parts, and materials with multiple uses and life cycles.

Design for disassembly, prolonging the service life of the building components through reusing them in other building projects, is the optimum solution. There is a need for innovative design strategies that consider future demolition and provide flexible structures. Industrialized, standardized, flexible, and demountable systems can create buildings with higher quality and adaptability and overall better environmental characteristics.

A standardized and flexible system can improve the facade renovation to result in a faster, more economical, higher quality, and environmentally friendly building than traditional renovation methods (Sadafi, 2012).

The design for disassembly aims to reduce the consumption of materials, cost and waste in the construction, renovation and demolition. Moreover, it increases the service life of buildings while making them material banks for the future (Heinlein, 2019; Guy, 2005). Material recovery can maximize economic value and minimize environmental impacts by reusing, repairing, remanufacturing, and recycling (Ellen Macarthur Foundation, 2017; Mule, 2012).

However, the European building sector has not yet been able to devise a structural, large-scale renovation process and systematic approach. Many facade solutions have been developed in recent years to solve the problem of a large-scale renovation (Sijpheer, 2016). Most of them result in individual building measures. They are pilot projects and are based on a customized application. There is cost and time saving by making an approach suitable for more than one different building typologies.

Building Information Modeling (BIM) is a tool that can contribute to overcoming the current difficulties of circularity applications and achieving an efficient design of a circular, standardized, prefabricated system for energy facade renovation.

BIM allows design and construction teams to work more efficiently and obtain the data needed to benefit operation and maintenance activities. BIM software is ideal for making complex components that can be standardized and prefabricated off-site. This can save time and money as on-site construction demands less time. Additionally, there are more opportunities to design flexible, modular components that fit together, with the necessary tolerances and create an adjustable façade system.

BIM is an overall process of creating and managing information about buildings. Based on intelligent models and supported by a cloud platform, BIM combines interdisciplinary data to create digital representations of buildings throughout their entire lifecycle, from planning and design to construction and operation. More importantly, from this study, BIM technology can be a valuable tool for storing and managing component performance information for future reuse. Moreover, BIM finds a crucial role in considering sustainability in the design. Over the last years, it has become a priority to recognize the contribution of BIM the efficiency of sustainable projects. With useful tools and features, BIM develops construction process f through a sustainable purchasing system (Goyal, 2020).

On top of this, sustainability initiatives are being viewed as extra work because the potential profits are not visible to the stakeholders. A clear business case is a strong motive for all stakeholders of the supply chain. However, they focus on short-term goals and benefits like short-term profit, which does not benefit long-term perspective goals such as sustainability (Popa, 2019). However, long-term investment and partnership could mean long-term savings by working together to maximize the collective gain. A designing tool that is easy to use and can facilitate circularity and make the end result visible from an early stage could be the solution to the stakeholders that are still arguing about CE feasibility and profitability.

The study by Ganiyu et al. (2020) identifies several key areas where automatic clash detections, design error reduction, early stakeholder cooperation, visualization, simulation of waste performance, and waste management reporting are just a few of the BIM characteristics that could aid in attaining the circular economy in construction. (Ganiyu et al, 2020). Also, BIM is often referred to as a 3D model where all information is stored.

If BIM is already in use with library specifications and required tolerances, the architect can already use it at the design phase. This will help in a faster decision making, whilst analyzing the options available at the table with a larger, long-term picture of sustainability. Smart features are included in BIM-designed objects. For example, a window recognizes that belongs in a wall and have properties connected with it, such as size, composition, and maker. BIM software is a natural choice for pursuing a CE in the building sector because of its tremendous processing capabilities. The manufacturer's warranty, spare parts, and physical load attributed to each object can all be stored within the building model, and this information can be linked to the object's service life.

Summarizing, energy renovation, circularity and BIM technology are three different topics that this thesis will try to combine to strengthen the sustainability of the built environment. As mentioned above, the design of the optimum components for energy renovation can be supported by the principles of circular design and create an even more efficient end product. BIM technology and more specifically a BIM library can be used as the ideal tool to promote circularity.

In every step of the process, early engagement and collaboration are crucial. BIM can help in this regard, as it is the only technology-driven solution that can support digital design and production procedures. From a technological point of view, the suggested BIM components library is perfectly suited to circular design that focuses on standardized components, to enable mass production. Standardization is the key aspect for a successful circular design and the link between CE and BIM. As a result, this library facilitates automation while still being adaptable enough to allow for some customization. A component-based library can offer the majority of the benefits of standardization and also a degree of adaptability.

The aim of the thesis is to investigate how the CE concept is currently interpreted and operationalized within the practice of energy renovations and explore what tool might further support the design for a CE.

1.2. Problem statement

A very large percentage of the European residential building stock is aging and does not meet the required energy efficiency standards. The requirement to make short-term energy upgrades on these buildings in order to enhance performance and comply with existing rules poses a significant problem. Consistent approaches are needed for large-scale application of suitable technologies in crucial points such as the façade to save energy, time and minimize cost by guiding designers to the use of the ideal design strategies.

The design of each building is based on different design principles, energy demands and users' needs. Thus, the need to renovate almost 90% of the European existing building stock, creates a big challenge for the current construction sector as there is no standard way to approach the number of the existing buildings in need of energy improvement (Vovos, 2021).

The costs of deep energy renovations are often as high as the costs of demolition and constructing new buildings (De Groote, 2016). Up to now, most renovation projects use customized prefabricated façade systems for nZEB renovation, which is not the most efficient approach. On the other hand, prefabricated façade components with fixed dimensions are unlikely to fit into the existing buildings due to the different dimensions between the buildings. The existing state-of-the-art prefabricated façade systems cannot solve this problem because they are customized solutions that do not aim for mass production (Sijpheer, 2016).

Moreover, the construction sector represents one of the most significant sources of waste generation in the EU, with nearly one billion tons of construction and demolition waste annually. This sector also contributes a third of the annual EU GHG emissions (Benachio et al., 2020). Accordingly, construction represents one priority area for intervention within the EU Action Plan for the CE. Increasing resource efficiency through slowing, closing, and narrowing material and energy loops, is key to moderate climate change (Gallego-Schmid, 2019).

According to the Ellen MacArthur Foundation, the CE approach involves three important aspects "designing out waste and pollution, keeping materials and products in use, and the regeneration of natural systems" (MacArthur Foundation, 2013). However, several authors have raised the difficulty of having a common definition of the CE concept (e.g. Lieder and Rashid, 2016; Yuan et al., 2006). This led some authors to revise the CE definition based on an extensive literature review (Geisendorf, 2018). Their findings are that "the circular economy is most frequently presented as a combination of reduce, reuse and recycle activities" and that "the main aim of the circular economy is considered to be economic prosperity, followed by environmental quality". Their findings also highlighted the lack of consideration for the systematic shift required for the adoption of the CE approach (Kirchherr et al., 2017).

In general, the overall concept of CE is complex, and it includes business, technical, life cycle, legislation and other aspects that all are connected. The literature for the circular design, which focuses also on many other things, such as material selection and use, product attachment and trust, does not discuss much about the design process and details of technical design in CE. Design as a general concept is used loosely in the context of CE. How the requirements are set and what responsibilities the designer is expected to have blur the boundaries between technical design and other operations, such as business and service planning and the models they are based on (Zeb, 2021).

The question that arises, therefore, is whether the available design knowledge, tools and methods sufficiently support design practice in tackling the complicated challenges encountered in practice, which often require interdisciplinary collaboration and co-creation. To date, most studies have been theoretical and conceptual. There has been a lack of empirical investigation into how the concept of circularity is interpreted and implemented in practice by designers, particularly case-based evidence in which both the contexts of design and business are considered (Dokter, 2021).

There are many gaps in the existing circular design frameworks. Most authors recognize the need for a systematic, and integral approach but, very few provide such frameworks. There is a still a lack of detailed frameworks that conclude to specific design options (Bocken et al., 2016; Leising et al., 2018). Finally, industrial parameters are insufficiently considered in the current construction industry, clear guidelines on how to apply the concept of the CE are still to be fully developed (Vovos,2021).

According to Jawahir and Bradley (2016), the technologies required for the long-term application of circular economy have not yet been adequately considered. (Jawahir, 2016). Thus, a significant gap must be bridged between limited supply and high demand for innovative circular technologies in order to achieve the benefits of the circular economy. Nevertheless, this transition to a circular economy requires, assessment and designing tools that can support circularity from an early stage, whose development is still at an early level of development (Malabi, 2021).

In parallel to the development of the CE, the use of building information modelling (BIM) has gained traction worldwide (Charef et al., 2021) and many countries have established standards and guidelines for the implementation of BIM. The development of digital technology has led to a whole revolution in the manufacturing industry. The goal is to achieve much efficient processes combined with high environmental respect and quality.

Designing a sustainable renovation for the existing buildings requires a comprehensive and systemic management approach of the buildings' characteristics and the design parameters. Renovation components and techniques should have higher level of standardization, and digital and automation capabilities should be created.

BIM can support and promote circularity in the building environment and especially in the energy façade renovations, but it hasn't been fully used yet for that purpose. Some studies have looked at the use of BIM for waste reduction, or the management and minimization of construction and demolition waste. Other studies have attempted to link CE to BIM to collect data on building materials characteristics and assess their circularity (Rahla, 2012). But there are no studies that explore the possibilities of the implementation of BIM technology in the design stage of a project to promote circularity and create a group of data management that can provide the designers with the necessary information for circular, prefabricated components specifically for energy façade renovation with a flexibility to fit in different building needs and typologies.

Concluding, after a presentation of the above general problems about energy renovation, circularity and the use of BIM to promote them that need to be addressed, the **specific problem of the thesis** that combines them all is the lack of a standardized prefabricated circular facade system that can be adjusted and flexible. Additionally, a BIM tool that can facilitate a circular renovation design haven't been developed yet.

1.3. Research question and sub-questions

Based on the Background and the problem statement the research question and the sub-questions are defined.

Research question:

- How can a **BIM components library** facilitate the design of a **circular standardized facade renovation system** that meets the **energy-saving measures,** and it is **adjustable**?

Sub-questions:

In more detail, the research question will be divided into three topics:

- Energy renovation
- Circularity
- BIM technology

These areas will be analyzed separately and combined, and their common aspects will be highlighted and merged in order to create the optimum design solution for the circular renovation façade system. The sub-questions below are divided per topic and there are also some additional sub-questions that combine and connect two or more topics.

- Energy renovation:
  - What are the strategies of an energy renovation?

- Circular Economy:
  - What are the circular design principles for the components?

- Additional:
  - What flexibility of the components is needed?
  - How can a BIM technology support circularity and sustainability in the design phase of the facade renovation?

- BIM technology:
  - What are the characteristics, the structure and the end format of the BIM library?
  - How can a BIM library suggest the optimum design solution based on each building characteristics?

1.4. Research objective

Design a **circular components library,** with **BIM software** that could provide design solutions for the design of **energy façade renovations.**

The design will be for renovations of existing buildings with new components that will be retrofitted.
The library will consist of some standardized components, as core elements, and their different configurations, so the final façade system will be adjustable to many different buildings. The library will provide the designers with all the information for the design and construction of the components.
The main focus of the design will be on the management of the data and the structure of the BIM library.
The main research question will be answered with the application of this BIM tool that will be developed and throughout the process of the development of this tool.
The final façade system provided from the library will be depended on the **characteristics of the building** that it is going to be renovated. Thus, the way that those characteristics will be used from the library to provide the designer with the optimum design solution, in terms of adjustability to each project, will be also developed.

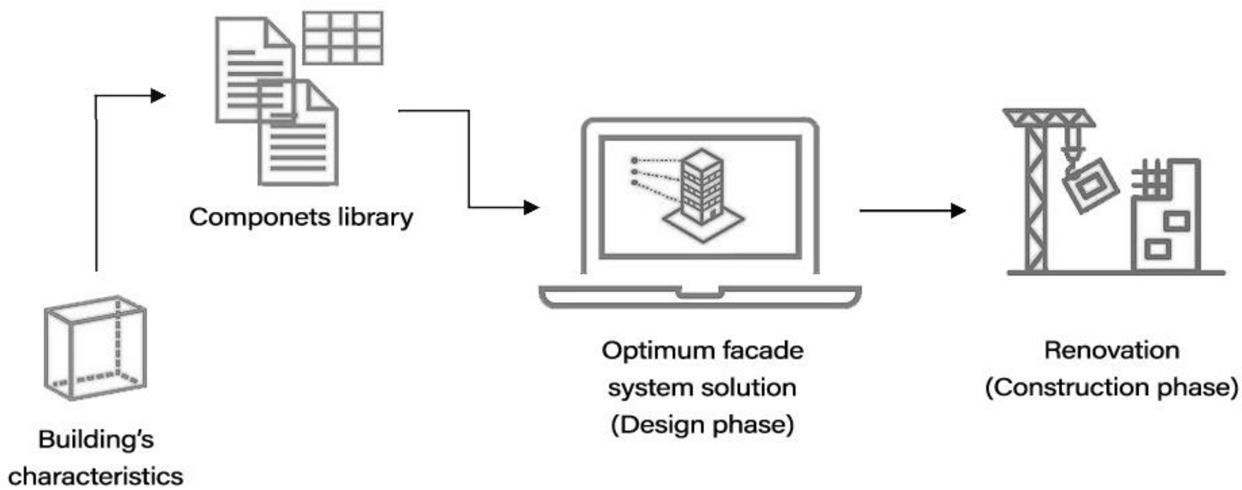


Figure 1: Diagram for the input and output of the design phase

1.5. Scope of research

The scope of this research focuses on the design of a circular BIM components library for energy renovations. The main focus will be to create an adjustable and flexible façade system based on the circular components of this BIM library that could be mass-produced and easy to apply.

This research focuses on the circularity of the components during the design phase (the design principles and criteria, materials, flexibility, production and construction). The reason is that the design phase offers room for changing and adapting the building characteristics and process. The research focuses on the existing building stock of Europe and especially on the residential buildings thus there are the ones that have to most urgent need for energy renovation because of their energy consumption (24% for residential, 8% for commercial buildings) (IPCC, 2015).

According to Brand's layers diagram, and as it will be analyzed below, there are six different building layers (site, structure, skin, services, space plan, stuff). This thesis will focus on the envelope, thus the skin layer of the building (Brand, 1994).

Moreover, the research investigates the additional information from the building that is going to be renovated. This information needs to be applied in the design phase along with the components library to extract an efficient output from the design phase.

The BIM library will be designed in such a way so it can be applied to several energy renovation designs. However, because it will be impossible to apply the system in every building, a case study has been selected to validate the final result.

There are some limitations of this thesis because of the current level of application of CE. Most of the studies use literature review as their methodology. The fact that they do not use case studies as research methodology can result in the lack of understanding of the implementation strategies, barriers, challenges, and benefits of circular economy in a construction project. Additionally, there is still a lack of information regarding circular economy in the construction industry. Circular economy is a new concept trying to be implemented, therefore not many studies can be reviewed for theoretical background.

A complete renovation design strategy needs to have solutions for the outer cell of a building, which includes the façade, the roof and the balconies. However, the focus of the thesis will be only in the façade of the existing buildings due to time limitations and the attempt to develop more a tool and a methodology than a complete solution.

1.6. Methodology

In this thesis a design-based research approach is adopted to answer the research questions that are defined in the **introduction** phase. The **research** phase consists of six main parts:

Part 1: Literature review and evaluation
Part 2: Data collection and current practices research
Part 3: Design methodology formulation with the requirements and generic design tools and principles
Part 4: Finalization of the design
Part 5: Verification of the design with its application in a case study

Regarding Part 1, this research selects and evaluates the literature on three fields of study: The Energy Renovation, the Circular Economy, and the BIM technology. The information has been obtained through "Google Scholar".

Then in Part 2, the necessary data are collected and the current practices in circular energy renovation are analyzed.

Afterwards, during Part 3, the retrieved knowledge of the literature and the analysis of the current practices contribute to formulate a design methodology consisting of a list of necessary requirements and generic design tools, principles and criteria.

Based on the design by research methodology, in Part 4 the final design of the circular BIM components library is formulated. Furthermore, the final design is applied in the selected case study situation for further elaboration.

The last part is Part 5 where the final design and its application are evaluated according to the set of criteria to formulate a final answer to the research question. The validation through the case study will be achieved with the necessary analyses to identify the level of circularity, the energy savings and mainly the efficiency of the adjustability of the designed system. Essentially, the main research question will be answered through the above process and with the application of the BIM tool that will be developed.

Conclusion & Reflection: After completing the research parts conclusions can be drawn about the applicability of the circular BIM components library for energy renovation. Recommendations are given on approach improvements and any possible future research. Also, a reflection on the process and the result of the research is presented.

The following diagram shows the steps that are going to be made to conclude to the optimum end result.

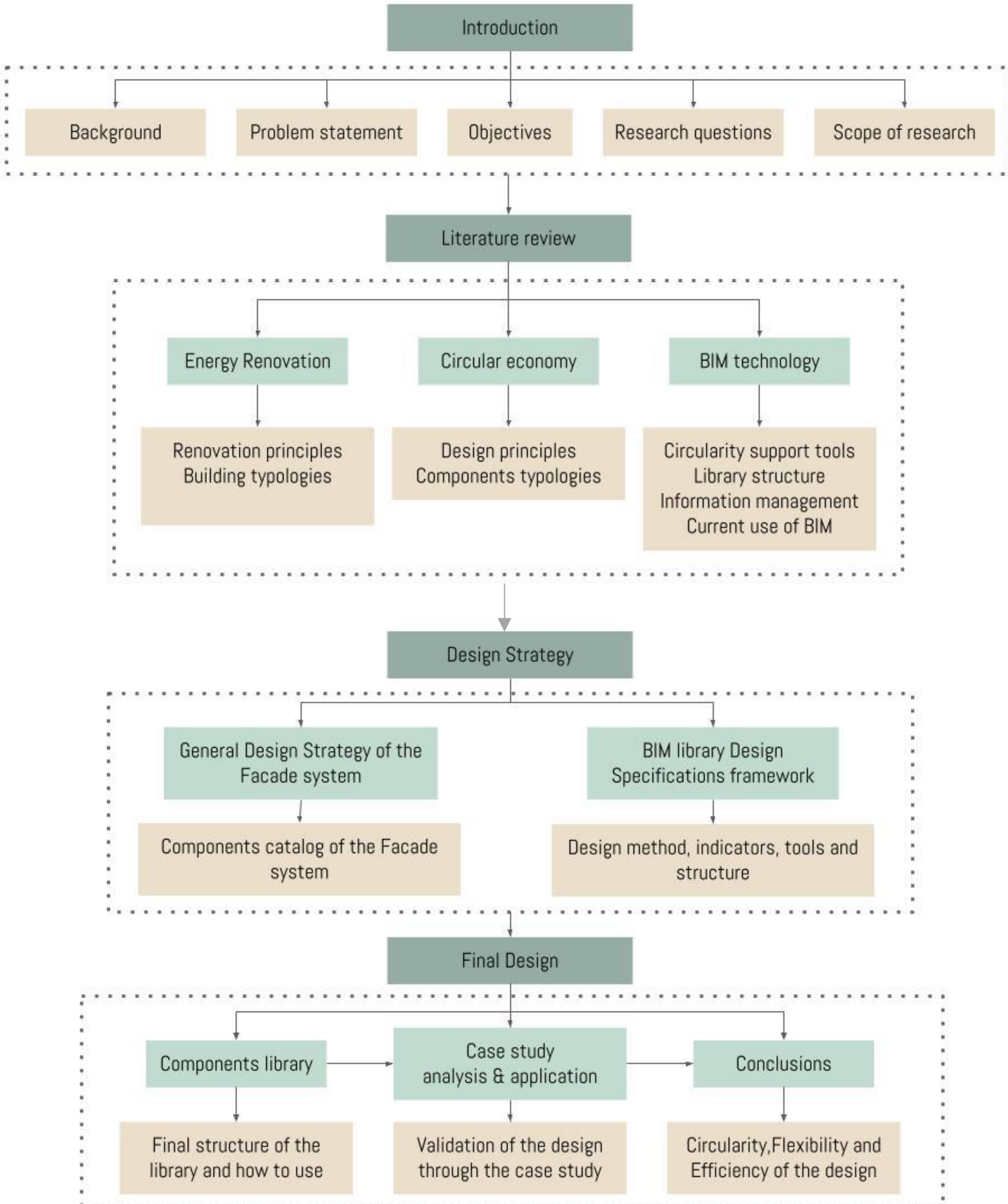


Figure 2: Diagram of the methodology steps that are going to be followed

Literature review

2. Energy renovation

This chapter will answer the following sub-question:

- What are the strategies of an energy renovation?

Over the last years the concentration of CO_2 has increased due to the burning of fossil fuels, like coal and oil. The CO_2 gas creates the greenhouse effect, which results in a higher global temperature. There is a need for a rapid improvement of the energy efficiency to achieve a reduction in the global energy use and promote the environmental sustainability (Annex50, 2012). The goal of the European Union is to become climate-neutral by 2050 and to create an economy with net-zero greenhouse gas (GHG) emissions. This is also the goal of the Paris Agreement in 2016 where it was decided that the countries of the EU would be transformed into a modern, resource-efficient, and competitive economy with net-zero greenhouse gas emissions.

By 2050 the goal is to reduce the emissions in the building sector by 88-91%, which is the largest of all sectors with nearly 40% of the energy-related CO_2-emissions in Europe. Buildings consume energy directly due to their operation along their lifespan, and indirectly due to the embodied energy in the materials and components. Energy use has been a widely used measure of the environmental impact of buildings and the most important parameter to optimize because of its global significant impact (Andrade, 2019). This reduction in energy consumption in the building sector can only be reached when all existing buildings become energy neutral with deep renovation (Konstantinou, 2014).

There is no common definition for "**deep renovation**". All projects, however, share certain basic characteristics, such as a desire to raise the bar for accomplished energy performance, maintain consistency between short- and long-term measurements. A deep renovation can lead to energy savings of 60-90% (Konstantinou, 2014). An energy renovation market is emerging in Europe and playing a strong role as a stabilizer of the building sector and consequently of the European economy.

Conejos (2014) claims that the largest portion of natural resources savings as well as the minimization of the environmental impacts are in retrofitting and redeveloping existing buildings rather than producing new energy-efficient buildings (Conejos et al., 2014). There is a shift in thinking in the perception of sustainable building design in the last years, going from a creative and innovative approach to a restorative and regenerative one. The main reasons of this change are founded in the fact that an enormous proportion of all the materials ever extracted in human history are in today's built environment and that the understanding of the real value of this built environment in terms of sustainability has improved through technological development and research.

More than the 75% of the European building stock has been built before 1990, i.e. before the introduction of the first energy performance regulations in several EU countries (Häkkinen, 2012). Residential buildings account for the biggest segment of this stock and are responsible for the majority of the sector's energy consumption. Within the existing European stock, a large share (more than 40%) - widespread in urban areas - is built before 1960s with low insulation levels and old and inefficient systems (BPIE , 2011).

The refurbishment of the existing building has several advantages. First of all, the construction impacts are reduced, because the building demolition is prevented. Also, the material costs and embodied energy impacts are lower because less materials are used. Additionally, refurbishment is feasible within shorter period of time. Moreover, the minimum disturbance of the occupants during the renovation, without the need of them to be relocated and the minimum time and cost of the refurbishment process is important for an efficient renovation. Moreover, the price of materials extraction is increasing as are the negative environmental impacts due to the natural constraints of the limited stocks of ores and other resources. Thus, the research in sustainability in construction has focused on emerging themes such as durability, adaptability, design for the environment, design for deconstruction, closed materials loops and dematerialization (Kibert, 2007).

Prefabrication of the retrofitting components has the potential to achieve high performance results while minimizing on-site construction time. Large-scale renovation solutions should save CO_2 emissions, through reducing the operational energy, but also foresee savings in the material use, through circular approaches to components' reuse. (Konstantinou, 2015).

Besides the fact that residential buildings are the biggest segment of the building stock that is responsible for the majority of the sector's energy consumption, there are additional reasons to choose the refurbishment of residential buildings as the most urgent task (Konstantinou, 2014):

- **Functional shortcomings** like each residence size and floor plan arrangement, depending on the occupants' needs and the family size. Also, research has shown that the average space needed for each person in residential buildings has increased (Andeweg, 2007).
- **Financial motives**, because a facade renovation will increase the value of the residential building (Appleby, 2013). Consequently, the rents will raise resulting in restructuring the socio-economic group living in the residential buildings. Thus refurbishment is a way to regenerate social problems of a residential building or a whole area.
- **New legislations** and **requirements** for the energy efficiency of residential buildings, that have been established to achieve the 2050 sustainable goals. E.g., in the Netherlands the residential buildings must have an energy label (from A to G). This way the government wants to motivate the landlords to improve the energy efficiency through refurbishment and if they do so the government provide them with financial support.

This project will develop a tool for circular energy refurbishment of building envelops. The methodology and process are based on the premises that:

- Façade refurbishment is one of the most efficient ways of reducing environmental impacts of European building stock.
- European building sector is facing huge needs of renovation; façade refurbishment is among the most urgent tasks.
- Although there are some technological solutions, optimal solutions are still not fully developed.
- External walls have an extensive effect on building performance and several aspects must be considered when developing new concepts.

2.1. Energy Renovation Strategies

As already mentioned, a significant portion of Europe's residential building stock is aging and does not meet current energy criteria. The need to complete short-term and long-term energy upgrades on these buildings to improve performance and meet current regulations forms a big challenge (Ochoa, 2015). For mass application of feasible technologies in essential building parts like façade, consistent design methods are required. These methods can save time by creating and suggesting efficient and economical design techniques for each case.

A wide range of retrofit technologies are available, and several studies have been carried out in order to identify optimized solutions in consideration of the cost-effectiveness, the improvement of energy performances and indoor comfort (Ma, 2012). Because of the age of the European building stock and the new regulations for improving the energy performance of the existing buildings, there is a need of extensive solutions for the renovation of the envelops as they offer a great potential of energy saving.

SUSTAINABILITY ASPECTS

It is defined that the overall sustainability of the developed concepts and technological solutions of the project has to be assessed considering the following aspects (Haase, 2020):

- Durability and buildability
- Impact on energy demand for heating and cooling
- Impact on renewable energy use potential and on daylight
- Environmental impact of manufacture and maintenance
- Indoor air quality and acoustics
- Structural stability and fire safety
- Aesthetic quality and effect on cultural heritage
- Life cycle costs and need for care and maintenance
- Disturbance of the tenants and of the site

Considering the above general sustainability aspects, at the beginning of every renovation project a proper strategy must be defined. There is a wide variety of functional and energy efficiency challenges that the building industry has to solve. The renovation strategies can be divided in five main methods (Konstantinou, 2014):

1. Replace

One of the most common methods of refurbishment is the replacement of the existing façade. The original façade is completely removed and a new façade that has better energy performance is applied. The replacement can also happen only in specific components, e.g. the windows.

2. Add-in

This method is generally applied when the existing façade must be preserved e.g., due to the building's monumental value. With this method the interior surfaces are covered with insulation. This strategy is often accompanied with the replacement or improvement of the windows from single to double/triple glazed.

3. Wrap-it

This method uses a second layer around the external surface of the building. This second layer can incorporate insulation, cladding of the balconies or second façade. The main advantage is that it can solve any thermal bridging by increasing the thermal resistance of the envelope.

4. Add-on

The add-on method consists of a wide variety of upgrades that can be applied. A common example of an add-on is a solar buffer space as a passive measure for the indoor comfort e.g., second skin.

5. Cover-it

This method is mostly used to create internal courtyards and atriums in the buildings. It is common to cover these spaces by using transparent surfaces in order to increase heat gains while at the same time allow the direct sunlight to reach the interior when it is needed.

The Replace method seems the most adequate for this study in order to achieve the desired energy savings. However, the suitable method or methods for this study's façade system will be selected in the next phase (design strategy) where all the parameters will be gathered and there will be created a clear overview of the right potential approach.

Renovation projects, have unique characteristics (e.g., existing assets and operations) and are subject to construction uniqueness. Additionally, minimizing the time of the renovation, the energy loss during the construction and the on-site labor are very crucial aspects for the efficiency and the sustainability of the design. The solution is the design for mass production with the use of prefabrication, industrialization and digitalization of the façade renovation process and the façade system.

PREFABRICATION

Prefabrication describes the production of modules in a controlled environment like a factory. The prefabricated modules can then be transported to the construction site and installed in a relatively short period of time without the need of extent on site work and assembly.

INDUSTRIALIZATION

The primary motivation for an industrialized renovation of buildings includes reducing construction time and cost and improving delivery and quality of the end-product. Also, industrialization helps to address construction uniqueness. It is a building system that is enabled by product and process standardization and supported by repetition, continual learning, and experience feedback. (Bertelsen, 2004).

DIGITALIZATION

Digitalization has been gradually implemented for designing, constructing, and operating buildings and infrastructure assets. One of the digitalization tools that keeps on getting popularity and has done some major developments is BIM. As a digital tool, BIM is a modelling software for the planning, design, construction, and operation phases of a building project. Except from the visualization, BIM is known for its efficiently data management throughout the building lifecycle with all stakeholders involved from the early design phase (Abrishami, 2021).

2.2. Components parameters for an Energy Renovation

According to Knaack (2007), the common functions of a façade are (Knaack, 2007):

- Natural lighting
- Waterproofing
- Protection against UV radiation
- Energy Generation
- Ventilation
- Push and pull forces from wind loads
- Vapour diffusion
- View out
- Interior loads
- Noise
- View- in
- Heat cold insulation
- Appearance of building
- Self-weight

When it comes to the components of an energy façade renovation system there are several elements that need to be used to achieve sufficient energy savings and fulfill the needs of façade functions.

Element	Description	Design principle
Insulation	Material with high thermal resistance that opposes the transfer of heat between areas at different temperature	Heat protection
Glazing	Transparent material provides visual connection daylight	Heat protection Passive solar heating Sun protection
Window frames	Components for fitting and operation of glazing	Heat protection Ventilation
Sealants	Material used to seal the building fabric and prevent uncontrolled air and water flow	Heat protection/ air tightness Weather proofing
Finishing-cladding	Material of the final rendering, give final impression	Protect the construction underneath Heat protection/ air-tightness

Figure 3: Overview of elements used in the building envelope energy upgrades (Konstantinou, 2014)

However, the final composition and order of the layers of the components are depended on several climate and energy performance parameters. The **climate** characteristics of the design location are crucial for the identification of necessary elements of the façade components. Similarly the **energy saving demands** and approaches will define the design of the components.

CLIMATE

As already mentioned, the scope of this study will be limited in Europe. There are many the differences in the weather conditions across Europe, such as temperature, humidity and solar radiation. The most widely used general climate classification to categorize the different climates is the Köppen-Geiger system. Most of the counties in Europe belong in the **mild cold climate** condition which is generally the north-central countries, following by the **mild warm climate** with the southern countries (Vovos, 2021). Over the last years, the demand for cooling has been increased and the demand for heating has been decreased in Europe, even in northern countries with colder climate (Vovos, 2021).

The percentage in energy consumption for heating in southern Europe is generally less than the northern countries during the winter period because of the warmer climate. However, according to BPIE survey buildings built in 1950s in south countries have an average consumption for heating similar with buildings of the same period in north countries which means that the energy performance of these buildings are not sufficient for both climates (Vovos, 2021).

DESIGN STRATEGIES FOR nZEB

In terms of comfort, there are several main comfort requirements (*Table 1)* that are independent from the climate conditions of the location of the building.

Temperature range (^oC)	20-25 (for heating)	23-26 (for cooling)
Humidity	60-25 (relative humidity, %)	
Indoor air quality (Air flow)	7 l/s/person	0.7 l/s/m2 (external envelope)
Lighting	100-200 lux (illumination level)	2-5% (daylight factor, DF)
Noise	20-40 (sound pressure level, dB(A))	

Table 1: Benchmark comfort requirements (Konstantinou, 2014)

However, buildings in different climates have different design strategies for nZEB. The climate conditions that mainly affect the building energy consumption:

- external air temperature
- wind velocity and direction
- solar radiation
- Infrared radiation.

If we consider the above mentioned mild warm and cold climate as the main general different climate zones in Europe some general nZEB strategies for the buildings in each climate can be set (Vovos, 2021):

Mild warm climate:

- Insulation
- Energy efficient transparent surfaces (with very low to low U-value, medium to high solar heat gain coefficient (SHGC))
- Operable and movable shading systems to prevent summer over-heating
- High thermal capacity
- Balanced ventilation with heat recovery

Mild cold climate:

- Insulation
- Limited fenestration area
- Glazing with very low SHGC
- Wind shields
- Shading from direct sunlight in summer
- Heat recovery ventilator to ensure indoor air quality
- Solar powered AC equipment (day-time cooling)
- High thermal capacity

A concept that follows the environmental principles and design is the "**Trias Energetica**". This strategy is the most commonly used to ensure that sustainable measures are implemented efficiently. The bellow scheme illustrates three steps that rank the sustainable criteria for the building industry. The first step is the reduction of the energy demand. The second step is the use of sustainable, renewable energy sources as much as possible and the third, if still more energy is needed, is the use of fossil fuels as efficient as possible (Konstantinou, 2014).

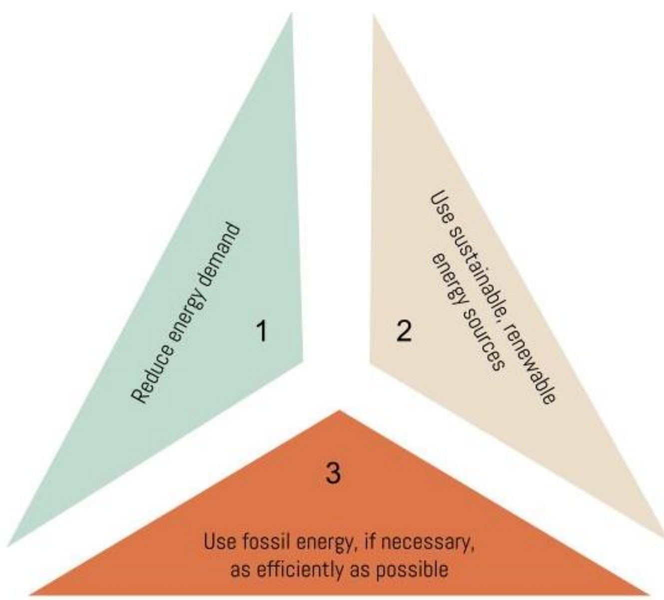


Figure 4: The "Trias Energetica" principles

The Trias Energetica concept includes two types of measures that have to be used during a renovation of a residency, the **passive** and the **active**. Passive measures make use of the design and the properties of the building envelope in order to keep the indoor climate in the comfort levels. The active measures are all the systems such as heating and cooling systems or solar power technologies and are used to fill the gap where the passive measures cannot achieve the desired comfort (Konstantinou, 2014). The *Table2* below gives an overview of these measures in conjunction with Trias Energetica steps.

1.Reduce energy demand			2.Use sustainable, renewable energy sources			3.Use fossil energy as efficiently as possible			
Passive measures			Active measures						
Heat protection (summer +winter)	**Passive solar use (winter)**	**Avoid over-heating (summer)**	**Electricity production**	**Active solar use**	**Heat generation**	**Heating**	**Cooling**	**Ventilation**	**Lighting and appliances**
Insulation	Direct gain	Sun control	Photovoltaic	Solar collectors	Biomass	High efficiency	Electrical cooling	Heat recovery	Efficient lighting
Insulated glazing	Indirect gain (Trombe wall, sunspaces)	Natural ventilation	CHIP		Geothermal energy	Heat pumps	Thermal cooling	Increased efficiency distribution	controls
Airtightness	Daylight	Thermal mass				District heating	Storage		Efficient appliances

Table 2: Passive and active design principles with Trias Energetica (Konstantinou, 2014)

The aim of **the passive design** is to reduce the energy demand of the building by taking advantage of the local climate and environment elements and the building characteristics (e.g. building layout, orientation, materials). Passive principles can be classified into three basic functions (Konstantinou, 2014):

1. **Heat protection**
   - Increasing the airtightness and thermal resistance of the building.
   - Insulation to prevent the heat flow between spaces with temperature difference.
   - Insulated windows to supply the interior with light and fresh air. Need to be well insulated and with no thermal bridges.
   - Sealants to minimize infiltration.
2. **Solar heat gain**
   - Solar control with shading systems to minimize heat gain during warm months.
   - Heat gain from the sun and direct solar gain during the cold months of the year. This can be achieved through the transparent elements placed on the south orientation of the façade that can collect, store and distribute solar energy.
   - Solar buffer space as an intermediate space between the interior and the exterior to encircle the heat from the solar irradiation, e.g. second skin façade.
   - Indirect solar heat gain from high thermal mass components, like the Tromp wall and the attached sun spaces.
3. **Heat rejection**
   - Ventilation is the most common strategy to for heat rejection, to remove the indoor heat and release it to the exterior space.

However, passive measures alone do not ensure the minimization of energy demand in all seasons especially in central European countries where heating is the main reason of energy consumption. The **active measures** are necessary to produce and distribute the energy demand for heating, cooling, ventilation, lighting and appliances (Konstantinou, 2014). Some of the active measures that can be effectively used in a façade design are:

Electricity generation: Generate electricity from renewable energy resources can reduce drastically the energy demand in buildings and can replace a big percentage of the energy produced through fossil fuels. The most common technology that uses renewable sources to produce energy in building scale is **photovoltaic panels** that use the solar radiation. The efficiency of the PVs is determined by the orientation and the angle of the panels surface. A very important factor that contributes majorly to this system is the climate, that strongly influences the energy production of the PV panels.

Water heating: Another active measure that can cover the how water demand of a building is the solar collectors. Solar collectors actively use the solar radiation to warm the water of the building. Through this process great amount of energy and fossil fuels are saved.

Heat generation and ventilation: Geothermal energy, heat pumps and heat recovery system are some of the active measures that can efficiently cover the heating and ventilation demands of the building interior spaces and minimize the fossil energy.

2.3. Conclusion

In order to achieve an efficient energy renovation of a building envelope, there are specific sustainability aspects that need to be considered. Those aspects are:

- Durability and buildability
- Impact on energy demand for heating and cooling
- Impact on renewable energy use potential and on daylight
- Environmental impact of manufacture and maintenance
- Indoor air quality and acoustics
- Structural stability and fire safety
- Aesthetic quality and effect on cultural heritage
- Low life cycle costs and need for care and maintenance
- Minimum disturbance of the tenants and of the site

Minimizing the time of the renovation, the energy loss during the construction and the on-site labor are very crucial aspects for the efficiency and the sustainability of the design. The solution is the design for mass production with the use of **prefabrication, industrialization** and **digitalization** of the façade renovation process and the façade system.

Renovation projects have unique characteristics that should be used in a way that mass production can be achieved to reach the maximum efficiency of the design and the construction process. To do that, the components needed for the façade system of an energy renovation should be analyzed.

COMPONENTS OF ENERGY RENOVATION FAÇADE SYSTEM

Façade systems have several common functions (Knaack, 2007):

- Natural lighting
- Waterproofing
- Protection against UV radiation
- Energy Generation
- Ventilation
- Push and pull forces from wind loads
- Vapour diffusion
- View out
- Interior loads
- Noise
- View- in
- Heat cold insulation
- Appearance of building
- Self-weight

These functions along with the specific needs of energy renovation create a number of main components that can achieve these energy façade system design and play a crucial role in the efficiency of the end-product:

1. Insulation
2. Glazing
3. Window frames
4. Sealants
5. Finishing-cladding

However, there are differences in the optimum materials, their thickness, the order of the layers of the components and the position and orientation of the different components on the building façade (e.g. windows, shading systems, pv panels). The specific elements and components that are required for the façade system are strongly dependent to the climate conditions of the building location. However, some general guidelines for nZEB could be given by dividing the Europe's climate in mild cold and warm climate.

Mild warm climate:

- Insulation
- Energy efficient transparent surfaces (with very low to low U-value, medium to high solar heat gain coefficient (SHGC))
- Operable and movable shading systems to prevent summer over-heating
- High thermal capacity
- Balanced ventilation with heat recovery

Mild cold climate:

- Insulation
- Limited fenestration area
- Glazing with very low SHGC
- Wind shields
- Shading from direct sunlight in summer
- Heat recovery ventilator to ensure indoor air quality
- Solar powered AC equipment (day-time cooling)
- High thermal capacity

Even if the differences between the requirements of the two climate zones can be seen as minor, they can highly influence the end-result and create great differences in the components of the "same" façade system.

Nevertheless, based on the "Trias Energetica" there are three steps that rank the sustainable criteria for the building industry and can be useful during the design of the components.

1. Reduce energy demand
2. Use sustainable, renewable energy sources
3. Use fossil energy as efficiently as possible

And consequently, base one these steps there are several passive and active measures that need to be followed to achieve an efficient sustainable façade refurbishment.

Passive measures:

- heat protection
- passive solar use
- avoid over-heating

Active measures:

- electricity production
- active solar use
- heat generation
- heating
- cooling
- ventilation
- lighting and appliances

The above sustainable measures should be taken into account during the design of the energy façade system. The next step will be to conclude to design strategies for the standardization of the components and to the level of flexibility in order to fit the system in different climate conditions. These design strategies will be done considering all the previously mentioned requirements, needs and function of façade energy renovation.

3. Circular Economy

This chapter will answer the following sub-questions:

- How circular economy and energy renovation strategies can be combined to achieve the desired result?
- What are the circular design principles for the components?
- What flexibility of the components is needed?

During the efforts to stimulate sustainable development, the circular economy represents the most recent attempt to reduce the pressure on the environment by creating harmony between the economy, environment, and society.

Several authors (e.g. Bocken et al., 2016; Ellen MacArthur Foundation, 2013) argue that the concept of linear economy “take-make-use-dispose” results in increased demand of natural resources, carbon emissions, environmental pollution and waste generation. The building sector is responsible for around 39% of the global human-induced emissions, with manufacture of building materials and products accounting for 11% (Pomponi, 2017). Moreover, a big amount of building materials is wasted during construction and demolition.

Furthermore, a huge amount of the extracted materials in human history are in today’s built environment, and this material stock is expected to grow even more in the next years. The result of this process is the negative environmental impacts and the increased cost of raw materials and waste generation from the construction sector (Conejos, 2007, Kibert, 2007). The solution to this problem is the designs and systems with long life-span. The concept of Circular Economy (CE), also known as Circularity, can create and facilitate these designs and systems with optimizing current and future resource loops by narrowing (efficient resource use), slowing (temporally extended use) and closing (cycling) resource loops (Conejos, 2007; UN, 2017).

The circular economy concept was first mentioned in the 1970s. The most recent and most commonly used definition of the circular economy came from the Ellen MacArthur Foundation (EMF) in 2013, describing it as an “**industrial system that is restorative and regenerative by design**”. The EMF developed the conceptual model known as the butterfly model, to explain that material cycles are closed in a circular economy model. According to the model, there is no waste in a fully circular economy as the residual flow can be used to make new products, thus closing the loop. The EMF defined the circular economy as “an economic and industrial system that is restorative and regenerative by design and aims to retain the value and quality of products, components and materials at their highest level at all times, distinguishing between biological and technical cycles.” The model consists of three parts: the middle part is the economic model; the left side forms the biological cycle while the right side is the technical cycle. The center of the model is the start point where renewable energy is first extracted from nature and then the products are manufactured and sold in the market. At the end of the product life, instead of disposing it as a waste, the model tries to circle the product to the economic model through the biological or technical cycle (Ellen MacArthur Foundation, 2013).

Focusing o the **technical cycle** that is most related to this research, there are several characteristics to consider. The technical cycle consists of finite materials, that can be recovered and often restored at their end of teir life. The cycles that the technical materials go through, are the following (Durmisevic, 2010):

1. Design for Maintenance _The first scenario aims to repair components. To enable maintenance of the product or building, the structure should allow removal and replacement of single components.

2. Design for Reuse _The second scenario focusses on extending the lifetime of a complete building, product, or component at the end of their functional life cycle, by enabling reuse of the separated components in new configurations. The components don't need to be re-manufactured but can immediately be re-used for similar or different functions. In terms of environment impact, this is the most convenient option, because of the minimal energy and material use.

3. Design for Remanufacture _The third scenario is based on remanufacturing components at the end of their functional life cycle, so that they regain their nearly original condition and can be reused for the same function. Quality control is needed to ensure that the remanufactured components meet the required properties for their function.

4. Design for Recycling _In this fourth scenario components and materials are designed in such a way that they can easily be recycled into new products (up-cycling) or recycled into waste that can safely be disposed (down-cycling).

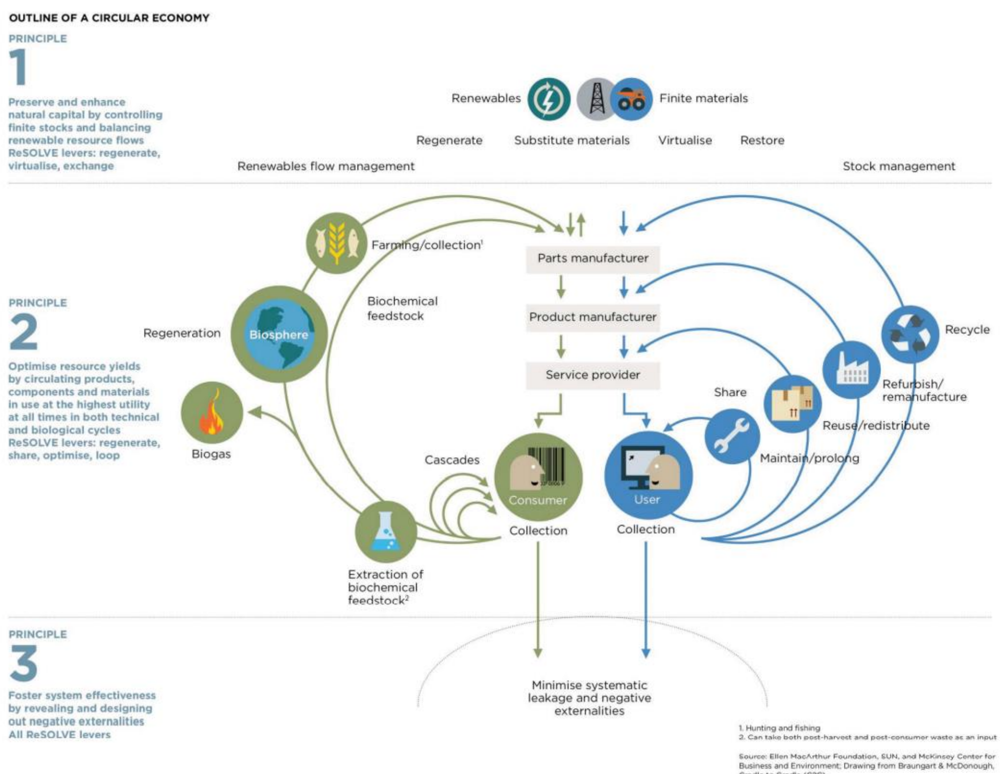


Figure 5: The three principles of circular economy shown for the technical (blue) and biological (green) cycle (Ellen MacArthur Foundation, 2013).

Buildings consist of many components which could be replaced by "circular building components" during the natural maintenance and retrofitting. Thus, gradually the building stock can be more circular. Developing such circular components is necessary to reach the goal of European Union to improve the operational energy-efficiency of buildings through retrofitting. However, this will require huge changes throughout the building sector (Malabi, 2021).

CE offers considerable potential to address the environmental challenges in the design of elements in the built environment, yet it is in its early stage and there are several technical and non-technical challenges to overcome in its implementation (Ghisellini, 2016). These challenges are based strongly on the design of the products that it does not aim for durability, easy maintenance, disassembly, and reuse (Pheifer, 2017). To date, there have been limited actual studies into the implications of the circular economy for the practice of design. Therefore, this thesis will explore what design knowledge, tool and method is needed to support a circular design.

3.1. Circularity in the Built Environment

Pomponi and Moncaster have given the following definition to a circular building (Pomponi, 2017):

"A circular building' is a building that is designed, planned, built, operated, maintained and deconstructed in a manner consistent with Circular Economy principles."

However, creating a circular building is difficult. Buildings are complicated structures made by many materials with different life cycles and, due to their long lifespan, they rarely change use during their service life. Brand's defined the shearing layers of buildings, based on the hierarchy of building components in the structure. The six main layers of a building are sorted from the shortest to longest life span in a building (Brand, 1994):

- Stuff: These consist of the movable elements of a building such as furniture, kitchen appliances, lighting, etc. They usually have a life span of 0 to 5 years and are thus changed often.
- Space plan: This layer consists of the elements that form the building such as internal walls and floors. A commercial building can typically change these elements every 3 years, whereas a residential building changes around 30 years.
- Services: This represents the electrical, mechanical, and plumbing systems but also elements such as elevators or escalators. These elements need renovation or replacement typically every 7 to 15 years.
- Skin: This represents building elements in contact with the external environment, thus the façade and the roof of the building. Since it is the part that faces the weather, a life cycle of around 30 years is expected. During the building life cycle, it is almost a certainty that the façade will undergo a complete renewal or a significant renovation at some point (Guldager, 2018). For this reason, it is crucial that the façade can be easily disassembled when the time for renovation arrives.
- Structure: This represents the skeleton of the building including the foundation and loadbearing elements. The structure's life is expected to range from 30 to sometimes even 300 years.
- Site: This represents the location of the building. The site's life span is infinite, and the site is independent from the construction.

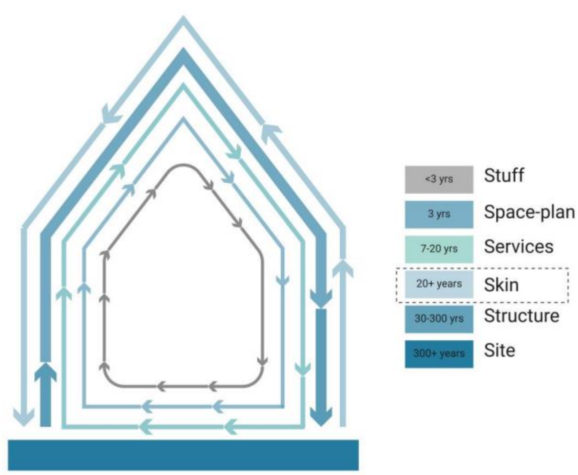


Figure 6: Layers of a building and its respective lifespans (Brand, 1994).

“The building is always tearing itself apart. Also, a building consists of many standard manufactured products, that are assembled in a unique way. This makes the disassembly process of every building different” (Pomponi, 2017). Thus, buildings should be redesigned into a structure in which all layers are able to change independently.

A circular building model enables the change of materials or components during different stages of the life cycle of a building. For the built environment, this means that when building materials have lost the required quality for their function so they have reached their technical, functional, or economic service life, they can be reused with the same or another function (Durmisevic, 2010). In order to achieve circular buildings, it is necessary to focus on the micro-level (products and components). CE requires a design in which buildings are considered as a group of components, elements and materials with different and multiple functions and life-cycles (Rahla, 2021). Thus, this research focuses on the **skin layer** and more specifically the circular products and components.

THE R’ PRINCIPLES

Initially, the CE concept was based on the **3R’s** principles, **Reduce, Reuse,** and **Recycle** (Rahla, 2019). The 3R’s principles were later extended to a **9R’s** framework that includes more actions for a more effective transition towards CE. (Potting, 2021):

- **Refuse**: Made a product unnecessary by abandoning its function or proposing the use of a different product with better functions and fewer impacts
- **Rethink:** Boost the product use and adopt smarter strategies like sharing economy or products with multiple functions
- **Reduce**: Minimize raw materials, waste and energy consumption
- **Reuse:** Reuse a product for the same purpose when it reaches its end-of-life
- **Repair**: Fix or maintain a damaged product so it can be used again with its original function
- **Refurbish**: Restore an old product and update it
- **Remanufacture**: Use parts from a damaged product to make one with the same function
- **Repurpose**: Use parts from a damaged product to make one with different function
- **Recycle**: Recover waste to manufacture a new product with same, higher (upcycle), or lower (downcycle) qualities
- **Recover**: A process of retrieving energy and fuel from non-recyclable materials by incineration

Scaling up the CE principles to buildings promises to reduce negative environmental impacts by extending the materials and components lifespan and make them reusable at the building’s end-of-life. Designing for CE means designing for **adaptability, flexibility,** and **disassembly**. In that way the design process is able to reduce the use of raw materials and the generation of waste.

CIRCULAR BUILDING PRINCIPLES

To achieve circularity in the built environment, several design principles should be followed. The design principles should consider the entire life-cycle of the building. Many authors developed lists of design principles for implementation of a circular economy in buildings (Abma, 2020). Despite some small differences between the authors, they all share several design aspects. These required circular design principles in order to achieve an efficient use of resources/materials and minimize the energy consumption throughout the life cycle of a building are:

1. **Design for Disassembly and Deconstruction (DfD)**: This design principle refers to the design of building components that can be disassembled and their elements can be separated without any damage. In that way the components and materials can be efficiently recovered and reclaimed. The technical key factors that this design should follow are the components **durability** and **easy assembly process**, and the **reversibility** of the connections. (Durmisevic, 2010). Also, allows for resource-efficient **repairs**, **maintenance**, **replacements**, as well as the **reuse** of construction materials, products, and components. Offsite construction and modularity of the components are important features to consider designing for disassembly.

2. **Design for Reuse**: this design principle refers to the potential of the building components and materials to be reused, repaired, remanufactured, or recycled to reduce the use of raw materials and non-renewable resources. To guarantee suitability, the elements must be safe and healthy to reuse and consist of a single recyclable substance. Design for reuse applied together with the DfD principles ensures reaching the circular economy in the built environment.

3. **Design for Flexibility and Adaptability**: This design principle refers to the consideration of future change of use or requirements in the design process to extend the life span of a building or its components and to prevent the building of being demolished. The future changes in users and needs should be taken into consideration during the design phase in order to avoid demolition and unnecessary social, financial, and environmental costs. Buildings should be as adaptable as living systems, as these have proved to be sufficiently adaptable (Ellen MacArthur Foundation, 2013). Design for Flexibility can convert components into dynamic adaptable systems, that can be modified according to the needs of the users. Because the component is able to respond to changing inputs, its lifetime will be expanded.

4. **Design for Durability**: Designing or using high quality durable long lifespan components and materials that are easy to maintain and upgrade and can handle having multiple service lives. This design principle could minimize the need for replacement. Choosing the right material at the initial design stage is crucial, to reassure that the components are able to withstand the typical wear and tear of repeated recovery and reuse cycles.

5. **Design for Recycling:** Design for recycling is a principle, where the design takes account of the recyclability of materials and components. This concept is not just about reuse being possible but also about it being possible to continue it in the long term, cycle after cycle and reduction of construction waste.

6. **Design for Optimization**: This principle describes the selection of materials with the proper mechanical properties for its use and the minimization of the materials used as well as the number of different types of components and materials used. The optimization may include the use of new materials to improve the structural behavior (composite materials, FRP, glass, high strength steel, high strength concrete, etc.) that fulfill the rest circular design aspects and the use of materials with high recycling rate. Optimization can also be done in terms of shapes/dimensions to enhance/enable future adaptability/flexibility by avoiding over ordering and onsite material cut-offs or by simplifying the

building form, using lightweight structures or reducing the customers’ spatial needs by optimizing floor areas.

The earlier the above circular principles are considered in the design process, the higher is the chance to positively influence the performance of the building over its life span. Benachio et al. (2020) also emphasize the necessity to implement circular economy principles from the project design phase. The potential to consider those principles in the earlier stages of a project can help assess the reuse percentage of the components and materials that will be used and choose the most circular components, as well as better manage all the resources that will be used throughout the life cycle of the building (Benachio et al. 2020).

These circular design principles are the fundamental principles that will be used in this study for the design of the circular components that will form the façade system for sustainable renovations.

3.2. Design principles of the components

Although, other building parts can have tolerances in centimeters, tolerances in building facades are in millimeters. Apart from the lower lifespan, facades can contribute to at least 20% of the cost of construction, can have a surface to floor area ratio of around 40% for most tall buildings. The parameters mentioned above and a drastic impact on operational energy, and therefore the impact of facades in the building overall footprint can be quite significant. Therefore, the need to develop new façade systems with circularity principles and evaluate current facades and ensure it is reused at its highest value and least impact on the environment becomes essential.

In a façade renovation all the previously mentioned design principles for circular buildings should be applied to the façade system, thus the components of the façade, the materials and the connections between materials and facade components. The principles mainly aim to improve the flexibility and adjustability of the building.

To be able to create a circular facade that is designed for easy maintenance, disassembly and efficient re-use of components and materials, the structure of the facade should have a certain flexibility. Following the principles of the CE, the structure should enable components to be eliminated, added, relocated or replaced. To increase the flexible capacity of the facade, separation should be possible at two different levels (Henry, 2018):

1. Separate building components to enable easy disassembly of the building layers.
2. Separate materials by using as much as possible standardized single-materials, instead of a composition of different materials laminated together.

The main circular technologies and design choices for the components that make easier to close the material loops are summarized below (Eray, 2019):

• **Compatibility**: The building components can be easily reused in different assembling stages and reconfigured several times. The simplicity and minimization of the connections, flexible fixing systems, and standardized dimensions are the features that maximize components compatibility to their reuse potential.

• **Reversibility**: The building components can be easily disconnected from the other building elements. Dry, mechanic connections such as bolts and screws are thus more effective than wet and chemical joints to achieve a demountable component. The high reversibility of the connections is important because allows the recovery of the components at the end-of-life stage and facilitates their maintenance and repair within the operational stage.

Higher demands on the building flexibility and performance should not cause more waste. The principles of **design for disassembly** could solve this conflict. Design for disassembly, for prolongation of service life of the building components through reusing them in other building projects is the optimum solution. There is a need for innovative design strategies that consider the future demolition and provide flexible structures. Industrialized, standardized, flexible, and demountable systems can create buildings with higher quality and adaptability and overall better environmental characteristics.

Standardized and flexible system can improve the facade renovation in such a way that result in a faster, economical, higher quality and environmentally friendly building in comparison with the traditional renovation methods (Sadafi, 2012).

The design for disassembly aims to reduce the consumption of materials, cost and waste in the construction, renovation, and demolition. Moreover, it increases the service life of buildings, while making them material banks for the future (Heinlein, 2019; Guy, 2005). The material recovery can maximize economic value and minimize environmental impacts through subsequent reusing, repairing, remanufacturing, and recycling (Ellen Macarthur Foundation, 2017; Mule, 2012).

A **modular** system for façade renovation should be able to support the adaptive character of the buildings. Thus, a level of adjustability of the components so they can fit to different building typologies and needs and correspond to each building changes is necessary and crucial to achieve the desired sustainable outcome of the refurbishment.

The design should use prefabricated and/or modular components and be consisted of simple structure and forms that will allow standardization of components and dimensions. The design should also complements labor practices, productivity and safety.

CONNECTIONS

The challenge is how to design a facade system that consist of components that can be replaced several times, without the need to disassemble the whole system. The main technical problem is the connections between the components. The connections should be able to provide relatively easy disassembly, reassembly, and plugging-in of components. To achieve these design aspects the connections should have several characteristics (Durmisevic, 2010):

- Functional independence of materials and building components: Separation of functions in the building component is beneficial for disassembly, so the change or replacement of one function will not affect the others.
- Industrialization and standardization of materials and building components to achieve faster assembly and disassembly process on-site.
- Small number of different relations: The less building components possible.
- Order accordingly to the Life cycle:
    - Components and materials with short lifecycles need to be disassembled first and thus assembled last and the opposite for the ones with long lifecycles.
    - The base elements of the system should have the longest lifecycle of all components.

Moreover, the connections have to be **detachable** in order to follow the principles of design for disassembly and fulfill the desired requirements for a flexible and adjustable façade system. Hillebrandt (2019) presents the advantages of detachable components during the buildings life-cycle (Hillebrandt, 2019):

- Efficient and quick assembly during the construction phase.
- Easier maintenance and replacement of the components during the operation phase.
- More efficient reuse of the components in their end-of-life phase, consequently less disposal cost and waste.

MATERIALS

While flexibility and adaptability of the building structure are necessary to create a circular building, in the Circular Economy the focus lays on the properties of the used materials: their quality, their recycling possibilities and their health. Opting for materials with a high potential for circularity is an important step in facilitating a circular design economy, simply by insuring the material reusability. Sourcing of the materials, the production method and their lifecycle are relevant parameters to be taken into consideration to assure circular qualities. Certain criteria for circular materials are defined (Geldermans, 2016):

1. The material needs to be of high quality, regarding functional performance.
2. The material needs to be of sustainable origin to be able to endlessly provide nutrients for new material life cycles.
3. The material needs to be non-toxic.
4. The material needs to be coherent with the biological cycle or with one or more technical cycles.
5. The dimensions need to be standardized, based on the modular coordination and dynamic capacity demands of the design.
6. The connections between materials and components need to be dry and simple.
7. The technical lifespan of the material needs to be based on its functional performance time.

Standardization of dimensions is a method to increase the reusability of materials or building components in other systems (Geldermans, 2016). However, to maintain diversity in the built environment, standardized elements should enable assembly in different configurations. For an easy recyclability and separation, homogeneous or easily separable materials are favorable. Composite materials might be a better option if the whole component is easily reusable. Materials need to be healthy to be reused or recycled.

In terms of material type, one highly sustainable material group that is often considered as circular is the biobased materials. Biobased materials do offer significant benefits, with most important "the wake of our climate and environmental crisis is their renewable sourcing" (Jones, 2017). Various platforms offer support and guidance for better understanding of the material implications and the right choice. E.g. the Danish webpage Material Pyramid offers a calculator to estimate the CO2 footprint of selected construction materials (Materialepyramiden, 2021).

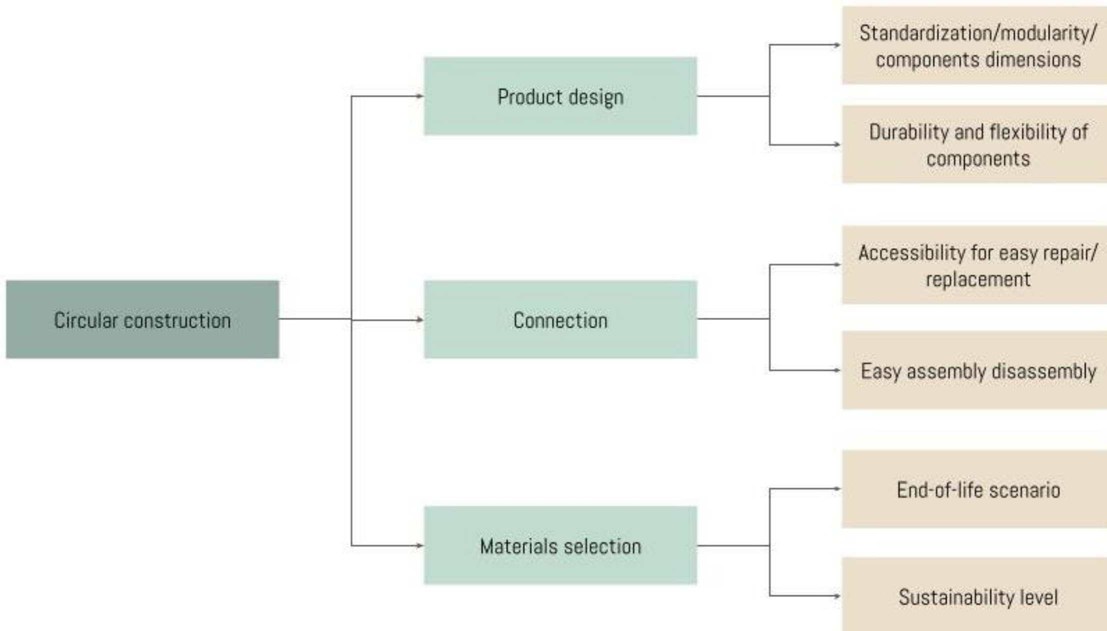


Figure 7: Circular components main aspects

Summarizing, the main point that need to be considered form this chapter is that each element of the façade system has its own lifespan and lifecycle which strongly affects the entire system (Pomponi, 2017). Compatibility and reversibility are very crucial aspects in designing circular components. They need to have characteristics such as durability, demountability, standardization, some flexibility etc. Additionally, special attention should be paid to the design of the connections between the elements of each component and between the components and the selection of the materials for each element.

3.3. Industrialization/ Standardization/ Prefabrication/ Modularity

As was already stated to previous chapters, the building industry is responsible for a waste of a significant number of natural resources which has great environmental impact (Ellen Macarthur Foundation, 2017; Rashid, 2015). To solve the problem, new building system concepts should be designed that are sustainable and follow the circularity principles. In that way, the waste construction materials can be reduced, and the service life of buildings can be increased. A circular design is based on **flexibility, modularity,** and **standardization** that improves the quality of life of its residents and minimizes the use of virgin material (Ellen Macarthur Foundation, 2017).

As an alternative to the conventional building systems, prefabrication, modular and standardized systems are adopted in the building design. The offsite manufacturing processes can offer greater precision, shorter construction times, safer working conditions and better quality, as well as promote recycling and reduce waste (Smith, 2010). These design solutions can create **reusable** and **recyclable design concepts**. Nevertheless, the repetition of these solutions can create a monotonous landscape, thus the design needs to be thoroughly studied and decided.

There are many ways on how to make building components reusable. Design for reuse and disassembly requires close attention to both functional, technical and aesthetical aspects. General solutions for DfD are prefabrication standardization and modularity. These aspects highly reduce waste and maximize re-usability.

- **Prefabrication:** Reduces the amount of on-site waste, and the effectiveness and possibility for direct recycling of the material increases.
- **Modularity:** Makes it easier to replace, manage and reorganize various parts of the building.
- **Standardization:** Increases the re-usability of a building component. Elements with varying sizes have reduced compatibility and are less likely to be reused.

An element, designed to be easily replaceable and removable, needs to be independent from the other elements. Thus, dry connections should be used (screws/bolts), which are easier to assemble and glued or nailed connections should be eliminated.

More analytically the main production solutions for the implementation of circular design in the built environment, prefabrication, modularity and standardization are described below.

PREFABRICATION

Prefabrication is the manufacture of parts of the final structure on a site different to its definitive location. This labor is usually manufactured with controlled conditions inside a factory. Prefabrication is used to ensure e.g. reclamation, reusability and recyclability, construction time optimization, enhanced assembly and disassembly, enhanced adaptability, avoidance of waste materials, etc. A lot of research has been made to speed up the building renovation process, by utilizing prefabricated components and complete façade systems. These solutions provide reduction in construction time, cost, energy consumption, and occupants' disturbance. However, all the existing facade solutions for large-scale renovations are pilot projects and are based on a customized application approach (Vovos, 2021).

According to Smith (2010), four different principles must be considered for prefabrication (Smith, 2010):

1. **Cost:** Prefabrication is much more cost efficient than other onsite methods of construction. This is because cost consists of three aspects on which prefabrication has a positive impact: material, labor and time.
2. **Schedule**: In traditional onsite construction processes, each work has to wait until the precedent one has been completed, in a factory, teams may work together allowing more sections to be constructed simultaneously. Time savings may also apply due to the early decision-making regarding prefabrication, so schedule savings may be realized from the start of construction.
3. **Labor**: With offsite fabrication, technical changes including machinery in the factory, evolutions in material science and digitalization like BIM have a positive impact in the labor productivity in construction.
4. **Quality**: There are two concepts to evaluate quality; quality of production and quality of design. As soon as production quality increases, design becomes more standardized but with higher quality (customized design leads to production inefficiency). Prefabrication can increase the precision of the products and allow a greater control over each element and limits the risk of errors.

MODULARITY

Modularity refers to a system subdivided into smaller parts called modules that can be independently created and used in different systems. (Nady, 2021). Modularity Is used to e.g. allow components' adaptability and flexibility (upgrade, disassembly, replacement, reconfiguration, reuse and recycling), build cheaper standard buildings and lean production.

Modularity uses modules. The modules should be similar and able to work alone or with other modules. Once the project starts the operation phase, it should be possible to add, replace, or take away modules without affecting the whole design and its characteristics. (Nady, 2021).

There are many expressions to describe the term "modular", some of them are presented in order to define the main characteristics and meanings of the term (Vovos, 2021):

- They are co-operative sub-systems that form products, manufacturing systems, etc.
- They have one or more, well-defined functions that can be tested in isolation from the system
- They are independent and self-contained and can be combined with other modules to achieve overall function.

Modular building system is also one way to achieve standardization. To connect standardized products as puzzle pieces, modularity helps to make this as flexible as possible. Multiple variations can be made possible without having to change the entire design.

Modularity in construction often emerges as prefabricated and standardized components or modules designed for manufacture, assemble and disassemble as quickly as possible. The building time needed for these modules is often lower than traditional building systems. Additionally, modularity can also work in cohesion with the design for disassembly concept. Then each module can be disassembled from the project to be moved to another one. As the proposal is to work towards improving buildings lifespan, it is therefore important to think about how the modules can work in this way.

Modular construction has many advantages, but also some disadvantages that need to be discussed to consider modular above traditional construction:

The advantages are:

- Production and construction speed and efficiency
- Cost-effectiveness in construction
- Improved safety
- Improved environmental impact

The disadvantages are:

- Extra planning and construction effort required
- Complex coordination
- Transportation difficulties
- Increased costs due to its complexity

STANDARDIZATION

Standardization is the organization and completion of a substantial proportion of final work through regularity and repetition, before installing the elements in its final position (Gibb, 2001). As a result, it is closely related with prefabrication and pre-assembly. It also works by ensuring accurate fit and interchangeability of components, specially ensuring the compatibility between the different interfaces of the elements.

Standardization is used to e.g. maximize recovery of materials at end-of-life, ensure reuse and recycling options, limit the number of different components used, avoid material off-cuts, prolong product lifespan, etc.

In standardization there is regularity, repetition and a record of successful practice (Gibb, 2001). The main advantages of standardization in the construction industry are (Yasin, 2017; Ulrich, 1993; Aapaoja, 2014):

1. **High quality and quality control:** By product repetition, the quality will be better than with customization. Fewer mistakes will be made because those have been solved in the earlier stages of the production.
2. **Faster production time:** With repetition and mass production, a smart and faster logistics setup can be made which speeds up the production process.
3. **Lower production and construction costs:** Because of the standardized product being produced in high volume, it will lower. Construction will be easier and quicker because the workers will know what to do and less people will be needed.
4. **Less use of raw materials and less waste:** Standardization will maximize the reuse potentials thus less raw materials will be used and less waste will result.
5. **Less CO2 emissions:** with the reuse, less products will be manufactured, and consequently lower CO2 emissions will be created.
6. **Better understanding of the products requirements:** This leads to fewer claims, conflicts and change of orders, and therefore also less unplanned costs.
7. **Increased safety and knowledge of the product**
8. **Easier to obtain replacement parts**

However, standardization is not an easy concept to achieve and has some barriers similar to the ones of the concept of reuse (Pasquire & Gibb, 2002; Aapaoja, 2014):

- Flexibility is the biggest problem due to the different users' needs.
- Lack of projects in the building industry to learn from.
- Lack of collaboration, trust and commitment in the building industry.
- Traditional contracting and construction management methods are preventing the application of standardization.
- High investment costs in product development and performance for a manufacturing firm at the start that can be demotivating.

Except of solving the above barriers, there are also some other ways to achieve standardization (Yasin, 2017):

- Find the most popular sizes and models that are being used in the production process of the element that need to be designed
- Set specifications to optimize the quality, production process and method

As it can be retrieved from the analysis of the above solutions, modularity is included in standardization because of their interchangeability. As standard designing allows exchanging modules, it involves designing based on modularity. Modularity promotes a flexible design that allows changing elements or components without changing the entire design. Prefabrication cannot be either conceived without modularity and standardization, so all these concepts are closely related, and they depend on each other.

Another solution that is strongly connected to the previous ones is industrialization, thus it will be also described below.

INDUSTRIALIZATION

Industrialization is the production of building elements and components, under controlled circumstances and in a repeatable process. In construction, industrialization means eliminating or reducing on-site activities by mass production, constructing element in specialized facilities and transporting them to construction site. The industrialized elements can be used in several buildings with different characteristics. The quality of the building parts will be controlled in the manufacturing and assembly process either in the factory or the building site. Furthermore, the repeatability of the process makes the manufacturing easier and faster (Sadafi, 2012). However, industrialization involves investment in equipment, facilities and technology.

There are found two main principles aiming for industrialization: **lean construction** and **buildability/constructability**.

1. **Lean construction** is a methodology aiming at smoothing out the whole construction process while product requirements are realized during all the phases (Bjönfot, 2005). The main goal is to eliminate waste.

2. **Buildability/constructability** is a process and product-based principle. In contrary to modularity, buildability/constructability is more a goal than a means for product and process efficiency (Bjönfot, 2005).

It is obvious that Industrialization and all the above-mentioned construction solutions share many aspects and guidelines. Their aim is to reduce complexity in assembly and reduce construction cost and increase efficiency and quality of the end-product. Thus, is one of these solutions is pointed out, the rest of them should be also considered.

3.4. Flexibility of the Components

As previously mentioned, to achieve the desired façade renovation systems, the components of the system need to have a level of flexibility to be able to fit to different projects and be efficient. The level of flexibility that is needed will be discussed in this chapter.

The concept of flexibility is defined as the capacity of buildings for physical change and adaptation according to changing circumstances. Flexibility as an inclusive concept covers the related concepts of modularity and adjustability and it is achieved by designing the fixed elements, which are the components in a way to allow change.

ADJUSTABILITY

The term of adjustability is presented in this section with the aim to incorporate its principles in the façade system that will answer the research sub-question about what flexibility is needed for the renovation system. Adjustability is the key factor that is needed to achieve same system application in different situations, and it is strongly related to modularity, since modularity is one of the factors that can help to solve common problems for large numbers of projects.

The goal of this thesis is to create a façade system for renovation that can fit in most of the **residential buildings** in Europe and in the **different climates** while increasing their **energy performance**. The European goal is to renovate around six million buildings per year until 2050. Industrialization and standardization of the process with a level of flexibility can lead to faster construction, lower prices and better quality. The main idea of the standardization with a level of flexibility approach is design products that can be adjusted to different contexts with minimum changes while trying to achieve energy efficiency, low cost, and high quality of mass production (Vovos, 2021).

"**Adjustability** in construction is possible if the whole system is based on the combination of various components and allows for small changes that have been determined during the design process. This can be implemented during system manufacturing according to the demand and the incorporation of the designed components" (Vovos, 2021).

Furthermore, it is already explained that because the possibility of changes in building needs throughout its lifetime, another way of constructing is required, and **standardization** combined with **BIM** provides the opportunity to set new benchmarks in terms of flexibility. Because of that, different flexibility-related strategies have been studied and developed in a previous chapter. The main of those strategies are:

- **Design for disassembly**: Use of prefabricated components, which are later joined all together onsite and can be easily disassembled. The building units may be inserted or removed over the time to accommodate changes.
- **Design for reuse**: Standard forms and modules can be reused easily if they are in good condition. It is easier to identify their recyclability and condition when they are produced offsite.
- **Design for change**: As said above, necessities of people change throughout the lifetime. Because of that, giving the possibility for modifications is essential.

When focusing on the components level, the **characteristics of the components** that are strongly influenced and connected with each building project and thus need a certain level of flexibility are:

- **Layers:** The type of elements that are included in the components, their order and materiality.
- **Measurements:** The size of the components and the thickness.

The building parameters that affect the above characteristics are:

1. Age & Region
2. Typology (type, function, dimensions)
3. Energy demand (climate)

Based on these parameters, the different options that can be found will be explored.

1. Age & Region

The older buildings represent the majority of the building stock, which have low energy performance and need refurbishment. In Europe there are around 25 billion m2 of useful floor. The European countries are divided based on climatic, building typology and market similarities into three regions (Vovos, 2021):

- The North & West region: Austria, Belgium, Switzerland, Germany, Denmark, Finland, France, Ireland, Luxemburg, Netherlands, Norway, Sweden, and United Kingdom.
- The Central & East region: Bulgaria, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovenia, Slovakia.
- The South region: Cyprus, Greece, Spain, Italy, Malta, Portugal.

Half of the building stock is located in the North & West Europe. The rest 36% is located in the South region and the 14% in the Central & East regions. Most of the existing buildings had been built until 1990. In the North and West region the number of the buildings before 1960 is higher than the one for the period 1961-1990. On contrary, in Southern and Central & East Europe, most of the buildings have been built between 1961-1990 (Vovos, 2021). In general in Europe the BPIE study has shown that a large share (more than 40%) is built before 1960s with low insulation levels and old and inefficient systems. Approximately the 55% of the building stock has been built between 1945-1990 and also that the 85% of the building stock is older than 20 years (BPIE , 2011).

2. Typology

The age of the building and its location strongly affects the building shape, dimensions and typology. Building typology refers to the study of a group of buildings which have similarities in their type, function and/or form.

The buildings typology, in terms of function, that the study will focus on, as previously mentioned, is the **residential buildings**. The reason of this selection is that residential buildings are the biggest segment of the existing building stock (75% of the total stock) and are responsible for the majority of the sector's energy consumption (BPIE , 2011).

The residential buildings are divided in sub-categories with different characteristics (Konstantinou, 2014). The types of residential buildings are (Konstantinou, 2014):

- **A single-family or detached house:** A house that is detached from its neighbors on all sides, with open space around it so it is exposed to the weather conditions and views from all directions. This gives the possibility of more flexible floorplans, and the variation in size and design of the building and the surrounding spaces are limitless.
- **Terraced or row houses:** Single-family houses built in a line, with their two walls to be shared, separated with a small cavity, or adjacent to each other. All the entrances of the houses are on the façade that faces the street. Most of the time this type of houses is in cities where the space in the urban environment is limited because they can provide higher densities while preserving more space for exterior interventions (Konstantinou, 2014). With this type of houses less materials are needed and there are less heat loses because of the shared walls between the buildings. Additionally, the typical construction of this type is based on repeatability to reduce design and construction costs with the same simple design for all the buildings.
- **Multi-family houses:** Buildings that contain more than one family with several housing units and referred to as apartments or flats. This building type can be perceived as terraced houses or detached in the case of row houses type; the entrance of the bluing is common for all houses at the ground floor level. A common form of multifamily houses is the apartment blocks. They existed since earlier years, but became very popular after the Second World War, when there was extreme housing shortage and the need for higher densities. As a result, new fast, economical and efficient construction methods were introduced to cover the demand.

The difficulty to decide the type that should be tackled in the study is that there is any type that is strongly dominant across Europe to be selected. The building stock by type of residences differs significantly across the Europe. Some countries have more single-family residences and others more multi-family residences. Consequently generally in Europe, the percentage of single-family and multi-family residences is almost equal (Vovos, 2021).

Additionally, there are differencies even between the buildings of the same country and with the same typology. These differencies are regarding the construction characteristics, the structure type, the envelop type and the form. A presentation of the more general spesifications can already facilitate the decision of the design approach that needs to be followed. However, a more detailed and targeted analises still needs to be done for the selection of the optimum design strategy for the study.

Residential building Construction Characteristics

The European building stock has buildings from different countries with several climate variations, different traditions, materials, and construction methods. This situation leads to a very diverse sum of buildings that is complicated to be analyzed and to make the same conclusion for all. Based on the selection of the buildings age and region there are different construction characteristics and structure and envelope types. The construction characteristics are mostly influenced from the construction techniques of each time period. Every period has a different culture and technology that influence a lot the goals that need to be achieved on each of them. *Table 3* presents the main characteristics of each time period between 1950-1990.

Time period	Benchmarks	Characteristics
Post-war years 1950-1975	The years after World War II Reconstruction Urban planning based on modernism ideas	Non-traditional building systems High housing production Cheap and quick construction Functional, sunny airy houses Middle-rise (up to 4 floors) and high-rise residential buildings with generous distance between them
Prosperous years 1975-1990	Economic growth Energy crisis in 1973	Higher quality of construction First awareness of more “energy efficient” buildings First building refurbishments in order, historical buildings

Table 3: Building characteristics per period (Konstantinou, 2014)

Building structure types

There are three main structural types that can be categorized in (Konstantinou, 2014):

1. **Loadbearing external walls:** The façade supports both the weight the roof and the internal floors but also works as the barrier between the interior and the exterior climate. The walls are solid, constructed from monolithic or composite elements, perforated with opening for light and air.
2. **Skeletal frame:** This was the main method of the post war period. The horizontal elements (beams) are supported by the vertical elements (columns). This construction method can be made from reinforced concrete, steel or timber beams and pillars. This type of construction allows the analysis of the wall in the load-bearing structure and the filling, which is then the element that determines the space, thus allows the façade to have bigger openings (Knaack, 2007).
3. **Box-frame structure**: Also popular in the postwar years. This type allowed fast construction and it was used in industrial and apartment buildings. This structure was considered are more economical due to the greater building depths that were allowed (Vovos, 2021).

Building envelops types

To be able to clarify the design decisions and the level of flexibility that is needed for the facade components the variations of the building skin in Europe’s existing building stock need to be explored. The building envelope consists of the most crucial elements of the building that influence the indoor climate and the aesthetics of the building, that are both very important for the façade renovation design approach. These elements are the roof, the exterior wall, the ground floor and the windows. A study of Konstantinou (2014) made a detailed classification of **traditional** and **non-traditional** construction methods that refers to the building envelope and analyze the characteristics of each method regarding both the structure, the windows and the roof and were they were located (Konstantinou, 2014). This classification will be methodically introduced and used, where necessary, as a guidance in the next phase of this study. However, its main aspects could be already presented.

An important parameter that influenced the construction methods and helped the transition from traditional to non-traditional methods after 1950 is the introduction of new materials specific for thermal insulation. Furthermore, the classification clarifies that the location of the building had great influence in the construction method used. The importance of the classification is that collects and analyzes all the different construction techniques that have been used during the years for the building envelope. These are the techniques and characteristics of the existing building stock and will affect the design process of the standardized façade system. Also, the final level flexibility of the façade components will be concluded based on these techniques.

Dimensions

The developed façade components and consequently the façade system should be able to be adjust their dimensions to each building requirements, so the system will provide an efficient solution for several different projects. Based on the above building envelop types, the **most frequent measurements,** if there are any, needed for a façade system should be identified in the next phase of the study.

3. Energy demand

This parameter was introduced in chapter 2.2. As was concluded, there is a number of main components that can achieve these energy façade system design:

4. Insulation
5. Glazing
6. Window frames
7. Sealants
8. Finishing-cladding

However, the specific elements and components and their dimensions that are required for the façade system are strongly dependent to the climate conditions of the building region. There are some general guidelines for nZEB but still the influence of climate can create important differences between the different project needs. The study will be located in Europe. Also, the potential case study building is located in Amsterdam, thus The Netherlands will be in the scope of research, and it remains to determine if the area of Europe that will be used to the study will be wider or will be limited to the Netherlands.

3.5. Conclusion

To answer the research sub-questions of the above analyzed topic of circularity (-What are the circular design principles for the components? and -How circular economy and energy renovation strategies can be combined to achieve the desired result?), there are several circular design principles that should be followed during the design of an energy façade renovation to facilitate and strengthen the sustainability and the energy efficiency of the project. The earlier these circular principles are considered in the design process, the higher is the chance to positively influence the performance of the building over its life span. Moreover, the design principles should consider the entire life-cycle of the building. The **circular design principles of the components** are:

1. **Design for Disassembly**: This allows for resource-efficient **repair**, **maintenance**, **replacement**, as well as the **reuse** of materials and components. It can reduce the consumption of materials, costs, and waste. Moreover, it increases the service life of buildings, while making them material banks for the future.
2. **Design for Reuse**: The building components and materials can be used again to reduce the consumption of raw materials.
3. **Design for Flexibility and Adaptability**: Takes into consideration the future change of use or requirements in the design process to extend the life span of a building or its components.
4. **Design for Durability**: Designing or using high-quality durable components with a long lifespan and materials that are easy to maintain and upgrade with the ability for multiple service lives.
5. **Design for Recycling:** The design takes account of the recyclability of materials and components (also for future reuse).
6. **Design for Optimization**: The selection of materials with the proper mechanical properties for their use and the minimization of the materials and different components used.

Also, the **compatibility** and **reversibility** of the components are crucial so the components can be easily disassembled and reused, reconfigured, and recombined many times. The selected connections and materials of the components play a crucial role in the design and should be able to follow the above principles and facilitate the circular strategies.

Furthermore, a **standardized** system can improve the facade renovation in such a way that results in a faster, economical, higher quality, and environmentally friendly building. However, to maintain diversity in the built environment, standardized elements should have a certain flexibility. Thus, a level of **adjustability** of the components, so they can fit to different building typologies and needs and correspond to each building changes, is necessary and crucial to achieve the desired sustainable outcome of the refurbishment. The design should use **prefabricated and flexible** components and be consist of simple structure and forms that will allow standardization of components and dimensions. The design should also complement labor practices, productivity, and safety.

- **Prefabrication:** Reduces the amount of on-site waste, and the effectiveness and possibility for direct recycling of the material increases.
- **Modularity:** Makes it easier to replace, manage and reorganize various parts of the building.
- **Standardization:** Increases the re-usability of a building component. Elements with varying sizes have reduced compatibility and are less likely to be reused.

This study will focus on standardization, by considering both prefabrication, modularity and industrialization if needed. The attempt of the study is to give a solution for the design and production of standardized façade components. However, the lack of **standardized methods** and practices to help the implementation of circular economy in the built environment is one of the main barriers in the construction sector towards the circular principles (Benachio et al., 2020). To overcome this barrier, a detailed design based on the main aspects of standardization should be developed that has the necessary level of flexibility to be adjusted to the changing needs. The kid of standardization and flexibility that the components will have as units and as a façade system (many components combined together), the necessary tolerances and the different configurations of the components that are needed will be the main focus of the study.

To answer the sub-question about the level of flexibility that is needed for the components of the façade system, modularity and adjustability are the key factors. **Modularity** can facilitate mass production strategies. The use of a limited set of modules to create several product alternative forms will be beneficial for the design. The use of modules to build a wide range of houses has been defined as one of the necessary methods to improve the energy performance of the building industry. **Adjustability** in construction is possible if the whole system is based on the combination of various components and allows for small changes that have been determined during the design process.

In more detail, the **parameters of the components** that are strongly influenced and connected with each building project and thus need a certain level of flexibility are:

- **Layers:** The type of elements that are included in the components, their order and materiality.
- **Measurements:** The size of the components and the thickness.

The building parameters that affect the above characteristics are:

Age & Region: The age and the region of a building can influence its façade characteristics and its needs for an efficient energy renovation. Therefore, a specific time period and a specific area of Europe have to be selected for this study. However, the limitations should not be too narrow in order to conclude in a more complete and flexible final design.

Typology: Even if the decided buildings typology that is going to be used to this study is the residential buildings, there are several additional characteristics that can still create great differences between the buildings of the same typology. These characteristics are:

- Construction characteristics: Different time periods and historic benchmarks lead to different construction approaches
- Structure types: It is also connected with the building age and has influence on the number and size of openings and the overall appearance and structural performance of the building.
- Envelop types: There are two main categories; Traditional and Non-traditional that lead to differences in the openings, roof, materials etc.

All the above parameters lead to buildings with different dimensions, openings, materials used. They are strongly dependent on the region of the building and influence the energy performance of the building and consequently the measurements that need to be taken to improve the energy performance.

Energy demand: There are some main characteristics regarding the energy demand of a façade system, regarding the climate of each region, that can contribute to the formulation of the design specifications for the façade components. However, climate conditions play a crucial role and can strongly influence the needs and requirements of a façade renovation.

Since the region of the study is Europe and the potential case study building is located in Amsterdam, The Netherlands will be in the scope of research. Nevertheless, the specific area of this study will be decided in the next phase (Design strategy), when the design criteria and the possibilities of BIM library will determine if studying a wider area, to have more accurate results for the efficiency of the developed design tool, is feasible during the limited time period of the thesis.

Also, the final level of flexibility that is ideal for the components of this study will be decided in the next phase. BIM technology will contribute to this selection, thus an investigation of the possibilities of the program regarding the level of flexibility and the standardization of the design should be made.

4. BIM technology

This chapter will answer the following sub-questions:

- How can a BIM technology support circularity and sustainability in the design phase of the facade renovation?
- What are the characteristics and the structure of a BIM library?
- How can a BIM library suggest the optimum design solution based on each building characteristics?

Building Information Modelling (BIM) is the digital representation of a built asset, containing relevant information such as the building geometry, material properties, and quantities of elements (Cetin, 2021). According to the National Institute of Building Sciences "A BIM is a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition"

BIM has been used by many actors in the architecture, engineering, and construction sector for various purposes, including design, design visualization, design optimization, cost estimation, construction planning, maintenance and facility management. It can be used also for detection of conflict, interference and collision, building performance and structural analysis, prefabrication and automated assembly (Azhar, 2011).

BIM is accomplished with object-oriented software and consists of parametric objects representing building components that may have geometric or non-geometric attributes with functional, semantic, or topologic information (Andrade, 2019). For example, functional attributes can be construction time, labor demand, and building cost; semantic information can be interdependency of elements, hosting components, and incompatibility between objects; and topologic attributes can be universal positioning and orientation of objects.

The technical core of BIM is the software tools that enable 3D modelling and information management. The main point of this technology is that it makes it easier to collect and share data. The integrated process involves collaboratively developing and using a computer-generated parametric 3D model of a building (Akanbi, 2017). Within this model, all involved stakeholders share information during the whole life cycle of the building. This means that the static hierarchy of decision making, where each phase must deliver specific things in specific moments of the project, is transformed into a dynamic decision-making process (Durmisevic, 2010). This leads to an integrated design due to efficient collaboration of all stakeholders and continuous availability of highly accurate, consistent, and reliable building information.

"Nowadays, BIM has grown significantly in many countries and cities around the world and is considered a major driver for the digital transformation and innovation of the construction sector" (Sam, 2019).

Design with BIM has several benefits to each stage of a building life cycle; thus it is broadly preferred as a design tool. Those benefits are:

Preconstruction benefits:

- Feasibility of the project is clear from the first moment
- Increased Building Performance and Quality
- Improved collaboration between different actors involved

Design Benefits:

- Earlier and more accurate visualizations of a design
- Corrections are automatically made, since used elements are parametric are employed
- Generation of consistent drawings from early stages of the project
- Calculation of costs during the design stage
- Improvement of energy efficiency and sustainability

Construction and fabrication benefits:

- Use of design model as basis for fabricated components: If the design model is transferred to a BIM fabrication tool, it will contain an accurate representation of the building objects for fabrication and construction.
- Quick reaction to design changes
- Synchronization of design and construction planning
- Better implementation of lean construction techniques

Post construction benefits:

- Better management and operation of facilities
- Integration with facility operation and management systems

During the design phase, the requirements for building high quality and accurate BIM model consist of three essential attributes (Weygant, 2011):

- Visual representation: BIM relies on the accurate representation of a building in 3D, and the same applies to the components used in the building.
- Embedded BIM object information: Associating essential product information to the objects that form the building is a key BIM benefit.
- Modelling techniques: The objects should be parametric, with certain limitations when it needs to be modified e.g., when the size of a door changes, then the door frame will change too.

Those attributes shape a precise and parametric final design model that can be efficiently adjusted to the design changes through the process.

The decision to adopt BIM methodology was made on the basis that this seemed to be the fundamental principle adopted in Architecture, Engineering and Construction Industry (AEC). This was not only reinforced in the literature but has also been acknowledged through several different studies and numerous worldwide governmental reports. BIM can also help in managing information and decision-making through transparent coordination processes and a common data environment.

Apart from building geometry, BIM allows extracting usable information such as: façade orientations; location as defined by latitude, longitude, and altitude; number of floors; window position; usage behind the façade and wall composition (Ochoa, 2015).

Moreover, BIM gives a possibility to embed additional information from the early planning stage. This distinguishing feature of building life cycle information accumulation makes BIM applicable to construction for deconstruction concept. If stored properly, the information on building requirements, planning, design, construction, maintenance, history and modifications can be collected and accessed at the end of life of the building. Moreover, BIM has the ability to simulate building performances such as cost estimation and energy consumption; thus, it can effectively support sustainability and circularity.

4.1. BIM and circular design

The characteristics and principles of BIM technology, that were presented in the previous chapter, can be extremely helpful to facilitate sustainability and circularity of façade renovation and promote and support the optimum selection of the components for the façade system.

BIM finds a crucial role to consider sustainability in the design areas that include building orientation, form, **envelope**, building energy modeling, material selection, site and logistics management, water usage, etc. (Jin, 2016). Over the last few years, BIM has been recognized for delivering sustainable projects to improve efficiency (Ayman, 2020). Currently, considerable research has been done in order to achieve an integration of sustainability in construction and BIM, thus the combination between building projects design and BIM can help to improve the accomplishment of sustainability goals (Andrade, 2019).

Wong and Fan highlighted two major contributions of BIM to sustainable building design (Wong, 2013):

1. BIM can reduce inefficiencies in traditional construction processes by allowing integrated project delivery through effective information sharing between all of the project stakeholders
2. BIM can help optimize building design to reduce natural resource use and waste.

Especially regarding CE, the use of BIM goes beyond these two main benefits. More recently, some authors explored more specifically how the current BIM uses could support the transition to CE. They came out with specific BIM uses for designing and managing projects and materials through the building lifecycle (Charef, 2021). With the use of BIM, it is possible to design the building elements and manage the project in such a way that they could be disassembled and reused after the building lifespan. Some key areas where BIM capabilities could help in achieving the circular economy in construction are automatic clash detections, design error reduction, an early collaboration of stakeholders, visualization etc. (Akinade et al., 2017).

BIM is the most adequate tool for the application of circularity principles in the design phase, especially regarding prefabrication and standardization. BIM technology has increased the accessibility to standardization and prefabrication technologies. The relation between **prefabrication, standardization, industrialization** and BIM is an interesting approach that could have great benefits for construction and design cost reduction, time-saving, and waste reduction (Charef, 2021).

As earlier discussed, prefabricated, standardized and industrialized building systems have often been described as potential solutions in the sustainable construction process, moreover with their integration with CE. Prefabrication, standardization and industrialization advantages include shorter project plans, cost savings in the project, easier assembly-disassembly, better product quality, and reduced waste (Cavalliere et al., 2019).

The main strategies to improve CE for prefabricated, standardized building systems with the use of BIM are (Minunno et al. 2018):

- Design for disassembly (to improve the end-of-life deconstruction)
- Track the product lifecycle

The components that are designed through BIM contain smart features, for example, a window knows it belongs in a wall and the group of data (family) that this component belongs will have attributes associated with it, which contain the size, composition and manufacturer. This is one of the characteristics of BIM software that makes it a logical fit for the implementation of CE in the construction industry. The comprehensive information for the components that are stored within the building model can also contain the manufacturer's warranty, spare parts and physical load attributed to each element and **assembly instructions** for the components.

Furthermore, BIM has its own life-cycle, similarly with the circular life cycle. BIM's life cycle consists of the following phases: idea, design, analysis and optimization, fabrication, construction, logistics, operation and demolition. The capability to obtain lifecycle information makes BIM suitable for a circular economy process. With the use of BIM software, the whole life cycle is taken into account from the early design phase. This provides many advantages. due to the detailed building model that allows for a more careful evaluation to determine whether it meets the project's functional and sustainable requirements. Thereby early evaluation of design alternatives is available using analysis and simulation tools to increase the overall quality of the building. The automatization of a parametric model and data sharing increases consistency and design speed (Meyer, 2018).

BIM has also a "green dimension" which is believed that has good potential to enhance environmental sustainability and circularity over building life cycles (Sam, 2019). **Green BIM** is the use of BIM to provide data for energy performance evaluation and sustainability assessment (Sam, 2019). Usually, Green BIM is used for analyzing and optimizing building performance (e.g., indoor climate, energy, daylighting, site) (Habibi, 2017) and for the integration of life-cycle analysis (LCA) into the building design process (Xue, 2021). A BIM-based approach can predict the outcomes of a construction and minimize its environmental impact throughout its life-cycle.

Some of these BIM uses for a circular built environment are (Charef, 2021):

1. a digital model for a sustainable end-of-life
2. material passport development
3. project database
4. data checking
5. circularity assessment
6. material recovery processes
7. material banks

The above BIM uses will not be analyzed in this thesis. The study will only focus to these uses if it is needed to support end strengthen the sustainability and circularity level of the result of the BIM tool that it will be developed.

4.2. BIM library characteristics

To be able to design an efficient BIM library with circular façade components it is necessary to analyze and fully understand the characteristics and the general structure of a BIM library and its functionality. In this chapter, more thorough research of the steps to design a BIM library has been done.

In BIM modelling, object classes (e.g., walls, doors, slabs, and so on) describe how object instances behave, how they "are structured, how they are edited and how they behave when their context changes" (Sacks et al., 2018). A BIM model can consist of a large number of objects, representing physical and functional information. The objects contain information about their geometry, location, relation to other objects etc. A BIM is able to contain all available and relevant information about every single component of a building (BAMB2020, 2017). As a result, a library of BIM objects is a group of objects that may be specified by a BIM authoring platform or created by the designer to construct unique digital representations of components (Sacks et al., 2018).

With the rapid rise of BIM technology in the Architecture, Engineering and Construction field, a large number of BIM libraries have been available online. These libraries usually have thousands of BIM components. BIM components not only contain the **geometric** information of the building components (such as length, width, depth, etc.), but also the **semantic** information of the building components (such as materials, manufacturers, fireproof rate, etc.), in addition to the **association** information between the components (e.g. a door being embedded in a wall) (Li, 2020). It can be concluded that with the help of BIM objects, data sharing throughout a building life cycle can be better achieved.

Regarding CE, a BIM components library offers the majority of standardization benefits and also a degree of flexibility that the construction sector needs to succeed in order to adopt circularity. The library can provide to the client the choice to select from a standardized set of components, guaranteeing their quality and circularity and with also a degree of adjustability (Li, 2020). Thus, the developed BIM components library should contain enough BIM components with different variations to ensure that the result will be efficient and flexible.

STRUCTURE OF BIM LIBRARY

A BIM library is a group of component families. Each family has one type of component with its different possible configurations and the elements that this component is consisted of.

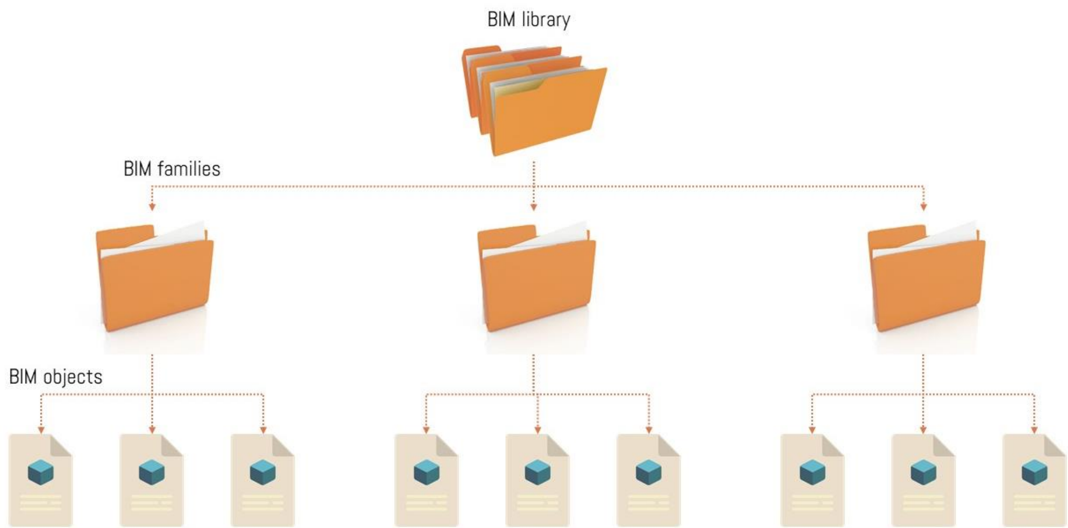


Figure 8: Representation of the BIM library structure

The BIM components are called **BIM objects**. A BIM object is the combination of detailed information that defines the position and the behavior of the object and geometry that represents that object's physical characteristics (McPartland, 2017).

Figure 9: BIM object creation representation (https://www.bsigroup.com)

Additionally, the objects can be described as 'generic' or 'specific' (McPartland, 2017):

- Generic objects are used during the initial design phase as placeholders as a visual expression of the need for a specific object to be selected at a later stage.
- Specific objects are the manufacturer objects that are actually used.

The structure of a BIM library is more than just a classification system, it divides a collection of objects in mutually exclusive, hierarchical sets consisting of members with one or many common properties (Ekholm, 2011). To facilitate wider BIM applications, the library should also be able to organize the objects and indicate their relations with clarity, consistency and extensibility. The domain ontology of BIM objects is crucial in developing a well-structured and easy to use library. It presents the classified hierarchies of classes, class definitions by defining terms, definitions, attributes, classes, and hierarchies of BIM objects (Gruber, 1995).

As mentioned, the BIM objects should be more than just a graphical representation of the physical building object, but a cluster of information needed in the project lifecycle. In a sense, the substance to define the objects lies in the definition of the objects' information, the parameter templates and the information format that meet the construction needs.

An example of a BIM library for sustainable design is the **LBNL Modelica Buildings library**. It contains dynamic models and control systems for building energy simulations (Kim, 2015). It supports the simulation of heating and cooling systems, controls, heat transfer through building envelope, as well as airflow models. The library is being developed and some packages and components have been validated. However, this library focuses only on the energy performance and sustainability of the building and does not consider the circular design principles.

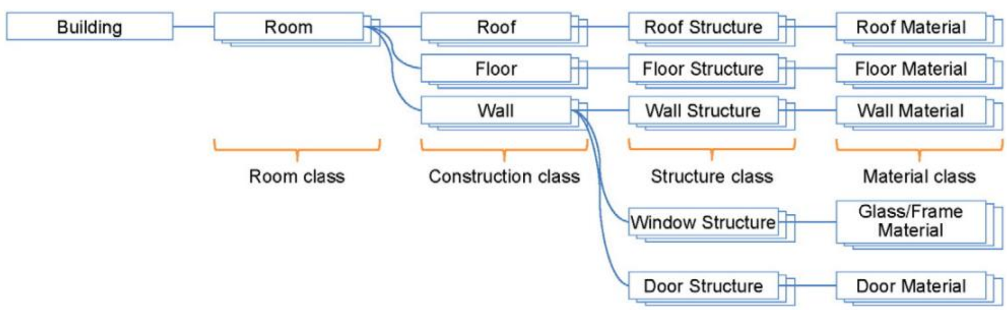


Figure 10: Schematic object hierarchy of building components in the Modelica BIM library (Kim, 2015)

BIM objects can be made available in a range of file formats, suitable for different software e.g. Revit, ArchiCAD etc. and they can also be provided in open exchange formats, like **Industry Foundation Classes (IFC).** This format type enables the users to manage and exchange data between different software. IFC is a neutral data format and non-proprietary. IFC is supported by about 150 software applications worldwide which is extremely important and necessary as construction becomes increasingly collaborative (McPartland, 2017; Groh,2018).

A BIM library has several characteristics and specifications that define the abilities of the library and the additional data that are connected to it. The idea of this thesis is to create a BIM object library based on a set of components, that can be used to different projects. It is also considered how CE design principles can be implemented in the library, so the resulted decisions will have the desired level of circularity. The proposed framework will introduce the utilization of a BIM object library formed by a set of core components or elements. These components will be identified by a process of rationalization, standardization, and optimization. The method and the process that will lead to these decisions needs to be analyzed to identify what additional data can BIM have regarding circular and energy design and the possibilities of this BIM tool that will add to the development of circularity and sustainability in the building design process.

4.3. Conclusion

BIM is already used to **support circularity and sustainability** and to configure the sustainable building envelope, considering both energy conservation and life cycle costs. Some of these BIM uses are:

1. a digital model for a sustainable end-of-life
2. material passport development
3. project database
4. data checking
5. circularity assessment
6. material recovery processes
7. material banks

Design with BIM has several benefits to each stage of a building life cycle; thus it is broadly preferred as a design tool. The two major **contributions of BIM to sustainable building design**:

- BIM can reduce inefficiencies in traditional construction processes by allowing integrated project delivery through effective information sharing between all the project stakeholders
- BIM can help optimize building design to reduce natural resource use and waste.

Moreover, BIM is the most adequate tool for the application of circularity principles in the design phase, especially regarding **prefabrication** and **standardization**. The main strategies to improve CE for prefabricated, standardized building systems with the use of BIM are:

- Design for disassembly (to improve the end-of-life deconstruction)
- Minimize the used materials and different components
- Track the product lifecycle

However, as is mentioned above, most of the studies and developed BIM tools to support circular design have focused on assessments and validations of the building design and components. There are no tools that can provide the designers with the necessary information for the optimum selection of the components for a circular design and especially for façade renovation design.

In this thesis, BIM is used not only as a design support tool but also as a method to create and manage information for a façade renovation project by its linked database consist of building elements. The main reason to integrate BIM technology tools in the design process is to deliver an accurate, efficient and sufficient design for each building project, to decrease the (calculation/assessment) effort and to speed up the project process. The use of a supportive BIM tool can enable the selection of sustainable and circular materials and components during the design phase and can also potentially help quantify the amount of them which can potentially be recovered at the end-of-life and reused.

This study will try to design a BIM library that includes all the relevant data regarding the circular standardized façade components and will be able to provide suficient solutions for a energy façade renovation to different building cases. The BIM library will include information about the elements, their materials, the components that these elements create and the façade system that will be the end product of the design. Moreover, the BIM tool will be ale to conclude to the best possible solution considering the context of each building project.

BUILDING LEVEL ← COMPONENT LEVEL ← ELEMENT LEVEL → MATERIAL LEVEL

About the **characteristics and the structure of a BIM library**, the aspects that need to be taken into account are that in a BIM library, BIM components contain the **geometric** information of the building components (length, width, depth, etc.) and the **semantic** information of the building components (such as materials, manufacturers, fireproof rate, etc.), in addition to the **association** information between the components (e.g. a door being embedded in a wall). Additionally, the library can provide the client with the choice to select from a standardized set of components, guaranteeing their quality and circularity and also a degree of adjustability. Thus, the developed BIM components library should contain a sufficient number of BIM components with different configurations to ensure that a sufficient result can be obtained for the design process.

The **structure** of a BIM library is more than just a classification system, it divides a collection of objects in mutually exclusive, hierarchical sets consisting of members with one or many common properties (Ekholm, 2011). To facilitate wider BIM applications, the library should also be able to organize the objects and indicate their relations with clarity, consistency and extensibility. The domain ontology of BIM objects is crucial in developing a well-structured and easy to use library.

The idea of this thesis is to create a BIM object library based on a set of components, that can be used to different projects. It is also considered how CE design principles can be implemented in the library, so the resulted solutions will have the desired level of circularity. The format type of the library will be IFC because it is an open exchange format that enables the users to manage and exchange data between different software and facilitates the collaboration between the different stakeholders.

The proposed framework will introduce the utilization of a BIM object library formed by a set of core components or elements. These components will be identified by a process of rationalization, standardization, and optimization.

Concluding, BIM can be described as the tool that can facilitate the merge of the circularity and energy renovation principles for a more sustainable façade renovation system. The detailed method of this contribution of BIM is going to identified in the next phase (Design strategy) of the study.

The steps that will be followed so the BIM library will be able to suggest the most sufficient result are:

1. Initially, analytical tools should be applied to the core elements to select similar elements in order to determine the degree of variation and flexibility that is necessary to satisfy a number of different projects with similar but also different characteristics.
2. The next step is to specify the elements requirements (e.g. materials, energy performance etc)
3. The third step is the optimization of the components to follow standardization and circularity principles and optimize the use of materials and elements. This phase will make sure that the components are suitable for mass production and sufficiently sustainable and circular.
4. The last step will be the application of the design to a case study building.

Despite all the above-mentioned information about the contribution of BIM in the façade renovation design, there are still gaps that need to be filled. To be able to fully grasp the potentials and the structure of a BIM components library, a more practical approach needs to be done. In that way, the process and the steps that need to be taken for an efficient BIM library design will be clear and accurate. Additionally, it will be clear what type of format is needed for the end result of the library how the main research question is answered, which still remains quite vague.

Design strategy

5. General renovation design specifications and components

The thesis due to the needs of the project is based on **Research through Design**. An evaluation of the project will be made through the developing process. Additionally, the final design will be evaluated through the application in one or ideally in two case studies with different characteristics.

The purpose of the thesis is to develop a façade renovation BIM components library with the use of Revit program, to facilitate the design of façade renovations. However, before developing this digital design, the analog design of the more general façade renovation system needs to be developed.

5.1. Design strategy

In order to start designing a façade renovation system, specific parameters need to be set. Firstly, as it was previously mentioned in the literature review, to achieve the European goal regarding the energy savings, the aim of the design is a deep renovation (60-90% energy savings) (BPIE, 2011). Additionally, the circularity strategies will be followed as much as possible to conclude the most circular and sustainable design concept.

To decide the façade system that will be used for the thesis renovation system, the components and the system of the renovation program of the selected case study, other renovation solutions (Aguirre, 2018; Avesani, 2020; More-Connect, 2019; Konstantinou, 2017; Paiho, 2015; Torres, 2021) and the analysis of the different façade renovation solutions (Konstantinou, 2014) were taken into account. Based on those the selected façade system was the ventilated façade, or rainscreen façade system. Ventilated façade is a Wrap-it renovation solution (Chapter 2.1).

The ventilated facade system consists of a substructure that connects the façade system with the existing structure. The façade panel consists of thermal insulation, water insulation, air gap and finishing layer of cladding. Due to the air gap between the insulation and the cladding the heating of the air in the air gap creates the so-called stack effect. The air goes from the bottom to the top of the façade generating continuous ventilation in the air gap. Any water penetrating the cavity is drained away and does not pass the insulation. The ventilated façade draws air through the cavity, aiding in the removal of heat and moisture from rain or condensation. Second, the rainscreen blocks some solar gain and accommodates continuous insulation, considerably reducing heating and cooling costs. The substructure is needed to support the cladding and usually consists of vertical and/or horizontal fixing rails fixed on the existing building with brackets. Additional brackets may be used to fix the cladding to the supporting rails. The insulation is usually rigid insulation boards to be able to stand by itself without an additional supporting layer on the structure (Konstantinou, 2014). A ventilated façade can facilitate the industrialization of the components because it is a fixed system that can be modified and adjusted to the needs of each building's renovation.

The main aspects of the ventilated façade are (Konstantinou, 2014, Bikas, 2017):

Advantages:

- Energy savings. Improvement in the building's energy performance.
- Heat protection. Increases thermal resistance and air-tightness to the required level.
- Better acoustic insulation. Combined with the heat protection leads to greater comfort inside the building.
- Diverse external finishing.
- Different insulation types and thicknesses that give high flexibility to the thermal performance of the system.
- Technical durability. Protection of the walls from corrosion due to weather conditions and solar radiation.

Limitations:

- Thermal bridging of the fixings.
- High cost, although compared to other façade systems (e.g. second skin) and considering the energy savings that can be achieved, the cost is not that high.
- Added structural weight on the existing façade, thus lightweight cladding material should be applied.

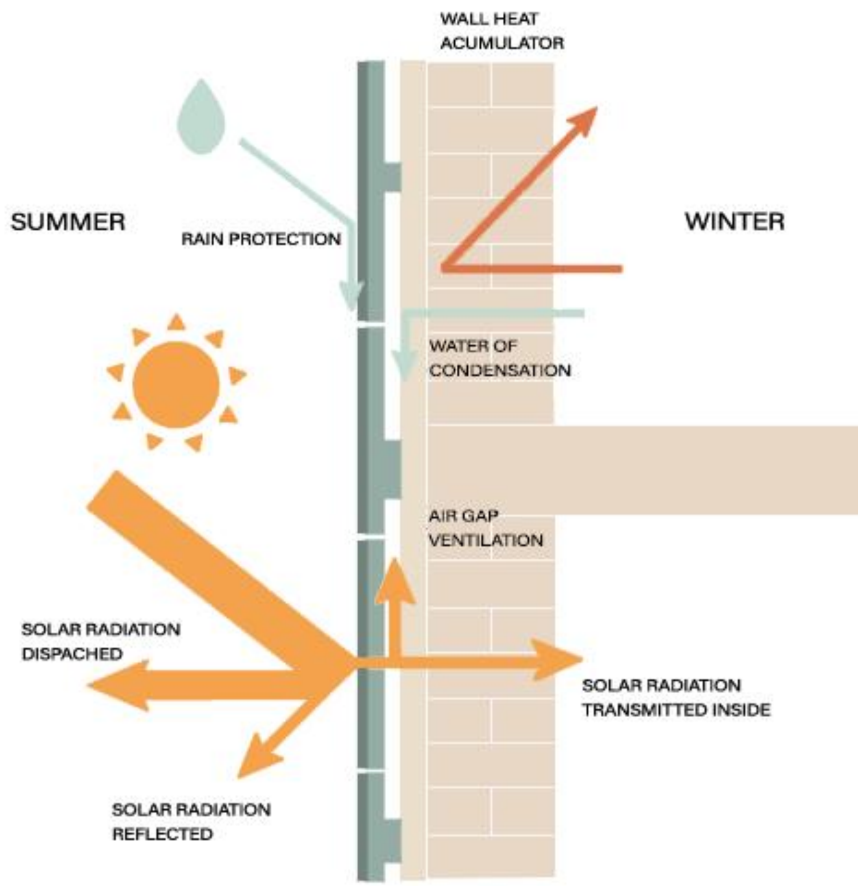


Figure 11: Representation of how the ventilated façade works (Source: https://stonesizepanels.com/ventilated-facade).

The main idea of the design is to create a modular facade system with high standardization and flexibility. More specifically, the design concept based on the analysis of T. Konstantinou (2022) will be a prefabricated rainscreen façade with either smaller or bigger module units with preassembled components of different functions (Konstantinou, 2022). It will be a unitized system that will be fixed on the existing building with the necessary substructure.

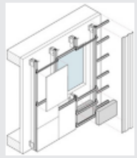
Design principle			Reference project	Degree of industrialization
Prefabricated rainscreen façade		• Outer skin (rainscreen), the air cavity, the substructure and the insulation layer • Outer skin consists of prefabricated, passive and active elements • Based on the principle of ventilated façade, which can be assembled off-site	• BuildHEAT (Avesani et al., 2020) • BRESAER (Aguirre et al., 2018), (Capeluto, 2019)	Prefabrication Reproduction

Figure 12: Overview of the applicable design concepts, linked to reference state-of-the-art projects, and most important degree of industrialization (Konstantinou, 2022).

For this type of renovation system the selected existing building's facade should be as flat as possible to facilitate the application and the efficiency of the new façade. Additionally, the facades with high repetition on their components are the most ideal for the application of this system and for this research in general. Thus, the most suitable residential building type is the Multifamily type (Chapter 4).

DESIGN CONCEPT

The concept of the design is to have a structural mesh frame where the different components will be added as filling elements to this mesh. Thus, the three main categories are the **substructure** that is necessary for the support of the new façade panels, the **frame mesh,** and the **filling panels.**

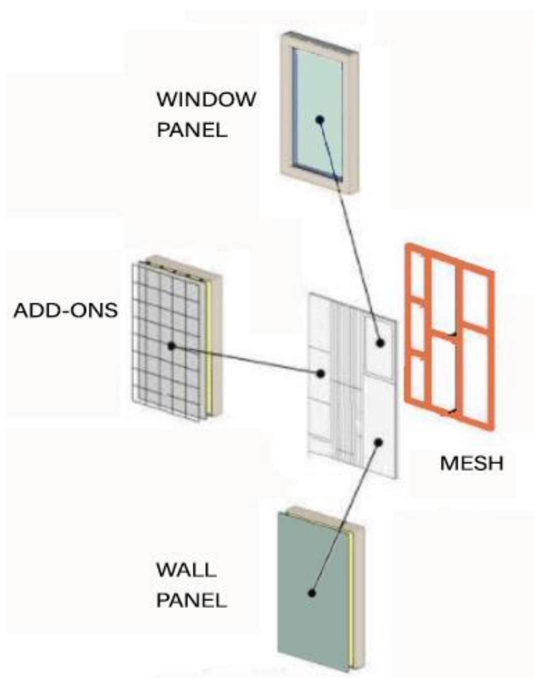


Figure 13: Design concept of the façade units.

The modular industrialized units will act as an additional outer skin. To achieve the maximum degree of industrialization, insulation must also be incorporated into the façade. The modules will be preassembled off-site to minimize the on-site labor. The system will be designed with perimeter joints that ensure watertightness and air permeability.

The modules can have the maximum possible size or be smaller. The design will keep both types as choices for the library. However, both module types will have height equal to the floor height. For the smaller modules the width will be related to the façade openings and blind panels. For the larger module the width will depend on what suits to each façade.

The smaller modules can lead to easy transport, greater manageability in the installation and maximum adaptation to different façade arrangements or facades with more complex geometries and their only disadvantage is the greater number of joints that increase the weak points. The bigger modules can have larger space of continuous insulation, thus less thermal bridging problems and fewer connections.

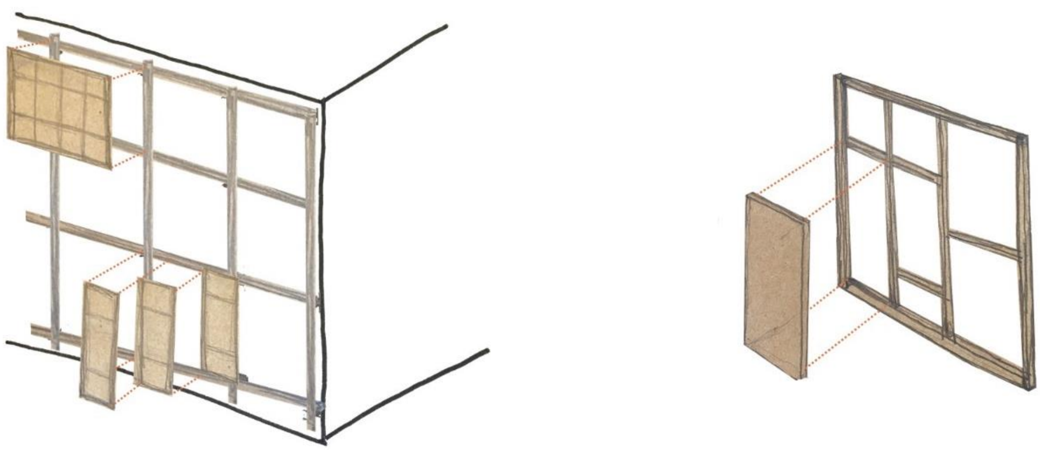


Figure 14: Sketches of the concept for the panel of the façade system and the idea of the frame mesh with the fillings.

A facade system has many different components that need to be categorized according to their necessity, flexibility, function, etc. The right categorization will also facilitate the development of the library and will help the designers to use the library more efficiently. The first step of the design is to identify the core components that are necessary for a successful and efficient energy renovation. Each component will be designed to improve the energy performance of the existing building.

However, to reach the energy goal of an nZEB renovation, except for the core components, some additional components need to be included to have a more energy-efficient and sustainable façade renovation system. These add-on components can further improve the energy performance of the building compared to a system with only core components. The core components and the suggested add-on components will be further analyzed and explained in the next chapter (Chapter 6.2.).

To this point, it must be clarified that this part of the thesis intends to develop a general design, thus the following components and their selection regarding materials, dimension etc. are used as a primary reference to finalize the façade system in an analog design. Afterwards, the design will be digital, and the BIM components library will be created, and different configurations will be added so the system can be adjusted to different buildings.

5.2. Renovation components catalog

For each energy facade renovation and specifically for the proposed façade idea of the panelized prefabricated rainscreen system there are some core components that are necessary to any renovation project and are also the minimum measures to upgrade the energy performance of the building. Thus, by analyzing the parts of the system presented in the previous chapter, the core components of façade design are:

CORE COMPONENTS

1. Substructure (support system)
    1. Brackets
2. Panelized unit:
    2. Panel frame mesh
    3. Wall (opaque panel)
    4. Window (transparent panel)

The circularity and sustainability aspects of each component will be analyzed. The main aspects of the selected types of each component and their energy performance will be highlighted. Also, the materials, connections and design choices of each component and of the entire system will be presented.

BRACKETS

The substructure of the proposed system only consists of fixing brackets. There is no need of additional substructure elements (e.g. rails) due to the mesh frame of the façade panels that can support the panels sufficiently.

The brackets are a set of industrialized components that connect and stabilize the new façade system with the existing building's structure. The fixing brackets must be designed to meet the durability and resistance requirements of the façade. The anchoring point of the brackets on the existing façade is the slab edge. The distance between each bracket depends on the size of the façade panels and the division of the façade system.

The material of the bracket is extruded aluminium or steel. For this design the selected bracket was aluminium because it is recyclable, and it is lighter and has higher proportion of recycled material compared to steel. The bracket had to allow and facilitate the disassembly of a façade unit without interfering with the rest units of the system. Thus, the selected design is a hook that is preassembled at the side of the unit and can be fixed in the corresponding fixing parts of the support system attached on the existing façade. In this way the brackets make the maintenance and replacement of the units easy and quick, and the entire façade system is highly circular.

An example of this idea was selected in the ENSNARE project and used at the plug and play project (Jorge, 2021; Torres, 2021).

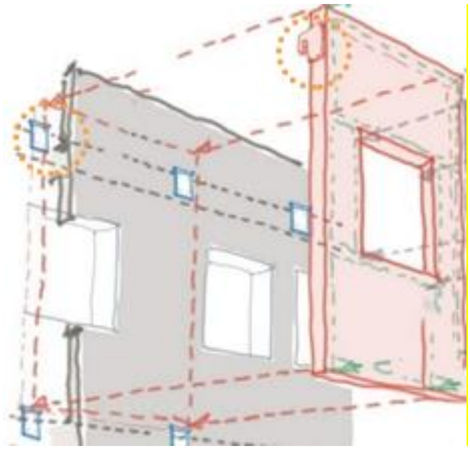


Figure 15: concept representation of the hook support system (Jorge, 2021)

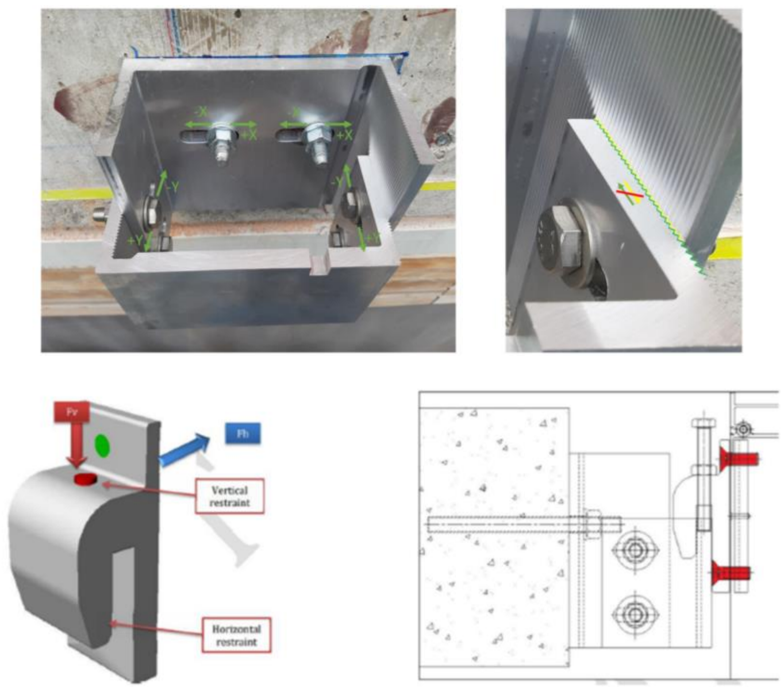


Figure 16: Hook bracket design (Torres, 2021)

The assembly of the façade will be from the outside of the building and the **tolerances** of the system for all three directions need to be established. There are open investigations in this field that can provide new solutions to the necessary three-dimensional regulation that generally foresees tolerances **of 30mm in all three directions** (Herzog, 2004).

The bracket will be not designed into detail because this is out of the focus of this research. The above design is a representation of the key design aspects that need to be included in the design of a support system for a circular renovation façade system.

PANEL FRAME MESH

The panelized units of the new light façade system have a frame mesh that its material will be also aluminium (like the brackets) and the gaps of the mesh will be able to have different fillings depending on the needs of each building project. The division of the unit is also depended on each building requirements. The frame mesh consists of vertical and horizontal structural elements, called mullion and transoms, connected to each other and anchored with the brackets to the existing structure of the building. To make the design for the creation of the BIM library simpler, the mullions and transoms will have the same profile type and only their length will be parametric. The dimensions of the gaps will be also parametric depending on the type of fillings.

However, there is a specific range for the width, height, and thickness of the panelized units. The limitation in the measurements of the units due to the means of transport are (www.mitma.gob.es. Ministry of transport. Spain government):

- **Maximum height:** The general standard for the maximum height is 4 m. However, there are some exceptions. Specific vehicles can carry a maximum height of 4.50 m. However, the height of the components will be limited to maximum **4 m** to avoid the need of special vehicles.
- **Maximum width:** The general standard for the maximum width is **2.55 m**.
- **Maximum length:** Maximum distance between hitch pivot axis and rear of trailer is **12.6 m.**

To summarize, the height of the unit, as was already mentioned, will be adjusted to the floor height of each building, up to 4000 mm and the width can be from 900 mm if smaller panels units will be used to 6000mm so I will not be too difficult to transport and assembly. The thickness of the unit depends on the filling panels type and size and the production company and it will be determined in the next step.

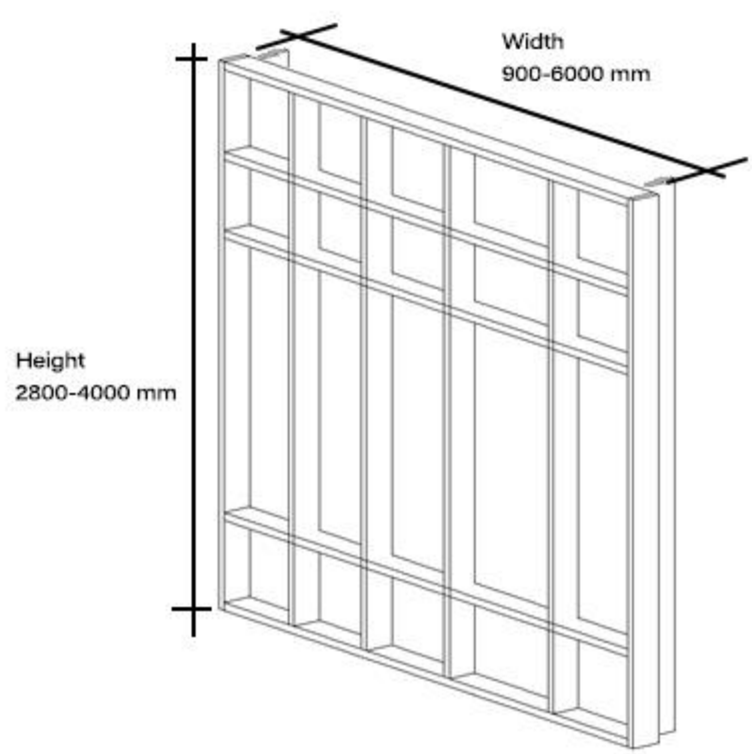


Figure 17: Representation of the industrialized aluminium mesh frame of the units

WALL PANEL

The wall panel of a ventilated façade system consists of the following layers, from the interior to the exterior (Theodosiou, 2015):

- Insulation
- Installation system
- Air cavity
- Cladding

- <u>Insulation</u>

Insulation is one of the core elements of a wall panel. It provides heat protection to the building. It improves the thermal resistance and reduce heat flow through the wall. There is a wide variety of insulating materials for a façade renovation. Their insulating effect is caused due to the low thermal conductivity of enclosed air (Konstantinou, 2014).

There is a wide range of different types of insulation materials. The choice of the material is determined by the thermal and moisture properties, fire resistance, sound insulation, strength, cost, suitability, circularity and ease of installation (Konstantinou, 2014). The aim is to use an insulation material that is environmentally friendly themselves and do not contain or release pollutants, from the production process or their chemical composition (Knaack et al., 2012).

Figure 18: Mineral wool sheets

Mineral wool and more precisely rockwool is the selected insulation material due to its properties (Konstantinou, 2014; https://www.rockwool.com):

- It has low embodied energy comparing to other insulation materials.
- It has very high fire resistance.
- It has very good thermal and acoustic performance.
- It has high recyclability.
- It does not contain any toxic flame retardants
- It is a circular product
- It is a durable insulation material

- It can have a high percentage of recycled content
- It can also be manufactured from secondary materials (materials that are recycled and used again)

However, due to its porosity, it should be used in applications that are protected from direct contact with water. Thus, a hydro-windproof membrane is suggested between the insulation and the air gap.

The rockwool insulation comes in different forms such as batts, blown material, boards with a wide range of application in building constructions (Konstantinou, 2014). Different forms of insulation are adequate for different applications. For this thesis design the selected form will be the insulating boards, because they are rigid and can be cut to size and be accurately installed. The thickness of the rockwool that is normally used for the ventilated façade system is around 150mm.

Insulation material	Density	Thermal conductivity λ (W/mK)	Water vapor diffusion resistance index μ	Fire resistance class Euroclass	Forms available	Applications	Insulation thickness for U-value 0.2 W/m²K	Embodied energy Mj/kg
Rockwool	20-40	0.031-0.040	1-2	A1	Batts, blown material, boards	Exterior wall, cavity, ETICS, floor, loft, roof	16-22	16,8

Table 4: Rockwool insulation properties (Konstantinou, 2014)

- **Installation system**

The type of the installation system depends on the selected cladding type and cladding material, and it is considered part of the cladding choice, thus it will not be further analyzed.

- **Air cavity**

The installation system creates the air **cavity** between the **insulation** and the **panel**, creating a ventilated façade (Konstantinou, 2014). The air cavity creates a thermal buffer between the wall and the external environment. The size of the cavity is important for the efficiency of the ventilated façade. The cavity size varies between **20-300 mm** (Barabash, 2016).

- **Cladding (Finishing layer)**

The cladding is the final exterior layer of the facade and the most exposed layer to the weather conditions. There is a wide range of cladding materials, that often come in form of panels, and when it comes to industrialized façade panels, which is the façade component of this design, their variation and selection are essential in order to prevent the repetition of the final design and aesthetical weak façade renovations without character. A cladding panel in order to be circular should be demountable from the other wall layers, durable, reusable, recyclable etc. Most construction materials used as cladding in new buildings can also be applied in refurbishment. They range from ceramic tiles and bricks to plastic, steel or textile (Konstantinou, 2014).

For the purpose of this design several cladding materials were selected based on their sustainable and circular properties. Additionally, for each material a company was selected based on their location, so they will be close to the Netherlands, the location of the selected case study (see Chapter 8) and their sustainability aspects. The selected types of cladding are:

1. **Phenolic panel (Selected company_ Trespa Meteon):**

   The **Trespa® Meteon®** phenolic panel is an architectural solution that offers both technical and aesthetic benefits. Trespa® Meteon® panel is a decorative high-pressure compact laminate according to EN 438-6:2005 with **thicknesses of 6 mm** or greater for outdoor applications. The sheets consisting of layers of wood-based fibres (paper and/or wood) impregnated with resins and surface layer(s) on one or both sides, having decorative colors or designs. A transparent topcoat is added to enhance weather and light protecting properties. These components are bonded together with simultaneous application of heat and high specific pressure to obtain a homogeneous non-porous material with increased density and integral decorative surface (www.trespa.com). The fixing of the panels can be either visible or invisible, depending on the aesthetical needs of the design.

   There are three aspects that need special attention:

   - **Ventilation.** The facade cladding needs to be properly ventilated with a certain ventilation cavity depth and a certain dimension of the ventilation inlets and outlets.
   - **Tension-free fastening**. The facade cladding needs to be able to expand and shrink independently from its load-bearing sub-frame due to heat and moisture influences.
   - **Sub-frame**. The panels must be installed on a sub-frame of sufficient strength and permanent durability.

   Although this type of cladding may not be the most sustainable one, it is still considered as a good choice due to Trespa Second Life program that reassures the second life use of the components (www.vevdl.com/en/projects/trespa-second-life). Additionally,the aim of Trespa company is to further build on durability by making the manufacturing of our products more and more sustainable through the reduction of the environmental impact, minimizing the use of raw materials and improve the LCA model to have a more accurate idea of the panels lifecycle and what improvements can be done (Trespa, 2021).

Figure 19: Phenolic panel façade design application (Source: www.trespa.com)

2. Natural stone composite panel (Selected company_ Steni):

Composite panels with a surface of aggregated natural stones. These façade panels require minimal maintenance and can be cleaned easily. Moreover, they have easy installation, pre-cut format and high durability with up to 60 years warranty (https://www.steni.com). The panels' production process allows for a wide range of standard formats, with a **width of up to 1,195 mm** and a **length of up to 3,495 mm**. natural stone composite façade panels have a low carbon footprint. They produce **14–17 kg of $CO2/m^2$** (https://www.steni.com). They have a life-cycle analysis and an Environmental Product Declaration (EPD) and can be delivered to regular public waste treatment facilities at the end of their useful life. Also, the panels may be upcycled (https://omnisusa.com/projects/kristian-augusts-gate-13/#).

Figure 20: Steni up-cycled facade panels, Tullinløkka, Oslo (Source: https://omnisusa.com/projects/kristian-augusts-gate-13/#)

3. Thermally modified timber (Selected company_ Thermony and EcoChoice)

Timber is a renewable and sustainable material. However, it is not very durable, especially for cladding which is exposed to the climate conditions. To become more durable timbre needs to be treated with chemical coatings which means that at its end-of-life it is not biodegradable and can't be burned. Thus, the sustainability and circularity of the material decreases extremely. To solve this problem, one of the alternatives is the thermally modified timber, a viable and long-lasting solution that utilizes no chemicals during the manufacturing process but only heat and steam. During the modification, the moisture content is removed, and the chemical and physical properties are altered, giving it extended durability without chemical intervention. So, at the end of its life, it is biodegradable and not dangerous and considered a sustainable cladding solution (Archipro Team, 2020).

The main advantages of this type of cladding material are (Archipro Team, 2020; thermory.com/company/):

- It is 100% wood product
- The wood becomes more durable, even abundant timber like pine and spruce that couldn't be used outdoors, and its moisture content decreases
- It is more resistant to heat and weather
- The expected lifespan is at least 25 years
- It is sustainable without toxic chemicals
- The fixing connections of the cladding can be hidden providing a smooth look
- The elements can have interlocking ends, thus less waste and cost.
- It has easy installation

Figure 21: Wood cladding application (Source: https://ecochoice.co.uk/).

4. Terracotta (Selected company_ MOEDING)

The terracotta panel is an extruded, double leaf, **30 mm thickness** panel from clay. These panels are a completely sustainable and circular solution. The panels are made 100% form clay bricks. The material is free of harmful additives and excludes the use of heavy metals. The careful handling of the resources, production using ecologically sensible production processes and complete reusability at demolition are the factors that characterize this sustainable construction material (www.moeding.de/the-moeding-ceramic-facade). The terracotta panels, form the MOEDING company, can be incorporated in both horizontal and vertical support systems and the panels can be oriented in either a horizontal or a vertical layout.

Panels are available in 18 standard colors and 4 standard finishes. The tiles are absolutely proven in terms of their worth and are used in a large proportion of all projects **with tile lengths of up to 1,500 mm**. For the different tile types, there are different installation systems. Moreover, the terracotta panels are hollow structures thus they are not heavy as a cladding solution and are also lighter than natural stone and glass panels.

Panel material	Terracotta	Natural stone	Glass
Dry Weight	hollow structure, 30-32kg/m2, 70% weight of the Nature Stone	2.4-2.7kg/m³	2.5kg/m³

Table 5: Comparison between terracotta, natural stone, and glass panel
(Source: www.terracottafacadepanels.com/sale-10764994-building-facade-exterior-wall-cladding-recyclable-material-terracotta-panels.html)

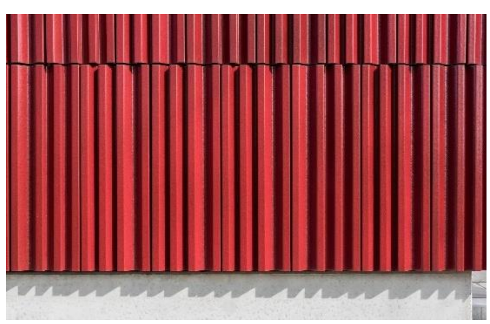


Figure 22: Terracotta façade panels (www.moeding.de/the-moeding-ceramic-facade)

WINDOW PANEL

“Window is a key component to energy efficient buildings. Window regulates air exchange in the interior space, daylight, solar gains, view etc. Windows are one of the first components to be addressed in retrofitting, as they are the building envelope component with the highest thermal transmittance” (Konstantinou, 2014).

The majority of the windows in the existing buildings stock, normally single glazed or uncoated double glazed, have a U-value around 6-3 W/ m^2K respectively, which is far over the minimum requirements (Konstantinou, 2014). The replacement of the old windows with new, double-glazing, high-performance windows improve both the thermal resistance of the glazing and frame, as well as the airtightness. The new windows should incorporate ‘**trickle vents**’ in the top of the frame as well as **draught seals** for more efficient passive ventilation measures (Konstantinou, 2014). Limiting the thermal bridges around the windows should be a priority. The general strategy is to bring the window into line with the insulation layer (Konstantinou, 2014).

The new window needs to comply with legislative requirements. Each European country has its own limiting U-values for windows, most of them requiring **not higher than 2.2 W/m^2K**. Hence, the use of double glazing with Low E coating is the minimum requirement. Lower thermal transmittance may eliminate even further the heat losses. Regarding the frame, the replacement gives the opportunity to choose between different materials, designs an,d colors. However, the frames should also meet some of the standards for airtightness and thermal performance (Konstantinou, 2014). The necessary sealants need to be placed around the window frame to prevent air leakages (Konstantinou, 2014).

Glazing type	U-value (W/m^2K)	g-value	Thickness (mm)	Weight (kg/m^2)	Embodied energy (MJ/m^2)	Cost (euro/m^2)
Double glazing	1.3	0.75	24	20	469	25

Table 6: Double glazing properties (Konstantinou, 2014)

The different elements that the window component consists of are:

- <u>Glazing</u>

Glass is the element that allows the visual connection between the interior and the exterior space, provides daylight indoors, and affects the interior space quality. The retrofitted glazing panel can improve the existing envelope performance. The selections of the coating, the type and thickness of glazing can solve the problems of thermal performance.

Insulating quality is one of the glass weaknesses. **Multiple glass panes** with air cavity between them can improve the insulation value. Moreover, if the cavity between the panes is filled with a less conductive, more viscous, or slow-moving gas like e.g. argon the thermal improvement is even greater (Konstantinou, 2014).

Low-emissivity coating (**Low-E coating**) reduce the surface emissivity of glass. these coatings reduce the heat losses from the interior space of the building in cold climates or the heat gain from the exterior in hot climates, depending on the position of the coating layer (Konstantinou, 2014).

Thermal transmittance coefficient (**U-value**) is the main parameter that shows the performance of the window panel. The smaller the U-value the better the windows performance. Concluding, the final thermal conductivity depends on the number of panes, the depth of the cavity, the gas infill, and the coating (Konstantinou, 2014).

- <u>Window frames</u>

The replacement of a window frame is also one of the most common retrofitting measures. Window frames are available in different materials. the most typical materials are timber, aluminium, steel, and plastic. "The choice of the frame type depends on the properties and cost of the material, as well as the desired architectural expression" (Konstantinou, 2014). The weakness of the window frame is the thermal bridges that usually creates, thus window frames with thermal breaks were developed. Thermal break is an insulating material applied in the frame profile. When the retrofitted glazing is a more efficient solution with double glazing panes, bigger frames profiles are required, to deal with the increase in the pane weight (Konstantinou, 2014).

For this design project, the selected material for the window frame is aluminum, because provides structural integrity, precise and airtight construction, and easy maintenance and it is recyclable as was already discussed (Konstantinou, 2014).

The windows can be categorized regarding their opening type. Figure 15 shows the most common types that will be added later in the developed BIM library.

Figure 23: Different opening type windows

ADD-ONS

The core components are passive measures to reduce the energy demand. However, although they contribute to the improvement of the energy performance of the building, they are not sufficient to reach the desired energy reduction. Thus, some add-on components (active measures) are suggested to be used for extra improvement of the performance:

1. Sun shading
2. Flat plate solar thermal collectors
3. Photovoltaic panel
4. PVT Hybrid collector
5. Ventilation system

The above components are selected based on their energy contribution to the façade renovation and their design and assembly constrains and variations. In that way, the flexibility potentials of developed library can be tested more accurately.

<u>Sun shading</u>

The sun shading devices are the only passive measure in the selected add-on components. Sun shadings reduce cooling loads by controlling the solar gain to avoid overheating. Shutters, blinds and curtains are the most common types of sun shadings. Overhanging balconies can also be considered as sun shading measure (Konstantinou, 2014). Off course there are some more advanced devices thus more efficient but also more expensive and more complicated such as the adaptive sun shading which are not efficient in terms of cost for residential projects where the more typical solutions can improve the energy performance of the building.

Figure 24: Different types of sun shading devices

Flat plate solar thermal collector

A Flat Plate Collector is a heat exchanger that converts the radiant solar energy from the sun into heat energy using the greenhouse effect. It collects, or captures, solar energy and uses that energy to heat water for the building needs. Solar collectors are a more cost-effective solution for hot water applications compared to other water heating systems, because of their simple design, low cost, and relatively easy installation and they are capable to produce the necessary amount of hot water at the requested temperature (Buker, 2015).

Sizing a solar collector for use in a solar hot water or heating system depends upon the hot water demand. The amount and the size of the collectors depend on your hot water needs, temperature and consumption. A panel with surface of **1000 cm^2** heats about **10 litres** of water per day. Based on that the amount of residents and the needs in hot water need to be calculated to find the right amount of collectors for each building renovation project.

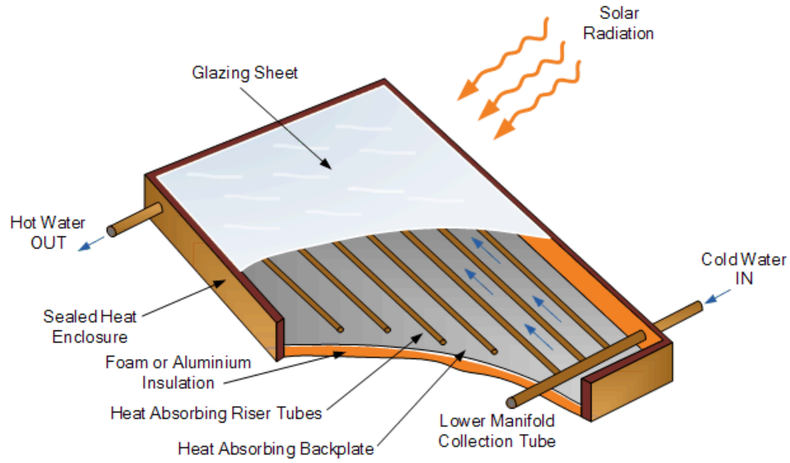


Figure 25: Solar thermal collector component layers (Camel solar)

Photovoltaic panel (PV)

The PV panels convert the sunlight into electrical energy that can be used to cover the electricity needs of the building. The PV panels will integrate on the building envelope an active (due to electrical energy generation) and a passive measure (as panels of the ventilated façade).

PV panels application on facades is a great solution. Except the energy generation, it also has other advantages:

- Provides facade insulation
- Can be used as façade and balcony glazing
- Provides noise reduction

There are different types of PV technologies available on the market with different characteristics and energy performances. Among them, the more traditional Crystalline silicon technology (rigid and more heavy panels with standard dimensions) features more power installed per m^2 in comparison to thin-film technologies:

Crystalline silicon technology (eff. from 16% to 20%) = 160Wp to 210Wp per m^2

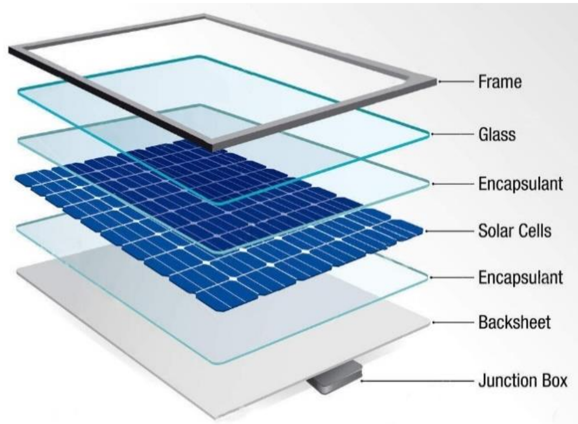


Figure 26: PV component layers (www.solarmeusa.com/blog/solarpanelstrength)

The stock dimensions for the PV panels (most cost-effective options) are (https://www.onyxsolar.com):

- 1700 x 1000 mm (60 cells)
- 1641 x 989 mm (60 cells)
- 1650 x 850 mm (36 cells)
- 1475 x 480 mm (16 cells)

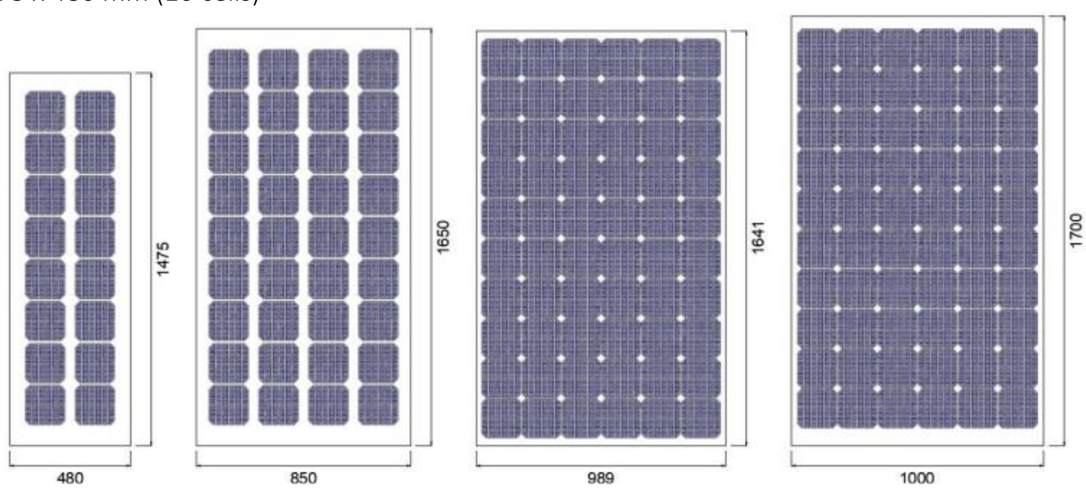


Figure 27: PV cost-effective size options (https://www.onyxsolar.com/product-services/technical-specifications)

The aesthetics of the PV units could be customized by using coloured glass (glass with ceramic frit or mass coloured glass) in combination with PV coloured cells.

Finally, the junction box is an important part of the PV units. The junction box is an enclosure on the module where the PV strings are electrically connected. It is possible to use different types of junction box:

- Rear junction box, located on the back side of the PV unit.
- Lateral junction box, on the edge of the glass lamination.

PVT hybrid collector

PVT (Photovoltaic Thermal Hybrid Collector) is a combination of a Solar thermal collector and PV cells that maximizes the solar gain and provides heat and electricity as an output. The two technologies complement each other and work more efficiently together (Bandaru, 2021; Camel solar). The heated water from the panels could be used for the needs of the building with the application of thermal collectors and heat pumps connected to the PVT panels.

PVT provides 85% more efficiency with 25% extra cost (compared to PV panels). However, PVT technology is not a simple plug and play technology as PV technology is. Moreover, the increase of temperature on the panels during power generation can reduce the efficiency of the PVT panels, which by summer can reach up to 25%. This problem is solved by cooling the PV cells layer with circulating water through the absorber on the backside of the PV panel. Moreover, the ventilated façade system that will be used is the most suitable type because due to the air cavity of the façade the PVT panels will be properly ventilated.

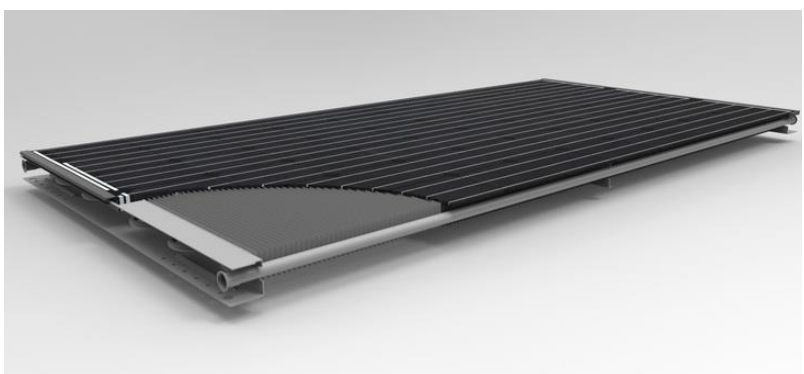


Figure 28: PVT hybrid collector panel (Bandaru, 2021)

The dimensions of the standard existing PVT collector are (Camel Solar):

- 1.6 m2: Length 1640 x Width 990 x Thickness 35 mm.
- 2.0 m2: Length 1950 x Width 990 x Thickness 35 mm.

The three previously mentioned technology applications have some dimensional limitations and some other important parameters that can influence the design (Jorge, 2021):

Parameters	Photovoltaic panel		Solar thermal collector		PVT hybrid collector	
	Max	Min	Max	Min	Max	Min
Length (mm)	4000	900	1685	1685	1580	1580
Width (mm)	2000	450	1025	1025	2880	480
Thickness (mm)	17,8	7,8	85	85	35	35

Table 7: Dimensional parameters of techology components

Parameters	Photovoltaic panel	Solar thermal collector	PVT hybrid collector
Access for maintenance	yes	yes	yes
Ventilation need	Ideally yes	yes	no
Need for air tightness	no	no	no
Need for water tightness	no	yes	no

Table 8: Other parameters of technology components

- <u>Ventilation system</u>

Among the active measures a heat recovery ventilation system is suggested to further improve the energy performance of the renovating building in terms of ventilation.

There are two different solutions for this measure (Pinto, 2013; www.siegenia.com):

- **The smart window (Climawin system)**: A window component with extra **heat recovery ventilation system** that will allow the outside fresh air to take thermal energy from the air-conditioned indoor air by means of crossing both air flows in a heat exchanger integrated in the window frame and **auxiliary system** that will provide air circulation, pressure drop control or variable air pressure into window gaskets.
- **The independent ventilation case (Aeromat VT system):** is an independent device placed next to the conventional window and works as a ventilation and heat exchange system.

Both cases are decentralized systems integrated into the window for ventilation and heat exchange. The main benefits are the improvement of air quality as well as an efficient use of energy with the heat recovery unit. All this is complemented by air filtering systems and automatic humidity, temperature and CO_2 and VOC concentration controls. Both solutions have easy installation and maintenance (Jorge, 2021).

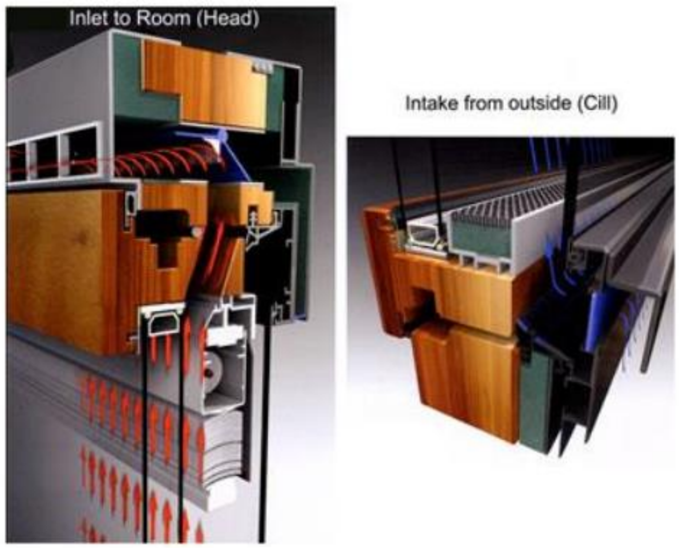


Figure 29: Climawin system (www.construible.es/2014/02/04/ventanas-inteligentes-con-ventilacion-y-recuperacion-de-calor-pasiva)

Figure 30: Aeromat VT system (https://www.siegenia.com/en/products/comfort-systems/window-ventilators/aeromat-vt-wrg)

The overall catalog of the components that will be used is presented below:

Category	Subcategory	Importance	Components	Elements	Type	Description	Design Principles
Substructure		Necessary	Bracket			Connections between the façade system and the existing building	Support, Connection with existing structure
Panelized unit	Frame		Mesh frame	Mullions		Elements of the mesh frame	Support, Connection with existing structure
	Panel (filling)		Wall panel	Insulation		Material with high thermal resistance that opposes the transfer of heat between areas at different temperature	Heat protection
				Installation system		Creates the air cavity and support the cladding	Support, cavity creation
				Cladding		Material of the final layer	Aesthetic result
			Window panel	Window frame	Standard frame	Components for fitting and operation glazing	Heat protection, Ventilation
				Glazing	Double glazing with low E-coating	Transparent material provides visual connection daylight	Heat protection, passive solar heating
		Add-on	Heat recovery ventilation system		Smart window frame	Ventilation and heat exchange systems that improve the air quality	Air quality, ventilation
					Ventilation case		
			Sun shading system		Shutter	Reduce cooling loads by controlling the solar gain to avoid overheating of the interior space	Solar control, Sun protection
					Blinds		
					Curtain		
			Thermal collector			Use solar energy to heat the water for the building needs	Warm water production
			PV panel			Use the sun light to produce electricity for the building needs	Electricity production
			PVT hybrid collector			Combination of a thermal collector and PV panel	Electricity and warm water production

Table 9: Façade components catalog

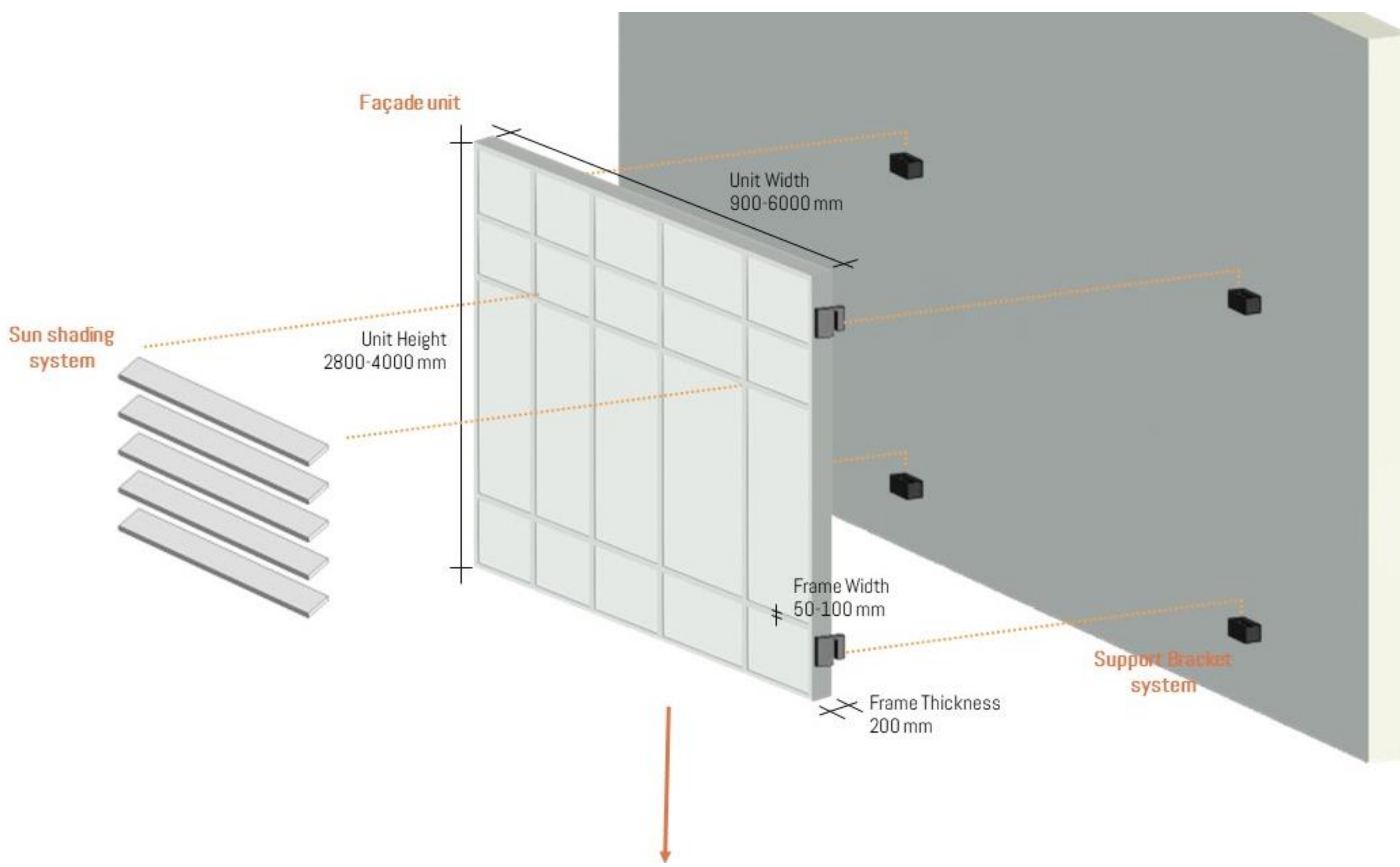
5.3. Complete renovation system

Summing up, the final renovation system shown below is a unit that consists of an aluminium mesh frame where the created spaces can have different dimensions and can be filled with different types of panels (e.g. wall, window, pv) depending on the needs of each renovation project.

The type of the supporting system that fixes the units in place and the connections between the aluminium mesh frame and the different filling panels are important for the reversibility and demountability of the system and therefor its circularity. For this, the connections need to be designed in a way that if a panel or a unit needs to be replaced or change configuration or type the disassembly will be easy and quick without the need to disassemble anything else but the component that needs to be removed. And correspondingly the assembly will be just as easy and quick.

This thesis will not very into deep to the design of these connections because the focus of this research is not into solving the circular energy renovation system design but on identifying how BIM software can be used to facilitate this design. However, a bracket solution was designed (chapter 6.2) as an example of the design approach that a circular façade system needs to have.

All the above components are the different components that the general façade renovation system needs to have and that will be included in the next step of the digital design, in the BIM components library. In the next chapters, the contribution of BIM to the renovation design and the way that the users will use the system will be analyzed.



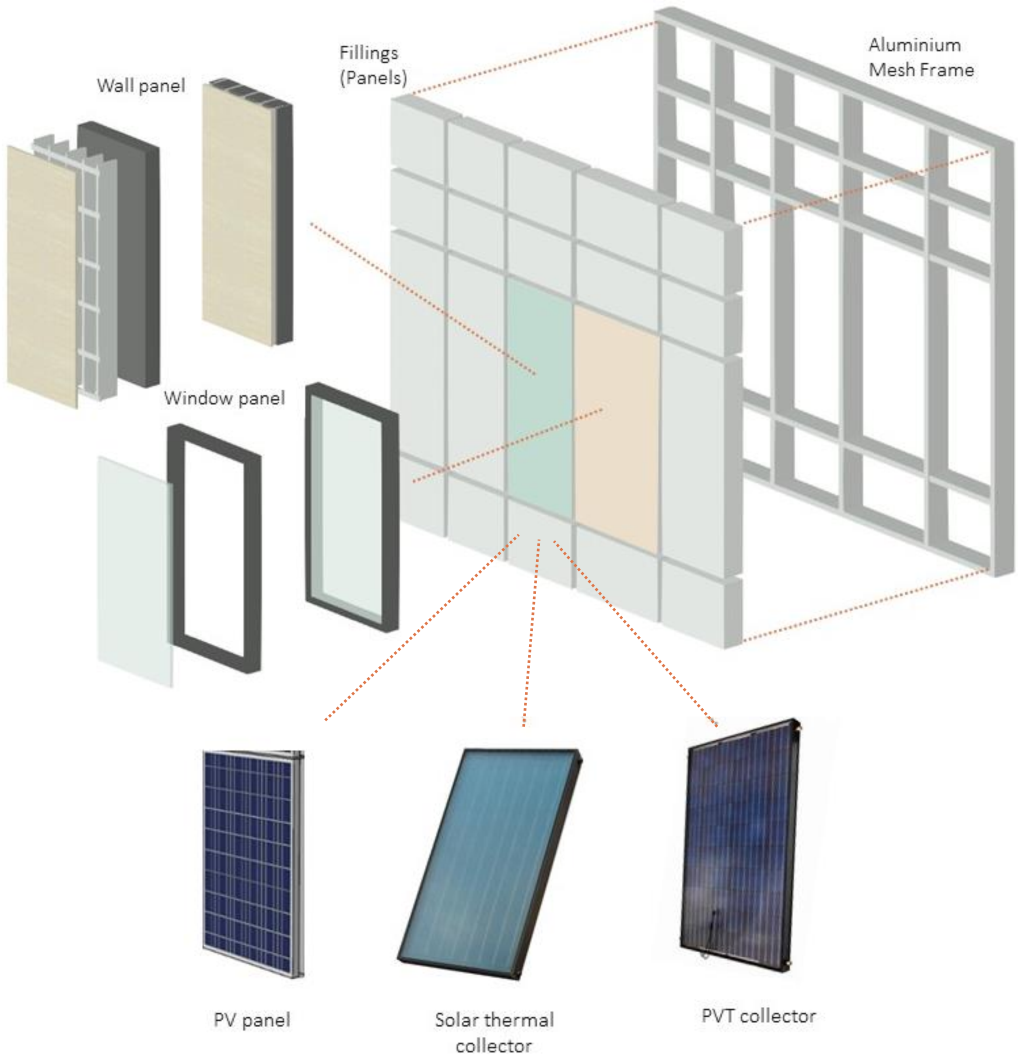


Figure 31: Façade system design with different possibilities

5.4. Different panel configurations

According to the potential needs of the façade system several unit designs will be presented with different panel configurations. In each façade renovation project, the selection of the right configuration will be made based on the building's orientation, energy needs, old and new façade design.

The different configurations are grouped in four types. The first type consists of units that have only opaque panels. There are two sub-categories. The Type1.a. has only active measure panels (pv, solar collector, pvt collector) and the Type1.b. has only wall panels (ventilated façade).

The maximum and minimum dimensions of the active panels based on the information presented in chapter 6 are shown in the Type 1.a.

Type 1. Completely opaque unit:

Type 1.a. Only active measure panels

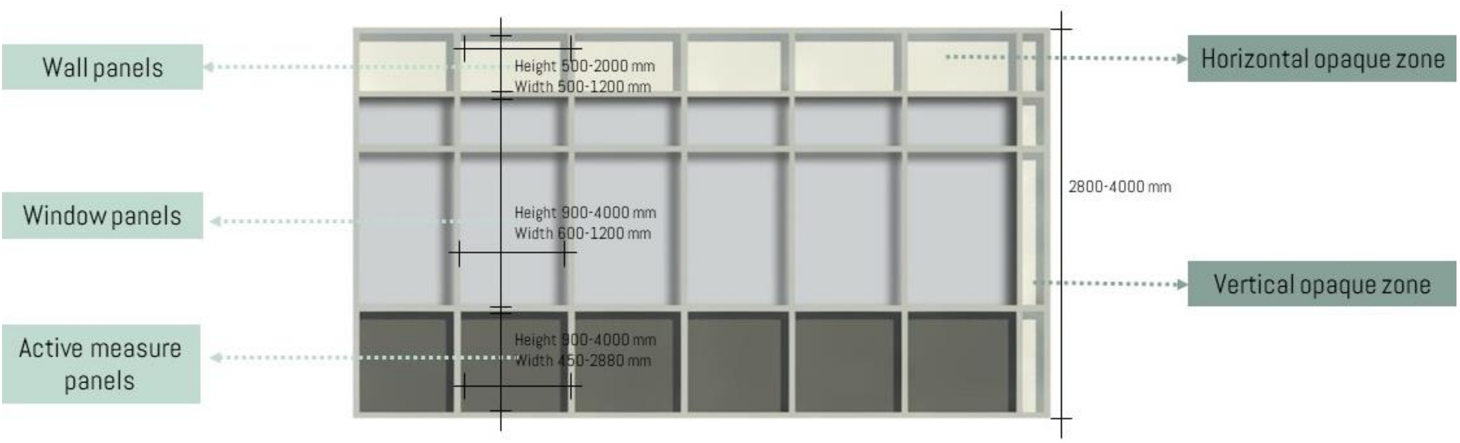
Figure 32: Type 1.a.

Type 1.b. Only wall panels

Figure 33: Type 1.b.

Respectively with the type 1 the other three types were created. In Type 2 the window to wall ration from the existing building is kept and the opaque panels are filled with wall panels or active panels according to the design and energy needs of the building. In Type 3 the window to wall ratio is maximized, which may be needed to some renovation designs that the existing glazing panels are not enough. Type 4 the panel size is maximized, and the mesh frame is sparser, so less material for the frame and a smaller number of panels are used. The more panels of Types 2 and 3 make them more adjustable to the existing structure configuration.

In Type 2,3 and 4 a horizontal opaque zone was created on top of the panel to hide the floor behind. Identically, a vertical opaque layer on the right side of the panel was created to hide the interior walls. These zones cannot be filled with active panels due to their small size, thus wall panels will be placed.



Type 2. Keep window to wall ratio of the existing façade:

Type 2.a. Only active measure panels (for the opaque parts)

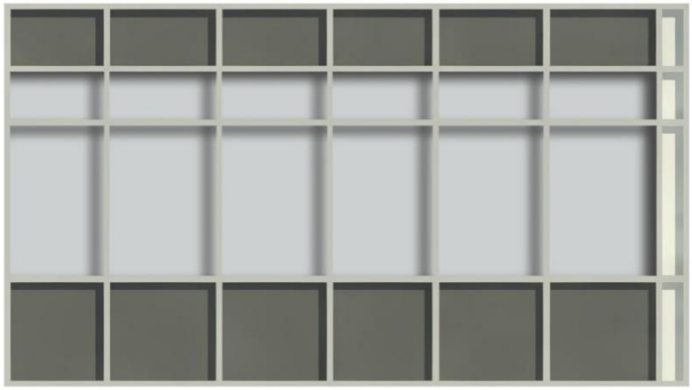


Figure 34: Type 2.a.

Type 2.b. Only wall panels

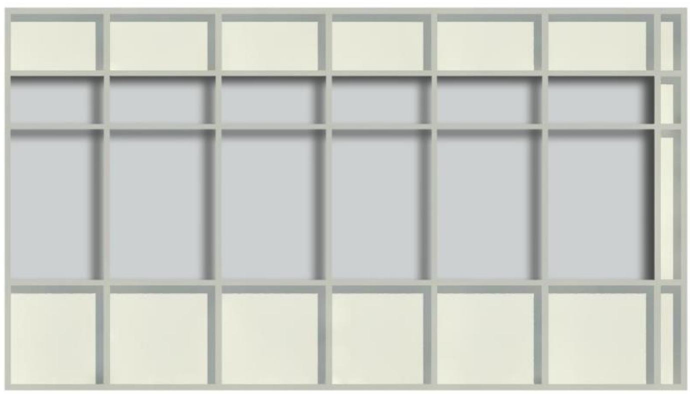


Figure 35: Type 2.b.

Type 2.c. Combination of wall and active measure panels

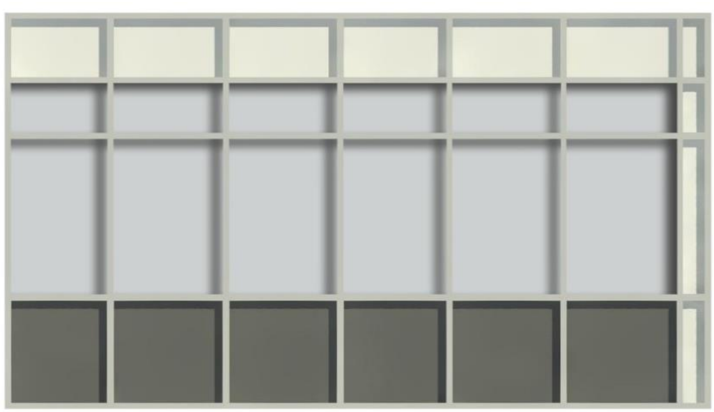


Figure 36: Type 2.c.

Type 3. Maximize the window to wall ratio:

Type 3.a. Only active measure panels

Figure 37: Type 3.a.

Type 3.b. Only wall panels

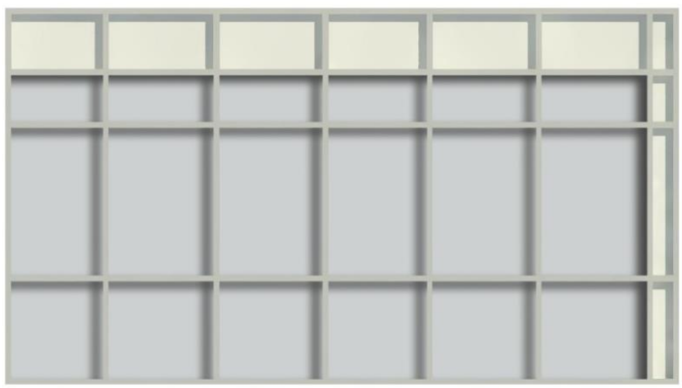


Figure 38: Type 3.b.

Type 4. Bigger panels with more sparse mesh frame:

Type 4.a. Only active measure panels

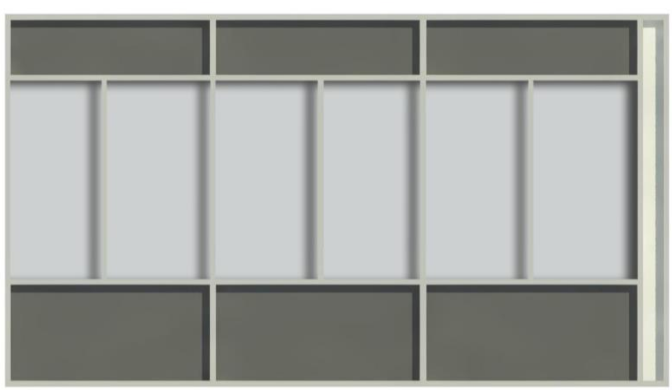


Figure 39: Type 4.a.

Type 4.b. Only wall panels (for the opaque parts)

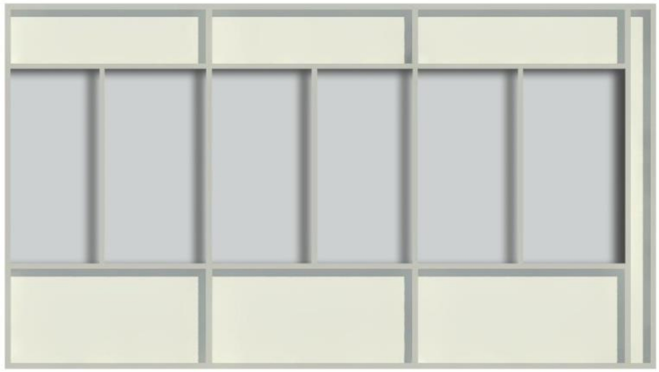


Figure 40: Type 4.b.

Type 4.c. Combination of wall and active measure panels

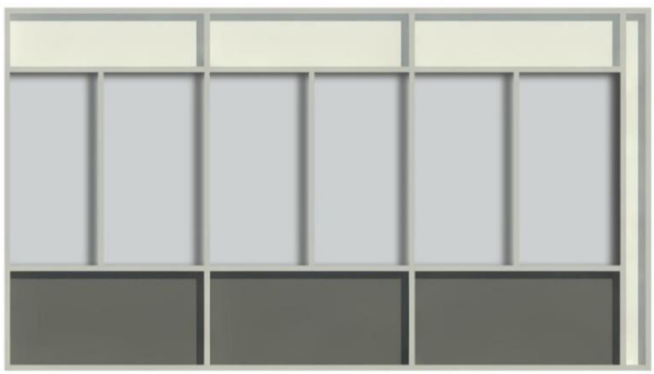


Figure 41: Type 4.c.

6. BIM library contribution & Design process

After the analog design of the façade system the next step is the digitalization of the system through the creation of a BIM library that will include all the necessary components for an energy façade renovation.

This chapter will analyze the possibilities that BIM gives to the design and how this system can be used from the designers and other stakeholders of circular energy renovation projects.

The most crucial part of this process is to identify the type of information that have to be attached to each component of the library and how this information will influence the design process and can facilitate the circular design. In order to do this identification, the information that is contained in a BIM object should be understood.

"The kind of information found in product data sheets and relevant technical details are combined with information on dimensions and functionality to represent the product in the most geometrically-effective way for designers to use within a BIM project. Adding in relevant specification associated with a project improves the object still further" (McPartland, 2017).

In this BIM library design, the objects' specifications have to focus on the circular design, the standardization, and the energy efficiency of the final result. Some manufacturers have their products in BIM 3D models. These BIM objects contain the 3D representation of the product along with the associated data, such as classification, material, model number, MEP connections, and service information. These types of data can be useful for the evaluation process of the components and the complete facade design efficiency.

The expected benefits of the BIM library are:

- Easier and more efficient sharing and collaboration between the BIM users (management, design, construction, maintenance, etc.).
- Time and resources efficiency with the minimum waste because of the better selection and management and tracking of the designed objects. Production speed is increased, and design and development costs are reduced. Additionally, the designers spend their time where is needed and prevents them from having to spend most of their time adapting to other professions' requirements as well as to their software limitations.
- Consistency and quality through a well-structured library with clearly defined properties, which are therefore easier to process and assimilate.

There are 10 key steps to creating a library that this thesis also follows (OnFly):

1. Examine the existing situation
2. Understand concerns and expectations
3. Define the content and tree structure
4. Choose a format
5. Implement a validation process
6. Further develop the library (future step)

The first two steps and a part of the third step have already been done. To complete the third step a list of evaluation indicators regarding energy performance, circularity, flexibility, etc. should be developed.

The format of the library should be a common format that can be used widely from the majority of the users; thus the selected format is the **Industry Foundation Classes (IFC)** (see chapter 5.2).

The validation process of the system will be the application to case study building with specific characteristics and needs. Also, the validation will be achieved through the list of indicators for the library.

6.1. BIM library Evaluation indicators

In order to be able to answer the research question, a list of indicators need to be made to evaluate the components of the BIM library and ensure that it can facilitate the design of a circular standardized renovation facade system that meets the energy saving measures and it is adjustable. Essentially through this evaluation framework, the method of how this can be done will be provided.

The main focus needs to be in:

- Circularity indicators
- Energy indicators

For the circularity aspect, as was already concluded in chapter 3.4, the circular design principles of the components are:

1. Design for Disassembly
2. Design for Reuse
3. Design for Flexibility and Adaptability
4. Design for Durability
5. Design for Recycling
6. Design for Optimization

The selection of the indicators will be based on the above principles, to ensure that the library can provide sufficient design solutions for energy renovation regarding circularity.
The selected connections and materials of the components play a crucial role in the design and should be able to follow the above principles and facilitate the circular strategies.
Also, the EOL phase should be considered as part of the asset lifecycle and should be linked to the design phase. The end-of-life solutions must be specified at the start of any new or renovation or refurbishment project. The will to have a circular building must be related, applied and verified throughout the entire life of the building.

For the energy performance aspect there are several indicators that could evaluate the library by providing different type of information (e.g. measurements, embodied energy, materiality, etc.). Some of them can also be shared with the circularity and influence both aspects. The main goal is to keep the energy performance of the building to a specific level, this can be done by setting some constraints on the parameters that influence the energy performance (energy production, U-value, embodied energy etc.).

The **Table** below shows the different types of data that will be attached to the library, how they can indicate the circularity and sustainability of the design, how they can be measured, who will use those data, and how this information can be used. The main question is "*What info do we need to attach to the library for more efficient results?*".

Data	Description	Level of focus/detail	Data source (the data-base)	Value type	User type	How the information can be used
Material	The type of material(s) used	Component	Manufacturer & LCA* for the type, amount and composition of the materials	Number of material layers & Kg/layer of material	Designer	Material influences the apparency and the energy performance and the durability of the system
Material composition	The amount of raw and recycled material(s)	Component		% of raw and recycled material /total kg of material of each layer	Designer, Manager	It is needed to know and track the amount of raw material that is used and know the end-of-life possibilities
Connections	Type and demountability of connections	Component & Façade unit	Fixed guidelines	Guidelines for a circular design (e.g. no chemical connections, demountable etc)	Designer	Connections is part of the design
Dimensions	The measurements of the component	Component	BIM software (automatically measures it in the model)	Height*length*width (mm)	Designer, Manager	Dimensions influence the design and energy performance
Count	The number of each component used	Components	BIM software (automatically measures it in the model)	Number	Designer, Manager	The designer should aim for the minimum number of components possible and the manager can track the needs of the components (maintenance, replacement, end-of-life use etc)
Durability	The lifespan of the component	Component & Façade unit	Manufacturer (information & guarantee)	Years	Designer, Manager	Influence the circularity of the design and based on the durability the maintenance needs and end-of-life solutions can be organized
Assembly description	Assembly details and demountability potential	Component & Façade unit	Manufacturer & fixed guidelines	Guidelines for a circular design	Designer, Contractor & builder	The designer will know how the assembly can facilitate the circular the design) and the builder will know how the system should be built
Maintenance	What type of maintenance is needed for each component & when	Component & Façade unit	Manufacturer	Guidelines for a circular design and energy performance	Manager	The manager will be aware of the specific maintenance needs of each component type
End-of-life solutions	Recyclability, reuse rate & reuse potential	Component & Façade unit	Manufacturer & LCA*	Guidelines for a circular design (reuse, remanufacture and recycle potentials available in the market)	Designer, Manager	The end-of-life solutions should be included in the design phase and the manager has to ensure that the designed solutions will be applied
Embodied Energy	The energy that is used to produce the component, including mining, manufacture and transport	Component, Façade unit & complete façade system	LCA* and/or BREEAM-NL**	MJ/kg	Designer	The designer will know the energy efficiency and sustainability of the design

Manufacturer	Company and region of production	Component	Manufacturer	Company name & location	Designer, Contractors & builder	Info for the region of company and the distance from the project and easily research the sustain. and circular. measures of the manufacturer
Transportation	Transportation type depending on the manufacturer, amount and size and location	Component & Façade unit	Manufacturer	Transportation type & number of routes & distance (km)	Designer, Contractor & builder, Manager	The transportation and its energy production will be influenced by the size of the design
Market standards	The standard sizes available in the market from the manufacturers	Component & Façade unit	Manufacturer	Height*length*width (mm)	Designer	If the design tries to be based on the market standards the final project is more cost, time and energy efficient
Constrains	Components' measurements	Component	Manufacturer	Edge geometry (min-max size) (mm)	Designer	The designer needs to know the boundaries of the design
Thermal transmittance (U-value)	Energy parameters of the component	Component	BIM software (Based on the product information)	W/m^2K	Designer	These data are important for the efficiency of the energy renovation design
Visual transmittance		Component (window)		Number	Designer	
g-value		Component (window)		Number (0.2-0.7***)	Designer	
Cost	Cost of each type of component (depending on the amount used)	Component & Façade unit & Complete Façade system	BIM software (based on the product & manufacturer information) & LCA*	$Euro/m^2$	Designer, Manager	The cost influences the feasibility of a design and need to be taken into account of the designer and the manager is responsible for the cost aspect of each phase of the project

Table 10: Data connected to each component of the library

*(Akbarieh, 2020; www.oneclicklca.com/), ** (Simhachalam, 2021), *** (Konstantinou, 2014)

Each one of the above data play a crusial role in the circularity, sustainability and energy performance of the façade system design. Analitically, how each parameter influences the circularity and sustainability level is shown below:

- **Material and Material composition**
  The materials choice strongly influence how sustainable and circular a design is. The designer should aim for materials with low embodied energy, high reusability and recyclability that can be used in a demountable system (Geldermans, 2016). Also, the material composition shows the percentage of raw and recycled materials. The higher the recycled percentage the more circular the material choice. In the same way, the energy performance is also influenced by the material due to the different energy parameters of each material type.

The information about the characteristics of the different materials used in a component can be given by the manufacturer. Additionally, LCA can facilitate the decision-making regarding the materials. As Pereira highlights, “BIM-LCA integration can currently be accomplished with material quantification for environmental impact assessment, environmental data integration in BIM materials, and data extraction and transfer between tools. However, there is a lack of knowledge regarding end-of-life impacts and their integration in the BIM environment” (Pereira, 2021).

- Connections
  For the connections, some guidelines should be attached to the library that will inform the designer on what to focus on when choosing or designing the connections in order to design for disassembly and reusability of the components and achieve the most circular façade system (Durmisevic, 2010; Hillebrandt, 2019).

- Dimensions and Count
  The size of the components and the façade units, the number of different measurements of each component type, and the number of total components of a design have high influence on the circularity of this design. As discussed in Chapter 3, the industrialization and standardization of the façade system can facilitate and support circularity (Gibb, 2001; Smith 2010). To maximize the standardization, the minimum different configurations of each component and the minimum amount of components should be the aim of the designer. Additionally, by minimizing the number of components, the materials that are used in the system are consequently minimized which is also in favor of circularity. For those reasons, providing the designer with the dimensions and quantity data can lead to achieving higher standardization and minimization of the façade components.

- Durability
  The lifespan of the components influences the circularity of the design. In this way, it is information that should be included in the attached data for the designer to have a better understanding of the lifespan of the design in order to think and design the possible end-of-life solutions.

- Assembly Description
  The assembly description parameters will provide construction guidelines for the assembly and disassembly of the façade system and its components for a circular design. This information can be used by the designer so he can choose the more efficient design in terms of circularity based on its demonstrability and assembly process. This parameter will also include all the info that is needed for the system to be built based on the manufacturer guidelines.

- Maintenance
  Maintenance is an important part of a project. This step can delay the need for the replacement of a component and prevent any wear and tear that can minimize the component’s lifespan. This connection between the maintenance and the durability of a product makes it relevant to circular design. Moreover, the lack of maintenance can reduce the energy performance of a façade system of a component. Thus, some guidelines regarding maintenance should be attached to the library, so the designer and the other stakeholders will know how to achieve the highest efficiency of the components.

- End-of-life solutions
  The end-of-life solutions and choices are crucial for the sustainability and the circularity of the design. The design phase should include the end-of-life solutions of the components. Thus, this parameter will inform the designer about the possible choices that are currently available in the market for each component, depending on its materials, connections, size, composition, etc. (Akbarieh, 2020).

- Embodied Energy
  The embodied energy is a crucial type of data for both circularity and energy performance of the design. The lower embodied energy the more circular and sustainable the design will be. By having this data attached to the library, the designer will know the energy efficiency and sustainability of the different design configurations so he will be able to make the most efficient choices. On click LCA plug-in for Revit can calculate the embodied energy of a design based on the other relevant date (transportation, material, manufacturer, energy parameters, quantity, etc).

- Manufacturer
  The distance between the project location and the components and the façade units' manufacturing location influences the circularity level of the design. The shorter the distance, the lower embodied energy of the design and the higher the circularity. Thus, the designer should select the manufacturer depending on the location of each project, among other parameters.

- Transportation
  The transportation parameter, like the manufacturer, influences the circularity of the design due to its importance in the value of embodied energy of the overall design. This parameter should include the means of transport, the distance, and the number of routes needed (depending on the size of the façade units that will be transferred).

- Market standards and constraints
  The market standards and constraints can help the designer to know what is possible and what is more widely used in terms of size in order to avoid any customization of the façade system components which comes in contrast with the aim for standardization and industrialization.

- Thermal transmittance (U-value), Visual transmittance and g-value
  These energy parameters of the components, even if they are not directly related to the circularity of the design, they influence the energy performance of the system and are crucial for the efficiency of the energy renovation.

- Cost
  The cost parameter is not directly connected with the circularity and the energy performance of the design. However, it is important information for the feasibility of the realization of the renovation design. If the cost of a design is extremely high, the project is more likely that it won't be constructed.

LIBRARY FLEXIBILITY PARAMETERS

Additionally to the above data attached to the components of the library, the flexibility level of the different parameters of the components should be also added. There are certain parameters that should be flexible to allow the library to be applied to many different buildings. Other parameters can be fixed without minimizing the level of flexibility of the library.

Parameters	Type	What influence the parameters
Panels Dimensions	Flexible	Existing building structure type and dimensions, Energy demand, Region climate, Orientation, Window to wall ratio goal
Panels finishing Material		Different Aesthetic design options
Panel type and number (wall, window, add-on etc.)		Energy demand, Orientation, Window to wall ratio goal
Panel layers type (thickness and material)		Orientation, Region climate, Energy demand
Panel layers number	Fixed	The panel's system (ventilated rainscreen, PV, PVT etc)
Frame profile type		The developed façade system
Fixing brackets type and thickness		The developed façade system, Existing building structure
Connections' system		The developed façade system

Table 11: Parameters' Flexibility

However, the fixed parameters could be also flexible if more than one types of façade systems will be added to the BIM library, in future research.

The way that these parameters can be adjusted to each project needs, and which is the process of this adjustment is included in the next chapter.

6.2. BIM library Design process

This chapter will explain the making process of the BIM components library. To create a BIM components library some certain steps should be followed. These steps are presented below:

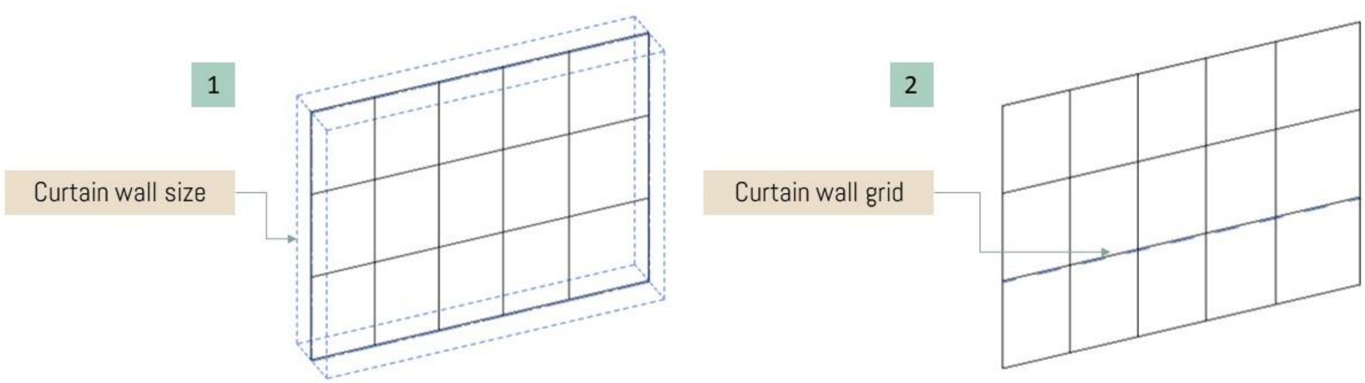
- Create the families (one for each component type) that will be included in the library.
- Attach the evaluation indicators to the families and the library.

BIM FAMILIES

The BIM library will include families for each different component that is needed for the façade system (see Chapter 6.2). The proposed façade units cannot be created as one component. They have to be divided in their components. In this chapter the potentials of each family type will be explored.

Firstly, the most crucial part of this process was to decide the type of families that fulfill the design principles of the proposed façade unit. Different BIM "systems" and types of families that could create the designed façade unit were tested. The selected BIM system, that was used for the digital representation of the analog façade unit design, was the curtain wall due to its great level of flexibility in all the different parts of the system (panels, mullions, grid, etc.) and its relevance to the design strategy façade system. However, the BIM components that can fit into the curtain wall system have to be initially designed for this type of system, and such components are hard to be found in the market.

The process of the design of the façade unit in BIM with a curtain wall is simple and specific. The designer has to decide the dimensions of the façade unit and add the grid of the mesh frame. Then he can start adding the components of the library to the unit (panels and mullions). The brackets and the add-on components (sun shading, heat recovery system) come as separate components and are independent of the curtain wall system of the façade unit.



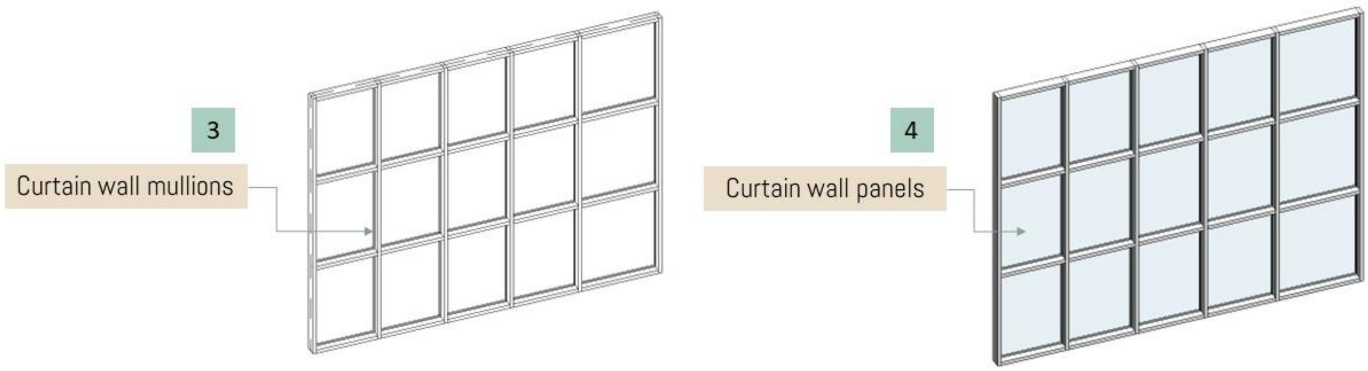


Figure 42: steps for the design of a BIM curtain wall unit in Revit

The different family categories are:

1. Support bracket
2. Profile -mullion
3. Wall panel
4. Window panel
5. Add-on panels (will include active measure panels families e.g. PV panels)
6. Add-on components (will include sun shading, ventilation system families)

The intention is to find components that are already available in the market and test if and how can be adjusted and used to the desired façade system design. When this isn't possible the component should be designed for the system based on the design strategies (see Chapter 6).

The thesis will analyze the process of one component family of the library and respectively the rest of the components' families should be designed. The selection of the sample component family will be made based on the availability of this component in the market. The customized design of the components that are not available in the market is out of the scope of this research.

Support bracket: Different configurations of the same type of support bracket. The type of the bracket is one, a simplification for this thesis research (see chapter 6.2). This type of bracket that was proposed in the design strategy could not be found as a BIM component from a manufacturer available in the market.

Thus, the bracket should be designed from scratch and the manufacturer and material information should be filled in. For the purpose of this thesis, a sample bracket shape that fulfills the design strategy needs was created.

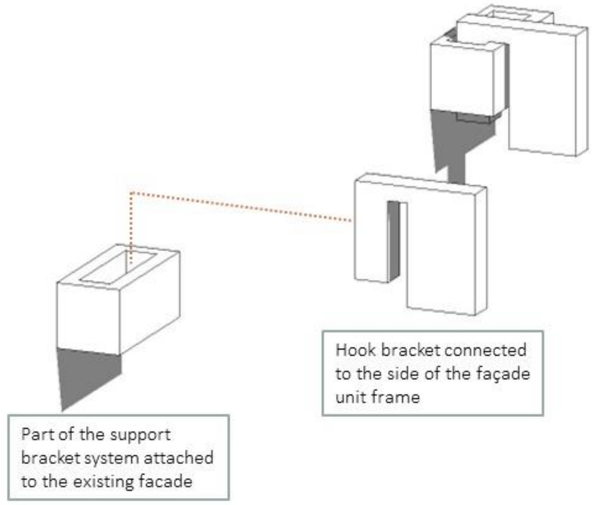


Figure 43: support bracket rough design impression

Profile -mullion: These families contain the aluminium profile types of the mesh frame for the façade unit. The mullions are by definition intended to be used for the curtain wall. Based on the design strategy of the system that uses the curtain wall for higher flexibility. There are a lot of different mullion profiles available in the market, with detailed manufacturer information, ready to be used. The mullion profile can also be created from scrunched or by 2D drawings or customized according to the needs of the project.

Wall, window and add-on panels: The panels families design process is similarly to the profile-mullion process. The panels families should be curtain wall panels families in order to function properly in a curtain wall frame and be adjustable to the frame gaps. With the BIM curtain wall system, the components of the façade units have great flexibility.

However, finding panel families for a curtain wall was a difficult process, because the available in the market curtain panel BIM components are extremely limited. Eventually, the wall and window panels have been found, but there are any active measure panels (add-on panels) for curtain wall. The available add-on panel families had fixed dimensions without any flexibility.

To apply the fixed add-on panels to the curtain wall system, the gaps of the mesh frame should be adjusted to the dimensions of the add-on panels. Another solution to this issue would be to create a customized curtain wall panel family, collect all the important data regarding the add-on panels and attach them to the family. This process will create a flexible active measure panel with all the data results regarding its energy performance.

Another issue regarding the wall panel (ventilated wall system) and the add-on panels, is that the insulation layer has to be added manually because there is any available panel family with the insulation layer embedded.

Add-on components: These component families have fixed dimensions, and they cannot be designed for a curtain wall. They are completely separate components, like the support bracket. Because these families are of secondary importance the unit doesn't have to be adjusted to them. The right types that fit the unit design should be found.

Based on the above findings regarding each component family, the focus will be in the curtain wall frame (mullions) and the filling panels (window, wall and active measure panels). Except the availability of these families in the market, the primary reason for their selection was that the frame and the panels create almost a complete façade unit, thus the conclusions from their analysis will be representative to the entire façade system.

EVALUATION INDICATORS

The previously mentioned data regarding circularity and energy performance (chapter 7.1) was intended to be attached to the component families of the BIM library through Revit.

However, this step was not possible because Revit has limitations in what type of information can be attached to a family or a library. The information can only be attached to the component after it is inserted in a project file and not in the family file. Essentially, the project file is where the designer creates his project and where he will upload the families of the library. The evaluation indicators should be already attached to the families before their insertion in the project file, but this was not possible. Thus, a different methodology was followed to overcome this issue.

Firstly, the steps to attach the additional data to a family are:

- Insert all the different component families that are needed to create the façade unit in a project file.
- Create a schedule in this project file, to add the attached data.
- Add the necessary evaluation indicators.

An important aspect of the use of schedules to attach the additional data to the families is that it facilitates the organization and the management of the data by creating a table where the data can be filtered and grouped in the desired way.

Most of the indicators of the proposed data table, of the previous chapter, already exist as options to be added to the schedule. However, most of them are not parametric. Also, this process is mainly manual with a very low level of automation.

Some additional steps to clarify the process need to be made:

- Each schedule category has different indicators choices. Also, each category includes different types of components. The category that includes all the components of a project file is the multi-categories. However, because the multi-categories schedule doesn't have all the possible data, especially the indicators regarding the energy performance, thus different categories of schedules have to be added, e.g. panel, mullion.

- The family indicator should be added to the schedule for better organization of the components and a clearer setup. With the family indicator, the components can be grouped and categorized to simplify their tracking process in the schedule tables.

- The Area should also be added to the data of the schedule table because it will be helpful for the window to wall ratio calculation. If the schedule is grouped according to the family type, the transparent and the opaque area can be counted. In this way, the designer can select which panel configuration solution is more suitable according to the desired window to wall ratio of the renovation design.

- The window panels are not included in the panel category of the schedules. There is a separate window schedule category for the windows of the façade unit.

- The Dimensions indicator should be divided into **Height**, **Width**, **Panel thickness** and **Length**. The Height, Width and Panel thickness can be found in the schedules' panel and window categories and the Length can be found in the Mullions category.

- Manufacturer indicator should be divided into the manufacturer and the manufacturer country.

Moreover, the most important aspects that were observed are:

→ The **dimension** indicators (height, width, panel thickness and length) and the **count** indicator are the only **parametric** data of the schedules. These data can facilitate the design process to increase the standardization and the manufacturing monitoring of the facade system. The exact number of different components and their different configurations will be available to the designer; thus he will be able to aim for the minimization of this number.

→ Most of the proposed data exist but their values are not provided by the manufacturer or the other stakeholders. A lot of data values are missing, and they have to be collected from the manufacturing and the construction companies to fill the gaps in the schedules and have all the necessary information for each component of the BIM library.

→ Except for the component level, data can be attached to the unit level with the schedule category of the curtain wall system.

A detailed representation of the above process and its key aspects based on the proposed data of chapter 6.1 is shown in Appendix B.

BIM LIBRARY

After the families are finalized, the library can be created. The steps for this process are:

- Save the project file, with all the different families that the library will include and their attached data, as a **Library** to the selected location.
- Organize the families of the library in different categories depending on the type and function of the components.

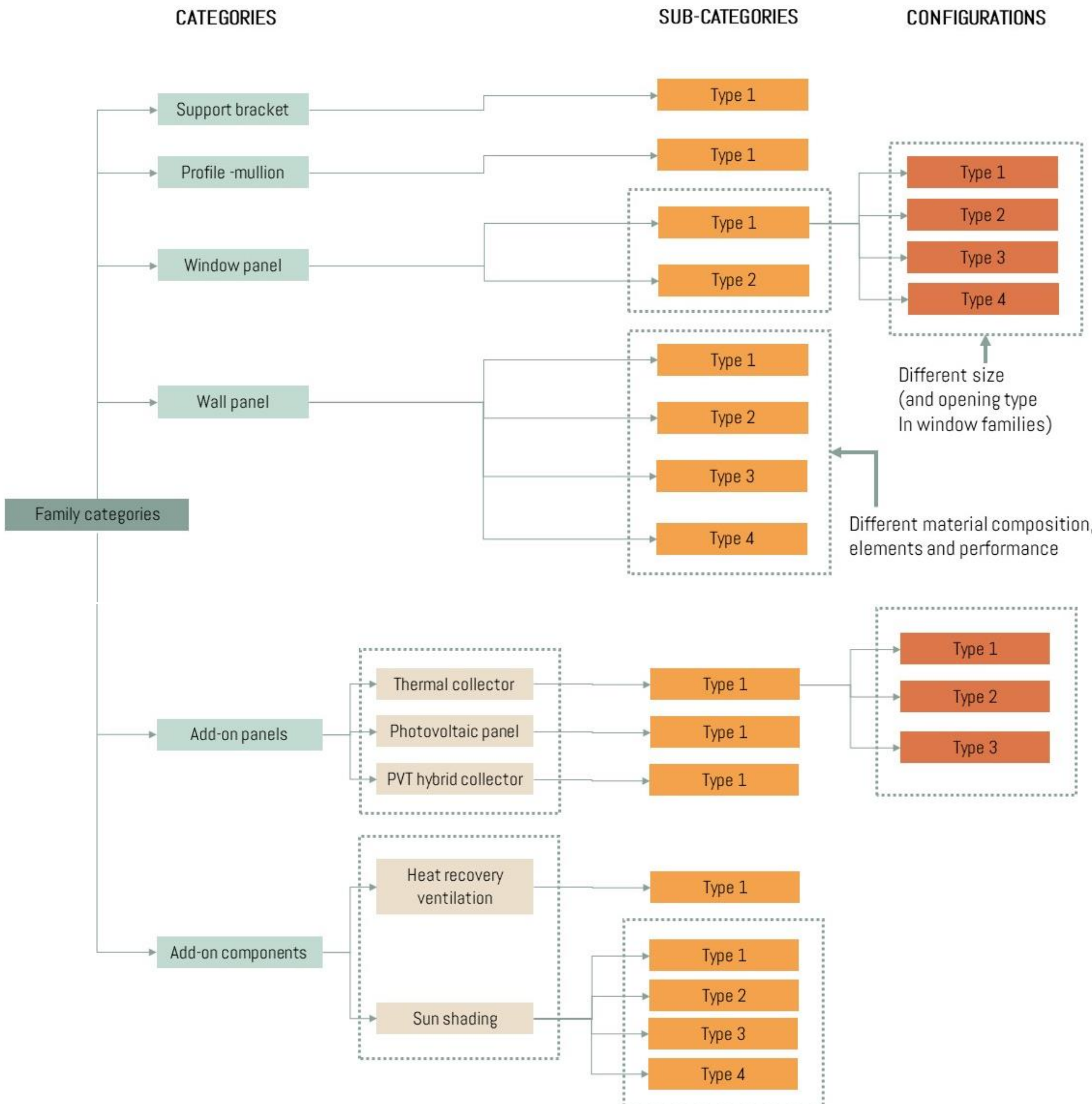


Figure 44: Families organization structure

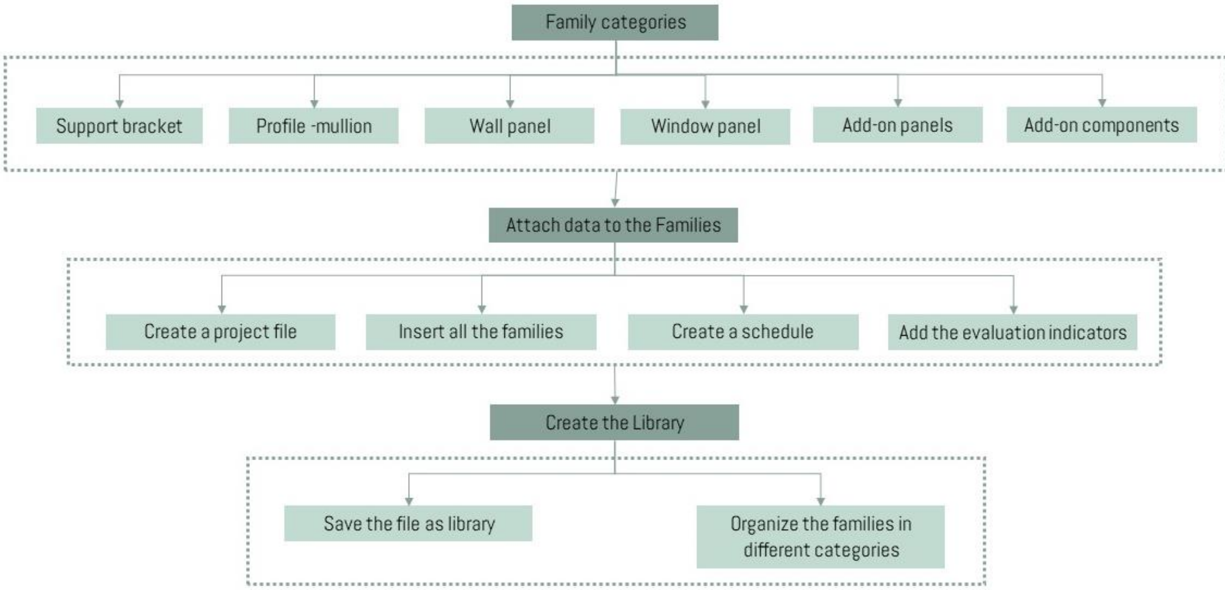


Figure 45: Steps for the BIM library creation

In that way, each family of this project will be saved automatically with its attached data from the previous steps to the selected location. Then different categories can be created to organize the families according to the component types.

Regarding the flexible parameters (see chapter 7.1), due to the decision to use the curtain wall families, the flexible parameters can function as expected without any constraint and be adjustable to the facade unit design specifications, according to each renovation project needs. Additional details regarding the flexibility of the system will be extracted from the application of the design in the case study building (chapter 7.2).

BIM library Validation through Application

7. Case study Building

A case study will be used to apply the general design and continue the research. This application will help to identify the level of flexibility of the library and the steps that need to be taken to be adjusted to each building needs.

Since the main focus is on the residential buildings, the case study is a residential building located in Amsterdam. The building is part of a pilot renovation project of ENSNARE (www.ensnare.eu).

The EU-funded ENSNARE project will work to improve refurbishment execution by digitizing the whole process and developing an industrialized façade system that facilitates the assembly and integration of passive and multifunctional building components. The project's methods and tools will aid the adoption of unique and highly efficient nZEB solutions, speeding the retrofitting pace and assisting in the transition of Europe's building stock into a highly efficient built environment. The project will focus on the creation of modular adjustable façade components as part of a full systemic approach (www.ensnare.eu).

All the above characteristics make clear why this case study is the optimum choice for this research. Both the thesis and the case study share the same general design principles for the façade system design and focus on digitalization and the developed BIM library can be integrated successfully and efficiently into the case study renovation process and give representative results.

Additionally, the selected building has several characteristics that can facilitate the process of digital application and research. Those characteristics are:

- Poor energy performance
- Repetitive façade elements with similar floors and openings (higher level of standardization)
- Load-bearing structure in good condition that can support the new facade

In general, buildings with the above characteristics should be considered the most suitable choices for the application of the façade design of this thesis.

7.1. Description and Characteristics

GENERAL INFORMATION

The case study building is located in Amsterdam, in Reigersbos street (Block 584). The building has 4 floors, and it was built in 1985. The ground floor has commercial typology, and the other floors have residential typology. Also, there are 30 dwellings.

The orientation of the building is shown below. The front façade of the building has West orientation.

Figure 46: Orientation of the case study building

BUILDING CONSTRUCTION

The building has the following structural details:

- Structure typology: Bearing walls
- Distance between slabs (floors): 2,52m
- Slab structure thickness: 0,27m
- Slab material: Concrete
- Height: 2,52m

Facade composition

For the West and East façades of the virtual building in Amsterdam, the façade is composed of:

1. Window: double glass with aluminium frames (including ventilation grilles on top), thickness: 100 mm.
2. Panel 1: non-insulated Trespa (HLP) plate (under the windows), thickness: 10 mm.
3. Panel 2: asbestos cladding, thickness: 10mm.

For the North and South façades of the virtual building in Amsterdam, the façade layout consists of:

1. Concrete wall, thickness: 200 mm.
2. Brick wall, thickness: 120 mm.

The envelope composition of the building in Amsterdam is categorized as a medium height structure adaptable for PV modules. Most windows are in the West and East facades. (The building drawings are shown in Appendix A).

Figure 47: West facade

Figure 48: East facade

The table below shows some additional façade characteristics (Jorge, 2021):

	West Façade	North Facade	East Façade	South Facade
U-value W/(m^{2}K)	2.8	2.8	2.8	2.8
g factor	0.43	0.43	0.43	0.43
Window-to-wall ratio	54%	7%	41%	24%

Table 12: Façade characteristics

According to the above Table, the thermal resistance of the components is far from adequate, based on the current standards (for the Netherlands U-value= 0.28 for wall and 2.0 for window).

Building services characteristics

The building is currently equipped with the following building system services:

- Heating system installed: The heating consists of an individual central heating system per house (CH boiler).
- Domestic hot water (DHW) system: CH boiler.
- Air-conditioning system: Not available.
- Mechanical ventilation system: The apartments are ventilated by exhaust air via joint ducts with roof ventilators per shaft. The air supply is via window grilles in the front and rear (it is expected that these are often closed). As a result, there are many damp issues.

- Low carbon Technologies for heat and electricity generation: Not available.

Energy characteristics

For the entire building the energy parameters are shown below:

Energy consumption for heating (kWh/m^2 year)	27.95
Energy consumption for cooling (kWh/m^2 year)	27.95
Façade total surface (m2)	1949.9
Windows number	442
Widow-to-wall ratio	38%

Table 13: Building's energy parameters

Renovation goals

The renovation needs to reach some certain goals and the final design solution should fulfill these goals. The following design process will focus more on the goals regarding circularity, standardization and flexibility rather than the energy performance of the façade system.

However, based on the services and energy characteristics of the building, the active measures of the proposed design strategy can highly improve the values and the overall energy performance of the building.

According to the building's typology and characteristics, the main goals of this renovation project are:

1. Maximize the standardization of the façade units and the overall façade system by minimizing the different panel configurations and the different types of components and units.
2. Improve the energy performance of the façade
3. Minimize the use of raw materials by selecting components based on their material composition.
4. Keep the existing window-to-wall ratio.
5. Maximize the use of active measure panels, to the extent that they are efficient.
6. Improve the window and the wall panels
7. Maintain the aesthetics of the existing building's façade.

The proposed design strategy can highly improve the existing building's structure and energy performance. Also, the designed façade units are a perfect match to buildings similar to this case study due to their great repetition and the flat facades.

7.2. Design Application

The application of the different panel configurations will work as the final validation of the design. Through this process, more solid conclusions will be drawn.

The first step in order to apply the design is to create the 3D model of the existing case study building in Revit. After that, the software is able to provide the designer with several information regarding the components of the existing building model. Some of this information is:

- → Construction structure
- → Dimensions
- → Materials and Finishes
- → Analytical properties
    - ▪ Heat transfer coefficient
    - ▪ Thermal resistance
    - ▪ Thermal mass
    - ▪ Absorptance
    - ▪ Visual light transmittance
    - ▪ Water resistance
    - ▪ Solar heat gain coefficient
- → Manufacturer
- → Description
- → Cost
- → Assembly description
- → Fire rate
- → Cost

Based on the above, the designer is able to know what the building needs to improve the energy performance and what types of components are needed for an efficient façade renovation.

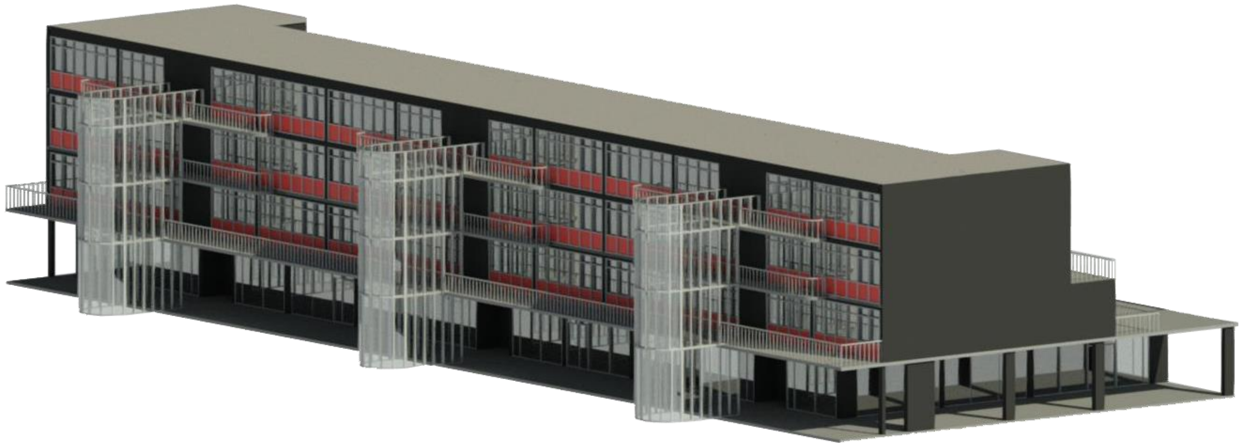


Figure 49: West façade

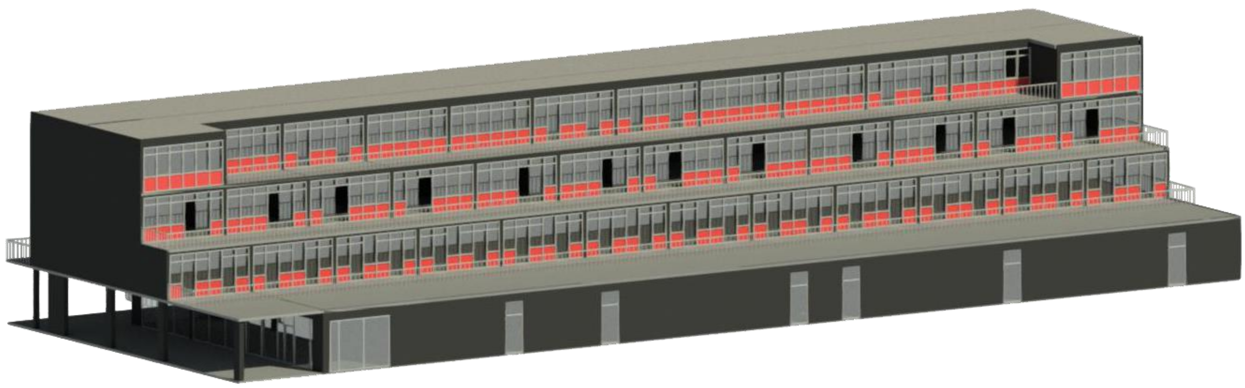


Figure 50: East façade

After the 3D model of the building and the BIM library design (Chapter 6.2), the designer should follow the steps below for the design process of the façade renovation system:

1. Decide and set the reference planes for the grid of the façade renovation system based on the existing building.
2. Add the families of the designed library for the circular energy façade renovation.
3. Select which panel configuration type (chapter 5.4) should be used to this building side based on its orientation, window-to-wall ration etc. and the renovation goals of chapter 7.1.
4. Create the mesh frame of one façade unit based on the created grid of step 1.
5. Add the different panels based on the selected panel configuration of step 3.
6. Multiply the unit and adjust any differences in the size of some panels.
7. Create schedules with the evaluation indicators of chapter 6.1.
8. Repeat steps 1-6 for a different design solution (different panel configurations).
9. Compare the different design solutions based on the values of the evaluation indicators.
10. Select the design solution that fits best to this building renovation project.
11. Repeat steps 1-10 for each side of the building to complete the renovation façade system for the entire building.
12. Step 9 can also be followed for the different design solutions of the entire building to have more solid and accurate results from the evaluation indicators.

The above design process can facilitate the decision making of a more circular and sustainable final design solution. The design solutions need to be compared from the designer by using the components that are included in the library and comparing the values of the evaluation indicators for the different design solutions.
The designer has to create a schedule and add all the data that he wants to see, and the schedule table will show the values of the evaluation indicators that are already attached to the components of the library.

Then, the design decision can be made based on the results of the solutions' comparison and the energy and circularity goals of each renovation design project.

For this specific case study building the key points of the design process are:

First of all the façade grid that the façade units should follow was designed according to the existing façade grid.

Then the façade unit types for each facade were selected based on the configurations of chapter 5.4:

> The north and south are mainly opaque thus the possible suitable configurations are limited to Type1. and the selection of the design that works best for each one is clear, based on the facades' orientation and the potential energy efficiency of the active measure panels. Thus the north façade will consist of Type1.b. and the south façade with Type1.a.
>
> For the east and west facades, that have openings the other types were the most suitable. However, to select the best solution the different panel configurations should be compared based on the evaluation indicators. Unfortunately, this was not possible due to a lack of information on the component families and consequently a lack of values for the indicators. For this reason, a rough guess was made to select the final configuration.
>
> The selected panel configuration for both facades was the Type4.c. to reduce the frame material as much as possible by using bigger panels and including some active measure panels but not only due to the orientation of these facades.

The main characteristic of the façade typology is the high repetition of the façade components. The ground floor is the only part that doesn't follow the façade grid of the upper floors. Thus some adjustments were made to the sizes of the openings of the ground floor, so it follows the facade grid. Also, the east and west facades are designed in a way so that half of the façade is the mirror to the other half.

Because, of the high repetition in the existing façade of the case study building, the comparison, selection and the application of the most efficient façade design is quite easy, and the library can provide sufficient results and information despite the obstacles in the automation of the entire process.

How BIM library can facilitate the process

The BIM library provides the designer with all the information that he needs to make the most circular and energy-efficient design decisions for the facade renovation. The number of components and their sizes can be counted from the software, and all the information about the evaluation indicators can be easily available to the designer. In this way, the designer can aim for the minimum number of components and different configurations of components. This table can also facilitate the manufacturing process and the standardization of the façade system, thus increasing its circularity level.

However, the current work interface set-up of Revit specifically and the way that the components are organized in the software do not promote the use of the developed BIM library during the design process to its fullest. It is not easy for the designer to select components only from this BIM library because the component families are categorized according to their type (door, wall etc.) and not according to the libraries.

During this design process with the use of the BIM library, the main difficulty was found in the comparison of the design choices.

In order to compare the different design solutions, each solution should be created in a different project file for the designer to be able to distinguish the results of the evaluation indicators for each design solution. Otherwise, if the solutions are in the same file all the values will be added together without any possibility to group them and categorize them by solution.

Only if each file has the data for each design solution the designer will be able to compare the values of the attached indicators and decide the best solution for each building renovation project.

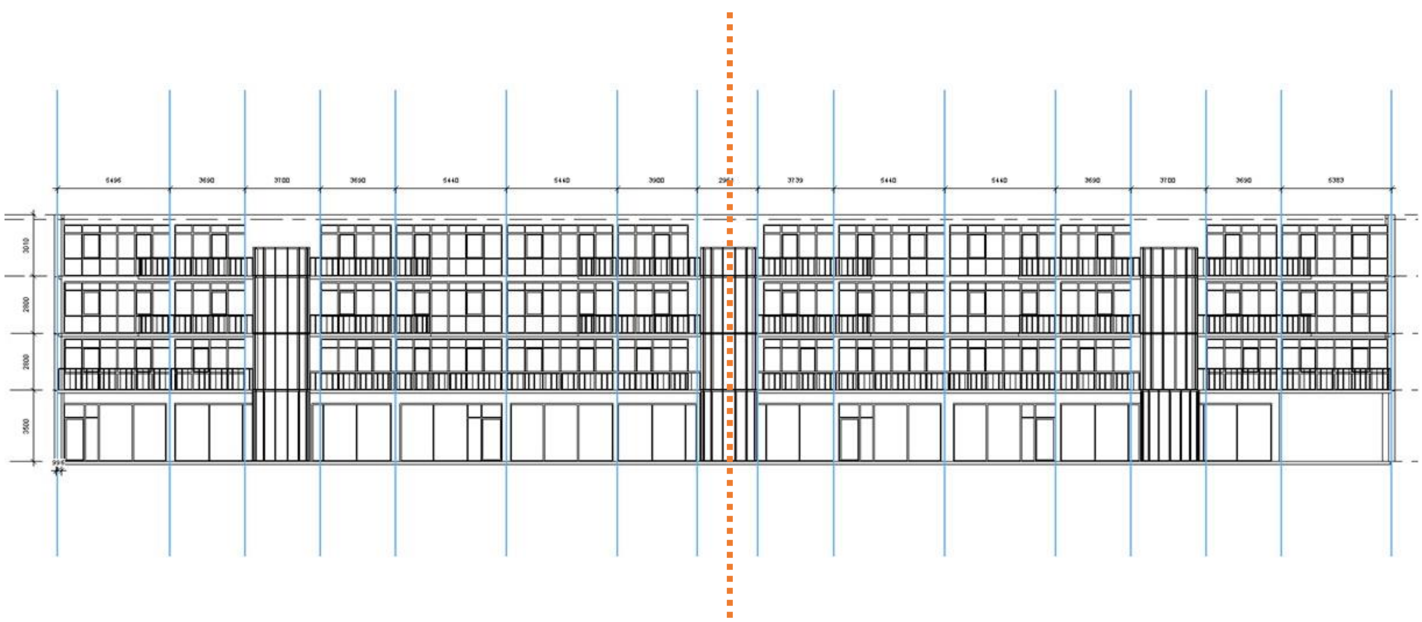


Figure 51: The grid of the façade division for the sizing of the units and the mirroring line.

Figure 52*:* The grid for the façade units' panels division according to the existing façade design.

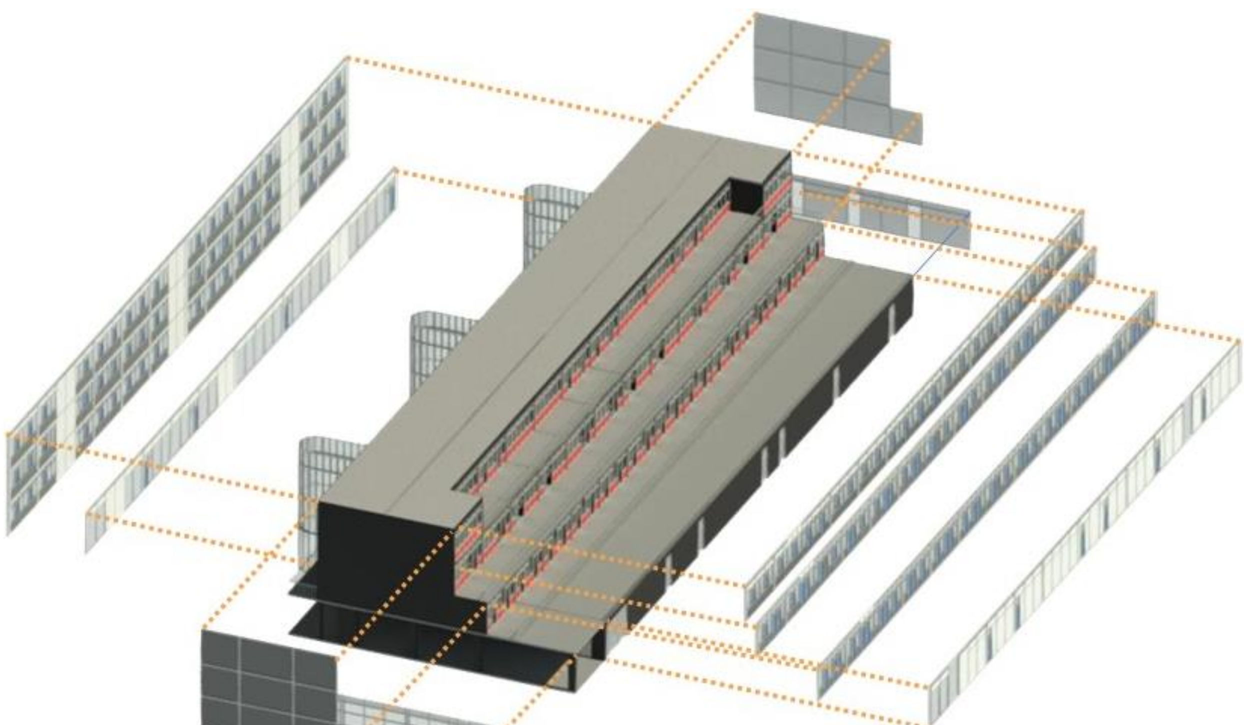


Figure 53: 3D exploded view of the necessary façade units for the complete façade renovation design.

Figure 54: Schematic impression of the assembly process of the façade units on the support brackets attached to the existing structure.

This thesis provides a Pragmatic perspective of the BIM library design and application and an instructional process for the user. The **plan → design → construct → operate** framework of BIM works well with the proposed BIM library that has the necessary attached information so the designer can initially plan and set the design needs of the renovation project so then he can go to the design phase and test and compare the different possible design choices based on the indicators of the library and select the final design.

However, after the application process and to raise the ambition of the project, it was noticed that the ontology of the interface needs to be modified to facilitate the design with this type of BIM library. The current structure of data has a rigid ontology. Several changes need to be done to improve the efficiency of the proposed library in the design process and consequently the efficiency of the final design choice regarding energy savings and circularity.

The current **Data structure** of BIM (IFC framework) is the following:

Discipline (e.g. Architectural) → **Category** (e.g. Window) → **Family** (e.g. double glass)

→ **Type** (e.g. 1.50m x0.60m)

This data structure is not very flexible and doesn't allow the designer to have all the possible different design choices that can be applied in a renovation building project.

What needs to change:

- The family should be added as a separate plug-in to be easier to distinguish the components of the library from the rest of the embedded components when selecting the design solutions. Another way to easily distinguish the desired components is if the components could be grouped not only based on their type but also based on their indicators (e.g. materiality, durability, energy performance). A modularization by content is needed, i.e. the definition of classes and properties are separated based on the knowledge domain they are related to, e.g. geometry, units of measurement, building components. The same thing has to be done for the proposed evaluation indicators.
- A Highlighting method for the components that belong to the BIM library should be created to help the designer know what he uses for his design. Additionally, highlighting any missing components or errors regarding the energy level and the circularity should be added.
- The designer should have the possibility to set an energy savings or circularity goal and the library should be able to short and ideally propose possible improvements in the choices of the components or materials and the best fit for these goals.
- The library should have higher flexibility on which parts of the modifying process of the families because currently is extremely manual and complex.
- Performance analytics attached to each component or each design choice and connected with the evaluation indicators to interchange information.
- Create different relationships and connections between the components based on the complete faced system assembly and parts (e.g. which support system goes with which types and sizes of façade units and the best panel combinations based on performance and energy savings.

8. Conclusions, Limitations and Recommendations

The intention of this thesis was to integrate the circular economy and the energy renovation principles through the use of BIM software to extract a more sustainable, circular and energy efficient façade design solution. The focus regarding BIM was the BIM components library and how it can facilitate the design of a standardized circular façade system for an energy renovation that can be adjusted to different building typologies.

The main stages of the thesis were:

- The research of the principles and the guidelines that need to be followed and the components that need to be used for the desired façade system and what are the functions of BIM software that will be useful to the project.
- The analog design of the circular standardized façade system and how it can be flexible.
- The digital design of the façade system with the creation of the BIM library.
- The validation of the design and the function of the library through the application to the case study building.

The findings of the thesis are based on the research of the existing frameworks and guidelines and the research by design of the BIM library.

The selected façade system, façade components, and overall strategy are only a sample of how the BIM components library can be created and can facilitate the design of a façade renovation system. Different façade solutions should be added and the potential functions of the BIM library with a wider group of façade components and systems should be explored.

As far as the BIM library is concerned, different design possibilities and functions that can facilitate the circular façade renovation system design were tested to end up with the selected method. The key points of the BIM library design and application process were highlighted. The findings of the thesis on the contribution of BIM to the circularity and sustainability level of a façade renovation project can be used to increase the efficiency of the energy performance and the standardization of the façade system.

The designed library consists of a group of BIM families, one for each façade component. The selected BIM system, that was used for the digital design of the façade unit, was the curtain wall due to its great level of flexibility in the different parts of the system (panels, mullions, grid) and its relevance to the design strategy of the façade system.

The library refers to the facade unit level because it has all the necessary elements for the complete façade unit system design and the evaluation indicators can have values in a unit level and not only to the component level that is the most common occasion.

The developed design of the BIM library was done with the use of Revit to identify the feasibility and the limitations of this idea. However, the intention of the thesis is to propose the creation of a general BIM library (not only Revit oriented) that can be added and used in different BIM-based types of software.

Moreover, the selected case study building was used because its typology is highly relevant to the research conclusions. Also, it was chosen for the high level of repetition of the existing façade design and the limited different components that allow for standardization and prefabrication possibilities.

This thesis was an attempt to analyze the principles, key points, and challenges of a BIM library design for circular energy renovation. This type of renovation will keep designers busy in the near future, thus solid and efficient solutions have to be found. For this reason, further research and applications in different case study buildings should follow this thesis approach. Nevertheless, the thesis's key points can be used for these types of renovation projects and further research.

Answer Research Question

The main research question of the thesis was:

> *"How can a BIM components library facilitate the design of a circular standardized facade renovation system that meets the energy-saving measures, and is adjustable?"*

After the thesis development and the extracted results throughout the process, the research question can be adequately answered.

A BIM components library can facilitate the design of a circular façade system for energy renovation in three main ways:

1. Provide easy and quick accessibility to the different circular components of the façade system.
2. Group and organize the components' families of the library according to their function and their relevance with other components of the system. This can help the designer have a clear idea of the system he is developing and the adjustments that need to be done according to each project's needs.
3. Attach data to the components of the library. Each component will have certain attached information that shows how circular and energy efficient is. The designer can use this information to compare the different components and component configurations and make the most efficient design choice in terms of circularity and energy performance.
4. Count the different components of the system and their different configurations. This can effectively contribute to the standardization of the system, the minimization of material waste and time, and it will improve its overall circularity level.
5. The adjustability of the system comes mostly from the selected design strategy of the curtain wall system in Revit (see chapter 6) which allows for a great flexibility level. As far as the BIM library is concerned the flexibility comes only from the families' categorization that allows the designer to choose and change the types of components of each category (wall types, window types, etc.) easily and quickly.

Limitations

Based on the answer to the research question we can conclude that the approach of the thesis did work. However, certain limitations of the BIM software reduce the flexibility of the final design and the automation of the design process.

Unfortunately, the entire process of the data attachment is extremely manual and complex and there is a crucial limitation. Although any kind of information can be added, most of the attached data to the components are not parametric. Thus they can only be used as descriptions and they cannot have an adjustable value according to the components' characteristics (e.g. changes to the components' dimensions), but a representative value per m^2 (e.g. for the cost, the embodied energy, etc.). in this way, the designer will have only an overview of the circular and energy aspects of each design choice, without very accurate results based on the configurations of the components.

Also, there are very limited choices of BIM components for a curtain wall system available in the market. And the BIM components that do exist are missing most of the information needed to fulfill the evaluation indicators. The same goes also for the BIM components that are not for a curtain wall system. For this reason, several assumptions were made due to the lack of information in all the BIM objects available in the market because of the time limitation and the scope of the thesis and the research question.

Additionally, the biggest contribution to the flexibility of the façade system design is from the selection of the BIM curtain wall system and not so much from the BIM library. The library can only facilitate the flexibility of the façade system design due to the fact that the components will be categorized and organized so the designer will be able to make easy changes and adjustments to the design solution.

Although the original ambition for this research was to come up with definitive answers and more efficient and automated solutions regarding the BIM library, this result was proved not to be attainable based on the current possibilities of the software. This thesis analyzed the BIM library potentials based on the families for the curtain wall system. If the scope of the design was different, the results regarding the BIM library performance could potentially be more efficient. Nonetheless, the findings show several aspects of BIM that if they are further evolved and automated, the application of circular design will be simplified throughout the entire façade renovation process, from design to construction.

During the decision-making of the design phase, in order to compare the different design solutions, each solution should be created in a different project file for the designer to be able to distinguish the results of the evaluation indicators for each design solution. Otherwise, if the solutions are in the same file all the values will be added together without any possibility to group them and categorize them by solution. Only if each file has the data for each design solution the designer will be able to compare the values of the attached indicators and decide the best solution for each building renovation project.

Moreover, the current work interface set-up of Revit specifically and the way that the components are organized in the software do not fully support the use of the developed BIM library during the design process. It is not easy for the designer to select components only from this BIM library because the component families are categorized only according to their type (door, wall etc.).

Recommendations

The main recommendations for the next steps, to solve some of the above limitations are:

- The results of this thesis should be tested and applied to different projects and buildings with different typologies to identify the possibilities and limitations of the digital system to its full extent.

- Based on the findings of this thesis, a complete BIM components library should be created with all the necessary circular components for an energy façade renovation and all their different types and configurations.

- The design should be further developed in detail. The connections between the panels and the mesh frame should be solved according to the circularity guidelines and more components should be added to improve the efficiency (more passive and active measures should be added to further improve the energy performance) and the flexibility of the BIM library.

- More detailed BIM components should be created by the manufacturers of each actual component so the system can have more realistic results. More component families for a curtain wall system should be added to the market from the manufacturing companies. The attached data for each component of the library should be also provided by the manufacturer based on the components' characteristics and limitations.

- Further research regarding the energy performance and the efficiency of the proposed façade system with calculations to extract more accurate results.

- Further research is needed to discover a tool that will allow the library to make recommendations to the designer for the most suitable and circular design solutions based on each energy facade renovation project's characteristics.

- The family should be added as a separate plug-in to be easier to distinguish the components of the library from the rest of the embedded components when selecting the design solutions. Another way to easily distinguish the desired components is if the components could be grouped not only based on their type but also based on their indicators (e.g. materiality, durability, energy performance). A modularization by content is needed, i.e. the definition of classes and properties are separated based on the knowledge domain they are related to, e.g. geometry, units of measurement, and building components. The same thing has to be done for the proposed evaluation indicators.

- A Highlighting method for the components that belong to the BIM library should be created to help the designer know what he uses for his design. Additionally, highlighting any missing components or errors regarding the energy level and the circularity should be added.

- The designer should have the possibility to set an energy savings or circularity goal and the library should be able to short and ideally propose possible improvements in the choices of the components or materials and the best fit for these goals.

- The library should have higher flexibility on which parts of the modifying process of the families because currently is extremely manual and complex.

- Performance analytics should be attached to each component or each design choice and connected with the evaluation indicators to interchange information.

- Create different relationships and connections between the components based on the complete faced system assembly and parts (e.g. which support system goes with which types and sizes of façade units and the best panel combinations based on performance and energy savings.

The main conclusion from this thesis is that the current data structure of the BIM library has limited potential to facilitate the façade renovation design. However, it can contribute to the decision-making of a more circular façade design to a certain degree and this contribution can be further improved with the application of the proposed recommendations.

Even if the final result of this research was not the expected one, this thesis can strongly contribute to the knowledge of the BIM aspects towards circularity and the application of BIM library in renovation projects to enhance the standardization and the circularity of the final design choice. The complete design process and realization of the BIM library may be difficult to be done but the final result will be a very practical tool for the designers and important support of the circular design.

References

Aapaoja, A., Haapasalo, H. (2014). The Challenges of standardization of Products and Process in Construction. In 22nd ANNUAL CONFERENCE of the INTERNATIONAL GROUP for LEAN CONSTRUCTION.

Abma, K. (2020). THE POTENTIAL OF COUPLING THE CIRCULAR ECONOMY AND ENERGY TRANSITION IN THE BUILT ENVIRONMENT. Utrecht University.

Abrishami, S., Martín-Durán, R. (2021). BIM and DfMA: A Paradigm of New Opportunities. Sustainability 13, 9591. https://doi.org/10.3390/su131795

Adams K. T., Osmani, M., Thorpe, T., Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. Proc. Inst. Civ. Eng. - Waste Resour. Manag., vol. 170, no. 1, pp. 15–24.

Aguirre, I., Azpiazu, A., Lacave, I., A´ lvarez, I., & Garay, R. (2018). BRESAER. In Breakthrough solutions for adaptable envelopes in building refurbishment VIII international congress on architectural envelopes, San Sebastian-Donostia, Spain.

Akanbi, L., Oyedele, L., Akinade, O. et al. (2018) Salvaging building materials in a circular economy: A BIM-based wholelife performance estimator. https://doi.org/10.1016/j.resconrec.2017.10.026

Akbarieh,A., Jayasinghe, L.B., Waldmann, D., Teferle, F.N. (2020) BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review. Sustainability journal. University of Luxembourg.

Akinade, O.O., Oyedele, L.O., Omoteso, K., Ajayi, S.O., Bilal, M., Owolabi, H.A., Alaka, H.A., Ayris, L., Henry Looney, J. (2017). BIM-based deconstruction tool: towards essential functionalities. Int. J. Sustain. Built Env. 6, 260–271. https://doi.org/10.1016/j.ijsbe.2017.01.002.

Andeweg, M., Brunoro, S., & Verhoef, L. (2007). Cost C16- Improving the quality of existing urban building envelopes: State of the art. IOS Press.

Andrade, B., S. (2019). Methodology for improving the net environmental impacts of new buildings through product recovery management. University of Waterloo, Canada.

Annex50, IEA. (2012) Project Summary Report. In: Zimmermann, M. (ed.). United Kingdom: AECOM Ltd

Appleby, P. (2013). Sustainable Retrofit and Facilities Management. London, England.

Archipro Team. (2020). Cladding and sustainability: what are the best options? Archipo. https://archipro.co.nz/articles/cladding-and-roofing/cladding-and-sustainability-what-are-the-best-options-archipro

Avesani, S., Andaloro, A., Ilardi, S., Orlandi, M., Terletti, S., & Fedrizzi, R. (2020). Development of an off-site prefabricated rainscreen fac¸ade system for building energy retrofitting. Journal of Fac¸ade Design and Engineering, 8. Available from https://doi.org/10.7480/jfde.2020.2.4830, in press.

Ayman, R, Alwan, Z and McIntyre, L. (2020). BIM for sustainable project delivery: review paper and future development areas Architectural Science Review Taylor & Francis 63(1) pp 15–33

BAMB2020 (2017). Framework for materials passports. EPEA Nederland BV. http://www.bamb2020.eu/blog/2018/01/02/framework-report/

Bandaru, S.H., Becerra, V., Khanna, S., Radulovic, J., Hutchinson, D., Khusainov, R. (2021). A Review of Photovoltaic Thermal (PVT) Technology for Residential Applications: Performance Indicators, Progress, and Opportunities. Energies, 14, 3853. https://doi.org/10.3390/en14133853

Barabash, A., Naumova, E., Zhuvak, O., Nemova, D., Olshevskiy, V. (2016). The Efficiency of the Ventilated Gap of the Double-Skin Facade Systems Using Fire Crosscuts. MATEC Web of Conferences 73,02006 TPACEE-2016

Beccali, M., Cellura, M., Fontana, M., Longo, S., & Mistretta, M. (2013). Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits. Renewable & Sustainable Energy Reviews, 27, 283-293. doi:10.1016/j.rser.2013.05.040

Benachio, G.L.F., Freitas, M., Do, C.D., Tavares, S.F. (2020). Circular economy in the construction industry: a systematic literature review. Journal of Cleaner Production 260

Bertelsen, S. (2004). “Lean Construction: Where are we and how to proceed.” Lean Construction Journal, 1(1), 46–69

Bikas, D., Tsikaloudaki, K., Kontoleon, K., J., Giarma, C., Tsoka, S., Tsirigoti, D. (2017). Ventilated Facades: Requirements and Specifications Across Europe. Aristotle University of Thessaloniki, Greece. Procedia Environmental Sciences. Volume 38, Pages 148-154.

Bjönfot, A., Stehn, L. (2005). Industrialization of construction-A lean modular approach. Luleå University of Technology

BPIE, Europe Buildings Performance Institute. (2011). Europe's buildings under the microscope, A country-by country review of the energy performance of building.

Braungart, M., McDonough, W. (2002). Cradle to Cradle: Remaking the Way We Make Things

Buker, S. M., Riffat, S. B. (2015). Building integrated solar thermal collectors – A review. Renewable and Sustainable Energy Reviews. Institute of Sustainable Energy Technology, University of Nottingham, Nottingham NG7 2RD, UK.

Camel solar. Camel solar catalog brochure. http://www.camel-solar.com/cs/wp-content/uploads/2021/01/Catalog-Camel-Solar-brochure.pdf

Capeluto, G. (2019). Adaptability in envelope energy retrofits through addition of intelligence features. Architectural Science Review, 62(3), 216229. Available from https:// doi.org/10.1080/00038628.2019.1574707.

Cavalliere, C., Dell'Osso, G.R., Favia, F., Lovicario, M. (2019). BIM-based assessment metrics for the functional flexibility of building designs. Automation in ConStruction 107, 102925. https://doi.org/10.1016/j.autcon.2019.102925.

Çetin, S., De Wolf, C., Bocken, N. (2021). Circular Digital Built Environment: An Emerging Framework. Sustainability, 13, 6348. https://doi.org/10.3390/ su13116348

Charef, R., Emmitt, S. (2021). Uses of building information modelling for overcoming barriers to a circular economy. J. Cleaner Production 285, 124854 https://doi.org/ 10.1016/j.jclepro.2020.124854

Conejos, S., Langston, C., Smith, J. (2014). Designing for better building adaptability: A comparison of adaptSTAR and ARP models. Habitat International, 41, 85–91.

D'Oca, S., Ferrante, A., Ferrer, C., Pernetti, R., Gralka, A., Rizal, S., Veld, P. (2018). Technical, Financial, and Social Barriers and Challenges in Deep Building Renovation: Integration of Lessons Learned from the H2020 Cluster Projects.

De Groote, M., Lefever, M. (2016). Driving transformational change in the construction value chain. Buildings Performance Institute Europe (BPIE)

Dokter, G. (2021). Circular design in practice: Towards a co-created circular economy through design. Technical report. Lic /Architecture and Civil Engineering / Chalmers University of Technology. Sweden.

Du, H., Huang, P., Jones, P. (2019). Modular facade retrofit with renewable energy technologies: The definition and current status in Europe. Energy & Buildings 205. https://doi.org/10.1016/j.enbuild.2019.109543.

Durmisevic, E. (2010). Green design and assembly of buildings and systems: Design for Disassembly a key to Life Cycle Design of buildings and building products. Saarbrücken, Germany.

Ekholm, A., Haggstrom, L. (2011). Building classification for BIM- Reconsidering the framework. In CIB W78-W102 2011: International Conference. CIB.

Ellen Macarthur Foundation. (2013). Towards the Circular Economy. Ellen MacArthur Foundation, Cowes, Isle of Wight, UK.

Ellen Macarthur Foundation. (2017). Cities in the Circular Economy: An Initial Exploration; Ellen Macarthur Foundation: Cowes, UK.

Elval colour (2016). BRAVO Ventilated façade system. Installation guide. https://www.vinkkunststoffen.nl/media/import/nl101_etalbond_FR_montagehandleiding_cassettes_pdf_001.pdf

Eray, E., Sanchez, B., Haas, C. (2019). Usage of Interface Management System in Adaptive Reuse of Buildings. Buildings. Department of Civil and Environmental Engineering, University of Waterloo, Canada.

Gallego-Schmid, A., Chen, H., M., Sharmina, M., Mendoza, J., M. (2019). Links between circular economy and climate change mitigation in the built environment. Journal of Cleaner Production.

Gasparri, E., Aitchison, M. (2019). Unitised timber envelopes. A novel approach to the design of prefabricated mass timber envelopes for multi-storey buildings. The University of Sydney, Australia. Journal of Building Engineering 26 100898.

Geldermans, R.J. (2016). Design for change and circularity – accommodating circular material & product flows in construction. Energy Procedia 96.

Geraedts, R. P., Remøy, H. T., Hermans, M. H., & Van Rijn, E. (2014). Adaptive capacity of buildings: A determination method to promote fexible and sustainable construction. Architecture otherwhere, 25, 3-7.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114, 11–32. doi.org/10.1016/j.jclepro.2015.09.007

Gibb, G., F. (2001). Standardization and Pre-assembly; Distinguishing myth from reality.

Goyal, L. K., Rai, H. S. (2020). BIM Approach for Sustainable Design of Flat Slab Buildings: A Review. IOP Conf. Ser.: Mater. Sci. Eng. 955 012012

Groh, J., Dubik, P. (2018). BIM as a tool to implement circular economy into construction projects' life-cycle. Aalborg University, The Faculty of Engineering and Science, Denmark.

Gruber, T.R. (1995). Towards principles for the design of ontologies used for knowledge sharing? International journal of human-computer studies, 43, pp.907-928.

Guldager Jensen, K. & Sommer, J. (2018). Building a Circular Future. Danish Environmental Protection Agency.

Guy, B.; Ciarimboli, N. (2005). DfD: Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building; Hamer Center for Community Design: State College, PA, USA.

Haase, M., Lolli, N., Thunshelle, K. (2020). RENOVATION CONCEPTS FOR RESIDENTIAL BUILDINGS Research status, challenges and opportunities. ZEN REPORT No. 19 ZEN Research Centre. Norwegian University of Science and Technology (NTNU) | www.ntnu.no

Habibi, S. (2017). The promise of BIM for improving building performance. Energy Build. 153, 525–548.

Häkkinen, T. (2012). Systematic method for the sustainability analysis of refurbishment concepts of exterior walls. Constr. Build. Mater. 37, 783–790. doi:10.1016/j.conbuildmat.2012.07.084.

Heinlein, F.; Sobek, W. (2019). Recyclable by Werner Sobek; Avedition Gmbh: Stuttgart, Germany.

Henry, Q. (2018). Circular Façade Refurbishment. Delft University of Technology, Faculty of Architecture, MSc Building Technology, Sustainable Design Graduation Studio.

Herzog, T. (2004). Façade construction manual. Faculty of Architecture. Munich Technical University.

Hillebrandt, A., Riegler-Floors, P., & Rosen, A. (2019). Manual of recycling : buildings as sources of materials.

Holzer, D. (2015). The BIM Manager's Handbook, *Part 1* (1st ed.). Wiley. Retrieved from https://www.perlego.com/book/993732/the-bim-managers-handbook-part-1-pdf

Honic, M., Kovacic, I., Aschenbrenner, P., Ragossnig, A. (2021). Material Passports for the end-of-life stage of buildings: Challenges and potentialS. Journal of Cleaner Production, Volume 319, 128702. https://doi.org/10.1016/j.jclepro.2021.128702.

Jawahir, I.S., Bradley, R. (2016). Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing. Procedia CIRP, 40, 103–108.

Jin, R et al. 2016 BIM-based Multidisciplinary Building Design Practice-A Case Study

Jones, C., Brischke, J. (2017). Circularity and Biobased Materials in Architecture and Design Evaluation of the Status Quo and Defining Future Perspectives. https://www.researchgate.net/publication/350849201

Jorge,N., Rilova, G., Bergado, H. (2021). ENvelope meSh aNd digitAl framework for building Renovation. ENSNARE. Grant Agreement n° 958445. https://www.ensnare.eu/

Kalz, D., E., Pfafferott. J. (2014). Thermal Comfort and Energy-Efficient Cooling of Nonresidential Buildings. Springer.

Kibert, C.J. (2007). Deconstruction: The start of a sustainable materials strategy for the built environment. Ind. Environment. 26, 84–88.

Kibert, C.J. (2007). The next generation of sustainable construction. Building Research & Information, 35, 595–601.

Kim, J. B., Jeong, W., Clayton, M. J., Haberl, J. S., Yan, W. (2015). Developing a physical BIM library for building thermal energy simulation. Automation in Construction 50, 16-28. Texas A&M University, United States.

Knaack, U., Klein, T., Bilow, M., Auer, T. (2007). Façades: Principles of Construction. Birkhäuser Verlag AG.

Konstantinou, T. (2014). Façade Refurbishment Toolbox. PhD research, University of Technology Delft, the Netherlands. https://repository.tudelft.nl/islandora/object/uuid:874ee906-6afa-4d5d-9af7- 22b825976325/datastream/OBJ

Konstantinou, T., Guerra-Santin, O., Azcarate-Aguerre, J., Klein, T., & Silvester, S. (2017). A zero-energy refurbishment solution for residential apartment buildings by applying an integrated, prefabricated fac¸ade module. PowerSkin, Munich.

Konstantinou, T., Heesbeen, C. (2022). 10 - Industrialized renovation of the building envelope: realizing the potential to decarbonize the European building stock. In E. Gasparri, A. Brambilla, G. Lobaccaro, F. Goia, A. Andaloro, & A. Sangiorgio (Eds.), *Rethinking Building Skins* (pp. 257-283). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-12-822477-9.00008-5

Konstantinou, T., Klein, T., Guerra-Santin, O., Boess, S., & Silvester, S. (2015). An integrated design process for a zero-energy refurbishment prototype for post-war residential buildings in the Netherlands. Paper presented at Smart and Sustainable Built Environments, Pretoria, South Africa.

Larsson, J., Eriksson, P. E., Olofsson, T., and Simonsson, P. (2014). "Industrialized construction in the Swedish infrastructure sector: core elements and barriers." Construction Management and Economics, Routledge, 32(1–2), 83–96.

Li, N., Li, Q., Liu, Y., Lu, W., Wang, W. (2020). BIMSeek++: Retrieving BIM components using similarity measurement of attributes. Computers in Industry 116. https://doi.org/10.1016/j.compind.2020.103186

Ma, Z., Cooper, P., Daly, D., Ledo, L. (2012). Existing building retrofits: Methodology and state-of-theart, Energy Build. 55, 889–902. doi:10.1016/j.enbuild.2012.08.018.

Malabi Eberhardt, L.C.; van Stijn, A.; Kristensen Stranddorf, L.; Birkved, M.; Birgisdottir, H. (2021). Environmental Design Guidelines for Circular Building Components: The Case of the Circular Building Structure. Sustainability 2021, 13, 5621. https://doi.org/10.3390/su13105621

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Nygaard, F. (2018). Energy & Buildings Design and construction strategies for reducing embodied impacts from buildings – Case study analysis. Energy Build.

McPartland, R. (2017). What are BIM objects. NBS.https://www.thenbs.com/knowledge/what-are-bim-objects

Meyer, C.L. (2018). Optimizing the use of critical materials in the built environment using Building Information Modelling (BIM). DELFT UNIVERSITY OF TECHNOLOGY.

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

MORE-CONNECT. (2019). D5.9 Analyses of the total renovation processes in the pilots https://www.more-connect.eu/wp-content/uploads/2019/07/MORE-CONNECT_WP5_ D5.9-Analyses-of-the-total-renovation-processes.pdf.

Mule, J.Y. (2012). Design for Disassembly Approaches on Product Development. Int. J. Sci. Eng., 3, 996–1000

Nady, R. (2021). When Beauty and Efficiency Meet: Modular Architecture. Retrieved 5 March 2021, from https://www.arch2o.com/language-modular-architecture/

Ochoa, C., E., Capeluto, I., G. (2015). Decision methodology for the development of an expert system applied in an adaptable energy retrofit façade system for residential buildings. Renewable energy 78. Climate and Energy Laboratory in Architecture, Faculty of Architecture and Town Planning, Technion e Israel Institute of Technology, Israel.

OnFly. How to create a BIM library in 10 steps, User Feedback.

Paiho, S., Seppa, I. P., & Jimenez, C. (2015). An energetic analysis of a multifunctional fac¸ade system for energy efficient retrofitting of residential buildings in cold climates of Finland and Russia [Article]. Sustainable Cities and Society, 15, 7585. Available from https://doi.org/10.1016/j.scs.2014.12.005.

Pasquire, C., Gibb, A. (2002). Considerations for assessing the benefits of standardization and preassembly in construction. Journal of Financial Management of Property and Construction, 73, 151-161.

Pereira, V., Santos, J., Leite, F., Escórcio P. (2021). Using BIM to improve building energy efficiency – A scient metric and systematic review. Energy & buildings 250, 111292. https://doi.org/10.1016/j.enbuild.2021.111292

Pheifer, A. G. (2017). Barriers and Enablers to Circular Business Models. https://www.circulairondernemen.nl/uploads/4f4995c266e00bee8fdb8fb34fbc5c15.pdf

Pinto, S., Castro, T., Brito, N., Gomes, T., Tavares, A., Mendes, J., Cabral, J. (2013). ClimaWin: An Intelligent Window for Optimal Ventilation and Minimum Thermal Loss. Centro Algoritmi - University of Minho. DOI:10.1109/ISIE.2013.6563790

Pomponi, F., Moncaster, A. (2017). Circular economy for the built environment: A research framework. Journal of Cleaner Production, 143, 710–718.

Popa, H, Batali, L and Berdigylyjow, M. (2019). The role of BIM in geotechnical engineering with application to deep excavations in urban areas in Proceedings of the XVII ECSMGE-2019

Potting, J., Hekkert, M., Worrell, E. (2021). Circular Economy: Measuring Innovation in the Product Chain. Policy Report. PBL Netherlands Environmental Assessment Agency. http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2016-circular-economy-measuring-innovation-in-product chains-2544.pdf

Pracucci, A., Vandi, L., Magnani, S., Baietta, A., Casadei, O., Uriarte, A., Vavallo, M. (2021). Prefabricated Plug-and-Play Unitized Façade System for Deep Retrofitting: The RenoZEB Case Study. Environ. Sci. Proc., 11, 9. https://doi.org/10.3390/environsciproc2021011009

Rahla, K.M., Bragança, L., Mateus, R. (2021). Implementing Circular Economy Strategies in Buildings—From Theory to Practice. Applied System Innovation. https://doi.org/10.3390/asi4020026

Rashid, A.F., Yusoff, S. (2015). A review of life cycle assessment method for building industry. Renewable and Sustainable Energy Reviews, 45, 244–248.

Ricci, F., Rokach, L., & Shapira, B. (2015) Recommender systems: introduction and challenges. In: Recommender systems handbook, pp. 1-34, Springer, Boston, MA.

Rovers, R. (2018). A GUIDE INTO RENOVATION PACKAGE CONCEPTS FOR MASS RETROFIT OF DIFFERENT TYPES OF BUILDINGS WITH PREFABRICATED ELEMENTS FOR (N)ZEB PERFORMANCE. More connect.

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018) BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers, John Wiley & Sons.

Sadafi, N., Zain, M., F., Jamil, M. (2012). Assessment of industrial and adaptable building components for a residential layout. International Journal of the Physical Sciences Vol. 7(2), pp. 338 – 348.

Sam, I., D., Hui, C., M. (2019). New Opportunities of Using Building Information Modelling (BIM) for Green Buildings. 15th Asia Pacific Conference on the Built Environment 5R Technology for Building Environment. Faculty of Science and Technology, Technological and Higher Education Institute of Hong Kong. Hong Kong

Sijpheer, N. C., Borsboom, W. A., & Opstelten, I. J. (2016). Results from first "NetZero Energy" projects in the Netherlands. Paper presented at the Sustainable Built Environment 2016: Transition Zero − SBE16, Utrecht.

Simhachalam, V., Wang, T., Liu, Y., Wamelink, H., Montenegro, L., van Gorp, G. (2021). Accelerating Building Energy Retrofitting with BIM-Enabled BREEAM-NL Assessment. Energies 14, 8225. https://doi.org/ 10.3390/en14248225

Smith, R. (2010). Prefab Architecture: A Guide to Modular Design and Construction. John Wiley & Sons: Hoboken, NJ, USA.

Theodosiou, T. G., Tsikaloudaki, A. G., Kontoleon, K. J., Bikas, D. K. (2015). Thermal bridging analysis on cladding systems for building facades. Department of Civil Engineering, Aristotle University of Thessaloniki, Greece. Energy and Buildings 109 (2015) 377–384.

Torres, J., Garay-Martinez, R., Oregi, X., Torrens-Galdiz, J.I., Uriarte-Arrien, A., Pracucci, A., Casadei, O., Magnani, S., Arroyo, N., Cea, A.M. (2021). Plug and Play Modular Façade Construction System for Renovation for Residential Buildings. Buildings, 11, 419. https://doi.org/10.3390/buildings11090419

Trespa. (2021). TRESPA. SUSTAINABILITY POSITION PAPER. Version 8.0, BROCHURE CODE I2501.

Ulrich, K. (1993). The role of product architecture in the manufacturing firm. Elsevier, 419-440.

UN Environment and International Energy Agency. (2017). Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector; Global Alliance for Buildings and Construction (GABC): Paris, France, 2017 van Stijn, A., Gruis, V. (2019). Towards a circular built environment. An integral design tool for circular building components. Department of Management in the Built Environment, Delft University of Technology, Delft, The Netherlands and Amsterdam Institute for Advanced Metropolitan Solutions (AMS), Amsterdam, The Netherlands.

Vovos, I. (2021). Energy Reduction Façade Renovation System for different building typologies and climates. MSc Thesis. Delft University of Technology, The Netherlands.

Weygant, R. S. (2011). BIM Content Development: Standards, Strategies and Best Practices.

Wong, K.D.; Fan, Q. Building information modelling (BIM) for sustainable building design. Facilities 2013, 31, 138–157.

Xue, K., Hossain, M.U., Liu, M., Ma, M., Zhang, Y., Hu, M., Chen, X., Cao, G. (2021). BIM Integrated LCA for Promoting Circular Economy towards Sustainable Construction: An Analytical Review. Sustainability 13, 1310.

Yasin, B., Rjoub, A. (2017). Standardization in Construction as a tool to reduce cost of housing for the low-income families in Jordan.

Zeb, A., & Kortelainen, J. (2021). Circular design, state of the art review: Technical design point of view. VTT Technical Research Centre of Finland. VTT Research Report No. VTT-R-01229-20

Appendix

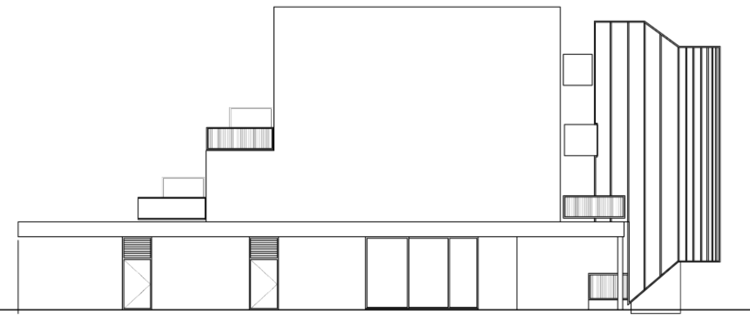
A. Case study drawings

Facades

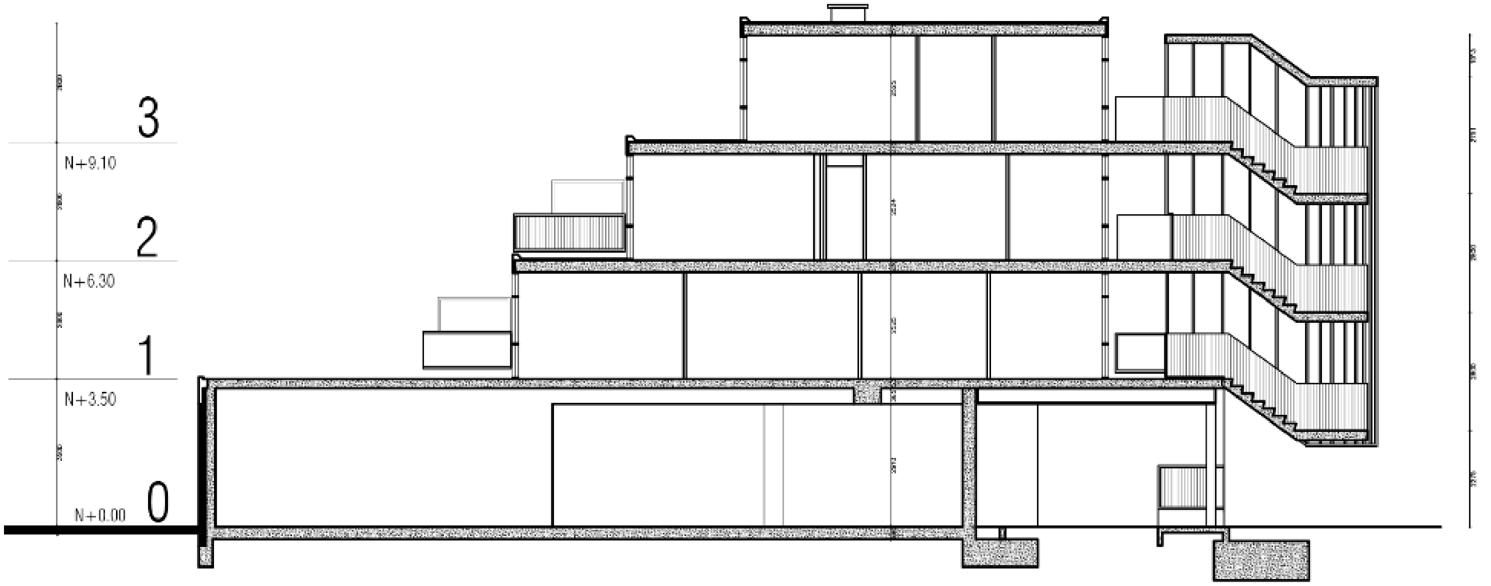
West Facade

East Facade

North Façade

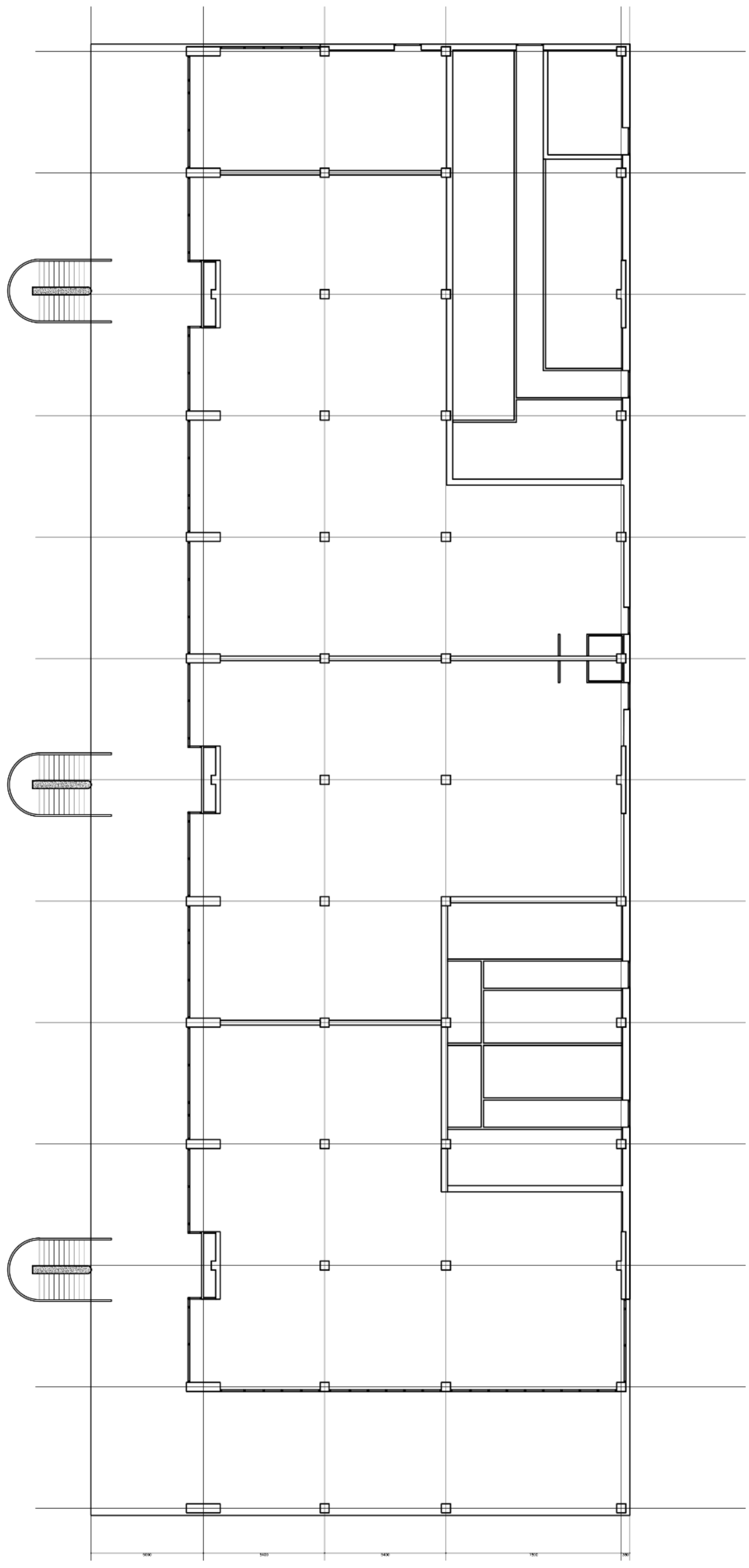


South Facade

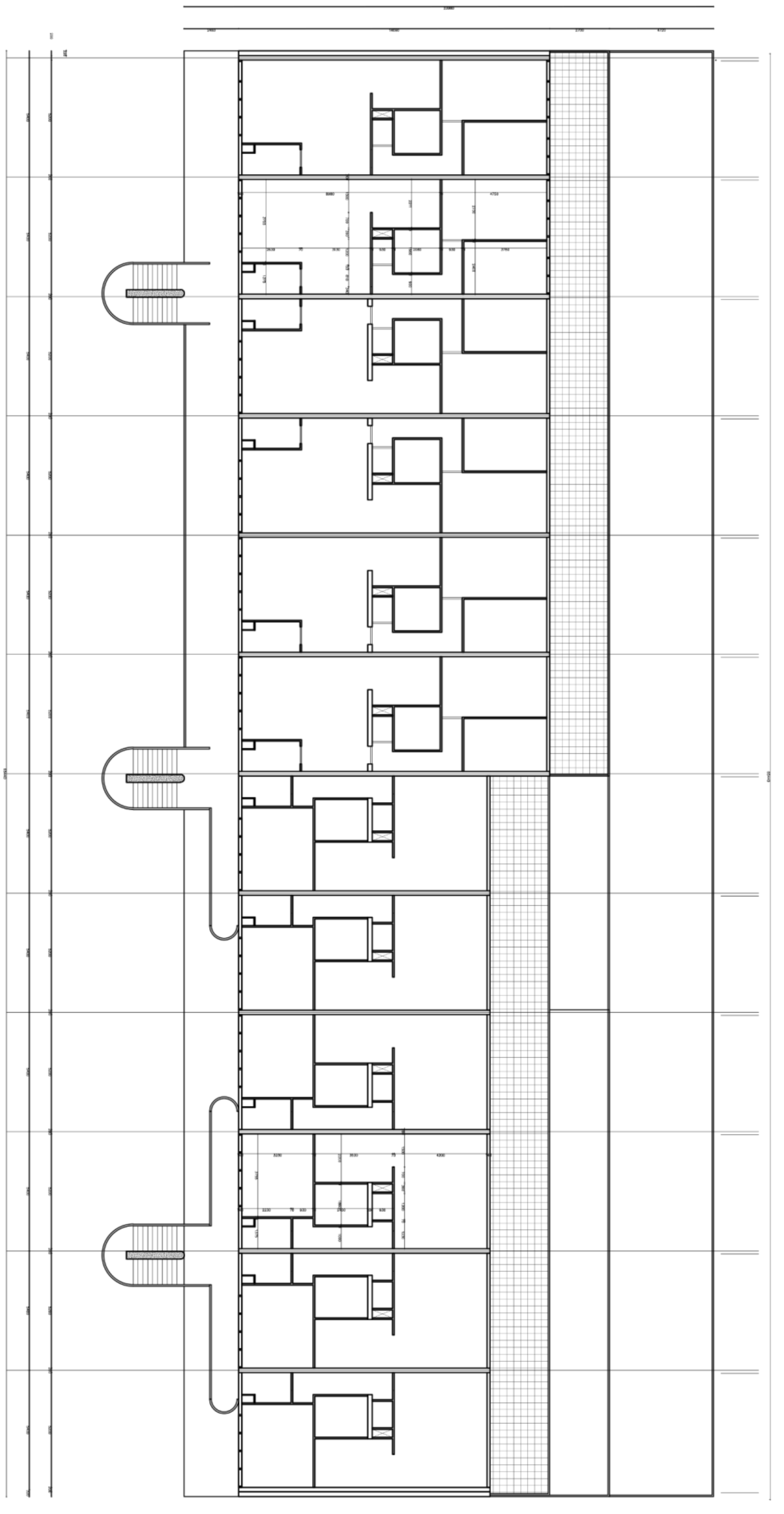


Section

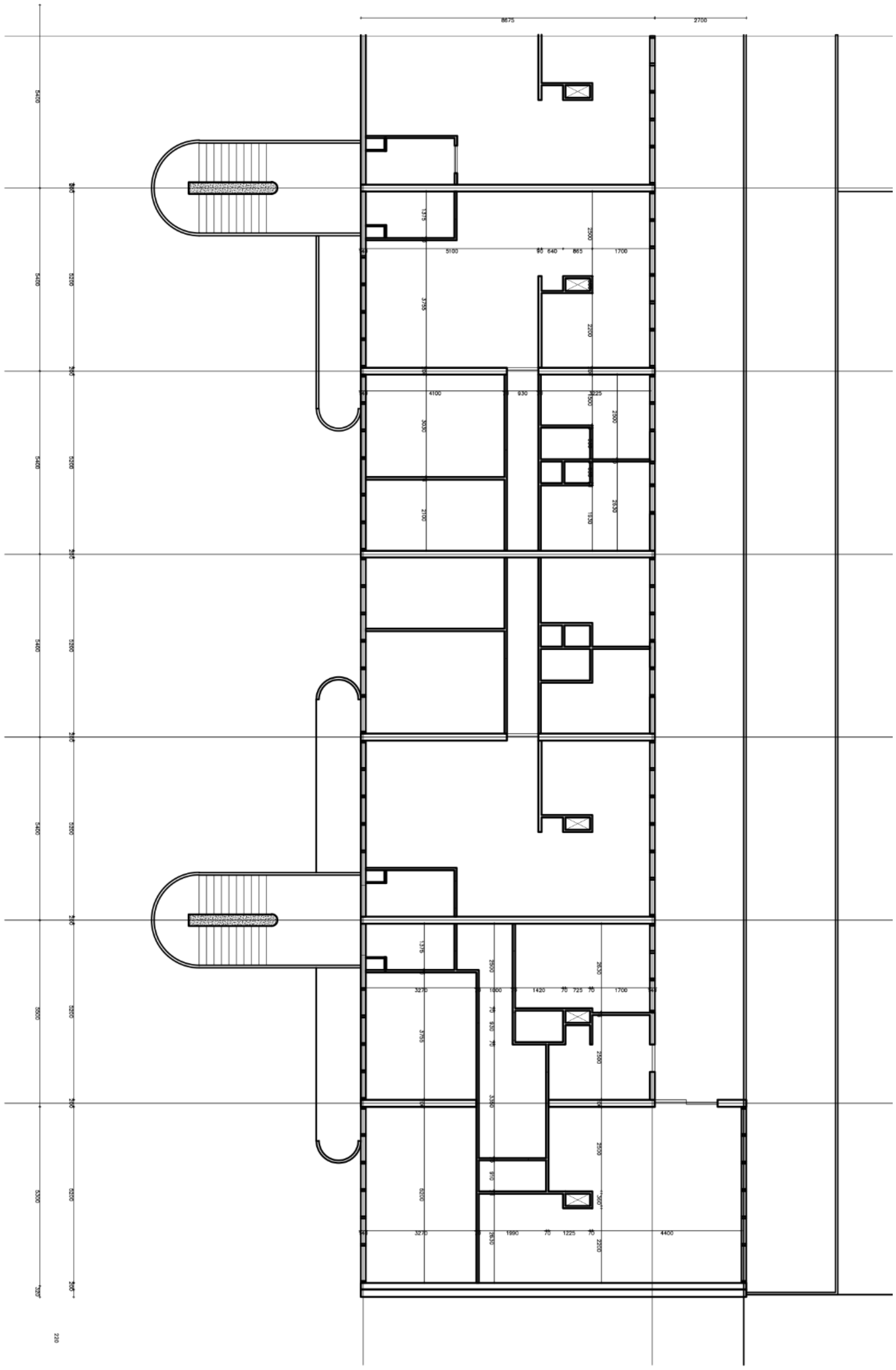
Plans



Ground Floor Plan



1st and 2nd Floor Plan



3rd Floor Plan

B. BIM library

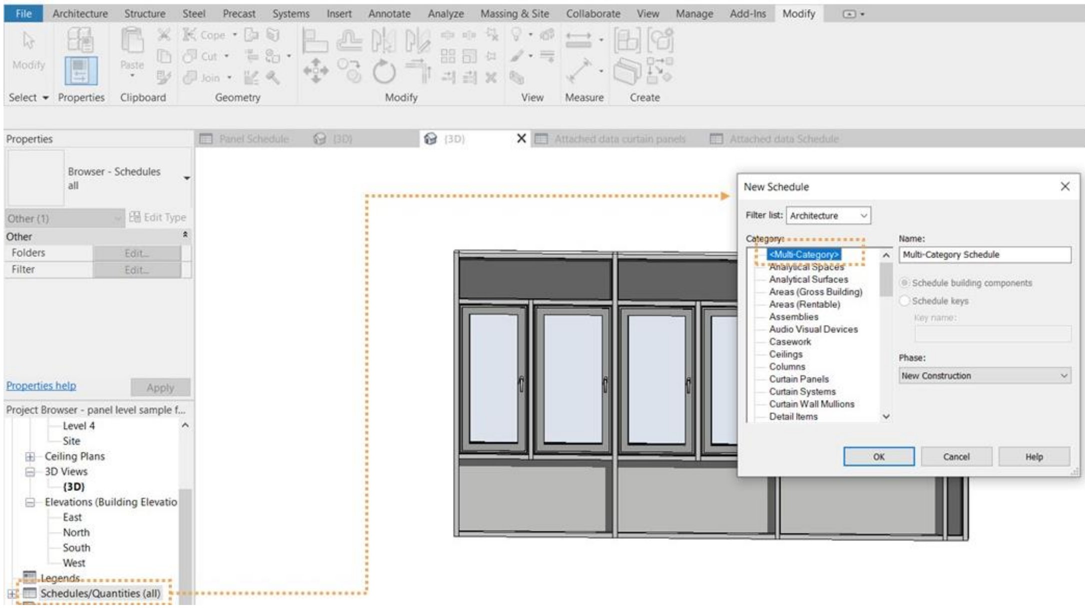


Figure 55: New schedule creation

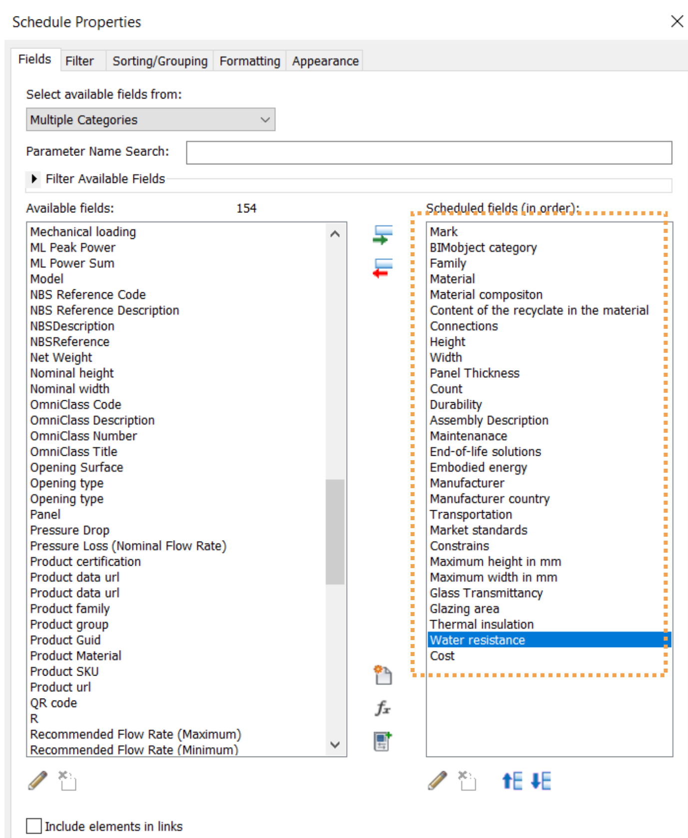


Figure 56: Evaluation indicators added to the families.

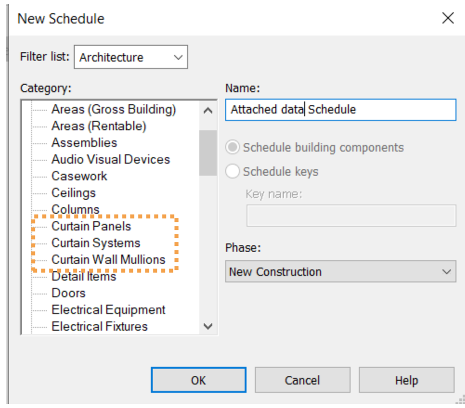


Figure 57: Different categories of schedule that should be added

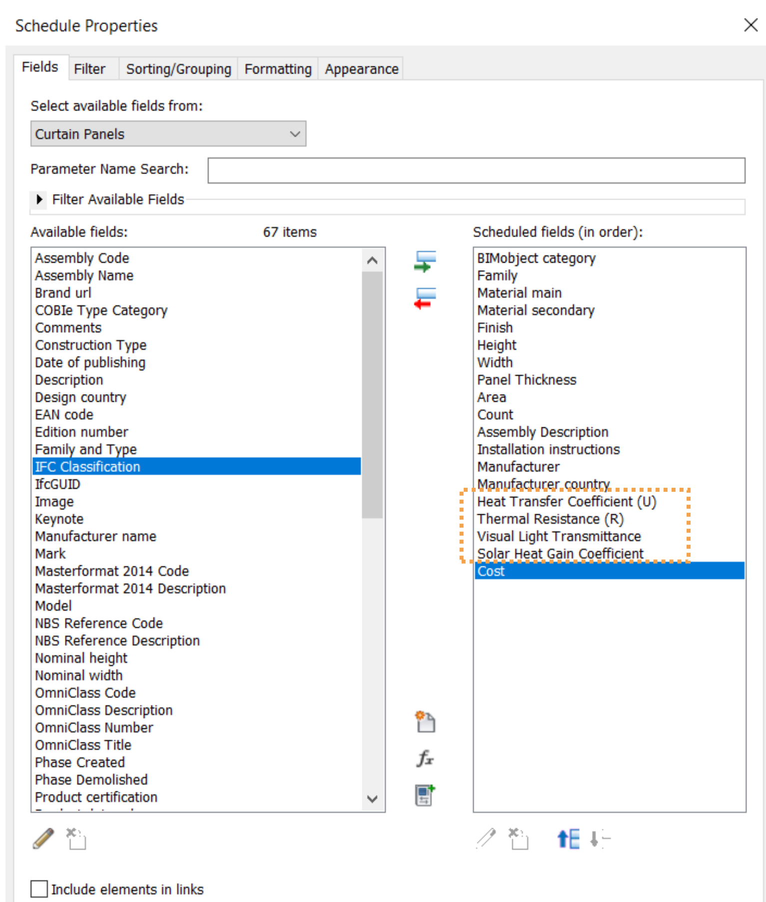


Figure 58: Example of the extra available indicators in each schedule category

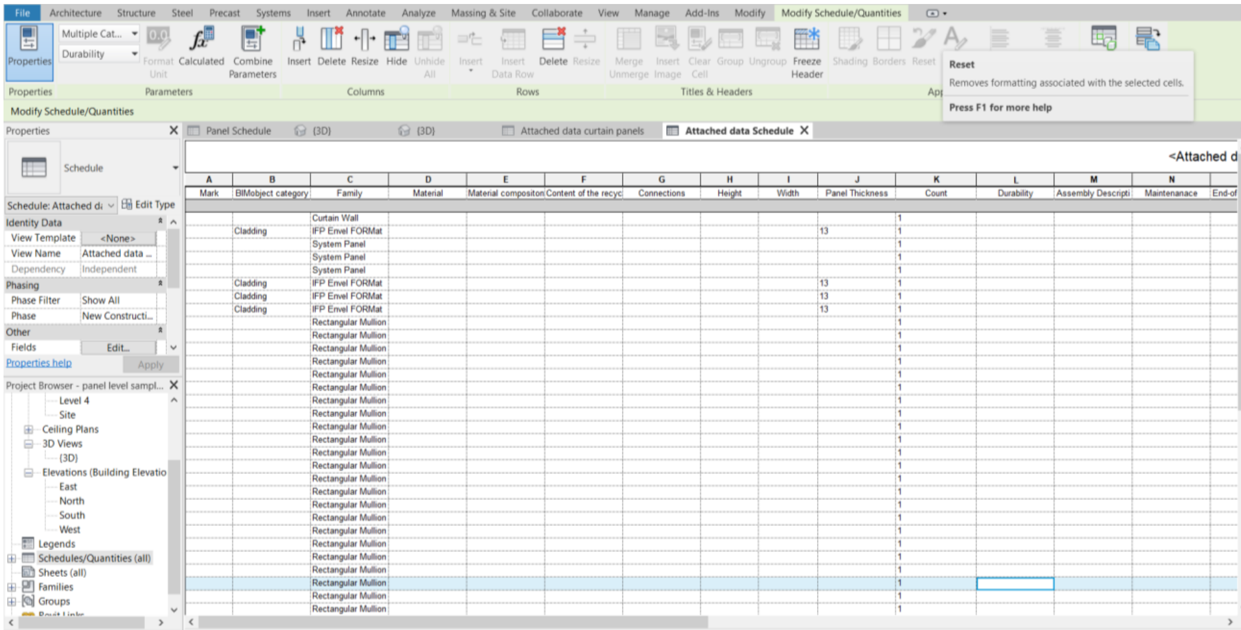


Figure 59: Lack of information to fulfill the evaluation indicators

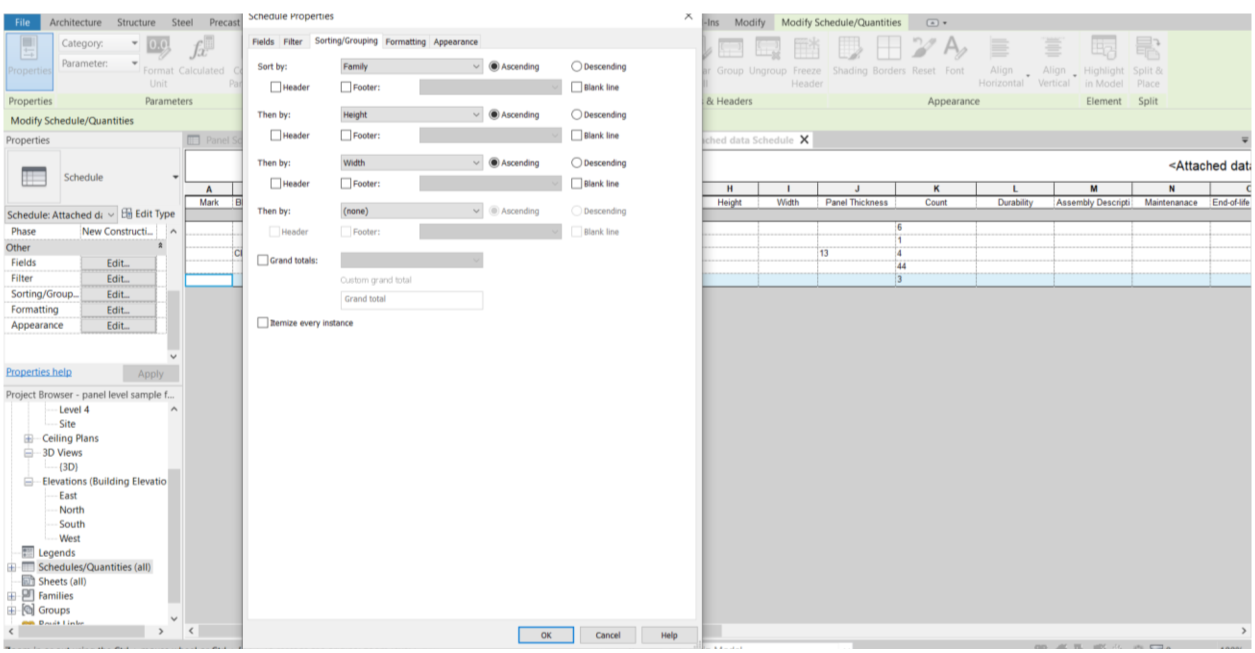


Figure 60: Grouping and filtering potential of the schedule table

C. Application

Case study building facades after the panelized façade units' application

Figure 61: East and West façade with the Type4.c. panels configuration.

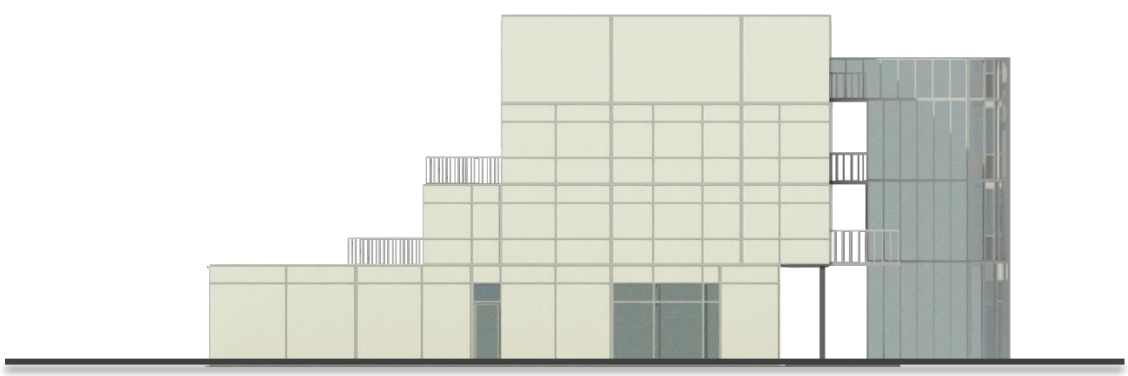


Figure 62: North façade with the Type1.b. panels configuration.

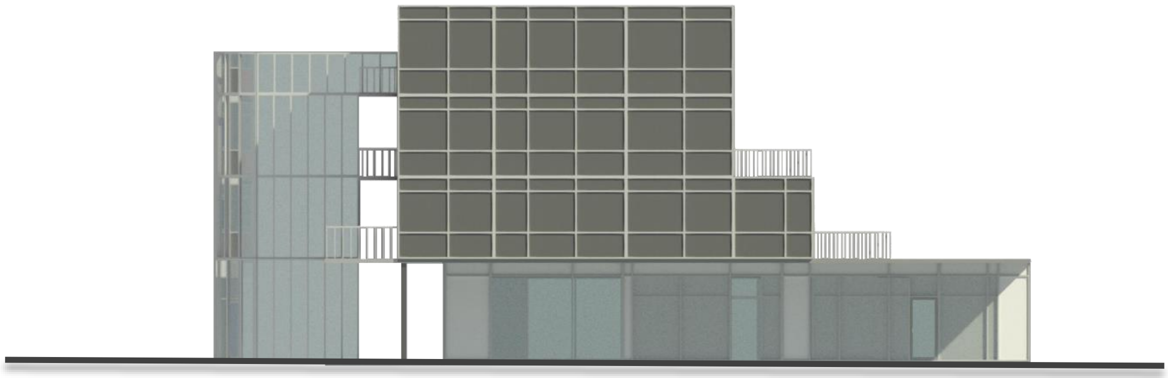
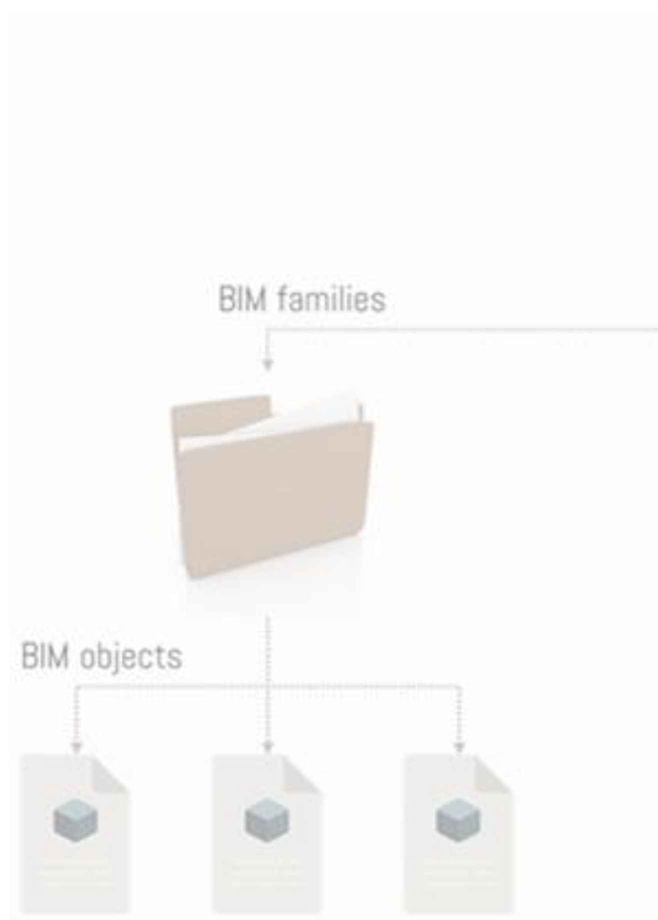


Figure 63: South façade with the Type1.a. panels configuration.


BIM families
BIM objects